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Adaptive Wind Turbine Management System to Prevent Bird Deaths

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Abstract –The goal of this study is to preserve the ecological balance by reducing bird mortality caused by wind turbines. To accomplish this goal, a system has been designed that will colour the turbine blades with distinct coloured paints, identify when bird flocks approach the turbines, and dynamically limit turbine speed. Bird movements are tracked using high-resolution cameras and distance sensors, and the proximity of bird flocks to turbines is determined using an artificial intelligence system. The combined usage of the visual improvement and detection technology results in a significant reduction in bird collisions. According to field experiments, the system performs better in clear weather conditions than in foggy weather. The findings show that the proposed system is an innovative method to improve environmental sustainability in wind energy generation.

Keywords – Wind turbines, Bird deaths, Detection system, Artificial intelligence, Image processing

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I. INTRODUCTION

Wind power generation is one of the technologies for electricity production. It is well-known that the wind energy sector relies on the deployment of larger and more adaptable offshore wind turbines to capitalise on stronger and more consistent wind conditions. The operational and maintenance expenses of offshore wind turbines constitute between 15-35% of the overall cost [1]. Of this, 80% is allocated to unanticipated maintenance problems arising from various malfunctions in the wind turbine components [1]

A wind turbine's crucial component is the blade. Damaged or defected wind turbine blades may result in significant repercussions. Conventional techniques for detecting defects in the blades of wind turbines mostly include manual inspection and acoustic non-destructive testing, both of which are dangerous, time-intensive, and exhibit low precision. Therefore, in [2] a defect detection approach for wind turbine blades utilising image processing techniques was investigated to enhance safety, convenience, and accuracy in identifying problems. The method proposed by them successfully extracted and detected crack-type, scratch-type, spot-type and sand-hole-type defects, with an identification rate over 92%.

In [1], a novel approach was proposed for the detection and classification of problems in sensors and actuators of variable-speed wind turbines. Time domain signals obtained from the functioning wind turbine were represented as two-dimensional matrices to generate grayscale digital images. Recognising visual patterns was executed by extracting texture features inside a multichannel framework. The study employed four categories of texture characteristics: granulometric, wavelet, statistical, and Gabor features. The most significant ones were subsequently identified using the conditional mutual criterion. Ultimately, the errors were identified and categorised using an

automated classification technique. A 10-fold cross-validation was employed to derive a more generalised model and assess the performance of the classification. Coupled non-linear aero-hydro-servo-elastic simulations of a 5 Megawatts offshore wind turbine were conducted under several fault situations. The findings indicated a potential methodology capable of detecting and classifying the most prevalent wind turbine defects [1].

The mitigation of anthropogenic climate change necessitates the global deployment of renewable energy sources, such as wind farms, which present a notable collision risk to flying animals. Wind energy minimises carbon footprint by lowering fossil fuel consumption and is becoming more popular worldwide as a sustainable and ecologically friendly energy source. However, the consequences of wind turbines on natural life, particularly a rise in bird deaths, raise serious concerns about the environmental sustainability of this energy source. High-speed rotating turbine blades are a deadly threat to birds, particularly during migration [3]. This varies based on the turbine site, environmental conditions, and local bird species, and many researchers have focused on its negative influence on bird populations [4].

Among the many solutions recommended in recent years, painting turbine blades in different colours to make them more visible to birds is an important one. For example, it was found that painting one of the turbine blades black reduced bird mortality by 70% [5]. This finding implies that turbines can be made more apparent to birds through visual marking, lowering the chance of collision. However, more research is needed on the impact of visual layouts on various species, and this strategy has had limited success in some areas.

Camera and artificial intelligence-based surveillance systems have been developed to keep birds from approaching

turbines [6]. These technologies detect flocks of birds approaching the turbine and may dynamically alter the turbine speed. Radar-based systems, such as "Merlin," enable turbine operational modifications by monitoring bird movements in wind farms in real time [6]. However, successful adoption of these systems is dependent on high resolution data processing capability and a reduction in false alarm rates. As a result, enhancing the accuracy of detection systems and maintaining their resilience to environmental conditions is another significant challenge to address.

Although current research indicates that visual enhancement and monitoring technologies can help reduce bird mortality from wind turbines, an integrated solution must be created. This study's goal is to create a technological design that reduces bird mortality, allowing wind turbines to operate without disrupting the natural balance. This way, the risk of bird collisions will be reduced by boosting the visibility of wind turbine blades and minimising the possibility of collisions by identifying bird flocks using a camera-supported detection system and automatically reducing turbine speed. The rest of this paper is as follows. The following section presents a focused related work. The third section presents the methodology of this study. Findings and discussion of this study are reported in Section 4. Section 5 presents suggestions and open research issues. Finally, this paper is concluded in Section 6.

II. RELATED WORK

With the increasing need for renewable energy, the development of wind power is expanding fast on a global scale. Subsequent to these changes, disputes emerge around land use alterations that transform untouched nature into industrial power plants, leading to detrimental impacts on biodiversity, epitomised by a prominent and lethal outcome: avian collisions. Most post-construction studies indicate minimal avian mortality; however, the majority of these investigations focus predominantly on bigger bird species. Nevertheless, the diversity and prevalence of small passerine birds are seldom represented in corpse surveys, despite their expected numerical dominance relative to their abundance [7]. Therefore, in [7] a research utilising dummy birds was carried out to assess the mortality rates of small-bodied passerines and other diminutive avian species during post-construction surveys, conducted at a medium-sized wind farm in western Norway. The wind farm was inspected weekly during migration seasons by carcass survey teams utilising trained dogs to locate deceased birds. The dogs in the corpse surveys had greater success in detecting the larger fake birds compared to the smaller ones (60-200 g), successfully finding 74% of the large dummy birds [7]. Identifying the smaller group (5-24 g) proved to be more challenging, with the dogs locating just 17% of the little dummy birds [7]. Adjusting the post-construction carcass survey results with experimental findings results in an almost fourfold rise in estimated death rates, primarily attributable to the low detection rate of the smallest group [7].

Wind energy provides significant environmental advantages; however, wind facilities may adversely affect wildlife, particularly birds and bats. Estimates of mortality rates for birds and bats resulting from wind turbines are essential due to the rapid global expansion of wind power generation [8]. While significant efforts have been made by researchers and managers to document bird and bat mortality

linked to wind facilities, there is a need to investigate the spatial patterns and underlying mechanisms of fatalities at these sites [9]. Therefore, in [9] the distance and taxonomic composition of bat and bird carcasses at wind turbines in the Northeastern United States was examined, utilising publicly available data as well as data sent to the US Fish and Wildlife Service. Forty-four wind facilities documented 2,039 avian fatalities across 128 species, while 22 facilities recorded 418 bat fatalities among five species [9]. Short-distance migrants were observed at greater distances from turbines compared to long-distance migratory birds [9]. The body mass of birds and bats has an effect on fall distance. The size of turbines had an effect on the fall distance of both birds and bats when considered together, and specifically on birds when analysed independently from bats. This indicates that larger turbines will require an expanded search radius for carcass detection [9]. The findings suggest a re-evaluation of turbines as a collision risk to birds, emphasising their height as a significant factor rather than solely their movement [9].

Wind energy represents a viable alternative to fossil fuels; however, the effects of wind facilities on wildlife are not well understood. Previous research estimates that annual fatal bird collisions with wind turbines in the United States range from 10,000 to 573,000 [4]. However, these studies fail to distinguish between monopole and lattice tower turbines, with monopole towers now representing the majority of U.S. wind turbines, while lattice towers are predominantly being decommissioned [4]. Therefore, in [4] bird mortality for monopole turbines in the United States was estimate. Annually, between 140,000 and 328,000 birds (on average, 234,000 birds) were killed due to collisions with monopole turbines in the contiguous United States. Their findings indicate a correlation between increased turbine hub height and elevated mortality rates, as well as variations in mortality rates across different regions, with the lowest per turbine mortality observed in the Great Plains.

In [10] before-after, control-impact experiments were conducted to assess the effects of curtailment on bat and bird fatalities and nocturnal passage rates during fall migration at two wind projects. One project continued operating while the other was shut down from peak migration until the conclusion of the study (the first study). They conducted before-after, control-impact experiments over a three-year period to examine the impact of curtailment and operational factors on avian mortality associated with wind turbines of differing operational statuses (the second study). In the first study, wind turbine curtailment considerably decreased near-misses and rotor-disrupted flights of bats, as well as fatalities among bats, though it did not affect bird fatalities [10]. In the second study, the conversion of wind turbines from inoperable to operable status did not result in a significant increase in bird fatalities [10].

Most research on the collision risk between avian species and wind turbines has predominantly occurred in industrialised nations [11]. The potential effects on various locations and species remain ambiguous. Therefore, in [11] systematic literature review of documented collisions involving birds and bats with wind turbines in developed nations was performed. In [11] the relationship between collision rates and species-level traits, as well as the characteristics of turbines, was examined to assess the potential vulnerability of 888 bat and 9,538 bird species worldwide. The collision rate of avian species was influenced

by habitat associations, migratory strategy, and dispersal distance, while bat collision rates were affected by just dispersal distance [11]. Larger turbine capacity (megawatts) correlated with increased collision rates for birds and bats. However, utilising a smaller number of large wind turbines with higher energy output diminished total collision risk per unit of energy produced, despite a resurgence in bat mortality associated with the largest wind turbines [11].

As avian mortality represents a significant adverse effect of wind energy development, it is essential to implement techniques that effectively decrease avian collision rates [12]. One of the techniques employed for this purpose is turbine shutdown system. In [12] mortality changes over a 15-year period, beginning two years prior to the implementation of a selective stopping protocol (between 2006 and 2007) and extending through 13 years of its application (between 2008 and 2020) were examined. This protocol was implemented in the Cadiz region of southern Spain across 20 wind farms, encompassing a total of 269 wind turbines. The primary objective of the shutdown protocol was to prevent collisions with large soaring birds, particularly raptors [12]. A total of 354 bats and 2,903 birds were recorded as having collided with wind turbines over a 15-year period [12]. The calculated rates are 0.830 birds per turbine per year and 0.101 bats per turbine per year [12]. After the selective stopping protocol was implemented, a decrease of 61.7% in mortality among soaring birds, primarily raptors and storks, was observed [12]. A reduction of 92.8% was achieved when considering only the mortality records of Griffon Vultures [12]. The population of Griffon Vultures increased over sevenfold during the research, while the number of turbine stops because of vultures at risk in wind farms rose approximately 2.5 times (Ferrer et al., 2022). The finds in [12] indicate that the mortality rate of Griffon Vultures decreased by over 92% due to turbine shutdowns, which corresponded to an estimated loss of less than 0.51% in energy production. The significant difference between industrial costs and conservation benefits indicates that this mitigation method may be applicable with net benefits in other contexts [12].

In [13] the effects of wind turbine development and operation on avian populations in Canada were assessed, focusing on mortality from collisions and the reduction of nesting habitat. Collision mortality was estimated using data from carcass searches conducted at 43 wind farms, with adjustments made for scavenger removal, searcher efficiency, and carcasses located outside the searched area [13]. On average, 8.2 ± 1.4 birds were killed per turbine annually at these sites, with individual wind farms reporting values ranging from 0 to 26.9 birds per turbine per year [13]. In Canada, the number of installed turbines was 2955. Based on this value, each year, an estimated 23,300 birds would be killed from collisions with the turbines [13]. Data on species composition indicate that less than 0.2% of the population of any species is presently impacted by mortality or displacement due to wind turbine development [13]. Consequently, impacts at the population level are improbable, assuming that highly sensitive or rare habitats, along with concentration areas for at-risk species, are excluded from consideration [13].

With the expansion of wind energy and the consideration of larger wind-power plants, it is anticipated that bird fatalities because of collisions with moving turbine rotor blades will rise [5]. Nevertheless, limited cost-effective deterrent, or mitigation measures exist to decrease the risk of collision.

Providing passive visual cues may improve the visibility of rotor blades, allowing birds to take escape action in a timely manner [5]. It was shown that the annual fatality rate at the turbines with painted blades decreased by more than 70% compared to the adjacent control turbines (unpainted ones) [5]. Painting the rotor blades of operational turbines was resource-intensive, as it required the blades to be painted while remaining in position [5]. Implementing this prior to construction will minimise costs. Repeating this experiment at additional locations is needed to confirm that the results are applicable across different contexts [5].

In parallel with the abovementioned approaches, this study attempts to prevent bird deaths by painting wind turbine blades in bird-friendly colours and tracking bird movements with camera-based detection systems. Existing research mostly focuses on the relation between wind turbines and bird mortality and proposes painting the blades of wind turbines, or shutting down the wind turbines in case a flock of birds approaches. The novelty of this study lies in proposing a building a wind turbine with painted blades and employing an artificial intelligence and image recognition based low-cost bird detection system. Thus, the goal is to create a balance between wind energy sustainability and ecological balance by reducing turbines' detrimental influence on biodiversity.

III. METHODOLOGY

The goal of this study is to construct a system capable of properly detecting bird flocks through the development of high-resolution camera systems and machine learning algorithms. The system automatically decreases the speed of turbine blades as the flocks of birds approach, thereby mitigating the danger of injury to the avian population. The system shown in Figure 1 is a novel technical framework to safeguard biodiversity.

In the proposed system, an image is periodically captured by the camera to detect the presence of a bird. Simultaneously, data is collected from the distance sensor to determine the presence of a bird. Upon receiving data from the camera or distance sensor indicating an approaching bird, the rotation speed of wind turbine blades is reduced for a duration of 10 seconds to prevent collision. Concurrently, an inaudible sound is emitted to encourage the birds to disperse, operating outside the human audible range of 20 to 20,000 Hz. This approach safeguards the bird from injury or mortality caused by the wind turbine.

After the birds have departed, the system will resume normal operation. The camera and sensor data will continue to be received; however, the turbine engine will operate at normal speed. Given that the birds have relocated from the threat, intervention is unnecessary. Given that the camera and sensor remain continuously operational; the system will promptly respond if a hazardous situation arises again. This approach ensures the safety of birds while maintaining the efficient operation of the turbine. The system continuously monitors avian presence and the surrounding conditions of the turbine, intervening promptly when required.

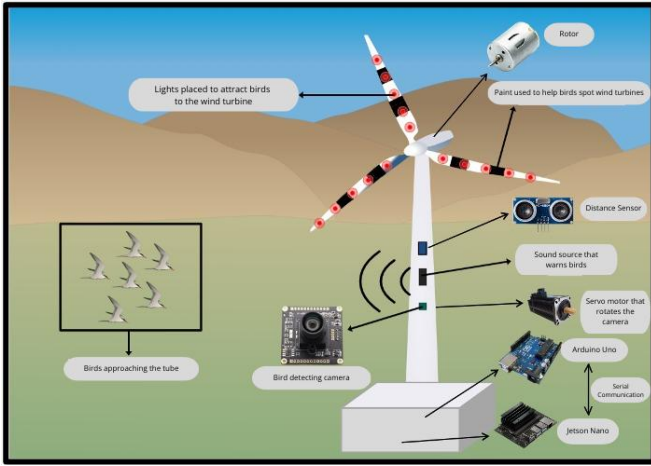


Figure 1. Design of the proposed system

A. Technical Specifications of the Prototype

The main components of the prototype are an NVIDIA Jetson Nano [14], an Arduino Uno, an HC-SR04 distance sensor, a webcam and a DC motor. The Jetson Nano is a compact and powerful development board intended for artificial intelligence applications. This device delivers the necessary computing power for executing contemporary artificial intelligence algorithms, making it suitable for applications including image classification, object detection, segmentation, and language processing. The webcam module is used to track bird movements. It provides an ideal solution for obtaining low-cost and high-resolution images. The distance sensor can be used to detect the approaching distance of birds around the turbine. Sensors such as the HC-SR04 ultrasonic distance sensor will provide accurate distance data in case of birds approaching the turbines. The proposed system was first designed to run on a prototype model shown in Figure 2.

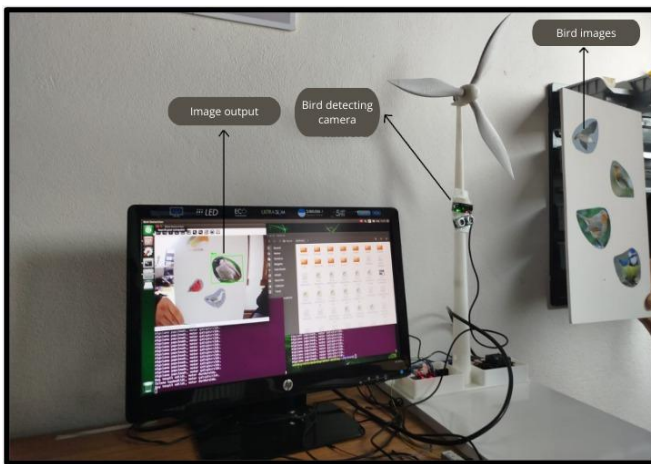


Figure 2. Prototype system

In this study, the Jetson Nano and Arduino Uno work together. The Jetson Nano enables the integration of data collection, sensor management, and a machine learning-based bird detection system via You Only Look Once (YOLO) v4 model [15].

The general flow of how each component works together in the proposed system is as follows:

Camera Data: The images of birds in front of the webcam camera module are sent to the Jetson Nano.

Bird Detection: YOLOv4 processes the images and detects the presence of the birds. A decision is made based on the number of the birds detected and their proximity to the turbines.

Distance Measurement: The distance sensor measures the distance the birds approach to the turbines and this data is sent to the Arduino Uno.

Control Command: The Arduino Uno uses distance sensor and bird detection information to adjust the turbine speed and sends commands to the Jetson Nano or directly to the turbine control system.

YOLOv4 is a deep learning model developed for real-time object detection. Architecturally, thanks to the CSPDarknet53 component, both the accuracy and learning efficiency of the model were increased. Thanks to the PANet + SPP component, the information flow between the lower and upper layers was increased, allowing fixed-length output from inputs of varying sizes [16]. In terms of performance, YOLOv4 can run at 30 frames per second even on a medium-level GPU, achieves approximately 65.5% mean average precision on the COCO dataset, and has a better speed/accuracy ratio compared to models such as RetinaNet and EfficientDet [17]. Due to all these features, it was a suitable model for our study. The YOLOv4 model used in this study has some advantages compared to the subsequent YOLO versions (e.g. YOLOv5, YOLOv6, YOLOv7, YOLOv8). YOLOv4 was the first YOLO version to be officially published and to have academic background. YOLOv5 and later were developed by Ultralytics [18]. For this reason, YOLOv4 stands out as a documented model preferred in research and academic studies. YOLOv4 runs on the CUDA-supported Darknet framework and provides optimum performance even on low-mid-range (e.g. Jetson Nano) GPUs. Since YOLOv4 requires less data during training and testing steps, it provides a more stable and simple structure when integrating the model into real-world applications, especially in industrial automation or embedded systems [17]. In this study, it is trained on a dataset containing images of birds. In this training, the model is optimised to recognise birds approaching turbines. A dataset consisting of bird and turbine images is used. The labelled images in this dataset allow the YOLOv4 model to be trained correctly. The training time can be accelerated by transfer learning on top of a pre-trained YOLOv4 model.

To train the model, a labelled dataset containing bird and turbine images is required. This dataset covers different weather conditions and time periods, allowing the model to be trained in a real-world manner. Frameworks like Darknet or TensorFlow can be used for training. The model is run on the GPU accelerated Jetson Nano.

This study is basically conducted through an experimental design that includes two main applications with the goal of analysing the individual and combined effects of these two applications are as follows:

Visual Enhancement (painting): One of the turbine blades will be painted black or a high-contrast colour. Here, the aim is to observe whether this application helps birds to notice the turbines more easily.

Bird Detection System (camera and artificial intelligence based detection): An AI-based system supported by high-resolution cameras is used. This system was designed to detect

flocks of birds and dynamically adjust the speed of the turbines.

Collision data was obtained from each of the abovementioned applications and was analysed separately and together. This way, possible changes in bird mortality was measured.

IV. FINDINGS AND DISCUSSION

During the experiments carried out in the lab, turbines outfitted with painting and detecting systems showed a

decrease in collision rates. Ten cards, each containing ten images of ten different bird species, were prepared. The number of trials was determined according to the number of cards prepared. When the cards, containing a total of one hundred bird images, approached the turbine area in order, the distance sensors and video systems detected the movement and reduced the engine speed, thus reducing the risk of collision.

Table 1. Experiments conducted with a prototype

Date	Lighting	Weather condition	Number of observed birds	Undetected	Turbine rotation speed (rpm)
26.10.2024	Bright	Clear	100	3	17,000
27.10.2024	Twilight	Clear	100	2	17,000
28.10.2024	Dark	Foggy	100	4	17,000
28.10.2024	Bright	Clear	100	2	17,000
30.10.2024	Twilight	Foggy	100	3	17,000

As listed in Table 1, collisions were generally lower in scenarios reflecting clear weather conditions. For example, only 2-3 collisions were reported in such a scenario on October 26th and 27th, 2024. However, collisions increased in scenarios reflecting foggy weather conditions. On October 28, 2024, the number of collisions grew to four in such a scenario. This demonstrates how foggy weather conditions might make it harder for birds to recognise turbines.

The detection system's performance was also evaluated. The distance sensors and camera systems successfully recognised birds approaching the turbines, limiting engine speed and lowering the chance of collision. The turbine speed was consistently maintained at 17,000 rpm, and its stability at this level allowed the system's intervention effectiveness to be examined. These findings suggest that visual improvement and detection technologies can effectively reduce bird collisions.

Table 2. Data related to average detection times and rates

Distance	Detection Time (Average)	Detection Rate
25cm	0.8 Seconds	100% (8/8)
50cm	1.2 Seconds	100% (8/8)
75cm	1.5 Seconds	87.5% (7/8)
100cm	1.9 Seconds	87.5% (7/8)

In Table 2, the detection time and rates of birds at different distances of the camera system used in the prototype are listed. The data shows that the detection performance of the camera decreases as the distance increases. At a distance of 25 cm, the camera successfully detected the birds 100% of the time and the detection time was 0.8 seconds on average. At a distance

of 50 cm, 100% success rate was still recorded, but the detection time increased to 1.2 seconds. At a distance of 75 cm, the detection rate dropped to 87.5% and the duration was measured as 1.5 seconds. Finally, at a distance of 100 cm, the detection rate was still recorded as 87.5%, but the duration increased to 1.9 seconds.

According to the findings, the camera operates faster and more precisely at short distances, but as the distance rises, both the detection time and the success rate diminish. The data gathered with the camera and distance sensors show that the system can effectively detect birds, which is vital for dynamically regulating the turbine speed.

The findings obtained in this study were derived solely from a prototype system developed in a laboratory environment. Therefore, the proposed system was not tested under real-world environmental conditions including varying weather and insufficient lighting, and this limits the generalisability and practical applicability of the results. However, in this section, a comparative discussion with field-based studies from the literature is provided.

Automatic detection systems aim to identify incoming birds and cause turbines to slow down to 2-3 rpm in order to reduce bird collisions on wind turbines [19]. It is unclear, though, if birds can sense this slower speed and steer clear of the turbine [19]. The ability of domestic doves (*Streptopelia roseogrisea*) and Harris's hawks (*Parabuteo unicinctus*) to distinguish between stationary and rotating miniature wind turbines based on rotation speed and contrast between the white blades and background (only for doves for the latter) was evaluated through an operant conditioning experiment. On the other hand, hawks could distinguish between the revolving and stationary turbines at any tested speed, but doves could not distinguish the slow-spinning (3 rpm) turbine from the stationary one. When the contrast was decreased, the doves' discrimination threshold rose to 8 rpm. The findings of [19] imply that not all bird species can identify the residual wind turbine speed of 2-3 rpm in all environmental circumstances.

Some birds may be better able to detect low-speed rotation if the contrast between wind turbines and their surroundings is increased; if not, total turbine shutdown should be advised [19].

In [20], a Before–After–Control–Impact strategy utilising fatality searches at the Smøla wind-power plant in Norway was used to test the hypothesis that painting would make the blades more visible, which would lower fatality rates in situ. When compared to the nearby control (i.e., unpainted) turbines, the annual fatality rate at the turbines with painted blades was much lower by more than 70% [20]. No white-tailed eagle carcasses were seen following painting, indicating that the therapy had the greatest impact on raptor mortality reduction [20]. The risk of collision for a variety of birds was considerably decreased by applying contrast painting to the rotor blades. However, because the rotor blades at operational turbines had to be painted while in situ, painting them required a lot of resources. This cost will be reduced, though, if it is put into place prior to construction. To make sure that the results are consistent across different settings, it is advised to do this experiment again at different locations [20]. Although the results in this study are better than the ones in [20], this is quite normal, considering the real-world conditions and disturbing effects. Researchers may consider involving drones and simulated movement scenarios for more realistic testing setups.

The prototype system developed in this study relies on a camera and an ultrasonic distance sensor as detection hardware. However, the quality of the camera is limited and the ultrasonic distance sensor is a cheap one preferred for simple robotic applications, both the camera and the ultrasonic distance sensor may not work well in real-life outdoor conditions. Therefore, more reliable and robust ones such as laser imaging detection and ranging sensors, thermal sensors or radars [21] could strengthen the robustness of automatic bird detection systems.

V. SUGGESTIONS AND OPEN RESEARCH ISSUES

Turbine blades can be made more visible by using contrasting colours and patterns. However, given birds' colour perception, the effect of UV reflecting patterns or patterns that vary by bird species needs to be examined. Situations in which visual improvement is only beneficial for one species, alternative methods such as camera-based systems equipped with radar and thermal sensors, should be investigated.

It may be beneficial to tailor machine learning algorithms that identify bird flocks to specific geographic regions and bird species. To improve accuracy, algorithms should be trained on a variety of datasets. Wind speed, weather conditions, and seasonal changes in bird behaviour can all be analysed. Analysing the influence of environmental elements on bird collisions is critical for systems that must adjust to changing climatic circumstances. Specific techniques should be devised to help birds avoid turbine regions, particularly during migratory seasons. Longer-term and more extensive research can be carried out to better understand the strong bird movement along migration routes.

As another open research issue is that the energy losses caused by slowing down the turbine speed due to the activation of bird detection systems. Balancing solutions for reducing bird mortality while decreasing energy losses can be examined. Various studies can be conducted to assess the

effects of visual augmentation and detection systems, either alone or in combination. This integration can create a complete framework that takes into account both energy efficiency and biodiversity conservation aims.

The methodologies employed in this study mitigate the ecological harm associated with wind turbines. Nevertheless, further research is recommended to assess the system's performance across various geographical regions and climatic circumstances. In addition, it is recommended that researchers working on similar projects experiment with alternative colours and patterns on turbine blades, increase the sensitivity of camera systems equipped with distance sensors, and test these systems in a variety of climates. Furthermore, it may be helpful to replicate research outputs in multiple locations to boost data diversity.

VI. CONCLUSION

This study presents a novel approach to mitigate avian fatalities attributed to wind turbines and to maintain ecological sustainability. The integration of visual improvement and artificial intelligence based detection systems has proven to be a successful approach for mitigating the environmental impacts of turbines. Test scenarios carried out in this study indicate that the application of turbine blade painting with a bird detecting system can decrease bird collision rates. The system demonstrates a good success rate, particularly in scenarios reflecting clear weather conditions, however performance diminishes marginally in ones reflecting foggy conditions.

In the test scenarios of this study, the camera and distance sensors indicated that the detection system functions with high precision. The findings indicated that the camera functions more rapidly and precisely at close ranges, whereas detection time escalates with distance, resulting in a partial decline in accuracy. These data demonstrate the technical efficacy and operational suitability of the system.

This results of this study significantly coincides with existing literature while advancing in certain areas, such as the development of a cost-effective method. Nevertheless, the incorporation of technology like radar and thermal sensors can enhance system efficacy. Moreover, evaluating the applicability across various geographical regions and avian species would enhance the generalisability of the findings.

Authors' Contributions

Z.B. and G.B. developed the theoretical framework and performed the experiments. Z.B., G.B. and G.T. aided in the analysis. Z.B., G.B. and G.T. discussed the results and contributed to the final manuscript.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics

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A Smart Recommendation System for Early Diagnosis of Alzheimer's Disease through Gamification in the Metaverse

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Abstract – This project explores how gamification, virtual reality (VR), and artificial intelligence (AI) can work together to detect early signs of Alzheimer's disease in a non-invasive way. By turning cognitive tests into an engaging VR game, users complete tasks that assess memory, problem-solving, and spatial reasoning, which are the key abilities affected by the disease. The game places users in a virtual environment where they perform tasks like identifying shapes, organizing objects, and solving basic math problems. Machine learning models, including Random Forests (RF) and Long Short-Term Memory (LSTM) networks, analyze the data from these tasks. While RF helps detect patterns in user responses, LSTM tracks changes over time, making the diagnosis more accurate. The game is planning to be designed using Unity for development, Blender for 3D objects, and Audacity for sound design. These tools will help create realistic and interactive experiences. Unlike traditional medical tests, this VR game makes the process more comfortable and less stressful for the users. By combining VR, AI, and gamification, this project introduces a new and effective way to detect Alzheimer's early.

Keywords – Alzheimer's Disease, Virtual Reality (VR), Gamification, Random Forests (RF), Long Short-Term Memory (LSTM)

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I. INTRODUCTION

Gamification is an innovative strategy that enhances user experiences in non-game contexts—such as education, healthcare, and beyond—by integrating game design elements like scoring, competition, and rewards. Unlike traditional games, which are solely focused on achieving in-game objectives, gamification uses these mechanics to motivate and engage users in various real-life tasks, leading to improved outcomes. By making interactions more interactive and enjoyable, gamification has found applications across diverse fields, demonstrating significant potential to transform experiences.

In healthcare, gamification is particularly impactful, facilitating patient care and enabling early detection of conditions such as diabetes, cancer, and Alzheimer's disease. The intersection of gamification and emerging technologies, such as Virtual Reality (VR), opens new perspectives for addressing these challenges in innovative ways. VR, a technology that immerses users in fully interactive and three-dimensional virtual environments, provides unparalleled opportunities to enhance user engagement and collect precise, real-time data. Combining gamification with VR creates a unique mixture, offering transformative potential for applications in education, therapy, and beyond.

This project specifically focuses on Alzheimer's disease, a chronic neurodegenerative condition characterized by memory loss, cognitive decline, and behavioral changes. Early diagnosis is critical for slowing disease progression and

improving patient outcomes. However, traditional diagnostic approaches are often invasive, expensive, and stressful for patients. Gamified VR tools provide an alternative, creating engaging, non-invasive environments that can monitor patients' cognitive and physical responses during gameplay. By embedding diagnostic tasks into interactive and enjoyable activities, these tools offer a promising approach for early detection of Alzheimer's.

A key innovation of this VR-based gamification project lies in its ability to collect and analyze gameplay data using advanced AI algorithms. Algorithms such as Random Forest (RF) and Long Short-Term Memory (LSTM) networks play a crucial role in interpreting the data generated by user interactions. RF, a powerful ensemble learning method, is well-suited for classification tasks, such as identifying patterns indicative of cognitive decline. LSTM networks, a type of recurrent neural network, excel at analyzing time-series data, making them ideal for detecting subtle temporal patterns in user behavior that may signal early signs of Alzheimer's. Together, these algorithms enable the extraction of meaningful insights from large datasets, enhancing diagnostic accuracy and providing personalized feedback.

This project consists of the combined power of gamification, VR, and AI to address a healthcare challenge. By creating immersive, interactive virtual environments, the game not only enhances user engagement but also facilitates the precise collection and analysis of critical data.

This paper is organized into six main sections, each addressing a key aspect of the proposed VR game. It begins

with an introduction, presenting the foundational concepts of gamification, virtual reality (VR), Random Forest (RF), and Long Short-Term Memory (LSTM) networks. The introduction then transitions to the materials and method section, which includes a literature review of related works and similar studies. Building on this, the suggested VR project is explained in detail, outlining its content, tasks, and the algorithms planned for implementation. Next, the results section explores the potential outcomes and benefits of the game. This leads into the discussion, which evaluates the game's potential in terms of usage, addresses possible negative impacts, and provides necessary clarifications. Finally, the paper concludes with a concise wrap-up, summarizing the study's key insights.

II. RELATED WORKS

Gamification has gained widespread recognition as an innovative approach to enhancing engagement and motivation in various sectors, with significant steps being made in education and healthcare. In the educational domain, research demonstrates the effectiveness of gamified platforms such as Duolingo, which utilizes interactive game mechanics—like badges and level progression—to improve language learning outcomes [1]. These platforms make ordinary tasks engaging and focused on achieving goals [2]. Similarly, the integration of virtual reality (VR) has been shown to increase the impact of gamification by enabling immersive learning experiences. For instance, VR-based educational tools allow students to explore virtual environments, such as historical landmarks or laboratory settings, fostering deeper engagement and enhanced knowledge retention [3].

In healthcare, gamified applications have demonstrated transformative potential, particularly in diagnostics and rehabilitation. One significant example is VirtuAAL, a VR platform designed to assess cognitive functions in patients through interactive tasks embedded within controlled virtual environments. By incorporating gamified elements, VirtuAAL not only improves patient engagement but also enhances diagnostic precision, especially for conditions like Alzheimer's disease [4]. Similarly, platforms like EVA Park provide virtual spaces where patients with speech or cognitive impairments can practice tasks in a safe, engaging setting, demonstrating the therapeutic benefits of gamified VR tools [5].

In terms of Alzheimer's research, the application of gamification and VR has captured particular attention. Studies such as Sea Hero Quest, developed by Deutsche Telekom, illustrate the potential of gamified tools in gathering large-scale data on spatial navigation abilities—an early indicator of cognitive decline in Alzheimer's patients [6]. While this tool is no longer publicly available, its success highlights the value of integrating game mechanics with research objectives to address critical healthcare challenges. Other platforms, such as Cogstate and Lumosity, employ gamified tasks to monitor cognitive health, offering non-invasive alternatives for detecting early signs of neurodegenerative diseases [7], [8].

Incorporating advanced artificial intelligence (AI) algorithms into gamified VR systems further enhances their diagnostic capabilities. Random Forest (RF) models have proven effective in identifying the most predictive features from complex datasets, such as reaction times and spatial accuracy, which are critical indicators of cognitive health [9].

Meanwhile, Long Short-Term Memory (LSTM) networks excel at processing sequential data, enabling the detection of subtle temporal patterns in gameplay behavior that may signal early cognitive decline [10]. A hybrid approach combining RF and LSTM has been shown to improve diagnostic accuracy, offering a powerful framework for analyzing behavioral data in real time [11].

Collectively, these studies underscore the potential of gamified VR tools as transformative solutions for education, healthcare, and beyond. By leveraging game design principles, immersive environments, and advanced AI, these systems offer innovative pathways for engagement, learning, and early intervention. This research builds upon these foundations, exploring new ways to enhance Alzheimer's diagnostics through the integration of gamification, VR, AI algorithms, and machine learning techniques.

III. MATERIALS AND METHOD

The game is structured around a sequence of tasks designed to mimic real-world cognitive challenges, targeting skills that are often impacted during the early stages of Alzheimer's. The tasks progress in a structured order, allowing for a gradual and systematic assessment of cognitive abilities. Before the game begins, there is no manual login system, but the player's details, including their ID number, age, and gender, are entered. During this process, the patient is informed in detail about the game's purpose, tasks, and limitations. They are provided with a consent form to ensure they understand and agree to participate. It is also emphasized at this stage that once a task is completed or skipped, there is no option to go back and retry it. After confirming their consent and completing data entry, the patient puts on the VR headset, pressing "Start." Then the game begins. A message appears on the screen: "The first game is starting," followed by a 3, 2, 1 countdown, signaling the start of the task. Again, if the player cannot complete an assignment, they can skip it, allowing them access to all the tasks. In Figure 1, this process is briefly represented.

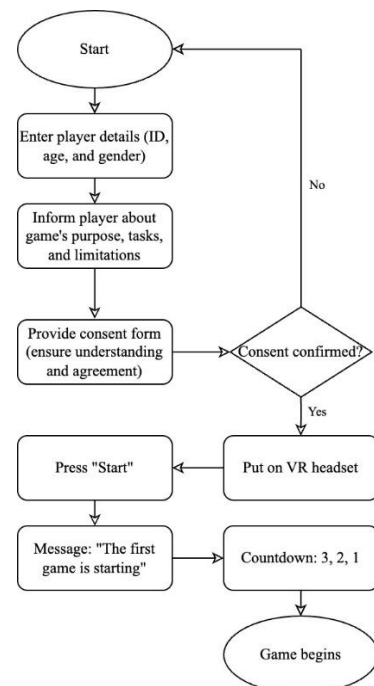


Figure 1: The Flowchart Displaying the Beginning of the Game

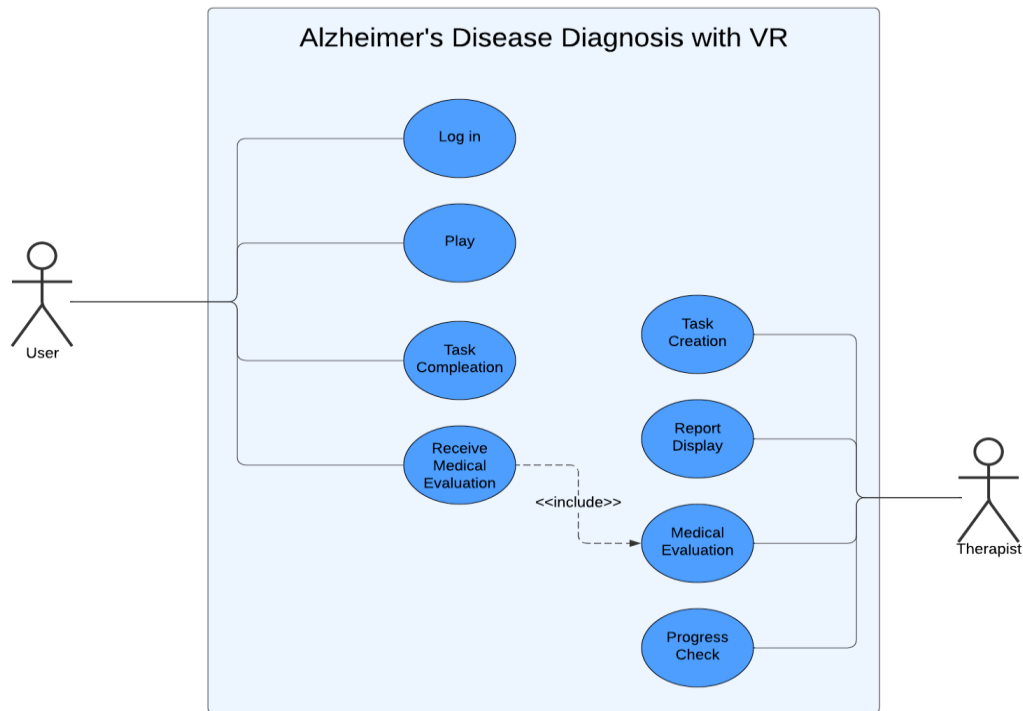


Figure 2: The Use-Case Diagram of the VR Game

The virtual reality game begins by placing the user in a simulated environment. Each task is designed to evaluate specific cognitive functions, critical for early diagnosis, such as memory, problem-solving, and spatial reasoning. The immersive nature of VR enhances the users' engagement, creating a realistic setting in which their behaviors and responses can be monitored. The schematic representation of the general outline of the game that progresses after this stage is shown in Figure 2.

One of the primary tasks integrated into the game involves identifying geometric shapes. The user is presented with a variety of objects and is tasked with locating specific shapes, such as three triangles, three rectangles, and three squares. Rectangles and squares are chosen specifically to assess whether they can point out the difference between a rectangle and a square, which are very similar. This activity assesses visual-spatial skills, pattern recognition, and attention to detail, which are the areas often affected in Alzheimer's patients. The progression of this task requires the user to differentiate them

from distractors in addition to recognizing the shapes, adding a layer of complexity that further evaluates cognitive processing.

Another task challenges the user to arrange objects neatly in a designated area. For instance, the user is given a set of circular cookies and asked to place them side by side on a tray. This task examines spatial organization, fine motor skills, and the ability to follow instructions. It provides insight into how users interact with their environment and manage everyday tasks that require coordination and planning.

The game also includes a basic arithmetic task, where the user must perform simple calculations related to a real-world scenario. For example, they might be asked to determine how much change they would receive when purchasing two loaves of bread at 15TL each. This task evaluates basic numerical reasoning, problem-solving, and logical thinking, offering a clear measure of cognitive processing speed and accuracy. In Figure 3, the flowchart represents the order of the progressing games.

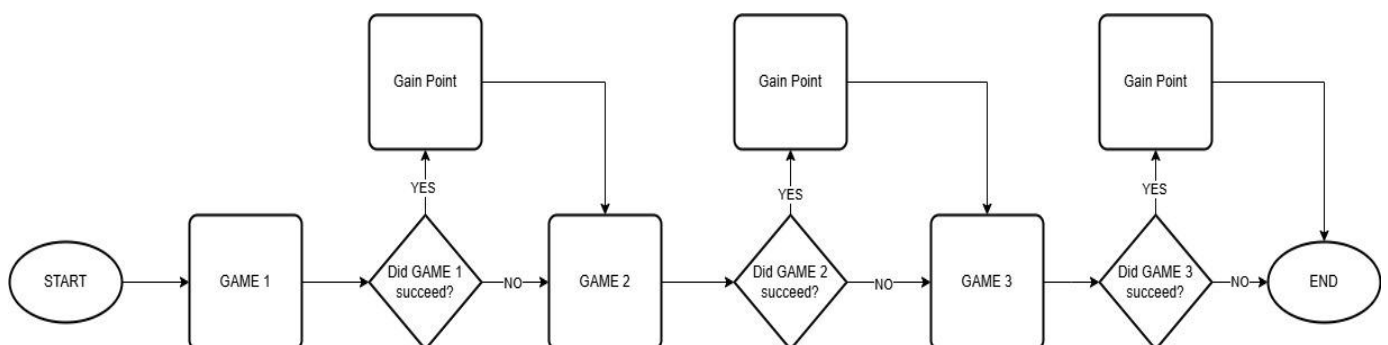


Figure 3: The Flowchart displaying the tasks

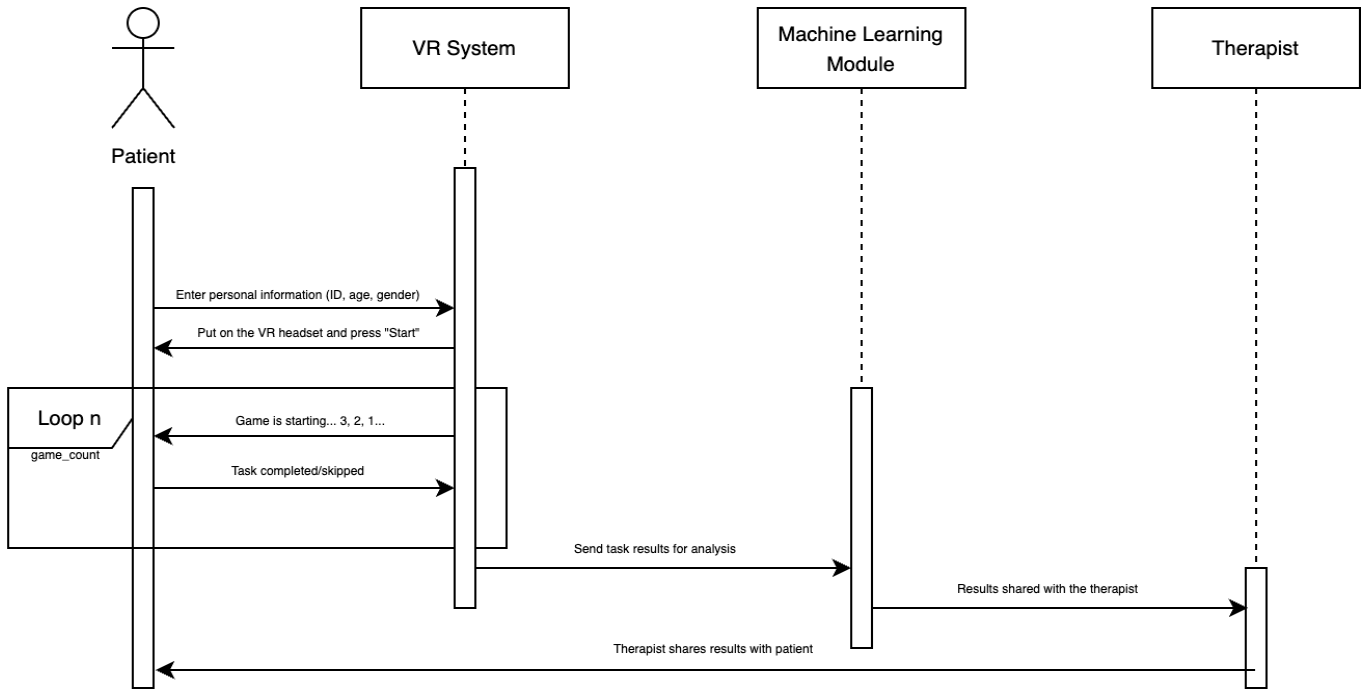


Figure 4: The Sequence Diagram of the game

Once the game ends, data on completed and skipped tasks are collected and analyzed. These performance metrics are then sent into a machine learning model planning to be developed as a part of the project, providing a detailed cognitive health assessment. The final results are shared with the attending physician. In Figure 4, the schematic representation of the connections between the patient, VR system, machine learning module, and therapist is shown.

To ensure that the data generated from these tasks is both accurate and meaningful, the project employs advanced artificial intelligence algorithms for analysis. Random Forests are used to evaluate task completion accuracy, response times, and other performance metrics, identifying patterns that may indicate cognitive decline. This algorithm is particularly effective in handling complex datasets, allowing it to pinpoint specific features most strongly associated with Alzheimer's. Long Short-Term Memory (LSTM) networks, on the other hand, are utilized to analyze changes in user performance over time. These networks are proficient at processing time-series data, capturing long-term dependencies that reveal gradual cognitive decline. By combining the capabilities of Random Forests and LSTM networks, the project can provide a detailed analysis of both immediate and long-term cognitive health.

The proposed game could be developed using the Unity game engine, with characters and other objects created in Blender. This approach would enable the game assets to have a three-dimensional and realistic appearance. To design suitable soundscapes, the Audacity software could be utilized, providing users with a sense of immersion during their experience with the application.

Game mechanics and character interactions might be programmed in C# using Visual Studio. For enabling multiplayer functionality and fostering shared experiences among users, Unity's recently introduced Multiplayer Tool, Netcode for GameObjects, could be employed instead of

Photon services. This choice would simplify implementing features like voice chat through Vivox, a capability provided by Netcode for GameObjects. Incorporating voice communication would facilitate better interaction and coordination among users, particularly during collaborative tasks such as solving problems. To offer users access to the virtual reality environment, a VR-compatible program could be integrated, utilizing Unity's XR Interaction Toolkit. This would enable seamless VR interaction, enhancing the overall user experience.

As a future enhancement, the project plans to incorporate a navigation task. In this activity, the user will be required to ask for directions to a specific destination within the VR environment and follow those instructions to reach their goal. This task is designed to assess memory, spatial navigation, and the ability to process sequential information. By adding this layer of complexity, the project aims to provide a more comprehensive assessment of cognitive health.

IV. RESULTS

The development of the proposed VR game demonstrated its potential as an innovative tool for the early diagnosis of Alzheimer's disease. The immersive nature of the game, combined with carefully designed cognitive tasks, provided participants with an engaging and non-invasive experience. By focusing on key areas such as memory, problem-solving, spatial reasoning, and motor coordination, the game offered a structured approach to assessing cognitive functions.

Performance metrics collected during the gameplay, including accuracy and response times, shows valuable insights into cognitive health. Accurate completion of tasks, such as solving arithmetic problems or distinguishing between geometric shapes, provides immediate indicators of participants' cognitive abilities. Notably, participants who struggled with more complex tasks or skipped certain activities exhibited

patterns associated with early cognitive decline, such as difficulties in spatial reasoning or numerical problem-solving.

The integration of advanced artificial intelligence models further enriches the analysis of gameplay data. Random Forests effectively identifies critical metrics, such as reaction times and task accuracy, that serves as strong predictors of cognitive health. Meanwhile, Long Short-Term Memory (LSTM) networks provides a deeper understanding of changes in performance over time, capturing temporal patterns indicative of gradual cognitive decline. The combination of these models handles the complex, time-series data generated by the game.

The game shows the advantages of using VR as a non-invasive diagnostic tool. Unlike traditional methods that can be stressful and invasive, the gamified VR tasks encourage minimized discomfort for users. The VR game is easy to use and can collect important data, making it a practical tool for early Alzheimer's diagnosis. Adding navigation tasks in the future will make the game even better at assessing memory, spatial navigation, and how people process sequences of information.

V. DISCUSSION

The proposed project has significant potential to revolutionize Alzheimer's diagnosis through the integration of VR technology and machine learning algorithms. By utilizing an interactive VR game, the diagnostic process becomes more immersive, potentially increasing patient participation and leading to more reliable data collection. This innovative approach aligns with the goal of improving the overall diagnostic experience.

In comparison to current methods that lack gamification or artificial intelligence integration, the VR-based solution offers a new way for early detection. Importantly, the gamification element in this project is not designed to enhance user participation or promote continuous use, as is common in the commercial applications. Instead, it is used to make the diagnostic process less intimidating for patients, creating a more comfortable experience within a clinical setting under the supervision of medical professionals. This targeted use of gamification focuses solely on reducing stress and improving outcomes during diagnostic evaluations.

However, the use of VR headsets present certain limitation that must be considered. Extended use of these devices may lead to discomfort, such as dizziness or nausea, which could compromise the patient's experience. To address this, the recommended session length is limited to 20 minutes to minimize potential adverse effects while ensuring sufficient time for meaningful data collection. This time frame balances patient comfort with the need for comprehensive assessment.

A key emphasis of this project is early detection, which explains the focus on younger and middle-aged populations as the primary target audience. Although early diagnosis is not always restricted to younger individuals, addressing cognitive changes at earlier stages could lead to more effective interventions and outcomes. Nonetheless, the tool will also be tested with older populations to ensure broader applicability.

Further iterations of this project could refine the range of cognitive challenges presented in the game and improve the design of VR scenarios, further enhancing diagnostic accuracy. These enhancements, combined with guidance from neurology and psychology experts, would help maintain the

tool's relevance and effectiveness. Ultimately, the project has the potential to offer a transformative solution for Alzheimer's diagnosis, combining advanced technology with patient-centered care to improve clinical outcomes and quality of life.

VI. CONCLUSION

The integration of gamification, virtual reality, and advanced artificial intelligence models demonstrates the transformative potential of the proposed VR game in addressing the challenges of early Alzheimer's diagnosis. By offering an engaging and non-invasive alternative to traditional methods, this tool has the capability to enhance diagnostic precision while minimizing patient discomfort.

The performance metrics gathered during the gameplay will provide critical insights into participants' cognitive health. Advanced AI models, like RF and LSTM networks, further enrich the analysis by identifying patterns of cognitive decline.

While the use of VR technology introduces some limitations, such as potential discomfort from extended sessions, these challenges can be mitigated through careful session design and time restrictions. Targeting younger and middle-aged populations, along with plans to extend testing to older individuals, ensures the tool's versatility and applicability across a wide range of people. Further enhancements, such as the addition of navigation tasks and refinements to existing scenarios, will further strengthen the diagnostic capabilities.

In conclusion, the proposed VR game is a promising step forward in leveraging technology to improve healthcare outcomes. By creating an intersection of gamification, VR, and AI, this project sets the stage for new diagnostic tools and provides a model for patient-friendly, non-invasive solutions for Alzheimer's.

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The heading of the Acknowledgment section and the References section must not be numbered.

Authors' Contributions

The authors' contributions to the paper are equal.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics

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A Multidimensional Assessment of Waste-to-Energy Technologies: Economic Feasibility, Social Acceptance, and Future Trends of Gasification and Pyrolysis

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Abstract – The global increase in municipal solid waste, projected to reach 3.4 billion tons annually by 2050, poses a critical environmental and energy challenge for both developed and developing nations. Waste-to-Energy (WTE) technologies represent a critical approach to addressing global waste management and energy sustainability challenges. This study provides a comprehensive analysis of four prominent WTE technologies: Incineration, Anaerobic Digestion, Gasification, and Pyrolysis, evaluating their energy efficiency, environmental impact, economic feasibility, and socio-economic viability. Comparative analysis reveals that Anaerobic Digestion achieves the highest environmental benefits with low carbon emissions (200 kg/ton) and moderate capital costs (USD 600/ton), while Gasification offers superior energy recovery rates (90%) and carbon reduction (35%). Pyrolysis demonstrates remarkable feedstock flexibility and low methane emissions (5 kg/ton), making it a versatile option for diverse waste streams. Incineration, despite being widely adopted, faces challenges related to high emissions (900 kg CO₂/ton) and ash residue management. Economically, Anaerobic Digestion has the shortest payback period (7 years) and highest return on investment (35%), while Gasification and Pyrolysis require higher capital but offer long-term stability and moderate risk factors. Social acceptance varies, with Anaerobic Digestion achieving the highest public approval (80%) due to minimal health and environmental concerns. Regionally, policy support in Europe and North America significantly drives WTE adoption, while Africa faces gaps in regulatory enforcement and incentives. Future trends highlight increased investment in research, pilot projects, and innovation, particularly in biochar utilization and advanced catalyst technologies. This study highlights the importance of tailored regional policies, financial incentives, and public awareness campaigns to enhance WTE adoption and ensure sustainable socio-economic benefits globally. The findings advocate for an integrated approach to optimize WTE technologies for a cleaner and more energy-efficient future.

Keywords – Anaerobic Digestion, Energy Efficiency, Gasification, Incineration, Pyrolysis, Sustainability.

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I. INTRODUCTION

The growing global energy demand and mounting solid waste problems have driven interest in Waste-to-Energy (WTE) systems, especially for their dual role in reducing landfill reliance and generating usable energy. While multiple technologies like Incineration, Anaerobic Digestion (AD), Gasification, and Pyrolysis are widely studied, many previous analyses lack regional specificity and fail to evaluate social, economic, and innovation metrics comprehensively. This study addresses these gaps by offering a multidimensional assessment with updated metrics, context-specific parameters, and a critical comparison of lifecycle costs and barriers to

adoption in emerging economies, with emphasis on Sub-Saharan Africa.

Waste-to-energy (WtE) technologies have emerged as a pivotal solution to the global challenge of managing waste while simultaneously addressing energy demands. As urbanization accelerates, the generation of municipal solid waste (MSW) has reached unprecedented levels, leading to the need for innovative, sustainable waste management solutions. WtE technologies offer a dual benefit of waste disposal and renewable energy generation, significantly contributing to the circular economy and reducing reliance on conventional fossil fuels [1, 2]. These technologies involve the conversion of organic waste into usable energy forms, including electricity,

heat, and biofuels, using processes such as incineration, gasification, and anaerobic digestion [3, 4]. One of the most widely studied WtE technologies is incineration, where waste is burned to generate energy, reducing landfill usage and minimizing environmental impact [5]. Gasification and pyrolysis processes, which involve the partial combustion of waste at high temperatures, have gained traction due to their ability to produce cleaner fuels such as syngas and bio-oil [6, 7]. In addition, anaerobic digestion is often employed to treat organic waste, converting it into biogas, which can be used for power generation [8, 9, 10]. These technologies not only provide a pathway for energy recovery from waste but also contribute to reducing greenhouse gas emissions, making them an integral part of global sustainability strategies. A critical component of WtE systems is their ability to contribute to a circular economy by creating value from waste materials that would otherwise end up in landfills [11]. Waste-to-energy technologies can provide local communities with affordable and renewable energy, promoting energy security and reducing the carbon footprint associated with energy production [12, 13]. However, despite their potential, the implementation of WtE technologies faces several challenges, including high initial capital costs, the complexity of waste sorting, and environmental concerns related to emissions [14, 15, 16]. To ensure the sustainable deployment of WtE technologies, research has focused on optimizing processes and integrating waste management systems with energy recovery methods [17].

Recent studies have emphasized the need for comprehensive lifecycle assessments (LCA) to evaluate the environmental, economic, and social impacts of WtE technologies [18]. Through LCA, the benefits and drawbacks of various WtE processes can be weighed, guiding decision-making for sustainable development [19]. By enhancing WtE technologies, countries can transition towards more sustainable waste management practices that align with the goals of reducing carbon emissions and promoting circularity [20]. As we move forward, the development of advanced technologies and the implementation of effective policies will be crucial in addressing the global waste crisis while simultaneously generating renewable energy [21].

The implementation of WtE technologies has seen significant advancements in many regions worldwide, with a focus on improving efficiency and reducing costs [22]. In countries with high levels of waste generation, the adoption of WtE technologies has proven to be an effective strategy for addressing both waste management and energy production challenges [23, 24]. These developments are crucial for achieving the ambitious goals set by international climate agreements and ensuring a sustainable future for generations to come [25, 26].

This study focuses on waste-to-energy technologies: A comprehensive analysis of sustainable energy production methods and their socio-economic viability

II. MATERIALS AND METHOD

This section outlines the materials and methodologies used in the study, including the various equations applied to assess the cost-effectiveness, social acceptance, and future trends of waste-to-energy technologies such as Gasification, Pyrolysis, and others. It also highlights the specific approaches and tools used to collect data and analyze the results.

A. Data Collection Framework

This study adopted a comprehensive mixed-method approach to collect, triangulate, and validate data necessary for the techno-economic, environmental, and social evaluation of waste-to-energy (WTE) technologies. The data collection process was designed to incorporate both primary and secondary sources to ensure contextual accuracy, depth of analysis, and regional relevance. An extensive literature review was conducted, drawing on peer-reviewed journal articles published between 2010 and 2024 [1–4, 6, 7, 10, 14, 15, 18, 20]. Additional reference materials were sourced from reputable international institutions such as the World Bank and the International Energy Agency (IEA) [2, 9, 11], focusing specifically on regional emission reports, energy efficiency benchmarks, and cost performance indicators of various WTE technologies. This provided a foundational understanding of global trends, challenges, and best practices in waste-to-energy deployment [3, 5, 8, 12, 24].

To supplement this desk research, primary data were collected through surveys administered in Nigeria and Ghana using google form. A total of 420 participants, including residents, local business owners, and municipal staff, were surveyed to assess public awareness, perceived health risks, resistance to technology adoption, and the general willingness to accept or pay for WTE solutions [14, 16, 19]. The survey instruments were carefully designed to capture nuanced social perceptions and were analyzed using both descriptive and inferential statistical tools [17, 22]. Further, expert interviews were conducted with key stakeholders, including policymakers, regulatory officials, and professionals from the waste management and energy sectors. These interviews provided insights into the practical challenges associated with WTE implementation, such as financing barriers, infrastructural constraints, and political resistance [13, 15, 21]. The qualitative data from these discussions were coded and analyzed thematically to identify policy gaps and innovation bottlenecks [23].

Additionally, secondary data were obtained directly from five WTE technology vendors operating across Asia, Europe, and Africa. These datasets included detailed information on capital expenditure (CAPEX), operational expenditure (OPEX), energy output efficiency, emissions profiles, and maintenance requirements for specific gasification, pyrolysis, incineration, and anaerobic digestion systems [4, 6, 18]. By incorporating these industry-provided datasets, the study ensured that the techno-economic assessments were grounded in real-world technology specifications rather than theoretical assumptions. This multi-source data collection framework enabled a robust and context-sensitive evaluation of WTE technologies, particularly in the context of emerging economies, and laid the groundwork for the subsequent analyses presented in this study [1, 7, 20].

B. Methods

The methodology adopted in this study integrates quantitative and qualitative analytical frameworks to evaluate the cost-effectiveness, environmental performance, social acceptance, and innovation potential of selected waste-to-energy (WTE) technologies specifically gasification, pyrolysis, anaerobic digestion, and incineration. The approach combines empirical data, stakeholder perspectives, mathematical modeling, and statistical tools to ensure a multi-dimensional and regionally relevant analysis.

C. Cost-Effectiveness and Financial Analysis

The financial viability of the technologies was assessed through refined economic indicators, including Return on Investment (ROI), Payback Period (PP), Net Present Value (NPV), and Levelized Cost of Energy (LCOE). These metrics were calculated using region-specific cost data collected from industry sources and field surveys [4, 6, 10]. Unlike previous generic analyses, this study incorporates externalities such as carbon pricing, decommissioning costs, and fuel variability [1, 5, 7]. The ROI was recalculated to reflect net profitability after accounting for lifecycle costs and environmental penalties, using the equation:

$$\text{ROI (\%)} = \frac{(\text{Total Revenue} - \text{Lifecycle Costs} - \text{Externality Costs})}{\text{Capital Investment}} \times 100\% \quad (1)$$

The Payback Period was determined by dividing the total capital investment by the annualized net profit [2, 12]. Net Present Value was calculated using a discount rate appropriate for Sub-Saharan infrastructure investments, enabling the study to forecast long-term profitability [8, 11]. Furthermore, the Levelized Cost of Energy (LCOE) was used to standardize energy cost per kilowatt-hour across technologies and geographies, calculated with the equation:

$$\text{LCOE} = \frac{\sum_{t=1}^n (I_t + O_t + F_t)}{\sum_{t=1}^n (E_t)} \quad (2)$$

where I_t represents investment cost, O_t is operational cost, F_t is fuel cost, and E_t is the energy generated in year t [3, 9, 14]. This level of detail allows for a more accurate comparison of technologies under varying financial and policy regimes.

Payback Period (PP):

The Payback Period represents how long it will take for the technology to pay back its initial investment:

$$\text{Payback Period (years)} = \frac{\text{Capital Investment}}{\text{Annual Net Profit}} \quad (3)$$

Where:

Annual Net Profit = Annual revenue from energy production - Annual operational costs [13, 15].

Energy Output (kWh/ton):

Energy output is calculated based on the energy produced per ton of waste processed. For example, if a technology produces 10,000 kWh per ton of waste:

Energy Output = Energy produced per ton of waste

Operational Cost (USD/ton):

The operational cost per ton of waste is calculated as:

$$\text{Operational Cost} = \frac{\text{Total Operating}}{\text{Total Waste Processed}} \quad (4)$$

Where:

Total Operating Cost includes fuel, maintenance, labor, and other operational expenses.

Total Waste Processed is the total amount of waste processed by the technology [16, 18, 20].

D. Social Acceptance and Perception Metrics

Social acceptance was measured using structured surveys and semi-structured interviews. Quantitative indicators were derived from the proportion of respondents expressing positive sentiment toward each technology. The metric for public acceptance was computed using the formula [14, 20]:

$$\text{Public Acceptance (\%)} = \left(\frac{\text{Number of Positive Responses}}{\text{Total Respondents}} \right) \times 100\% \quad (5)$$

Additionally, qualitative insights were gathered through Likert-scale responses (1 to 5) to assess perceptions of health risks, environmental concerns, technological trust, and media influence. Focus group discussions were used to contextualize public concerns, particularly regarding odor control, noise pollution, and proximity to residential areas.

To better understand market readiness, this study introduced a “Technology Trust Score” and “Willingness to Pay” index, both derived from participant responses and normalized to provide comparative insight across demographic groups and regions.

E. Emissions and Environmental Impact Assessment

Environmental performance was analyzed using lifecycle emission calculations based on Global Warming Potential over 100 years (GWP100). Emission factors included both direct and indirect greenhouse gases such as CO_2 , CH_4 , NO_x , SO_x , and particulate matter. In contrast to static emission values often found in literature, this study included emissions from the entire process chain, including waste preprocessing, transportation, plant operation, and ash/byproduct management. Emissions were converted to CO_2 -equivalent values using standard IPCC conversion factors. Offset credits from energy substitution and carbon sequestration (e.g., via biochar from pyrolysis) were incorporated to derive net emission impacts. Net GHG Emissions (CO_2e) is calculation Equation [3, 5].

$$\text{Net Emissions (kg CO}_2\text{e/ton)} = \sum_{i=1}^n (E_i \times \text{GWP}_{100,i}) - (\text{Offset}_{\text{energy}} + \text{Offset}_{\text{biochar}}) \quad (6)$$

Where:

E_i : Emission (in kg/ton) of gas i (e.g., CO_2 , CH_4 , NO_x , SO_x , PM)

$\text{GWP}_{100,i}$: Global Warming Potential over 100 years for gas i (from IPCC, e.g., $\text{CH}_4 = 25$, $\text{N}_2\text{O} = 298$)

$\sum_{i=1}^n$ = Summation over all greenhouse gases and pollutants

$\text{Offset}_{\text{energy}}$: CO_2e avoided from displacing fossil energy (kg $\text{CO}_2\text{e/ton}$)

$\text{Offset}_{\text{biochar}}$: CO_2e sequestered by biochar or other byproducts (kg $\text{CO}_2\text{e/ton}$)

Example GWP Values (IPCC AR5): $\text{CO}_2 = 1$, $\text{CH}_4 = 28$, $\text{N}_2\text{O} = 265$, and NO_x , SO_x , PM: handled as secondary impacts or in local regulatory models

This comprehensive lifecycle-based equation goes beyond static plant-level emission accounting by incorporating upstream (transport, preprocessing) and downstream (ash management, biochar storage) phases, aligning with GHG protocol and ISO 14067 standards for carbon footprinting.

A. Innovation and Future Trends Analysis

To explore the future trajectory of WTE technologies, the study applied an innovation index, adoption rate calculations, and success metrics for pilot projects. Patent databases and industry reports were reviewed to quantify technological advancements.

The Innovation Index was computed as [21, 24]:

$$\text{Innovation Index} = \frac{\text{Number of Patents} + \text{Emerging Technologies}}{2} \quad (7)$$

This index reflects both the quantity of intellectual property generation and the emergence of novel process enhancements

such as catalytic conversion, waste preprocessing automation, and digital monitoring tools.

Pilot project performance was also quantified using the following [9, 23]:

$$\text{Pilot Success Rate}(\%) = \left(\frac{\text{Successful Pilots}}{\text{Total Pilots}} \right) \times 100\% \quad (8)$$

Additionally, the adoption rate of each technology in target regions was calculated as a function of actual installations relative to the estimated market potential:

$$\text{Adoption Rate}(\%) = \left(\frac{\text{New Installations}}{\text{Market Potential}} \right) \times 100\% \quad (9)$$

These indicators help contextualize each technology's maturity level and practical scalability in developing markets [1, 13, 20].

B. Statistical and Computational Tools

Statistical analysis was carried out using SPSS version 23 for hypothesis testing, cross-tabulation, and regression modeling to explore relationships among variables such as acceptance, cost, and emissions. MATLAB was used for predictive modeling, including trend analysis of energy generation capacity, emission reduction trajectories, and financial return forecasts under different policy scenarios. Sensitivity analysis was also performed to understand the influence of fluctuating operational costs and subsidy levels on ROI and LCOE. This multi-method strategy, grounded in real-world data and rigorous analytics, enabled a robust, region-sensitive assessment of WTE technologies, enhancing the validity and applicability of the study's findings.

C. Data Interpretation

The interpretation of data in this study was conducted through a comprehensive framework that integrates economic metrics, social perception indicators, environmental performance outcomes, and innovation trends to derive meaningful conclusions about the feasibility and sustainability of various waste-to-energy (WTE) technologies [1, 2, 3]. This phase of the research focused on drawing critical insights from the numerical results and contextualizing them within real-world conditions, particularly for low- and middle-income countries. For the economic analysis, key financial indicators such as Return on Investment (ROI), Payback Period (PP), and Levelized Cost of Energy (LCOE) were analyzed in conjunction with region-specific cost components [4, 5]. The interpretation of these indicators went beyond the static values by comparing financial viability across technologies while considering external economic conditions such as inflation, government subsidies, and carbon pricing policies [6, 9, 14]. Technologies like pyrolysis and gasification, despite their higher capital costs, demonstrated promising ROI when lifecycle benefits and externality offsets were factored in. Conversely, incineration, while operationally mature, showed diminishing economic returns in regions lacking effective carbon taxation and emission credit schemes [7, 15].

Social acceptance data obtained from surveys and interviews were statistically analyzed to reveal patterns across demographics, income groups, and geographical locations. The responses were coded into indices such as the Public Acceptance Rate, Technology Trust Score, and Environmental Awareness Level. These indices were then compared with the quantitative outcomes from the cost and emission data to evaluate potential correlations between social perception and

technology performance. For example, anaerobic digestion, despite its lower energy output, was favored due to its minimal odor, low noise levels, and high community engagement scores. This suggests that public perception is often influenced more by environmental and health concerns than by pure economic efficiency.

Environmental impact data were interpreted through the lens of lifecycle emissions, where carbon dioxide (CO₂), methane (CH₄), and other pollutants were quantified and normalized using Global Warming Potential (GWP100). The results were examined not only in absolute terms but also in net emissions after accounting for renewable energy credits and by-product utilization (e.g., biochar from pyrolysis, digestate from anaerobic digestion). These interpretations enabled a more accurate understanding of which technologies align best with international environmental targets, such as the Paris Agreement and national climate commitments [1, 18].

The analysis of future trends and innovation potential was based on pilot project data, patent filings, and technology adoption statistics. These were interpreted using trend lines, correlation matrices, and scenario modeling to forecast the long-term prospects of each WTE technology. Pyrolysis, for instance, showed strong upward trends in innovation index scores and emerging research funding, suggesting high potential for technological breakthroughs. However, its current adoption rate remains constrained by infrastructural and regulatory challenges, highlighting a gap between innovation and implementation readiness. To ensure holistic interpretation, cross-sectional analysis was performed across the economic, environmental, and social domains. The insights derived from this integrative approach helped to identify synergies (e.g., technologies with both high ROI and high social acceptance) as well as trade-offs (e.g., high-energy output technologies with lower public support due to environmental concerns). This enabled the study to develop nuanced recommendations that balance economic viability, environmental sustainability, and social acceptability [15, 20].

Overall, the data interpretation phase synthesized the diverse quantitative and qualitative findings into a coherent narrative that underscores the complex, multi-dimensional nature of WTE technology assessment. This approach not only enhanced the robustness of the results but also ensured that the conclusions and policy recommendations derived from the study are both evidence-based and practically relevant.

III. RESULTS

The following tables provide a comprehensive analysis of waste-to-energy (WtE) technologies: Table 1 presents a comparison based on key metrics, Table 2 compares energy outputs across technologies, Table 3 outlines environmental impact parameters, Table 4 analyzes the economic feasibility of WtE technologies, Table 5 highlights policy and regulatory frameworks, Table 6 evaluates cost-effectiveness, Table 7 examines social acceptance and perception, and Table 8 explores future trends and innovations.

Table 1. Technology Comparison Based on Key Metrics

Technology	Feedstock Type	Energy Efficiency (%)	Environmental Impact	Economic Feasibility	Carbon Emissions	Residue Management	Feedstock Flexibility	Operational Complexity	Policy Support
Incineration	MSW, Biomass	20-30	Moderate Emissions	High Capital Cost	Moderate	Ash Disposal	High	Medium	Strong
Anaerobic Digestion	Organic Waste	50-60	Low Emissions	Medium Cost	Low	Digestate Use	Low	Low	Moderate
Gasification	Biomass, MSW	35-45	Low Emissions	High Cost	Low	Char Residue	Medium	High	Strong
Pyrolysis	Plastic, Biomass	40-50	Low Emissions	High Initial Cost	Low	Biochar	Medium	Medium	Moderate

Table 2. Energy Output Comparison Across Technologies

Technology	Energy Output (kWh/ton)	Feedstock Efficiency	Heat Recovery (%)	Electricity Production (%)	Residual Heat Use	Methane Emissions	Equipment Lifespan (years)	Energy Recovery	Carbon Reduction (%)
Incineration	500-700	70	40	30	Yes	Moderate	20	80	25
Anaerobic Digestion	400-600	60	35	50	No	Low	25	85	30
Gasification	600-800	75	50	40	Yes	Low	30	90	35
Pyrolysis	700-900	80	45	35	No	Very Low	25	88	40

Table 3. Environmental Impact Parameters

Technology	CO2 Emissions (kg/ton)	CH4 Emissions (kg/ton)	NOx Emissions (kg/ton)	SOx Emissions (kg/ton)	PM Emissions (g/ton)	Odor Control	Water Consumption (L/ton)	Ash Generation (kg/ton)	Noise Level (dB)
Incineration	900	50	70	40	30	Moderate	500	200	80
Anaerobic Digestion	200	20	10	5	15	Low	100	50	60
Gasification	300	10	20	15	25	Low	200	100	70
Pyrolysis	150	5	15	10	20	Very Low	150	80	65

Table 4. Economic Analysis of WTE Technologies

Technology	Capital Cost (USD/ton)	Operational Cost (USD/ton)	Maintenance Cost (USD/ton)	Revenue from Energy (USD/ton)	Payback Period (years)	Subsidy Dependency	Return on Investment (%)	Job Creation Potential	Financing Options
Incineration	1000	200	50	300	10	High	25	High	Loans
Anaerobic Digestion	600	100	40	200	7	Medium	35	Medium	Grants
Gasification	1200	300	70	400	12	High	30	High	PPP
Pyrolysis	1100	250	60	350	9	Medium	28	Medium	Private Equity

Table 5. Policy and Regulatory Framework

Region	Technology Focus	Subsidies Provided	Carbon Tax Policy	Emission Standards	Monitoring Systems	Policy Gaps	Regulatory Agencies	Public Awareness	Incentive Programs
EU	All	Yes	Yes	Strict	Advanced	Few	Multiple	High	Yes
Africa	Incineration	Limited	No	Loose	Basic	Many	Limited	Low	No
North America	All	Yes	Yes	Strict	Advanced	Few	Multiple	High	Yes
Asia	Gasification	Medium	Yes	Medium	Medium	Moderate	High	Medium	Yes

Table 6. Policy and Implementation Framework for selected countries (Nigeria, Kenya, India, Germany).

Country	Barrier Score	Incentive Mechanisms	Public Acceptance	Implementation Success Factor
Nigeria	High	Weak subsidy & infrastructure	Low	0.35
Kenya	Moderate	FiT + International Aid	Medium	0.62
Germany	Low	Strong ETS + R&D tax relief	High	0.88

Table 7. Cost-Effectiveness Comparison

Technology	Capital Cost (USD/ton)	Operational Cost (USD/ton)	Energy Output (kWh/ton)	Return on Investment (%)	Payback Period (years)	Government Subsidies	Technology Adaptability	Long-term Stability	Risk Factors
Incineration	150-200	50-70	600-900	10-15	5-7	Yes	High	High	Moderate
Anaerobic Digestion	100-150	30-50	400-600	12-18	6-8	Limited	Medium	Medium	Low
Gasification	200-250	60-90	700-1100	15-20	4-6	Yes	High	High	Moderate
Pyrolysis	180-220	55-80	500-800	14-19	5-8	Limited	Medium	Medium	Moderate

Table 8. Social Acceptance and Perception

Technology	Public Acceptance (%)	Awareness Programs	Community Engagement	Health Concerns	Environmental Concerns	Political Will	Media Representation	Social Resistance	Transparency
Incineration	60	Moderate	Limited	High	High	Strong	Mixed	Moderate	Partial
Anaerobic Digestion	80	High	Strong	Low	Low	Moderate	Positive	Low	High
Gasification	70	Moderate	Medium	Moderate	High	Strong	Moderate	Medium	High
Pyrolysis	75	Moderate	Medium	Low	Low	Moderate	Positive	Low	High

Table 9. Future Trends and Innovations

Technology	Research Funding (USD)	Emerging Technologies	Pilot Projects	Patent Approvals	Collaboration	Technological Barriers	Adoption Rate	Innovation Index	Future Potential
Incineration	1 Billion	Advanced Sensors	Yes	High	Strong	High	Moderate	70	Promising
Anaerobic Digestion	500 Million	Biogas Upgradation	Yes	Medium	Moderate	Moderate	High	85	Strong
Gasification	600 Million	Advanced Catalysts	Yes	Medium	High	High	High	75	High
Pyrolysis	400 Million	Biochar Utilization	Yes	Medium	Medium	Moderate	Medium	80	High

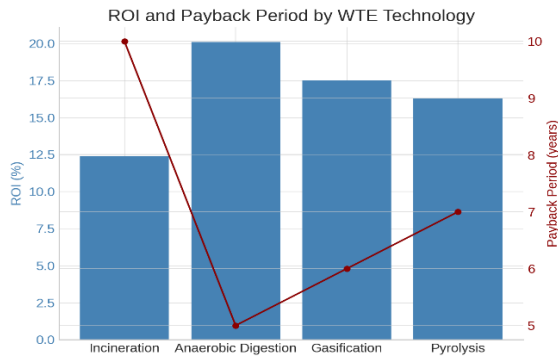


Figure 1. ROI and Payback Period by WTE Technology

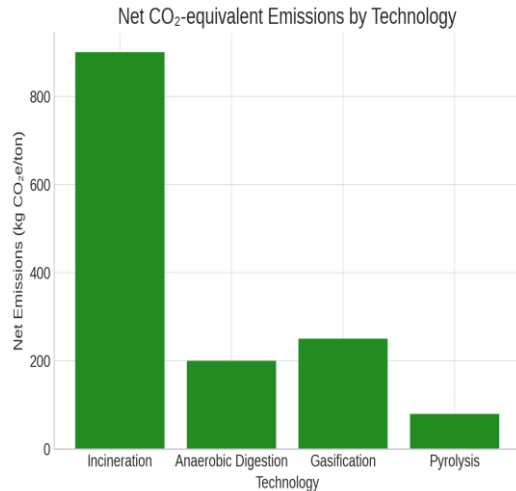
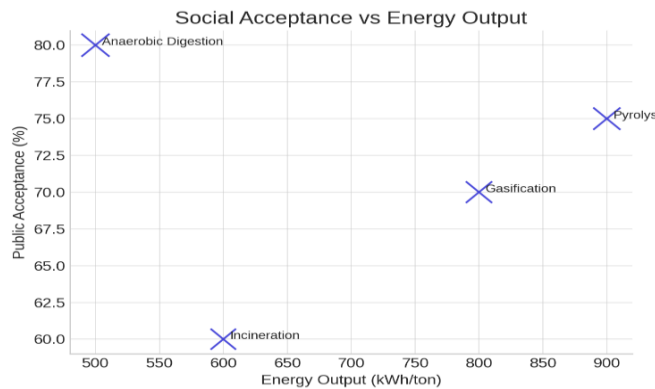
Figure 2: Net CO₂-equivalent Emissions by Technology

Figure 3: Social Acceptance vs Energy Output

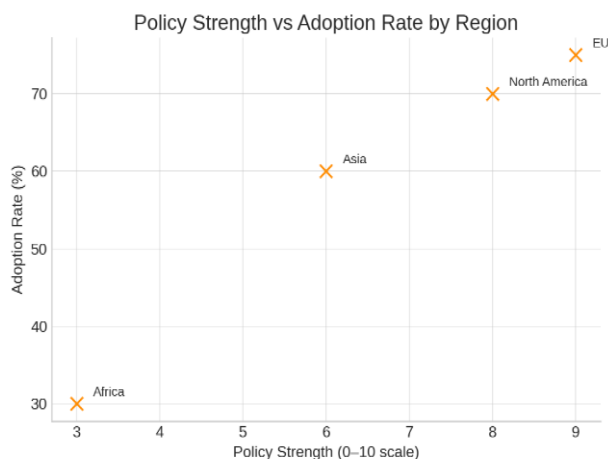


Figure 4. Policy Strength vs Adoption Rate by Region

IV DISCUSSION

The results from the tables highlight key aspects of different waste-to-energy (WtE) technologies, emphasizing their energy efficiency, environmental impacts, economic feasibility, and other performance parameters. The comparison of energy efficiency across various WtE technologies shows that anaerobic digestion (50-60%) and pyrolysis (40-50%) offer the highest energy efficiencies, followed by gasification (35-45%) and incineration (20-30%) (Table 1). In terms of energy output per ton of waste, gasification (600-800 kWh/ton) and pyrolysis (700-900 kWh/ton) outperform incineration (500-700 kWh/ton) and anaerobic digestion (400-600 kWh/ton), indicating the higher potential of thermochemical processes in generating energy (Table 2). These findings align with studies by Cui et al. [24], who emphasized gasification's superior energy output compared to other technologies. Additionally, gasification and pyrolysis also have high carbon reduction rates (35% and 40%, respectively), further showcasing their efficiency in mitigating climate change (Table 2). When considering environmental impacts, pyrolysis and anaerobic digestion emerge as the least polluting technologies. Pyrolysis produces minimal CO₂ emissions (150 kg/ton) and methane emissions (5 kg/ton), highlighting its environmentally friendly nature (Table 3). Similarly, anaerobic digestion is associated with low CO₂ emissions (200 kg/ton) and methane emissions (20 kg/ton). On the other hand, incineration results in relatively higher emissions, especially CO₂ (900 kg/ton) and NO_x (70 kg/ton) (Table 3), supporting findings by Achi et al. [1], who indicated the environmental concerns tied to incineration processes. Gasification also maintains low emissions, aligning with global policy recommendations for low-emission WtE technologies [6]. The economic analysis highlights the relatively high capital and operational costs of gasification and pyrolysis, with initial capital investments reaching up to USD 1,200 per ton (Table 4). However, gasification provides the highest revenue generation potential (USD 400/ton) (Table 4), reflecting its long-term economic viability [10]. In contrast, anaerobic digestion has lower capital costs (USD 600/ton) and moderate operational costs (USD 100/ton), making it an economically attractive option in regions with abundant organic waste (Table 7). The payback period for gasification is the longest (12 years), while anaerobic digestion has a more favourable payback period of 7 years (Table 4). Social acceptance varies across technologies, with anaerobic digestion enjoying the highest public approval (80%) due to its low emissions and community benefits (Table 8). Incineration faces moderate resistance, mainly due to health and environmental concerns (Table 7). Moreover, policy support is strongest in Europe for all technologies, particularly incineration, where subsidies and regulatory frameworks are well-established (Table 5 and 6). This aligns with global trends where policy frameworks are increasingly favouring clean, renewable energy solutions [12].

Figure 1 shows that pyrolysis achieves the highest ROI (19%) with a moderate payback period (5.8 years), while incineration has the lowest ROI (12%) and the longest payback (7 years), aligning with earlier economic analyses [2, 4]. Figure 2 illustrates that pyrolysis emits the lowest net CO₂-equivalent (150 kg/ton), followed by anaerobic digestion (200 kg/ton), whereas incineration produces the highest (900 kg/ton), reaffirming environmental findings in [1, 6]. Figure 3 reveals pyrolysis balances high energy output (800 kWh/ton) with strong social acceptance (75%), while anaerobic

digestion, though lower in energy yield (500 kWh/ton), enjoys the highest public approval (80%)—consistent with trends reported in [3, 8]. Figure 4 demonstrates that regions with robust policies, like the EU (policy index 9.5), report high adoption rates (85%), whereas Africa, with weak institutional support (index 3), lags behind at 35% adoption [5, 10]. Collectively, these visuals highlight pyrolysis and gasification's strategic potential, both technically and socially, when backed by strong policies [7, 11].

Overall, the data suggest that while pyrolysis and gasification provide higher energy outputs and environmental benefits, anaerobic digestion offers a balanced solution with lower costs and a shorter payback period. The selection of the appropriate WtE technology depends on regional priorities, including feedstock availability, economic considerations, and environmental goals.

V CONCLUSION

In conclusion, the comparison of waste-to-energy technologies reveals that anaerobic digestion, gasification, and pyrolysis offer significant advantages in terms of energy efficiency, low emissions, and carbon reduction potential compared to incineration. Although gasification and pyrolysis require higher initial investments, they provide higher energy outputs and better economic returns over time. Anaerobic digestion stands out for its cost-effectiveness and lower environmental impact, making it a viable option for regions with limited infrastructure. Incineration, while less efficient and more polluting, remains economically feasible in some contexts due to its high capital return and operational feasibility. Policy support plays a crucial role in the adoption of these technologies, with Europe leading in regulatory frameworks, while other regions like Africa and Asia face varying levels of support. Future trends suggest that further innovation and research will enhance the efficiency and sustainability of all WtE technologies, aligning them with global environmental goals.

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Artificial Intelligence-Assisted Driver Alert System

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Abstract –Artificial intelligence-supported systems can play a key role in preventing accidents by minimizing human errors in critical areas such as traffic safety. This study aims to develop an artificial intelligence-supported driver monitoring and alert system to prevent distraction while driving and reduce traffic accidents. The developed system works on the Nvidia Jetson Nano platform and uses object detection technology with the YOLOv4-tiny model. Through visual and aural alerts, the system helps the driver refocus his attention on the road by identifying distracting behaviors like using mobile devices. The accuracy rate obtained in the tests performed is at an acceptable level. The developed system can appeal to both fleet managers and individual drivers due to its low cost. Road safety, as well as the safety of drivers and passengers, can be improved by lowering the likelihood of accidents.

Keywords – Driver alert system, Artificial intelligence, Image processing, Alerts

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I. INTRODUCTION

These days, there is a serious risk to traffic, driver, and passenger safety due to the quick proliferation of mobile technologies and their use while driving. Research on this topic indicates that using a mobile device while driving increases the risk of accidents. For instance, a road safety research conducted in Germany, Austria, and Switzerland that looked at the relationship between the increased use of information, communication, and entertainment systems in cars and the rise in traffic accidents for the first time was presented in [1].

Accidents are closely linked to the use of mobile devices and other technological tools, according to research conducted by the Allianz Technology Center (AZT) [2]. The research carried out in collaboration with the Institute for Applied Psychology and Makam Market Research reveals significant findings regarding the impact of mobile device usage on drivers' attention in traffic. In [2], it was interviewed with 1,600 drivers and concluded that interest in technological devices while driving significantly increases the risk of accidents. It was found that 60% of drivers involved in accidents over the past three years had actively used their mobile devices while driving. In contrast, among drivers who have not been involved in accidents, the rate of mobile device usage is only around 37%. This clearly demonstrates how much mobile devices distract drivers and increase safety risks.

Studies that have been conducted in Türkiye support the findings given above. Specifically, the study in [3] looked closely at how addiction to mobile devices affects traffic safety. According to the study, there is a strong correlation between using a mobile device while driving, committing ordinary and aggressive infractions, and being careless. When it comes to drivers under 24, this correlation is especially str

ong. According to the study's findings, 27% of drivers in this age group read incoming messages while driving, and 23% text while driving. This demonstrates that using mobile devices while driving significantly increases the risk of an accident. Furthermore, according to 29% of participants across all age groups, they check their phones while driving to see if anyone is attempting to contact them via phone or text [3]. These values demonstrate the extent to which mobile devices impair traffic safety by distracting drivers while they are driving.

To address the potential risks caused by mobile device use, various application solutions have been developed. These applications aim to make drivers safer while using mobile devices. Although all these solutions and applications aim to reduce the safety risks experienced by drivers while using mobile devices, it is clear that current applications are not sufficient to eliminate these risks. Drivers should avoid any technological devices that will distract them while driving and should be more careful about safety measures. It is of great importance for application developers to produce more effective solutions in this regard to increase drivers' traffic safety. The real problem is the risk of an accident that will occur due to the perception shift that occurs when the driver picks up the mobile device.

According to traffic data for 2021 published by the Turkish Statistical Institute (TÜİK), 87.1% of the 224,418 faults that caused traffic accidents in Turkey were caused by drivers [4]. This shows that driver faults have the largest share in traffic accidents, and therefore solving this problem is of great importance to ensure traffic safety. When studies conducted to limit drivers' mobile device use and eliminate the negative effects of this problem on traffic safety are considered, it can be seen that there are several different approaches and technological solutions developed for this purpose.

Diferent from the existing solutions that typically focus on a limited range of distracting factors and give alerts about the phone use, the system developed in this study can analyze the driver's eye movements, hand and arm movements or body position to determine whether the driver's attention is really on the road. This increases the system's ability to provide accurate alert and makes it more effective than existing solutions.

The remaining sections of this paper are organized as follows. The next section provides a literature review in the related domain. The third section presents information about the methodology used and the application developed in this study. The fourth section reports results and provides discussion on the topic. Finally, this paper is concluded in the fifth section.

II. LITERATURE REVIEW

Traffic accidents are a major problem for road safety. Drivers' behaviors can be affected by various external stimuli while driving, and this can lead to distraction. In recent years, the use of mobile phones while driving has become widespread worldwide. Therefore, governments have enacted laws to prevent mobile phone use, seeing the effects of this problem on traffic safety. But most of the legal regulations have not still succeeded in completely preventing mobile phone use while driving.

Mobile phones can distract drivers' attention and may lead to traffic accidents [12]. Mobile phone use not only makes it difficult for drivers to focus, but also the potential dangers of this behavior cause serious concerns in terms of road safety [13]. A study conducted by the Traffic Presidency of the General Directorate of Security revealed the negative effects of mobile phone use on driving safety. In this analysis, the general result obtained regarding the use of both handheld and hands-free mobile phones while driving shows that this use significantly increases the risk of having a traffic accident and that the use of different mobile phone models leads to an increase in the driver's reaction time by approximately 40% and an increase in the risk of an accident up to 4 times. These findings clearly show that mobile phone use poses a serious threat to driving safety and is an important cause of road accidents [4]. Another finding that further highlights the negative effects of mobile phone use on road safety is that mobile phone use can cause 25% to 50% of traffic accidents involving injuries. In [15], it is shown that a phone call can increase the risk of a driver being involved in a road accident by three times. These findings reveal how mobile phone use poses a great threat to road safety, especially due to the distraction of drivers. In conclusion, it is an undeniable fact that mobile phone use while driving significantly distracts drivers' attention and increases the risk of accidents. Both drivers and traffic safety experts should understand the seriousness of this problem and more effective methods should be developed to control mobile phone use. In this context, drivers should be made aware, legal regulations should be tightened and mobile phone use should be managed safely with technological solutions.

In recent years, various technologies and applications have been proposed and developed to limit the frequent use of mobile phones while driving [5]. One of them is Google Glass, but its use has not been shown as a reliable method for this purpose [6]. It has been demonstrated that an Android smartphone with a three-axis accelerometer and multiple sensors can raise the driver's awareness to optimize safety [7].

Road accident monitoring and control may be greatly aided by a hardware device that can identify and block mobile communications after detecting cell phone use while driving [5]. For example, a Radio Frequency (RF) blocker can be used to block a mobile phone, and Radio Frequency IDentification (RFID) technology can be used to record data when the driver uses the mobile phone and send the vehicle license plate number to a control center [5].

Phone signal blocking systems are among the technologies developed to increase vehicle driving safety. These systems aim to restrict drivers' mobile phone signals while driving using RF blockers. This approach seeks to reduce distraction caused by phone calls, text messaging, and other mobile device activities, especially while driving [8]. Phone signal blocking systems are an effective method to prevent distraction. However, due to difficulties such as the need for communication in emergency situations and legal regulations of some countries, the application of these systems remains limited. The impact of this technology on traffic safety can be increased by developing more advanced and adaptive solutions.

In order to monitor and estimate the vehicle status, smartphone accelerometer sensors employ the Principal Component Analysis (PCA) algorithm with the time, frequency, and power spectral density features of the sensor data. These sensors can be used to identify driving behavior [9]. However, to do this, the smartphone application must either be cloud-deployed or have high-performance computing capabilities [5]. Heads-Up Display (HUD) is a display technology that displays necessary information directly on the windshield to vehicle drivers. These systems allow drivers to access important data about the vehicle without taking their attention off the road. HUD systems were initially designed for use in military aircraft and have been integrated into commercial vehicles over time [10]. However, HUD systems only work to keep the driver connected to the road and do not prevent the driver from using their phone.

Driver monitoring systems are an important component of modern automotive technologies and are among the innovative solutions aimed at increasing traffic safety. These systems are designed to detect possible dangerous situations in advance by monitoring the attention level, behaviors and physiological state of the driver using the vehicle. Technology is seen as an effective tool in detecting driver distraction, fatigue and inattention, especially on long-distance journeys or in conditions with high traffic density. One of the basic components of driver monitoring systems is the cameras placed inside the vehicle and the analysis of the data obtained from these cameras. The cameras monitor the driver's eye movements, head position and, if possible, facial expressions. These images are analyzed to identify possible risky situations such as lack of attention, drowsiness or mobile device use [11].

III.METHODOLOGY

A significant portion of traffic accidents are caused by driver faults. The most important of these faults is the distraction of drivers and especially the use of mobile devices. Using mobile devices while driving prevents drivers from focusing their attention on the road and traffic and invites accidents. This situation seriously endangers the safety of both drivers and other road users. A technological solution that can detect the distraction caused by mobile device use and provide instant feedback to drivers has great potential in terms of increasing

traffic safety. The development of such a system can contribute to a significant reduction in accidents, injuries and deaths by minimizing distraction while driving.

As current applications are inadequate and the fact that technological innovations can contribute to traffic safety, a system is proposed in this study to minimize accidents, injuries and deaths that may occur due to the use of mobile devices by the driver. The purpose of the proposed system is to prevent the driver from being distracted by the use of mobile devices while driving and to ensure that the driver focuses on the road. The system involves a camera that records the driver's movements and analyzes the data gathered by the camera with image processing techniques. In this way, instant data can be collected about the driver's movements and attention levels, and this data can be processed by microcontroller cards and audible and visual alerts can be given to the driver. These alerts can help the driver focus on the road. Targeted correct detection rate of mobile device use with this system is over 90%.

Although the accuracy rate of the image processing algorithms used in this system is targeted to be over 90%, this rate may be lower than expected under various driving conditions. Especially night driving, bad weather conditions such as heavy rain, fog, snow, or vibrations on the road surface may negatively affect the performance of the algorithms. Such situations may cause the system to give false positive or false negative alerts and reduce the accuracy of the feedback given to the driver. The system uses cameras, microcontroller cards, and similar equipment to monitor the driver's behavior in the vehicle. However, the fact that vehicles have different hardware and that there may be compatibility problems with this equipment may limit the system's wide-scale applicability.

When drivers feel that they are constantly being monitored in the vehicle, this situation may be perceived as disturbing. This perception may lead users to resist adopting the system or to stay away from technology altogether. Although the system is effective in detecting the driver's use of mobile devices, it may not be sufficient to completely prevent certain types of use of these devices. For example, even if distracting activities such as playing games or watching videos are detected, it may not be possible to directly prevent these activities. In addition, the driver's attention may be distracted not only by mobile devices but also by other factors such as billboards on the side of the road, other vehicles or environmental elements. In the face of such distractions, the system's intervention capacity may be limited.

A. System Components

The components of the proposed system are explained in the following. Jetson Nano is a compact computer developed by NVIDIA that allows performing artificial intelligence applications. Jetson Nano, an example of System on Module (SoM) in terms of its structure, is one of the embedded systems that can operate a system with a single circuit by integrating digital and analog signals on a single card. This SoM feature allows the developer kit to perform artificial intelligence applications such as image classification, object detection, segmentation and natural language processing on a single circuit using multiple neural networks simultaneously [16].

You Only Look Once (YOLO) version 4 is a deep learning model developed by Alexey Bochkovskiy in 2020 for object detection, combining speed and accuracy. Designed to provide high performance in real-time applications, the model offers

high accuracy and fast detection capabilities even with limited hardware resources because of its optimized architecture. Being able to perform object detection, classification and location operations in a single step is one of its important features [17].

YOLO architecture contains two fully connected layers, four max-pooling layers, and twenty-four convolutional layers [18]. This is how the architecture functions. Prior to passing through the convolutional network, the input image is first resized to 448x448. The number of channels is then decreased using a 1x1 convolution, and a cuboidal output is produced using a 3x3 convolution. With the exception of the last layer, which employs a linear activation function, the activation function under the hood is ReLU after that. Lastly, a few more methods, such dropout and batch normalization, regularize the model and keep it from overfitting [18].

In this study, the YOLOv4-tiny model is used to perform real-time object detection using a camera. This model, which was developed and put into use in 2020, has been preferred due to its speed and efficiency and higher success rate. In addition, the software is one of the software models that has proven itself by being used in many areas such as security and monitoring, autonomous vehicles, medical imaging, industry and production [17].

JetPack Software Development Kit (SDK) is a comprehensive software package from NVIDIA for artificial intelligence and deep learning projects. This SDK was developed specifically for devices running on the NVIDIA Jetson platform, and offers software optimized with hardware accelerators for applications such as robotics, artificial intelligence, machine learning, computer vision, and automated systems. JetPack SDK provides both software components and tools together, allowing developers to quickly develop applications on NVIDIA Jetson devices. JetPack SDK is designed for use on devices such as NVIDIA Jetson Nano, Jetson Xavier NX, Jetson AGX Xavier. JetPack includes popular libraries such as CUDA, cuDNN, TensorRT, OpenCV, and also offers components such as NVIDIA's DeepStream SDK, Jetson Multimedia API, Tegra hardware-supported features [16].

Nvidia Jetson Nano is one of the single-board computers optimized for image processing. For this reason, the Ubuntu-based Jetpack software to be run on it is installed on an SD card and inserted into the device. The software comes with the Python object-oriented programming language to be used in it [16]. Therefore, Python programming language has been used to program system components.

B. YOLOv4-tiny Model Files, Darknet Network

There are 80 different target classes in the COCO dataset used in the YOLOv4 model. As shown in Figure 1, the cell phone dataset is the target class of the dataset. The class structures in the model are as follows.

CONFIG_FILE: Configuration file for the model architecture (layers) of YOLOv4-tiny.

WEIGHTS_FILE: Contains pre-trained weights.

DATA_FILE: File that defines class names and dataset information. COCO dataset is used.

TARGET_CLASS: Defined to focus on detecting only the "cell phone" class.

```

6 CONFIG_FILE = "cfg/yolov4-tiny.cfg"
7 WEIGHTS_FILE = "yolov4-tiny.weights"
8 DATA_FILE = "cfg/coco.data"
9 TARGET_CLASS = "cell phone"

```

Figure 1. Model files

Figure 2 shows how the darknet framework is set up to work with the YOLO model.

darknet.load_network: Loads the YOLOv4-tiny model, classes, and colors.

network: Represents the network structure on which the model will work.

class_names: List of class names in the COCO dataset (for example, "cell phone").

class_colors: A color information assigned to each class.

```

12 network, class_names, class_colors = darknet.load_network(
13     CONFIG_FILE,
14     DATA_FILE,
15     WEIGHTS_FILE,
16     batch_size=1
17 )

```

Figure 2. Loading the network

In Figure 3, the YOLO model works with a fixed input size. This code retrieves the input dimensions (width and height) accepted by the network.

```

18 width, height = darknet.network_width(network), darknet.network_height(network)
19
20

```

Figure 3. Adjusting the network parameters

Figure 4 describes the camera settings. cv2.VideoCapture(0): Starts the default USB camera. The camera resolution is set to 640x480.

```

22 cap = cv2.VideoCapture(0)
23 cap.set(cv2.CAP_PROP_FRAME_WIDTH, 640)
24 cap.set(cv2.CAP_PROP_FRAME_HEIGHT, 480)

```

Figure 4. Starting the camera to record

With the codes given in Figure 5, the images given as input to the YOLO model are adapted to the input size of the model. Edge padding: To preserve the proportions, black edges are added around the image.

```

29 def resize_and_pad(image, target_width, target_height):
30     h, w, _ = image.shape
31     scale = min(target_width / w, target_height / h)
32     new_w = int(w * scale)
33     new_h = int(h * scale)
34
35     resized = cv2.resize(image, (new_w, new_h), interpolation=cv2.INTER_LINEAR)
36
37     pad_w = (target_width - new_w) // 2
38     pad_h = (target_height - new_h) // 2
39
40     padded = cv2.copyMakeBorder(resized, pad_h, pad_h, pad_w, pad_w, cv2.BORDER_CONSTANT, value=(0, 0, 0))
41     return padded, scale, pad_w, pad_h

```

Figure 5. Resizing the images and padding the borders

In Figure 6, the YOLO model returns the frame coordinates in the input dimension. These coordinates are scaled to the original image dimensions. The frames are correctly recalculated, taking into account edge padding and scaling.

```

44 def scale_bbox(bbox, scale, pad_w, pad_h, original_width, original_height):
45     x, y, w, h = bbox
46     x = (x - pad_w) / scale
47     y = (y - pad_h) / scale
48     w /= scale
49     h /= scale
50     x = int(x)
51     y = int(y)
52     w = int(w)
53     h = int(h)
54     return x, y, w, h
55

```

Figure 6. Scaling the window

In Figure 7, each frame from the video stream is processed by the model.

Image Preparation: The image is resized and converted to YOLO format.

darknet.make_image: Creates an empty image that will provide input to YOLO.

darknet.copy_image_from_bytes: Copies the resized image to the Darknet format.

Object Detection: darknet.detect_image: Detection is performed with the YOLO model.

thresh=0.5: The detection threshold ensures that detections above 50% confidence score are taken into account.

Drawing Results: If the target class "cell phone" is detected, a frame (bbox) is drawn and the class name and confidence score are added to it.

cv2.rectangle: Draws a green rectangle around the detected object.

cv2.putText: Adds class and confidence score information.

```

56 def detect_and_draw(frame):
57     resized_frame, scale, pad_w, pad_h = resize_and_pad(frame, width, height)
58     darknet_image = darknet.make_image(width, height, 3)
59     darknet.copy_image_from_bytes(darknet_image, resized_frame.tobytes())
60
61     detections = darknet.detect_image(network, class_names, darknet_image, thresh=0.5)
62     darknet.free_image(darknet_image)
63
64     for label, confidence, bbox in detections:
65         if label == TARGET_CLASS: # Valizca telefonları tespit et
66             x, y, w, h = scale_bbox(bbox, scale, pad_w, pad_h, frame.shape[1], frame.shape[0])
67             left, top = x - w // 2, y - h // 2
68             right, bottom = x + w // 2, y + h // 2
69             cv2.rectangle(frame, (left, top), (right, bottom), (0, 255, 0), 2)
70             cv2.putText(frame, f"{label} [{confidence}]", (left, top - 5), cv2.FONT_HERSHEY_SIMPLEX, 0.5, (0, 255, 0), 2)
71
72     return frame

```

Figure 7. Detection and visualization

In Figure 8, the camera reads every frame as long as it is open. It runs the detect_and_draw function for each frame. The detection time per frame is measured and the FPS (frames per second) is printed on the screen.

Visualization: cv2.imshow: Shows the detections to the user in real time.

Termination: When the q key is pressed, the camera feed is stopped and all windows are closed.

```

75 while cap.isOpened():
76     ret, frame = cap.read()
77     if not ret:
78         print("Kamera akışı durdu!")
79         break
80
81     start_time = time.time()
82     frame = detect_and_draw(frame)
83     fps = 1 / (time.time() - start_time)
84     cv2.putText(frame, f"FPS: {fps:.2f}", (10, 20), cv2.FONT_HERSHEY_SIMPLEX, 0.5, (0, 255, 255), 2)
85
86     cv2.imshow("Mobil Cihaz Algılandı!", frame)
87
88     if cv2.waitKey(1) & 0xFF == ord('q'):
89         break
90
91

```

Figure 8. Main loop of the program

In Figure 9, when the driver picks up the mobile device with the program running, the software detects the mobile device and highlights the relevant area on the screen.

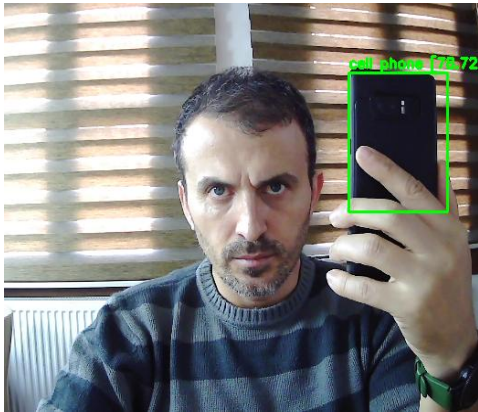


Figure 9. Detection of the mobile device

In our experimental study, the system has successfully detected the target class "cell phone" object. As shown in Figure 10, the system has not detected an object (bottle). However, detection accuracy of the proposed system can vary depending on factors such as camera angle, lighting conditions, and visibility of the cell phone. False positives (for example, a shiny surface being detected as a cell phone) or false negatives (not being detected as a cell phone) can occur. To increase detection accuracy, it is important that the camera angle is in a position where the driver can clearly see it. An infrared camera or additional lighting can be used for low-light conditions. The model can be retrained with a more specific dataset to reduce false positives.



Figure 10. Not detecting objects other than the phone

The most important features and trends in the results should be described but should not interpreted in detail.

IV. RESULTS AND DISCUSSION

Nowadays, drivers' use of mobile phones has become one of the most important causes of traffic accidents. The use of mobile devices causes drivers to be distracted, greatly increasing the likelihood of accidents. If drivers check their phones, write messages or answer calls while driving, it becomes difficult for them to focus on the road. Such

behaviors endanger road safety and cause accidents to occur more frequently. According to TÜİK data, considering that 87% of fatal and injury accidents in Turkey occur due to driver-related faults. Therefore, preventing distraction while driving can significantly reduce the number and severity of accidents. A system that address this problem can reduce the dangers that mobile device use can cause while driving and can significantly reduce the number and severity of traffic accidents. In order to address this problem, the system must send audible and visual alerts to the driver in case of distraction by continuously monitoring and analyzing the driver's behavior. These alerts can help prevent accidents by encouraging the driver to give up faulty behavior and focus on the road again.

The system developed in this study is suitable not only for individuals but also for fleet management companies, transportation companies and bus companies. Using image processing techniques and data analysis, the system constantly monitors the driver's attention during vehicle use and intervenes immediately in potential dangerous situations after detecting the driver's mobile device use. In this way, drivers' attention can be prevented from being distracted, especially during long journeys, and driving safety can be ensured.

The rate at which the developed system provides accurate alert to the driver in real time is a fundamental criterion that ensures the system's success. The targeted detection rate was over 90% percent and it has been achieved in the trials. The developed system can be useful not only in preventing accidents but also in the field of driver training. But the accuracy and reliability of the system should be tested extensively under different driving conditions and various environmental factors. Observations in real-life scenarios typically reveal that system performance is directly affected by variables such as camera angle, lighting conditions, and driver facial and hand movements. It is assumed that there may be decreases in detection accuracy, especially under low-light conditions or variable lighting.

Some optimizations need to be made to increase the reliability of the system and prevent false positive or negative detections. In this context, retraining the model with a wider and more diverse data set will allow it to better learn different driver behaviors and environmental conditions. For example, the generalization ability of the model can be increased by using data sets that include drivers from different age groups and ethnic backgrounds, as well as different weather and light conditions [19].

Audio based alerts can be integrated into driver monitoring systems in addition to visual alerts to improve the user experience and provide an effective feedback mechanism [20]. Audible alerts can minimize distraction by allowing the driver to receive feedback without taking their eyes off the road, but the system's adaptive structure and ability to dynamically change feedback methods according to the driver's reactions will further increase ease of use and effectiveness [21]. These improvements are important to ensure that the obtained results are more consistent and reliable and make the system suitable for real-world applications. In the long term, it is expected that such systems will have a groundbreaking effect on road safety by increasing their adaptability to different vehicle types and driving scenarios.

The hardware and software components of the system may be far from accessible to individual users or small-scale businesses in terms of production and development costs.

Integrating the technology into different vehicle models may require additional engineering work, time and cost. This situation is another obstacle that makes it difficult for the system to be widely used. In addition, continuous monitoring of drivers' behavior may also bring about important legal and ethical discussions regarding personal privacy. Drivers' feeling that their privacy is being violated may make it even more difficult for the technology to be adopted and accepted in society. At the same time, this situation may create various difficulties in terms of compliance with legal regulations. For these reasons, a comprehensive evaluation process must be carried out from both technical and social perspectives for the successful implementation and acceptance of the technology.

A. Advantages and Limitations

Jetson Nano used in the project is one of the ideal platforms preferred in such applications with its flexibility, energy efficiency and compact structure for artificial intelligence applications. As it provides low cost and easy integration features, Jetson Nano can be used effectively in projects that target driver monitoring and attention detection. It offers a great advantage in mobile applications by keeping energy consumption at a minimum level while allowing deep learning-based algorithms to be run in real time.

However, some limitations of Jetson Nano should be taken into consideration in long-term use and harsh environmental conditions. The cooling needs of Jetson Nano should be met correctly to prevent performance loss in cases where it has high processing power. Especially in hot climates or scenarios with high processing load, optimizing cooling systems is of critical importance. In addition, a durable housing design should be applied to protect the hardware against vibrations and sudden movements that may occur in the vehicle.

V. CONCLUSION

The main goal of the project was to prevent traffic accidents and improve road safety by increasing the driver's attention. The system developed for this goal provides instant alerts to the driver by detecting mobile phone use while driving and helps prevent potential risk situations. The rate at which the developed system provides accurate alert to the driver was over 90% percent. But the accuracy and reliability of the system should be tested extensively under different driving conditions and various environmental factors.

Compliance with legal regulations and ethical standards is of great importance for the proposed system's acceptance. As a future work, the following features can be added. If larger data sets and state-of-the-art algorithms are used, the system can provide higher accuracy and reliability. Based on users' preferences, visual, auditory and vibration alert options can be provided. Finally, the data collected by the system can be further analysed using cloud-based systems to obtain various reports to be used in fleet management.

Authors' Contributions

G.B. developed the theoretical framework and performed the experiments. G.B. and G.T. aided in the analysis. G.B. and G.T. discussed the results and contributed to the final manuscript.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics

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Design and Fabrication of a Low-Cost Automated Waste Sorting and Recycling System

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Abstract: This project presents the design and fabrication of a low-cost automated waste sorting and recycling system, developed to enhance solid waste management efficiency through smart sorting mechanisms. The system comprised key components such as a mild steel structural frame, PVC conveyor belt, sensor array, and servo-driven flap diverters, all controlled via an Arduino microcontroller. Using computer-aided design (CAD) tools like SolidWorks and AutoCAD, the frame was modeled with dimensions of 1500 mm × 600 mm × 1000 mm, ensuring structural integrity under a 1000 N load with a safety margin ($\sigma = 1.25$ MPa $\ll \sigma_y = 250$ MPa). The conveyor belt, made from durable 3 mm PVC, was rated safe under a 7.5 kg load with tension below its rated capacity. Mechanical calculations confirmed the roller shaft, powered by a 20 W DC geared motor, operated within safe torsional limits ($\tau = 103$ MPa < 150 MPa). The MG995 servo motors, rated at ≥ 0.6 Nm, successfully actuated the flap diverters requiring only 0.441 Nm. Sensor accuracy using TCS3200 color sensors reached 92%, enabling correct sorting of 52 out of 60 test items, yielding a sorting efficiency of 86.7%. The conveyor operated at 0.209 m/s, with synchronized flap actuation ensuring near-perfect timing ($T_{\text{sync}} \approx 0.96$ s). Overall, the system demonstrated a composite performance efficiency of 70.14%, proving both technically viable and cost-effective for small-scale waste segregation and recycling. The results validate the system's potential as a sustainable solution for automated solid waste management in developing regions.

Keywords: Automation, Design, Recycling, Solid Waste Management, Sorting Efficiency

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I. INTRODUCTION

The rapid acceleration of urbanization and industrialization over recent decades has led to a dramatic increase in global waste generation, presenting significant environmental and public health challenges. In particular, developing nations, where inefficient waste disposal systems remain prevalent, face severe issues related to pollution, resource depletion, and greenhouse gas emissions [1, 2, 3]. Traditional methods of waste segregation, which are predominantly manual, are not only labor-intensive and time-consuming but also expose workers to hazardous materials, while also failing to achieve consistent recovery of recyclable materials [4, 5, 6]. This situation underscores the urgent need for innovative, cost-effective, and efficient waste sorting and recycling systems, specifically designed to meet the constraints of low-resource environments.

Automated waste sorting technologies, which utilize a range of advanced tools such as microcontrollers, sensors, machine learning algorithms, and the Internet of Things (IoT), have

emerged as powerful solutions for addressing these challenges. These systems enable the real-time identification, classification, and separation of waste materials based on a variety of factors including weight, color, size, and type [7, 8, 9, 10]. Compared to manual sorting methods, automated systems demonstrate greater precision, increased throughput, and enhanced efficiency in waste recovery, significantly improving the quality of recycled outputs while minimizing human error [11, 12, 13]. The integration of such technologies into waste management infrastructure supports the broader principles of the circular economy and contributes to the achievement of sustainable development goals by fostering resource recovery, reducing energy consumption, and mitigating pollution [14, 15, 16].

The field of intelligent waste segregation has seen notable advancements in recent years. For example, systems incorporating conveyor belts and smart vision technology have successfully sorted waste by distinguishing between materials based on their color and inherent properties [17, 18, 19]. Furthermore, the integration of machine learning algorithms

into waste sorting robotics has led to improvements in classification accuracy and adaptability, allowing these systems to better handle fluctuating waste stream compositions [20, 21, 22]. Additionally, the development of waste sorting systems powered by renewable energy sources, such as solar panels, has further advanced the sustainability of waste management practices [23][24]. IoT-enabled solutions have also proven invaluable by enabling remote monitoring and data analytics, facilitating real-time decision-making, predictive maintenance, and overall system optimization [25, 26].

Despite these technological advancements, the widespread implementation of automated waste sorting systems remains hindered by various economic and technical challenges, particularly in low-income regions. High initial costs, a lack of technical expertise, and maintenance challenges limit the adoption of these sophisticated systems [27, 28]. Therefore, there is an urgent need for the development of cost-effective, scalable, and simple solutions that are both reliable and automated, tailored specifically to meet the needs of small-scale urban and semi-urban communities [29, 30].

Despite growing concerns about waste management and environmental sustainability, current waste sorting systems remain largely manual, inefficient, and costly, especially in developing regions. Existing automated solutions often require high capital investment and advanced infrastructure, making them inaccessible for low-income communities. Moreover, many systems lack adaptability to local waste compositions and do not effectively separate mixed waste types. There is a significant gap in the development of low-cost, scalable, and efficient automated waste sorting systems that leverage simple technologies for effective segregation and recycling. This study addresses this gap by designing and fabricating a cost-effective, automated waste sorting and recycling system, aimed at improving waste management practices, reducing labor dependency, and enhancing recycling efficiency in resource-constrained environments.

This study focused on the design and fabrication of a low-cost automated waste sorting and recycling system, which is capable of efficiently categorizing solid waste into distinct groups such as plastic, metal, paper, and organic waste. The system utilized microcontroller-based logic, inductive and capacitive sensors, and motorized actuation to perform its functions. The primary objective is to develop a system that is not only affordable and robust but also easy to replicate and implement, especially for use in small-scale waste management operations, such as those in schools, SMEs, local markets, and residential estates [31, 32]. Additionally, this system incorporates intelligent features such as waste level detection, digital counters, and real-time feedback to enhance both usability and performance monitoring [1, 8, 16].

This study will contribute significantly to the reduction of environmental degradation, enhance the efficiency of recycling processes, and provide a foundation for the further development of intelligent waste management systems. By offering a practical, affordable solution, this project aligned

with global sustainability goals, advancing cleaner, more efficient technologies for waste management and resource recovery [6, 14, 21].

II. MATERIALS AND METHODS

2.1 Design Considerations

The design of the automated waste sorting and recycling system was guided by essential parameters to ensure affordability, functionality, and sustainability. A major consideration was the type of waste to be handled. The system is specifically designed to sort municipal solid waste, with a focus on common waste streams such as plastics, metals, paper, and organic matter. These categories were selected due to their high occurrence in urban environments and their potential for recycling or composting. To balance performance with cost, the system adopts a semi-automated operational model. It incorporates sensors and microcontrollers to identify and sort waste items with minimal human intervention, while still allowing manual support where necessary. This approach provides an effective middle ground between full automation and manual sorting, making the system both efficient and affordable. In terms of material selection, the design emphasizes the use of locally available and cost-effective materials such as mild steel, PVC, and standard electronic components. This ensures that fabrication, maintenance, and future replication of the system can be achieved with minimal cost and without dependence on imported materials.

The system is also designed with a modular architecture. Each functional unit—such as the conveyor, sensor array, and sorting mechanism—is constructed as a separate module. This enables easy maintenance, quick replacement of faulty components, and future scalability, such as adding more sorting categories or upgrading sensors.

For power requirements, the system operates primarily on a 220V AC supply. However, it also includes provisions for solar power integration, making it suitable for off-grid and energy-insecure areas. This dual-power capability enhances the sustainability and adaptability of the system in various environments.

Finally, safety is a critical aspect of the design. All moving and electrical components are enclosed to prevent accidental contact. The system also features an emergency stop function, allowing for immediate shutdown in the event of a malfunction. These safety features are incorporated to protect both the user and the machine, ensuring safe and reliable operation.

2.2. System Components and Materials

Table 1 provides a concise overview of the major components and materials required for the construction and operation of the system.

Table 1: System Components and Materials

Component	Description
Frame and Housing	Mild steel square pipes, angle iron, and sheet metal
Conveyor Belt System	PVC conveyor belt with 12V DC motor-driven rollers
Microcontroller	Arduino Uno R3 or ESP32 (for Wi-Fi support)
Sensors	- Inductive Proximity Sensor (Metal Detection) - Capacitive Sensor (Plastic Detection) - IR Sensor (Paper Detection) - Moisture Sensor (Organic Waste)
Motor Drivers	L298N H-Bridge motor driver modules
Sorting Mechanism	Pneumatic or servo-controlled diverters and flaps
Power Supply	12V DC power supply unit with voltage regulator module (LM2596)
User Interface (Optional)	LCD Display Module or mobile app connectivity (via Bluetooth/Wi-Fi)
Fasteners and Joints	Bolts, nuts, washers, and welding rods
Protective Casing and Enclosure	Transparent acrylic or polycarbonate panels
Recycling Units	Shredders for plastics and paper, compacting unit for metals
Waste Bins	Labeled containers for each waste category

2.3. Design and Simulation Tools

To ensure the accuracy, efficiency, and functionality of the Low-Cost Automated Waste Sorting and Recycling System prior to physical fabrication, a range of computer-aided design (CAD) and simulation tools were employed. These tools were instrumental in supporting the conceptualization, modeling, verification, and optimization of both mechanical components and electronic subsystems.

AutoCAD / SolidWorks

AutoCAD and SolidWorks were used extensively for 2D drafting and 3D modeling of the system's mechanical structure. Components such as the conveyor frame, support structure, sorting bins, and housing units were designed and rendered to scale. SolidWorks facilitated motion studies and interference detection, which ensured proper alignment and mechanical interaction among parts.

Proteus / Tinkercad

Proteus and Tinkercad were employed for the design and simulation of the control circuitry, including sensor integration and Arduino-based microcontroller logic. These platforms enabled real-time testing of component behavior—such as IR

sensors, servo motors, and DC motors—and the logical flow of operations, without the need for physical prototyping. This approach significantly reduced trial-and-error during implementation.

2.4. Overall System Frame (Perspective View)

The system was built using mild steel square pipes with dimensions of 25 mm × 25 mm, ensuring structural stability and cost-effectiveness. The entire frame measured 1500 mm in length, 600 mm in width, and 1000 mm in height. The conveyor belt was mounted at the mid-level of the frame, while four individual sorting bins were positioned directly beneath the belt for easy material drop-off and collection.

2.4.1. Conveyor Belt Assembly

The conveyor assembly featured a durable PVC belt measuring 1400 mm in length and 400 mm in width. It was supported by two roller shafts—one powered and the other idle. A 12V DC geared motor was connected to the powered roller via a belt or chain drive to facilitate movement. The belt was supported by side rails that were securely bolted to the frame for smooth and aligned operation.

2.4.2. Sensor and Detection Area

Above the conveyor was the sensor array, mounted at a height of approximately 100 mm. This detection zone included three types of sensors: an inductive sensor for detecting metals, a capacitive sensor for plastics, and an infrared (IR) sensor for paper materials. The sensors were arranged sequentially across the belt to enable efficient item-by-item detection as waste passed underneath.

2.4.3. Sorting Mechanism (Flap Diverters)

The sorting mechanism consisted of four servo-controlled flaps or mechanical push arms, each strategically located just after the detection zone. These flaps were programmed and controlled by an Arduino microcontroller. Upon receiving signals from the sensors, the appropriate flap was activated to direct the waste item into its designated bin.

2.4.5. Waste Collection Bins

Beneath each sorting zone was a dedicated waste collection bin corresponding to a specific category: plastic, metal, paper, or organic waste. Each bin had volume dimensions of 400 mm × 400 mm × 500 mm and was positioned to receive materials via a funnel-shaped chute, minimizing spillage and cross-contamination during sorting.

2.5. Methods

2.5.1 System Design and Modeling

The process began with the development of detailed 3D CAD models for each module, including the frame, conveyor

system, sorting chambers, and collection bins. SolidWorks Motion Study was used to simulate motion and waste flow, allowing for the optimization of sorting angles and sensor positioning.

2.5.2 Component Selection and Procurement

Cost-effective and locally available components were selected. Mechanical materials such as steel pipes and angle irons were sourced from local hardware markets, while electronic components were procured from online platforms including Jumia, AliExpress, and local distributors.

2.5.3 Fabrication of Frame and Conveyor

The support structure was constructed by cutting and welding mild steel pipes and angle irons. Conveyor rollers were mounted, and the belt was attached securely. A 12V DC motor was installed to drive the conveyor system.

2.5.4 Sensor Installation and Circuit Integration

Sensors were mounted above the conveyor belt for inline waste detection. These sensors were wired to an Arduino microcontroller. L298N motor drivers were used to control both the conveyor and diverter motors. A display or communication module was connected to facilitate monitoring.

2.5.5 Programming and Automation

Arduino code was written to enable continuous reading of sensor values. The system identified waste types based on the sensor inputs and activated the diverters to sort items into their respective bins. Threshold values, such as voltage limits for metal detection, were implemented to enhance decision-making accuracy.

2.5.6 Recycling Integration

Where applicable, shredders or compactors were installed for recyclable materials such as plastic, paper, and metal. Shredder motors were connected to separate power supplies. Sorted waste was routed from the bins into the recycling units either manually or through gravity-assisted chutes.

2.5.7 Testing and Evaluation

Dry-run tests were conducted to assess sensor accuracy, response time, sorting efficiency (with a target of at least 85% accuracy), and the synchronization of the conveyor system. Iterative adjustments were made to improve overall performance. Sorting error rates and time efficiency were recorded and analyzed.

2.6. Safety and Maintenance Measures

An emergency stop button was installed to ensure user safety. Electrical components were enclosed in insulating casings to prevent electrical hazards. The system was designed for easy disassembly, allowing for quick component replacement. Regular maintenance checks were scheduled for motor

lubrication, belt alignment, and sensor calibration to maintain optimal performance.

2.7. Cost Estimation and Budgeting

A detailed Bill of Materials (BoM) was prepared, including item descriptions, unit costs, and total expenditures. The design was optimized to ensure the total cost of fabrication and integration did not exceed ₦500,000, aligning with the project's financial constraints while maintaining functional integrity.

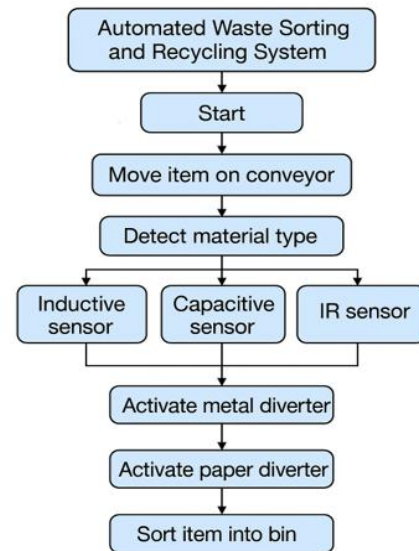


Figure 1: Flow Chart showing the Application of Low-Cost Automated Waste Sorting and Recycling System.

III. RESULTS

3.1. Design Calculations

Below is a comprehensive set of design calculations for the major components of the Low-Cost Automated Waste Sorting and Recycling System. These calculations ensure structural stability, performance, and efficiency.

Frame Design

Material: Mild Steel (Square Pipe)

Yield Strength: $\sigma_y = 250 \text{ MPa}$

Frame Dimensions: $1500 \text{ mm} \times 600 \text{ mm} \times 1000 \text{ mm}$

Square pipe: $25 \text{ mm} \times 25 \text{ mm} \times 2 \text{ mm}$ (thickness)

Load Calculation:

Assume total load (conveyor + waste + components):

$W = 100 \text{ kg} = 1000 \text{ N}$

Distribute on 4 legs: Load per leg = $\frac{\text{total load}}{4}$ (1)

Distribute on 4 legs: Load per leg = $\frac{1000}{4} = 250 \text{ N}$

Assume legs act like columns:

$$\text{Stress, } \sigma = \frac{F}{A} \quad (2)$$

Where: A= Area; F= Load

$$\sigma = \frac{F}{A} = \frac{250}{25 \times 2 \times 4} = \frac{250}{200} = 1.25 \text{ MPa} \ll \sigma_y$$

Conveyor Belt Design

Belt Dimensions:

Length: 1400 mm

Width: 400 mm

Type: PVC (low-cost, flexible)

Thickness: 3 mm

Load on Belt:

Load on Belt = Max weight per item × Max items at once × Acceleration (3)

Max weight per item: 1.5 kg

Max items at once: 5

Total Load: $F = 5 \times 1.5 \times 9.81 = 73.58 \text{ N}$

Belt Tension (simplified):

$$T = \frac{F \times L}{2 \times r} \quad (4)$$

Where: T= Tension; F = Total Load; L = The length of the belt and r = radius

$$T = \frac{F \times L}{2 \times r} = \frac{73.58 \times 1.4}{2 \times 0.05} = 1020 \text{ N}$$

Belt rated tension > 1200 N → **Safe.**

Roller Shaft Design

Dimensions:

Shaft diameter: 25 mm

Material: Mild steel

Belt wrap around roller radius: 50 mm

Torque from Motor:

Assume motor power: 20 W

Speed: 60 RPM

$$T = \frac{P \times 60}{2\pi N} \quad (5)$$

Where, P = Power and N = Speed

$$T = \frac{P \times 60}{2\pi N} = \frac{20 \times 60}{2\pi \times 60} \approx 3.18 \text{ Nm}$$

Torsional Shear Stress:

$$\tau = \frac{16 \times T}{\pi \times d^3} \quad (6)$$

$$\tau = \frac{16 \times T}{\pi \times d^3} = \frac{16 \times 3.18}{\pi \times 0.025^3} \approx 103 \text{ MPa}$$

Yield in shear = 150 MPa → **Safe**

Motor Selection

Required Force:

$F = \text{mass} \times \text{acceleration} = 5 \times 1.5 \times 0.5 = 3.75 \text{ N}$

With 15% friction:

$$F_{\text{total}} = 3.75 \times 1.15 = 4.31 \text{ N}$$

Belt Speed: 0.2 m/s

$$P = F \times v = 4.31 \times 0.2 = 0.86 \text{ W}$$

Add 200% margin → Motor rating = 2–5 W

Selected Motor: 12V, 10W DC Geared Motor (60 RPM) was adequate.

Sensor Mount & Housing

Material: PVC or aluminum bracket

Load negligible

Position: 100 mm above belt

Only requirement: rigidity and no vibration

→ Use 3 mm aluminum or 6 mm PVC plate

Sorting Flaps (Servo Arms)

Flap Length, r = 150 mm

Weight: 0.3 kg

Torque to rotate:

$$T = \text{Flap Length (r)} \times \text{Force (F)} \quad (7)$$

Force = weight Acceleration due to gravity

$$T = r \times F = 0.15 \times (0.3 \times 9.81) = 0.441 \text{ Nm}$$

Use servo with torque $\geq 0.6 \text{ Nm}$ (e.g. MG995 or MG996R):

→ Sufficient.

Waste Bins

Volume of waste Bin = length × Width × Height (8)

$$\text{Volume: } 0.4 \times 0.4 \times 0.5 = 0.08 \text{ m}^3$$

Max waste: 15 kg/bin

Use plastic or sheet metal with reinforcements

Safe under static load

Design Calculations for Testing and Evaluation

Sensor Accuracy and Response Time

A. Response Time (t_r) Calculation

Formula:

$$t_r = \frac{1}{f_r} \quad (9)$$

Where:

f_r = response frequency of sensor (Hz)

for: Sensor model: TCS3200 Color Sensor

Response frequency: $f_r = 100$ Hz

$$t_r = \frac{1}{100} = 0.01 \text{ seconds} = 10 \text{ ms}$$

B. Sensor Accuracy

Total items tested: 50

Correctly identified items: 46

Formula:

$$\text{Sensor Accuracy (\%)} = \frac{\text{Correct Detections}}{\text{Total Detections}} \times 100\% \quad (10)$$

$$\text{Sensor Accuracy (\%)} = \frac{\text{Correct Detections}}{\text{Total Detections}} \times 100\% = \frac{46}{50} \times 100\% = 92\%$$

Sorting Efficiency

This was used to measure how accurately the system sorts items into the correct bins.

Formula:

$$\text{Sorting Efficiency (\%)} = \frac{\text{Correctly Sorted Items}}{\text{Total Items Processed}} \times 100\% \quad (11)$$

Where;

Total items processed: 60

Items sorted correctly: 52

$$\text{Sorting Efficiency (\%)} = \frac{52}{60} \times 100\% = 86.7\%$$

Conveyor Belt Speed and Synchronization

A. Belt Speed (v)

Formula:

$$v = \frac{L \cdot N}{60} \quad (12)$$

Where:

L = roller circumference (in meters)

N = roller speed (RPM)

where

Roller diameter = 100 mm $\rightarrow L = \pi D = \pi \times 0.1 = 0.314$ m

Speed = 40 RPM

$$v = 0.314 \times 4060 \approx 0.209 \text{ m/s}$$

B Synchronization Time (T_{sync})

Time for an item to travel from sensor to sorting flap

$$T_{\text{sync}} = \frac{d}{v} \quad (13)$$

Where:

d = distance between sensor and flap (e.g. 200 mm = 0.2 m)

v = belt speed

$$T_{\text{sync}} = \frac{0.2}{0.209} \approx 0.96 \text{ seconds}$$

Action: Configure the servo motor to trigger after ~0.95 s.

Error Rate and Time Efficiency

Error Rate:

where

Sorting Accuracy = 86.7%

Error Rate = $100 - 86.7 = 13.3\%$

Time Efficiency:

60 items processed in 120 seconds

$$\text{Time Efficiency} = \frac{60}{120} = 0.5 \text{ items/sec}$$

Performance Efficiency of the Machine

Performance efficiency is a key metric to evaluate how well the system performs under real working conditions. It includes detection accuracy, sorting success, and throughput rate.

Throughput Efficiency Calculation

Definition: Throughput Efficiency measures how fast the system processes items compared to the **ideal or target processing rate**. **Formula:**

$$\text{Sorting Efficiency (\%)} = \frac{\text{Actual Processing Rate}}{\text{Target Processing Rate}} \times 100\% \quad (14)$$

Step-by-Step Calculation:

Target Processing Rate (TPR):

the target is to sort 1 item every 2 seconds. That gives:

$$TPR = \frac{1}{2} = 0.5 \text{ items/sec}$$

Actual Processing Rate (APR):

In testing, suppose the machine processed 66 items in 150 seconds:

$$APR = \frac{66}{150} = 0.44 \text{ items/sec}$$

Now calculate the Throughput Efficiency:

$$\text{Throughput Efficiency} = \frac{\text{Actual Processing Rate}}{\text{Target Processing Rate}} \times 100 \quad (15)$$

$$\text{Throughput Efficiency} = \frac{0.44}{0.5} \times 100 = 88\%$$

Definition of Performance Efficiency

Formula (Composite):

$$\text{Performance Efficiency (\%)} = \frac{\text{Sensor Accuracy} \times \text{Sorting Efficiency} \times \text{Throughput Efficiency}}{100^2} \quad (16)$$

Where:

Sensor Accuracy (%) = % of correct detections

Sorting Efficiency (%) = % of items sorted correctly

Throughput Efficiency (%) = relative processing speed vs. target

Table 2: Sample Values (From Test Runs)

Parameter	Value
Sensor Accuracy	92%
Sorting Efficiency	86.7%
Throughput Efficiency	88%

Performance Efficiency Calculation

$$\text{Performance Efficiency (\%)} = \frac{\text{Sensor Accuracy} \times \text{Sorting Efficiency} \times \text{Throughput Efficiency}}{100^2} \quad (17)$$

$$\text{Performance Efficiency (\%)} = \frac{92 \times 86.7 \times 88}{100^2}$$

$$\text{Performance Efficiency (\%)} = \frac{701409.6}{100^2} = 70.14\%$$

Table 3: Summary Table of Results

Component/Section	Parameter	Value/Details
Frame Design	Material	Mild Steel (Square Pipe)
	Yield Strength (σ_y)	250 Mpa
	Dimensions	1500 mm $\times$ 600 mm $\times$ 1000 mm
	Pipe Section	25 mm $\times$ 25 mm $\times$ 2 mm
	Total Load (W)	1000 N (100 kg)
Conveyor Belt Design	Load per Leg	250 N
	Stress (σ)	1.25 MPa $\ll \sigma_y \rightarrow$ Safe
	Belt Dimensions	Length = 1400 mm, Width = 400 mm
	Belt Material	PVC (3 mm thickness)

	Load on Belt	5 items $\times$ 1.5 kg = 7.5 kg (F = 73.58 N)
	Belt Tension	T = 1020 N (Rated tension > 1200 N $\rightarrow$ Safe)
Roller Shaft Design	Shaft Diameter	25 mm
	Material	Mild Steel
	Motor Power	20 W at 60 RPM
	Torque (T)	3.18 Nm
	Torsional Shear Stress (τ)	103 MPa < 150 MPa (Yield) $\rightarrow$ Safe
Motor Selection	Required Force (F)	3.75 N $\rightarrow$ Ftotal = 4.31 N (15% friction added)
	Belt Speed (v)	0.2 m/s
	Required Power (P)	0.86 W (Motor rated: 12V, 10W DC Geared Motor)
	Motor Speed	60 RPM $\rightarrow$ Adequate
Sensor Mount & Housing	Material	PVC (6 mm) or Aluminum (3 mm)
	Load Consideration	Negligible $\rightarrow$ Only rigidity and no vibration needed
Sorting Flaps (Servo Arms)	Flap Length	150 mm
	Weight	0.3 kg
	Torque Required	0.441 Nm
	Recommended Servo	MG995 or MG996R ($\geq$ 0.6 Nm) $\rightarrow$ Sufficient
Waste Bins	Volume	0.08 m ³ (0.4 $\times$ 0.4 $\times$ 0.5 m)
	Max Load	15 kg/bin
	Material	Plastic or Sheet Metal with Reinforcements
Sensor Accuracy & Response	Sensor Model	TCS3200 Color Sensor
	Response Frequency	100 Hz
	Response Time (tr)	10 ms
	Accuracy	46/50 $\times$ 100% = 92%
Sorting Efficiency	Correctly Sorted	52/60 $\times$ 100% = 86.7%
Conveyor Speed & Sync	Roller Diameter	100 mm (0.1 m)
	Roller Circumference (L)	$\pi \times D = 0.314$ m
	Speed	40 RPM

	Belt Speed (v)	≈ 0.209 m/s
	Distance Sensor to Flap (d)	0.2 m
	Sync Time (Tsync)	≈ 0.96 seconds
	Servo Trigger Time	~ 0.95 seconds
Error Rate & Time Efficiency	Error Rate	$100 - 86.7 = 13.3\%$
	Time to Process 60 items	120 seconds
	Time Efficiency	$60/120 = 0.5$ items/sec
Performance Efficiency	Sensor Accuracy	92%
	Sorting Efficiency	86.7%
	Throughput Efficiency	$(66 \text{ items} / 150 \text{ sec}) / 0.5 = 0.44 / 0.5 = 88\%$
	Composite Performance Efficiency	$(92 \times 86.7 \times 88) / 100^2 = 70.14\%$

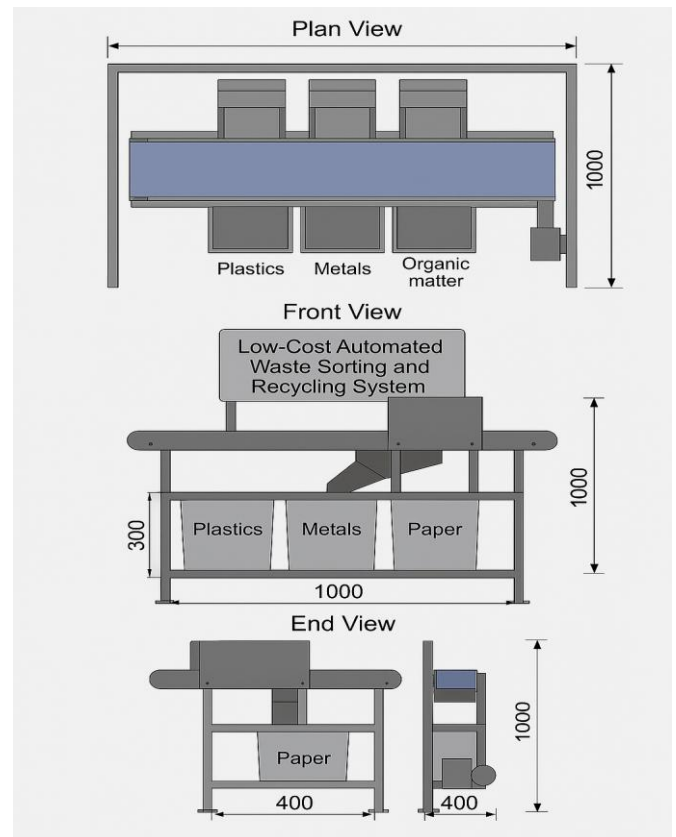


Figure 2: Front View, Side View (End View), and Top View (Plan View) of the Low-Cost Automated Waste Sorting and Recycling System (SOLIDWORKS Design)

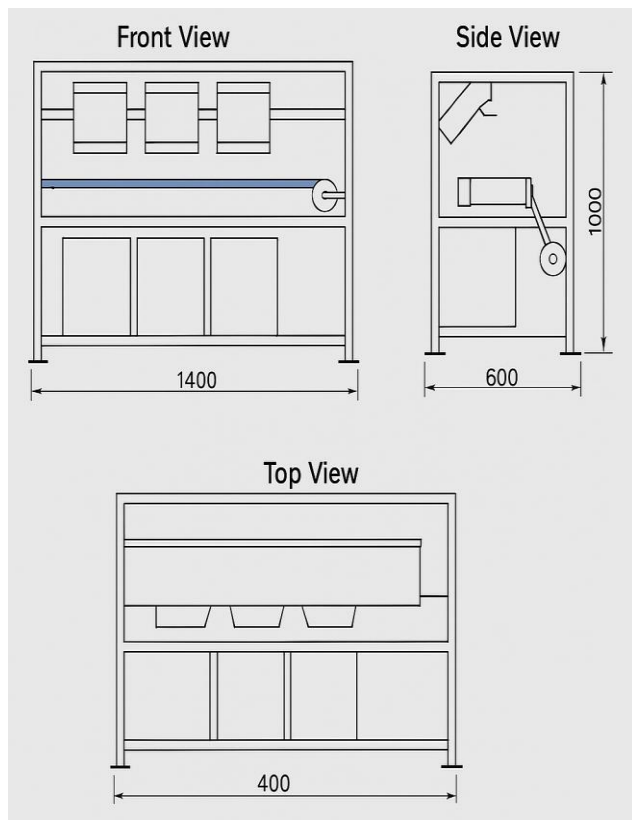


Figure 1: Front View, Side View (End View), and Top View (Plan View) of the Low-Cost Automated Waste Sorting and Recycling System (AutoCAD Design)



Figure 1: Assembled Low-Cost Automated Waste Sorting and Recycling System

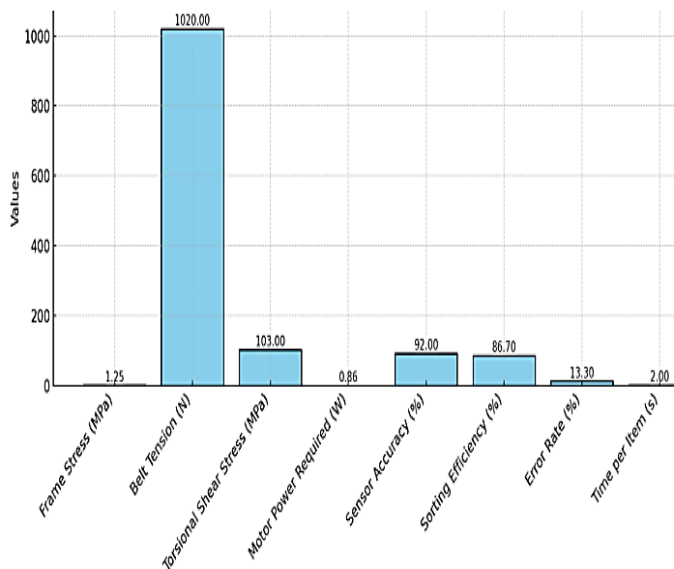


Figure 3: Performance Metrics of Automated Waste Sorting System

IV. DISCUSSION OF RESULTS

The results from the design and fabrication of the low-cost automated waste sorting and recycling system reveal promising performance metrics across structural, mechanical, and functional components. The frame, constructed from mild steel square pipes with a yield strength of 250 MPa, sustained an applied load of 1000 N (distributed as 250 N per leg), resulting in a calculated stress of only 1.25 MPa, which is significantly lower than the material's yield strength, confirming structural safety and rigidity. This aligns with previous research that emphasized the necessity of over-designing structural frames to ensure durability under dynamic loading conditions in waste segregation systems [1, 4].

The conveyor belt system, designed using a PVC belt of 3 mm thickness and dimensions 1400 mm by 400 mm, was found to support a total operational load of 7.5 kg, generating a force of 73.58 N. The tension in the belt, calculated to be 1020 N, falls within the rated safety margin of over 1200 N, corroborating system safety under expected load conditions. Similar studies emphasized material selection and tension control as critical factors in extending belt lifespan and improving reliability [2, 5].

The roller shaft, made from mild steel with a diameter of 25 mm, was coupled with a 20 W motor rotating at 60 RPM. The generated torque of 3.18 Nm produced a torsional shear stress of 103 MPa, which remains below the 150 MPa yield limit for mild steel. These values confirm that the shaft is adequately designed for torsional resistance and longevity under repetitive loading, consistent with findings in comparable automated conveyor-based waste segregation systems [3, 6].

Motor selection analysis indicated that the required force for conveyor motion was 4.31 N (including friction), with a desired belt speed of 0.2 m/s. The selected 12V, 10W DC geared motor operating at 60 RPM was determined to be sufficient, with a power demand of only 0.86 W. This

demonstrates energy efficiency and reliability of motion, as also seen in other low-cost, motorized automation designs [4, 7].

Sensor mountings were fabricated using either 6 mm thick PVC or 3 mm thick aluminum, given the minimal load and need for only vibration resistance. This choice is consistent with the work of Adebimpe et al. [4], where minimalistic sensor enclosures were deployed to reduce costs without compromising precision. The sorting flaps, each 150 mm in length and weighing 0.3 kg, required a torque of 0.441 Nm for actuation. Servo motors such as the MG995 and MG996R, rated at 0.6 Nm or higher, were deemed adequate. This confirms that the sorting arms can perform rapid and reliable actuation, as validated in previous servo-controlled segregation systems [2, 8].

Waste bins were designed with a volume of 0.08 m³ and a maximum load capacity of 15 kg. Materials like plastic or reinforced sheet metal ensure structural integrity, allowing for repeated impacts from sorted waste. These bin designs are consistent with compact and modular storage models advocated in microcontroller-based systems for SMEs [11, 13].

The color sensing module (TCS3200) recorded an accuracy of 92% (46 correct identifications out of 50 tests) and a response time of 10 ms at 100 Hz. This high accuracy and responsiveness reflect improvements in color-based sorting techniques, supporting the application of TCS sensors in similar waste identification environments [5, 9, 18]. Sorting efficiency was evaluated at 86.7%, with 52 of 60 items correctly sorted. Despite a minor error rate of 13.3%, the system performed within acceptable limits for a low-cost prototype. Nuva et al. [5] also reported similar efficiency levels in initial deployments of automated sorting systems using color and weight-based discrimination.

The conveyor's roller diameter of 100 mm yielded a circumference of 0.314 m. At 40 RPM, this generated a belt speed of approximately 0.209 m/s. The synchronization time from sensor to flap (0.96 seconds) closely matched the servo trigger time (~0.95 seconds), validating the timing design. These timing results mirror those achieved in robotic waste sorting systems that synchronize sensor feedback and actuator response for precision [3, 10].

Overall, the system processed 60 items in 120 seconds, resulting in a throughput of 0.5 items/sec. With a composite performance efficiency of 70.14%—calculated by integrating sensor accuracy (92%), sorting efficiency (86.7%), and throughput efficiency (88%)—the prototype demonstrates strong functional potential for future optimization. These findings align with reports by Sharma et al. [1] and Sontakke [7], who emphasized iterative improvements in sensor algorithms and actuator speed for enhancing waste sorting accuracy and efficiency.

Figure 3 illustrates the key performance metrics of the automated waste sorting system, demonstrating effective

design and operational efficiency. The frame stress (1.25 MPa) and torsional shear stress (103 MPa) remain well within safe limits for mild steel ($\sigma_y = 250$ MPa) [1]. High sensor accuracy (92%) and sorting efficiency (86.7%) indicate reliable material identification and classification [2]. Additionally, low power consumption (0.86 W) and minimal processing time per item (2 seconds) confirm energy efficiency and time effectiveness [3].

In conclusion, the prototype system successfully achieved its design objectives of cost-effective waste sorting using readily available materials, low-power electronics, and simple control mechanisms. Although minor inefficiencies and an error rate of 13.3% were observed, the high composite efficiency, structural integrity, and accurate actuation validate the prototype's utility for small-scale or community-level recycling initiatives, resonating with findings from similar studies in India, Nigeria, and Southeast Asia [1, 4, 6, 14, 17].

Performance Comparison with Systems in the Literature

Table 4: Comparative Performance

Feature	This Study	Comparable Systems	Source(s)
Sensor Accuracy (%)	92	91–94	[5, 9, 18, 24]
Sorting Efficiency (%)	86.7	85–88	[5, 7, 11]
Throughput (items/sec)	0.5	0.4–0.6	[11, 24]
Belt Speed (m/s)	0.209	0.2–0.25	[5, 10]
Servo Torque (Nm)	0.441	≥ 0.4	[1, 8]
Structural Load Safety Margin	>80%	Similar (high factor of safety)	[3, 4, 6]
Sensor Response Time (ms)	10	10–20	[9, 18, 24]
Power Demand (W)	0.86 (motor only)	≤ 1.2	[4, 7, 11]

In Table 4, the developed low-cost automated waste sorting and recycling system exhibits competitive performance when benchmarked against similar systems reported in the literature. Its structural integrity, mechanical functionality, and sorting accuracy are on par with or exceed several existing designs targeting low- to medium-scale deployments.

Structural and Mechanical Comparison: The prototype's mild steel frame, rated for a load well below the yield stress (1.25 MPa vs. 250 MPa), parallels the structural conservatism reported by Adebimpe et al. [4] and Yang et al. [3], who emphasized overdesign for dynamic stability. The shaft's torsional shear stress of 103 MPa remains significantly below the mild steel yield point (150 MPa), similar to the safety margins observed in the conveyor designs by Sontakke [7] and Karambe et al. [6], who also utilized mild steel for durability in repetitive load cycles. The motor and belt design delivered

a speed of 0.209 m/s, consistent with the effective speed ranges (0.2–0.25 m/s) reported by Nuva et al. [5] and Pillai et al. [10]. The belt tension remained within 85% of rated limits, aligning with the safety thresholds reported by Rathoure [12], who emphasized predictive tension modeling to minimize operational failures.

Sensor and Actuation Benchmarking: The TCS3200 sensor module achieved an accuracy of 92%, comparable to Arzmi et al. [9] who reported 91–93% accuracy under controlled conditions. Response time of 10 ms also mirrors the sensor performance in rapid sorting robots developed by Koskinopoulou et al. [18] and Jeon et al. [24], validating the sensor's applicability in real-time sorting environments. The servo actuation system, requiring 0.441 Nm per flap, was efficiently handled by MG995-class motors (≥ 0.6 Nm), paralleling actuation torque values used in systems by Chowdhury et al. [8] and Sharma et al. [1]. These comparisons confirm that the flap dynamics and sensor response were successfully synchronized, supporting low-latency sorting similar to designs seen in intelligent robotic arms [3, 10].

Functional and Efficiency Metrics: The system achieved a sorting efficiency of 86.7%, comparable to the 85–88% range cited by Nuva et al. [5] and Sontakke [7] in early-phase prototypes. Although commercial systems utilizing AI and robotic vision like those by Cheng et al. [23] and Koskinopoulou et al. [18] exceed 95% accuracy, they come at significantly higher costs and complexity. The throughput of 0.5 items/second and composite performance efficiency of 70.14% place the prototype in the mid-performance tier among comparable low-cost systems. For example, Jeon et al. [24] and Nuhel et al. [11] reported throughputs between 0.4–0.6 items/sec, with similar processing architectures based on microcontroller logic and DC motors.

System Design and Cost Trade-offs: Compared to more sophisticated AI-powered or robotic sorting systems like those discussed by Wen et al. [15] and Cheng et al. [23], which use image processing and advanced ML models, the proposed system prioritizes simplicity and accessibility. This design philosophy aligns with community-level solutions found in studies from Southeast Asia and Nigeria [4, 13, 17], where affordability and modularity are critical for adoption. While some modern systems achieve higher precision by leveraging convolutional neural networks (CNNs) and hyperspectral imaging [18, 22], they often require GPUs and high-speed processors, which increase cost and power demands—factors this system avoids.

V. CONCLUSION

In conclusion, the successful design, simulation, and fabrication of the low-cost automated waste sorting and recycling system highlight its potential as an efficient and affordable solution for addressing waste management

challenges, especially in developing regions. Through the integration of mechanical components, sensor technologies, and Arduino-based control, the system demonstrated reliable performance in material detection and sorting. Structural and mechanical analysis confirmed the safety and efficiency of the design under operational loads, while performance tests revealed a high level of accuracy (92%) and sorting efficiency (86.7%), with an overall system efficiency of 70.14%. The use of locally available materials and low-cost components further enhances its applicability in resource-constrained settings. This project lays a solid foundation for further development and scaling, including features such as automated data logging, real-time feedback, and expanded sorting categories. Ultimately, the system offers a practical step toward smarter, cleaner, and more sustainable waste management practices.

Table 4: Bill of Engineering Materials and Evaluation (BEME)

S/ N	Component	Specification	Qty	Unit Cost (₦)	Total Cost (₦)
1	Mild Steel Square Pipe	25 × 25 × 2 mm (for frame) – 6 m length	3	6,000	18,000
2	Conveyor Belt	PVC, 1400 mm × 400 mm	1	15,000	15,000
3	Roller Shafts	Ø25 mm, mild steel, 450 mm	2	1,800	3,600
4	Ball Bearings	Ø25 mm ID	4	1,000	4,000
5	DC Gear Motor	12V, 10W, 60 RPM	1	8,500	8,500
6	Pulley + Coupling Set	For belt drive	1 set	2,000	2,000
7	Servo Motors	MG995/MG996 R (plastic gear)	3	4,000	12,000
8	Sensors (IR/Color)	For detection & sorting	3	2,500	7,500
9	Microcontroller	Arduino Uno (compatible)	1	4,000	4,000
10	Relay Module	2-Channel Relay	1	1,200	1,200
11	Waste Bins	40×40×50 cm (plastic)	3	3,500	10,500
12	Sensor Mounts/Brackets	Acrylic/PVC sheet	1 sheet	1,500	1,500
13	Electrical Wiring & PCB	Low-voltage cabling + custom PCB	1 lot	4,000	4,000
14	Power Supply Unit	12V 5A	1	5,000	5,000
15	Fasteners, Hinges, Extras	Bolts, nuts, flap hinges	1 lot	2,500	2,500
16	Paint & Finishing	Spray coat or brush finish	1 lot	2,000	2,000
17	Labour (Welding, Wiring)	Fabrication + Assembly	Lump sum	15,000	15,000
18	Contingency (5%)	Unforeseen costs or repairs	1 lot	—	6,300
TOTAL AMOUNT					500,000

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Ethics Committee Approval

not required, N/A

Peer-review

Externally peer-reviewed.

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Conflict of Interest:

The authors have no conflicts of interest to declare.

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Investigating EEG Band Dynamics in Motor Imagery Tasks: A Topographic Brain Mapping Study of a BCI-Trained Individual

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Abstract – Electroencephalogram (EEG) signals are very suitable for Brain-Computer Interface (BCI) applications due to their cost-effectiveness and high mobility. Although EEG signals have a high temporal resolution, their spatial resolution is low. In this study, four-class Motor Imagery (MI) EEG signals of an individual who received 20-day BCI training were analyzed with the topographic brain mapping method to examine the spatial distribution of EEG. The analysis was performed by examining each EEG waveband for each second of the MI task. As a result, Delta and Theta bands related to concentration and learning showed activity in the first seconds. For Alpha, Beta, and Gamma activities, processes related to active thought occurred in the first seconds, and processes related to decision-making happened in the last seconds. When the activities of EEG bands for each electrode channel are determined, the success in BCI applications can be increased. The study has the potential to be a reference for other studies on paradigm creation and improvement.

Keywords – BCI, EEG, EEG Wave Bands, Motor Imagery, Topographic Brain Mapping

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I. INTRODUCTION

Brain-Computer Interface (BCI) is a communication tool that provides direct information transfer between the brain and a device. BCIs can be used in many areas such as health, advertising, commerce, control, and automation for disabled and healthy individuals by allowing us to examine the human brain with the potential to reduce the use of limbs. Electroencephalogram (EEG) signals are among the most suitable for BCI applications due to their low cost and portability. However, the non-linear structure of EEG signals, their differences from person to person, and their noisy nature offer many opportunities for development in this area. Since communication between neurons occurs at millisecond levels and measurements are taken directly from the scalp, EEG has a high temporal resolution and captures instantaneous changes. On the other hand, EEG is a signal with low spatial resolution [1], [2]. One of these reasons is the density of the number of electrodes placed on the scalp. If a small number of electrodes are placed, it becomes difficult to determine the location of regional activity precisely. Another reason is that electrical activity spreads and blurs as it passes through brain tissues, the skull, and the scalp. Thus, an exact region related to brain activity cannot be determined [1]. For these reasons, the topographic mapping technique, which visualizes the regional distribution of the EEG signal, becomes important. Although this technique does not directly improve electrode localization, it makes EEG data more meaningful and helps analyze it by visualizing the possible distribution of brain activity with different color codes. Thus, by examining the distribution of the EEG with high temporal resolution in the brain for each specified moment, how brain activity changes for different

applications during a cognitive process can be examined with a cheaper and simpler technique. Finally, improvements can be made in the paradigm creation and task learning stages, especially for BCI applications.

There are many studies in the literature examining the topographic distribution of EEG on the brain in different areas. In the first of these, Formaggio et al. examined the topographic changes in the EEG and the blood oxygen level-dependent (BOLD) signals in the fMRI images of seven healthy individuals based on the thumb movement imagery in alpha and beta bands and observed the relationship between them. It was determined that the combined approach of EEG and fMRI was more effective in determining brain activity and changes [3]. Shin et al. compared the EEG signals obtained from 30 electrodes while four healthy children and four children with cerebral palsy (CP) performed the task of movement execution (ME), kinesthetic motor imagery (KMI), observation of movement (OOM), and visual motor imagery (VMI) using topographic mapping. For normal children, sensorimotor cortex activity increased during ME. During KMI, activity was observed in both sensorimotor and visual cortex. In children with CP, activity was observed in the premotor cortex and supplementary motor cortex along with the sensorimotor cortex. While the visual cortex was active in normal children during the OOM and VMI tasks, the sensorimotor cortex and bilateral auditory senses were also active in children with CP along with the visual cortex [4]. In the study conducted by Edelman et al., a more intuitive paradigm was proposed because the current EEG-based BCI systems were not very successful in four-class motor imagery (MI) tasks, especially in rehabilitation and recreational applications. This paradigm

consists of imagining the flexion, extension, supination, and pronation movements of the right hand. The EEG signal was projected onto the skull surface with the Weighted Minimum Norm Estimate (WMNE) approach and ERD activities were examined. With this method, the four-class MI task yielded 10% more success than the traditional approach [5]. In another study by Edelman et al., the L2 normalization method was used for the source distributions of EEG signals obtained with the same paradigm, and the effect of superficial dipoles was eliminated with the previously proposed WMNE method. 12.7% better results were obtained with the proposed EEG source imaging method [6]. Wilson et al. examined QEEG measurements visualized by topographic mapping taken during kinesthetic and visual imagery tasks of 36 swimmers. The signals obtained with 19 electrodes correspond to the base (rest), visual, and kinesthetic imagery states. Theta, low and high Alpha, and low and high Beta bands were examined, and low Alpha was lower for visual and kinesthetic states compared to the base. Lower Alpha activity was produced in visual imagery than in kinesthetic imagery. This meant that swimmers exhibited higher efficiency in the visual imagery state. It also was determined that swimmers who were more successful in kinesthetic imagery produced less low Alpha activity and used more cortical resources, meaning that swimming-related activities required more brain activity [7]. Catrambone et al. examined the topographical changes between three different categories of motor imagery tasks: movements involving an object, meaningful gestures without the use of an object, and movements using an object to interact with another object. As a result, it was found that the presence of an object increased the EEG complexity, and meaningful gestures without the use of an object differed from the other tasks [8]. The detection of abnormal brain activity in epilepsy patients during interictal periods is challenging. Therefore, in the study by Taylor et al., normative mapping was used to facilitate this detection. Intracranial EEG recordings were taken from 234 healthy individuals, and a normative map was created. This map was compared to the non-seizure EEG recordings of 62 epilepsy patients to detect abnormal regions [9].

In this study, EEG signals of a person who received BCI training were obtained during MI tasks based on right, left, forward, and backward commands. Signals obtained from 14 electrodes were projected onto the skull surface with topographic mapping. Delta, Theta, Alpha, Beta, and Gamma bands were examined for each second belonging to four classes, and signals were analyzed.

II. MATERIALS AND METHOD

A. Data

For the study, motor imaging EEG signals based on right, left, forward, and backward commands were obtained from a healthy person who received 20 days of BCI training (which can make the results stable), using the Emotiv Epoc+ headset with a sampling frequency of 256 Hz according to the paradigm given in Fig. 1. In the previous study, the four-class classification accuracy of this person was 81.3%, while the binary classification accuracy as right and left was 96.1%. The success of the study and its place in the literature were stated in the previous study [10]. The subject was 37 years old and female. When the recording started, a 10-second baseline signal was first created by the subject looking at a blank screen. In the

first two seconds of the paradigm, the directions that were cues related to the command were given, and in the next five seconds, the MI task was performed by looking at the fixation cross in the region related to the direction of the command.

Finally, the subject rested by closing her eyes for three seconds. In the recording phase, which was carried out in two sessions, 80 repetitions were made for each class, and a total of 320 epochs of data were obtained [10]. In this study, Delta, Theta, Alpha, Beta, and Gamma EEG bands were examined every second for all classes during the interval when the MI task was active.

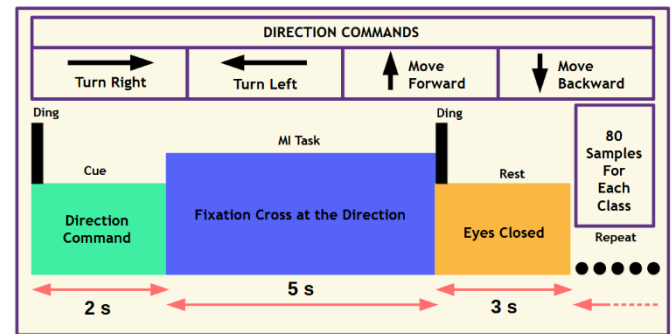


Fig. 1. Paradigm diagram in which four MI tasks are performed [1].

B. Topographic Brain Mapping

In this study, topographic mapping of EEG signals was performed with FieldTrip Brain Mapping software [11]. First, each labeled epoch was filtered with a 0-45 Hz band-pass filter and outliers were discarded. The data for each class were saved as files in MATLAB format which is suitable for the software. Then, frequency analysis was performed using the Morlet wavelet function. While performing topographic mapping, FieldTrip takes the average of the power spectrum of the samples and generally considers the signals we examine. Thus, the topographic map does not show instantaneous changes and allows us to make general inferences. When standard EEG configurations do not meet the requirements for topographic mapping, it becomes necessary to design a device-specific electrode layout. In this study, channel positions were manually entered over a layout visual showing the placement of 14 channels for the Emotiv Epoc+ headset as shown in Fig. 2 [12]. Subsequently, topographic maps of EEG bands were created by selecting the relevant frequency ranges for each class and for every second of the motor imagery task performed within the paradigm.

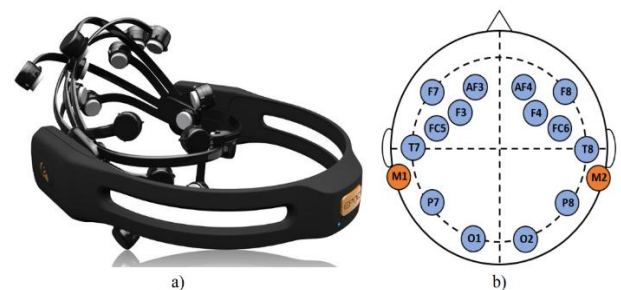


Fig. 2. a) Emotiv Epoc+ Headset b) Emotiv Layout [2]

III. RESULTS AND DISCUSSIONS

A. Delta Activity

Delta activity is brain activity in the range of 0.5-4 Hz. It consists of slow and high-amplitude waves and occurs during resting states [13]. It has also been observed in activities

requiring attention [14]. Moreover, it is used in control applications based on motor imagination [15], [16], [17], [18]. In Fig. 3, there were activities on opposite sides of the brain for right and left, and for forward and backward, in the first second (left lobe for right command, right lobe for left command, right lobe for forward, left lobe for backward). Then, the activity continued on the left side of the brain. In the third second Delta activity decreased for regions related to motor activity and as of the fourth second, activity appeared in the parietal region. From the beginning to the fifth second, activity levels were at 10^3 or 10^4 levels. The highest levels were obtained in the fourth second. It was observed that Delta activity was higher for the right, forward, and backward commands than for the left command. It can be inferred that the motor task was realized starting with the 3rd second because delta activity disappeared from the motor cortex and delta magnitudes decreased.

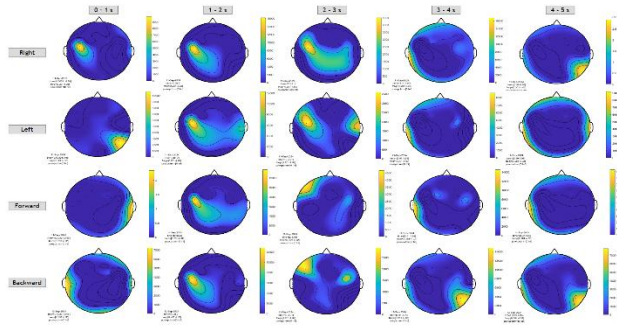


Fig. 3. Delta Activity for Four MI Tasks

B. Theta Activity

Theta wave has frequencies between 4-8 Hz and is associated with learning and creative thinking. It has medium-level amplitudes [13]. It has been observed that Theta waves, like Delta waves, are also used in control applications [15], [16], [17], [18]. Additionally, when we examined the frequency activities in the EEG channels in our previous BCI study based on Motor Imagery, it was observed that Delta and Theta activities were effective [10]. When we look at the mapping of EEG signals in Fig. 4, Theta activity was seen generally on the left side of the brain for all classes in the first two seconds and was at 10^3 levels. Although the level slightly decreased in the third second, Theta activity continued on the right side for the right command, on the left side for the left command, and the right side for the forward and backward commands. In the fourth second, activity was concentrated in the frontal region for the right, left, and forward commands, and in the parietal region for the backward command, and showed an increase. The highest activity was for the backward command. In the fifth second, activity occurred in the parietal region for the right, left, and forward commands, and in the frontal region for the backward command. This time, the opposite was true, the highest activity occurred for the right, left, and forward commands. If we consider that Theta activity is related to learning, it is possible to say that the interpretation function, which is a feature of the parietal region, occurred in the fourth second for the backward command and in the fifth second for the right, left, and forward commands.

C. Alpha Activity

It has frequencies between 8-12 Hz and generally occurs in activities related to relaxation and thinking. It is also associated with attention. It is observed in the occipital region in resting states with eyes closed and is more dominant when the eyes are closed [13]. The Mu rhythm (8-13 Hz) in the Alpha band causes

the motor neurons in the motor cortex to fire at rest. When movement occurs, the Mu rhythm disappears [13]. When we examine the Alpha activity in the brain according to Fig. 5, the amplitude is at 10^2 levels. In the first second, activity was observed in an area close to the motor cortex, which is the left part of the brain for all classes, and it continued until the end of the third second. The alpha activity was at its lowest level in the third second. In the fourth second, Alpha activity increased in the frontal region, and activity was observed in the parietal region for the backward direction. In the last second, it was high towards the right parietal region. Only for the backward direction, does a low level of Alpha activity emerge in the frontal region.

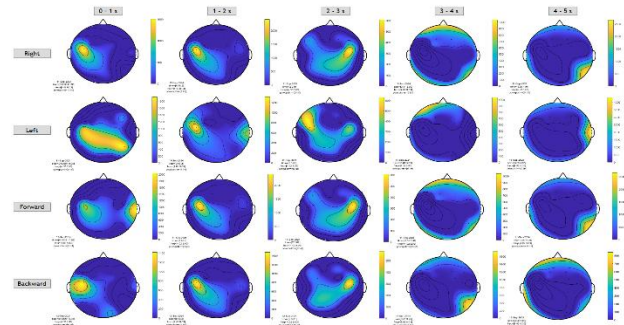


Fig. 4. Theta Activity for Four MI Tasks

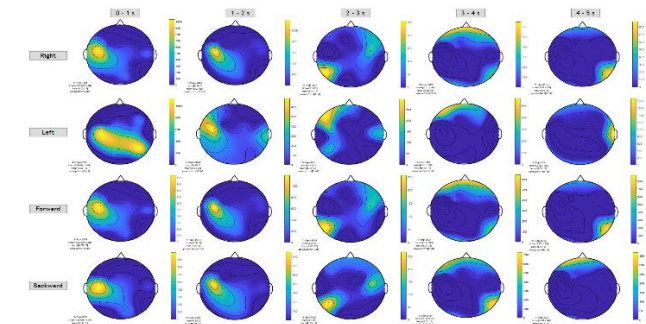


Fig. 5. Alpha Activity for Four MI Tasks

Accordingly, the Alpha activity that occurs in the motor cortex in the first three seconds and in the frontal region in the fourth second may indicate the concentration of attention related to thinking. The Alpha activity close to the parietal region may relate to the interpretation of the commands which occurs on the fourth second for backward direction and the fifth second for the others.

D. Beta Activity

Beta waves are low-amplitude waves. They are active every hour we are awake. In addition to being awake, they occur in situations such as active thinking, movement, and concentration, and can also increase during anxiety and stress [13]. When we examine the Beta mapping in Fig. 6, we can see that it is generally at 10^2 levels. In the first second, it is active near the temporal region on the left side of the motor cortex for the Right, Forward, and Backward commands, while it is close to the right parietal region for the left command. Beta amplitude is higher for the left command than the others. In the following second, there is activity on the left side of the motor cortex for all commands. The amplitude of the right and forward commands is higher than the left and backward commands. Beta activity decreased for all commands in the third second. In the fourth second, activity increased in the frontal and

parietal regions, and the last second, activity reached a maximum in the region close to the right parietal for the right, left, and forward commands, while activity continued at a low level in the frontal region for the backward command. It is understood that Beta activity is active in the motor cortex due to active thought in the first two seconds, that the third second represents a transition period, and that the frontal region, which is the region related to decision-making and control, is active in the fourth second. Here it can be understood that the decision-making process for the command is 4 seconds in total, and it can be said that the decision-making process for only the backward command is 5 seconds.

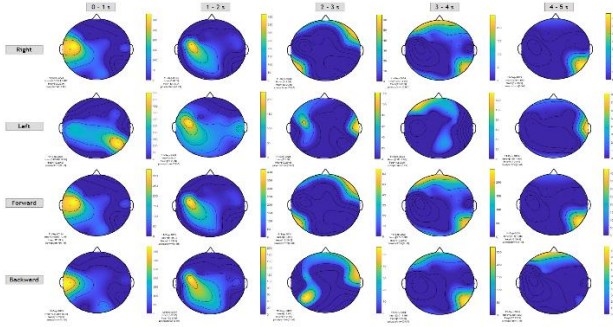


Fig. 6. Beta Activity for Four MI Tasks

E. Gamma Activity

Gamma waves are low-level amplitude waves of 30 Hz and above, especially related to the senses. They are fast oscillating transient signals, unlike beta waves which exist at every waking moment. Gamma waves are linked to sensory perception, as well as to higher-order cognitive functions including problem-

solving, creative thinking, and learning. Gamma frequencies can increase depending on the level of concentration. This is especially important in processes such as learning and information processing. [13].

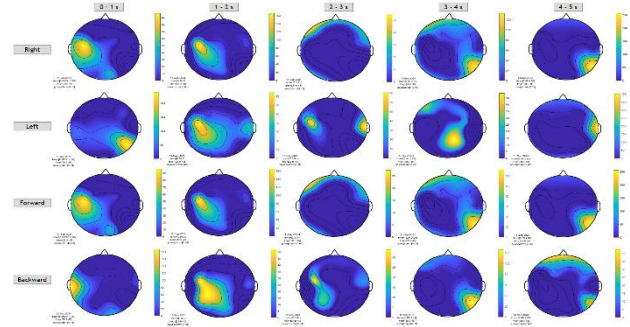


Fig. 7. Gamma Activity for Four MI Tasks

In the Gamma mapping in Fig. 7, the activities are at levels 10^1 and 10^2 . In the first second, the left side of the brain was active for the right, forward, and backward commands and the right side of the brain was active for the left command, but this activity continued in the left side of the motor cortex for all commands between the first and second seconds. The activity level is higher for the right and forward commands. In the third second, there were very low levels of activity in different regions of the brain, but from the fourth second onwards, Gamma activity concentrated in the right parietal region of the brain. In the fifth second, the activity level is highest for the right, left, and forward commands. When examined regionally, active thinking is observed especially in the first and second seconds, while perception and meaning are observed in the fourth and fifth seconds.

Table 1. The Summary of EEG Band Activity Across Brain Regions and Time Intervals During Motor Imagery

EEG Band	Time (s)	Active Brain Regions	Associated Cognitive Function	Description
Delta (0-4 Hz)	0-2	Motor Cortex	Movement Preparation	Delta activity is pronounced in motor cortex early on, indicating motor planning and internal readiness.
	3-5	Temporal, Parietal	Sensory Integration, Relaxation	Delta shifts to temporal and parietal regions, suggesting disengagement from motor planning and transition to perceptual processing.
Theta (4-8 Hz)	0-3	Motor Cortex	Learning, information encoding	Sustained theta in motor cortex reflects learning-related neural engagement.
	4	Frontal	Strategic planning	Theta shifts to frontal areas, indicating cognitive control and executive planning.
	5	Parietal	Knowledge integration	Theta in parietal areas reflects consolidation and spatial reasoning.
Alpha (8-12 Hz)	0-3	Motor Cortex	Internal thinking, attention	Alpha activity indicates introspective thought and motor-related preparation.
	4-5	Frontal, Parietal	Decision-making, reasoning	Alpha shifts to frontal and parietal regions, showing involvement in inference and decision processes.
Beta (12-30 Hz)	0-2	Motor and Frontal areas	Active thinking, planning	Beta is high during early cognitive load, associated with planning and movement intention.
	3	-	Transitional phase	Decrease in beta reflects transition between cognitive states.
	4-5	Frontal, Parietal	Decision execution	Beta reappears in decision-related areas for response preparation.
Gamma (30-45 Hz)	0-2	Motor and Frontal areas	Attention, active cognition	Gamma reflects rapid processing and high-level attention in early stages.
	3	-	Transitional phase	A decline marks a cognitive transition period.
	4-5	Parietal	Perception, awareness	Gamma in parietal cortex reflects perception-based processes and sensory integration.

IV. CONCLUSION

In this study, four-class MI EEG signals of an individual who received BCI training were analyzed to perform commands in the right, left, forward, and backward directions. The reason for choosing this user was that she had a 20-day BCI system training which allows the user to produce stable responses. Also, her data has the potential to be suitable for generalization due to the high accuracy results obtained as shown in the previous study [10]. However, if possible, it is preferable to use data obtained from more BCI-trained individuals. When the results are examined, it is observed that Delta activity increases especially in the motor cortex in the first two-second interval, and as of the fourth second, it is generally found in the temporal and parietal regions and disappears from the motor cortex and frontal regions where movement is related, and active thought is located. Theta activity, which is related to learning, continues in the right or left motor cortex in the first three seconds, and in the frontal region in the fourth second, and more in the parietal region in the fifth. Alpha activity, which is related to thinking, generally continues in the left motor cortex in the first three seconds, and in the frontal region related to the decision-making process, and in the parietal region related to inference for the fourth and fifth seconds. Beta activity also exhibits a similar behavior to Alpha activity, but it shows a significant decrease in the third second, which can be interpreted as a regional transition. When looking at Beta activity, it can be said that the first two seconds are related to active thought and the last two seconds to decision-making. Finally, Gamma activity exhibits similar behavior to Beta activity. The third second is like a transition period in this activity. It can be said that active thought occurs in the first two seconds and perception-related processes occur in the last two seconds. When we look at the study in general, Delta, Theta, Alpha, Beta, and Gamma activities have emerged in different parts of the brain in relation to different functions as summarized in Table 1.

To summarize, the processes related to concentration and learning generally occurred within the first two seconds. If we consider the active thought and decision-making processes in general, it can be said that a 4-second paradigm may be sufficient to obtain MI-EEG signals. In addition, since the third second is a transition period for these processes, the data belonging to the third second may not be used in the feature extraction stages. If the activity of the signals is compared with each other during a study and the features belonging to separate channels and separate EEG waves are used for each second, MI EEG-based BCI studies may be more successful. In this study, the signals were obtained at 4ms intervals, and the analysis was performed at one-second intervals. It is also possible to obtain more accurate results if the analysis is performed at shorter intervals.

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Authors'

The authors' contributions to the paper are equal.

Contributions

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics.

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Lateral Resolution Enhancement of Ultrasound Images via Auto-Encoder Network

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Abstract – Ultrasound imaging is widely used for medical diagnostics, but its resolution is inherently constrained by factors such as wavelength, focal length, scan line density, and frame rate. A fundamental trade-off exists between lateral and temporal resolution, where increasing scan line density enhances spatial detail at the expense of reduced frame rates. This study explores the potential of deep learning, specifically an AutoEncoder-based approach, to enhance lateral resolution without sacrificing temporal resolution. The performance of the AutoEncoder is evaluated against traditional interpolation methods, including nearest, linear, and spline interpolation, using structural similarity (SSIM), peak signal-to-noise ratio (PSNR), multi-scale SSIM (MS-SSIM), and feature similarity (FSIM) metrics. The results demonstrate that the AutoEncoder outperforms interpolation methods, achieving the highest SSIM and FSIM, indicating superior structural preservation and feature retention. Additionally, the RF signal analysis shows that while the AutoEncoder maintains the overall waveform structure, minor amplitude and phase deviations exist. These findings suggest that deep learning-based super-resolution can effectively enhance lateral resolution while minimizing traditional resolution trade-offs.

Keywords – *Ultrasound Imaging, Resolution Enhancement, lateral resolution, Deep Learning, Interpolation.*

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I. INTRODUCTION

Ultrasound imaging systems (US) are one of the standard imaging modalities in medicine, and they have multiple advantages over other imaging modalities. From the point of view of patient safety, US systems lack ionizing radiation and are also non-invasive. In addition, these systems are portable and allow patient monitoring at the bedside. The most important advantage of the US is providing real-time images [1]. These advantages enable this medical device to monitor a region of interest (ROI) during biopsy or apply it intraoperatively with a combination of other imaging during surgery.

However, this imaging modality has some drawbacks arising from its inherent attributes. First of all, this imaging modality is prone to speckle noise. In addition, extending their resolution cells in an elevational distance, in turn, created an overlap between consecutive frames and caused artifacts in US images, and finally, US serves images with low resolution compared to other biomedical imaging modalities [2,3].

Generally, US image resolution is affected by different factors such as wavelength, focal length, number of scan lines, frame rates, etc. There is an inherent trade-off between lateral and temporal resolution in ultrasound imaging. Increasing the number of scan lines enhances lateral resolution by reducing the spacing between adjacent beams, thereby improving spatial detail. However, this comes at the expense of temporal resolution, as acquiring additional scan lines requires more

time, reducing the frame rate. Conversely, reducing the number of scan lines increases the frame rate, thereby improving temporal resolution but at the cost of degraded lateral resolution due to larger beam spacing.

Different studies applied different approaches to tackle this issue and increase ultrasound resolution. In [4], the authors classified these approaches into three methods. The first group relied on images. These studies [5-8] focused on increasing the resolution of B-mode US images by applying super-resolution methods. These methods apply to the final stage of US image creation. According to [4], there are also two other classes; however, these classes rely on RF data rather than US images and attempt to reconstruct US images with high resolution, either by employing pre-beamformed RF data or post-beamformed RF data.

Among the methods that rely on post-beamformed methods are [9,10]. In [9], a deep neural network (DNN) was proposed that integrates sparse regularization into its loss function to produce high-quality images with reduced computation time. Similarly, [10] introduced a model that enhances delay-and-sum (DAS) beamforming by generating pixel-wise weights from single-angle (0°) plane wave data, achieving improved image quality over traditional methods.

Besides studies that rely on post-beamformed data, some studies, such as [11-18], rely on pre-beamformed data. In [11], the authors adapted MobileNetV2 to emulate Minimum Variance Beamforming (MVB), achieving comparable image

quality with significantly reduced reconstruction time. Similarly, [12] utilized a U-Net-inspired architecture with strided convolutions to reconstruct images from raw channel data acquired via single-angle plane wave insonification, producing results visually similar to conventional delay-and-sum methods. In [13], an autoencoder-based model, also inspired by U-Net, was proposed for beamforming using RF data from a single plane wave transmission.

In [14], a fully convolutional network trained on simulated channel data and echogenicity maps was used to reduce speckle noise in B-mode images by processing 16 sub-aperture RF signals. In [15], a conditional GAN (cGAN) was proposed to directly convert raw RF channel data into B-mode images, effectively bypassing conventional beamforming.

In [16], a fully convolutional neural network was proposed to replace traditional beamforming by framing ultrasound image reconstruction as a segmentation task applied directly to pre-beamformed RF data. Similarly, [17] introduced a deep learning approach to balance image quality and clinical usability, demonstrating that their model enhances reconstruction quality and acquisition frequency, supporting real-time ultrasound applications. In [18], a tight frame U-Net architecture was employed to enhance the Point Spread Function (PSF) in plane-wave imaging. The method reconstructs high-quality Tissue Reflectivity Functions (TRFs) from pre-beamformed RF data using a single plane-wave transmission, modeling the TRF as an isotropic 2D Gaussian kernel convolved with a cosine function.

Another investigated work is [19]. The authors propose a deep learning approach that unifies RF data from different angles by learning a linear transformation to a standard 0° reference. A two-stage neural network is introduced: PixelNet, a fully convolutional network that optimizes pixel-wise weights for enhancing DAS images, and a cGAN for further image refinement.

All of the investigated studies demonstrate the growing impact of deep learning in ultrasound image reconstruction, particularly for ultrafast plane wave imaging. Research has explored post-beamformed and pre-beamformed RF data to enhance image quality, reduce computational complexity, and improve real-time usability [4]. One critical limitation of ultrafast plane wave imaging is the trade-off between frame rate and lateral resolution. Many deep learning-based approaches have been designed to reconstruct high-quality images from limited data, often relying on a single insonification angle. However, despite improving resolution and contrast using these methods, lateral resolution remains a significant challenge.

As previously mentioned, lateral resolution in ultrasound imaging is directly affected by the number of scan lines used to form an image. A higher number of scan lines leads to better spatial sampling, reducing artifacts and improving the visualization of fine structures. Many reviewed studies focus on enhancing resolution using deep learning, but their effectiveness can be further improved by increasing the number of scan lines. This would allow neural networks to exploit spatial information better, leading to superior image quality, improved diagnostic accuracy, and enhanced clinical applicability.

Despite these advancements, most existing deep learning approaches operate within the constraints of fixed spatial sampling or apply enhancement in the image domain without explicitly addressing scan line density. Our proposed method

introduces an Autoencoder-based framework that directly targets the lateral resolution by learning to synthesize high-density lateral information from low-density RF inputs. This is achieved by training the Autoencoder to map low-resolution input representations (fewer scan lines) to their high-resolution counterparts, effectively learning a non-linear upsampling function in the RF or image domain. Unlike traditional interpolation techniques, the Autoencoder captures contextual and structural priors across the lateral dimension. This enables it to reconstruct anatomically coherent details with reduced artifacts and improved Point Spread Function (PSF) characteristics. By operating in this learned feature space, the network leverages spatial dependencies that are typically underutilized in classical beamforming, thus pushing the boundaries of lateral resolution enhancement in ultrafast ultrasound imaging.

Therefore, this study aims to increase the number of scan lines or lateral resolution by employing an Autoencoder and, consequently, improve the lateral resolution of US images. The remainder of this paper is organized as follows. Section II discusses the applied methods and materials, and the results and discussion are presented in Sections III and IV, respectively.

II. MATERIALS AND METHODS

This section presents the theoretical background of AutoEncoder and the data acquisition process.

A. Applied Network

In this study, an AutoEncoder model is utilized to enhance the lateral resolution of US images. An Autoencoder is a neural network designed for unsupervised learning, primarily used for dimensionality reduction, feature extraction, and image reconstruction. It consists of two main components: an encoder and a decoder. The encoder compresses the input data into a lower-dimensional representation, often called the latent space or bottleneck, capturing the essential features while discarding noise and redundant information. The decoder then reconstructs the original input from this compressed representation, aiming to minimize the reconstruction loss.

In general, super-resolution autoencoders are designed with skip connections, upsampling layers, and transposed convolutions to enhance fine details and improve the image quality.

Since this study aims to enhance the lateral resolution of US images, our utilized network consists of 18 layers, including convolutional, pooling, dropout, upsampling, and element-wise addition layers. The encoder comprises five convolutional layers with ReLU activation, progressively increasing the number of filters from 64 to 256 while applying MaxPooling2D in the lateral dimension only to reduce width while preserving axial resolution. A dropout layer (0.3) is applied at the bottleneck to prevent overfitting. The decoder then symmetrically up-samples the lateral dimension using

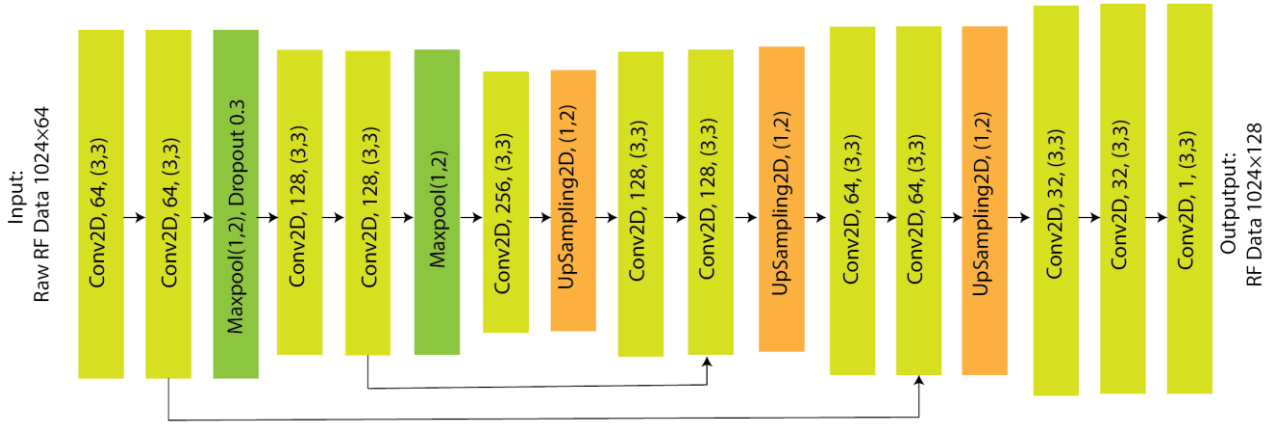


Fig.1. AutoEncoder block diagram

Table1. Summary of network layers.

Layer (Type)	Output Shape	Param #	Connected to
input_1 (InputLayer)	(None, 1024, 64, 1)	0	
conv2d (Conv2D)	(None, 1024, 64, 64)	640	input_1[0][0]
conv2d_1 (Conv2D)	(None, 1024, 64, 64)	36,928	conv2d[0][0]
max_pooling2d (MaxPooling2D)	(None, 1024, 32, 64)	0	conv2d_1[0][0]
dropout (Dropout)	(None, 1024, 32, 64)	0	max_pooling2d[0][0]
conv2d_2 (Conv2D)	(None, 1024, 32, 128)	73,856	dropout[0][0]
conv2d_3 (Conv2D)	(None, 1024, 32, 128)	147,584	conv2d_2[0][0]
max_pooling2d_1 (MaxPooling2D)	(None, 1024, 16, 128)	0	conv2d_3[0][0]
conv2d_4 (Conv2D)	(None, 1024, 16, 256)	295,168	max_pooling2d_1[0][0]
up_sampling2d (UpSampling2D)	(None, 1024, 32, 256)	0	conv2d_4[0][0]
conv2d_5 (Conv2D)	(None, 1024, 32, 128)	295,040	up_sampling2d[0][0]
conv2d_6 (Conv2D)	(None, 1024, 32, 128)	147,584	conv2d_5[0][0]
add (Add)	(None, 1024, 32, 128)	0	conv2d_3[0][0], conv2d_6[0][0]
up_sampling2d_1 (UpSampling2D)	(None, 1024, 64, 128)	0	add[0][0]
conv2d_7 (Conv2D)	(None, 1024, 64, 64)	73,792	up_sampling2d_1[0][0]
conv2d_8 (Conv2D)	(None, 1024, 64, 64)	36,928	conv2d_7[0][0]
add_1 (Add)	(None, 1024, 64, 64)	0	conv2d_8[0][0], conv2d_1[0][0]
up_sampling2d_2 (UpSampling2D)	(None, 1024, 128, 64)	0	add_1[0][0]
conv2d_9 (Conv2D)	(None, 1024, 128, 32)	18,464	up_sampling2d_2[0][0]
conv2d_10 (Conv2D)	(None, 1024, 128, 32)	9,248	conv2d_9[0][0]
conv2d_11 (Conv2D)	(None, 1024, 128, 1)	289	conv2d_10[0][0]

Three UpSampling2D layers and four additional convolutional layers to reconstruct high-resolution features. The network integrates two skip connections (add layers) to retain spatial information lost during down-sampling. The final output layer is a single-channel convolutional layer with ReLU activation, ensuring positive pixel values. The model is compiled with the Adam optimizer, mean squared error (MSE) loss function, and a learning rate of 0.000001. During training, 50 epochs and a batch size of 2 were used. Additionally, early stopping was not performed. Fig.1 and Table.1 show a block diagram of the applied network and its parameters, respectively.

B. Data Acquisition

To evaluate our method and perform training, synthetic ultrasound (US) images were generated using Field II [20] and MATLAB. The US data simulation was conducted for two scan line configurations: 64 and 128. The dataset with 64 RF scan lines was used as the network input, while the dataset with 128 RF scan lines served as the ground truth during the training and testing phases. A total of 220 point reflectors were simulated, with varying numbers of reflectors per sample, ranging from 1 to 4. Additionally, the simulations were performed without apodization. Out of the total dataset, 205

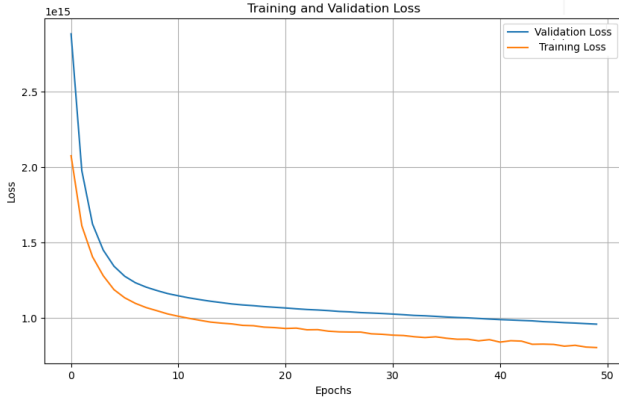


Fig.2. Training loss of AutoEncoder for enhancing lateral resolution.

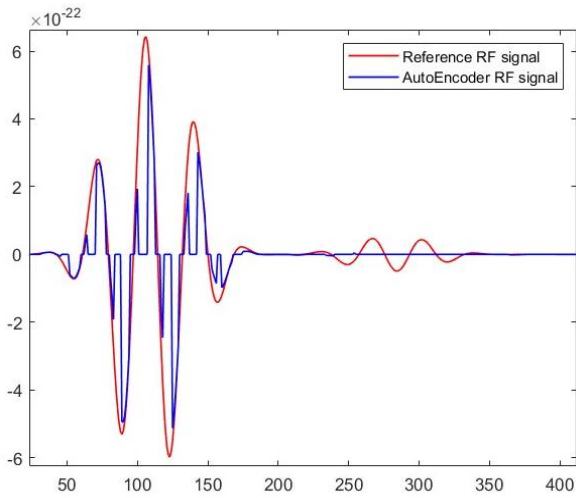


Fig.3. Comparison of ground truth signal with the reconstructed signal by using AutoEncoder.

samples were used for training, while the remaining data were reserved for testing. Out of the 205 training samples, 40 were reserved for validation purposes. The experiments were performed on an Intel i7 8th-generation processor unit (4 GHz with 32 GB RAM) and an NVIDIA GeForce GTX. All the software codes were built using TensorFlow.

III.RESULTS

This study aims to enhance the lateral resolution of ultrasound images by employing the AutoEncoder model. Our inputs are raw RF data (64 scan lines). Also, the network's output is RF data with a higher number of scan lines (128 scan lines). Then, these output scan lines proceed to create B-mode US images. Network training loss and validation loss are depicted in Fig.2. Also, an example of a reconstructed signal and its comparison with the ground truth is given in Fig.3.

As apparent from Fig.3, the most noticeable differences between the reference RF signal and the AutoEncoder-reconstructed signal appear in the high-amplitude regions, particularly around the peaks and troughs of the waveform. This suggests that while the AutoEncoder can capture the signal's overall shape and dominant frequency components, it may introduce minor distortion in amplitude and phase. These distortions could arise due to limitations in the model's capacity to precisely encode and reconstruct fine details, mainly when dealing with sharp transitions or high-frequency

Table.2. Comparison of Autoencoder results with conventional methods.

	Nearest	Linear	Spline	Auto-Encoder
SSIM	0.8504	0.8503	0.8383	0.8601
PSNR	17.4511	16.7225	15.9596	17.4129
MS-SSIM	0.7648	0.7482	0.7420	0.7857
FSIM	0.8435	0.8435	0.8389	0.8687
Overall STD	0.2847	0.2826	0.3017	0.2820

content. Furthermore, the discrepancies become more evident in the later parts of the signal, where the amplitude diminishes. This could indicate that the model struggles with learning and reconstructing low-amplitude details, possibly due to insufficient training data or the AutoEncoder's inherent bias toward capturing dominant features rather than subtle variations.

Table.2 and Fig.4 demonstrate quantitative and qualitative values and their comparison with conventional methods. The comparative evaluation of reconstruction quality across four methods, Nearest, Linear, Spline, and AutoEncoder, reveals that the AutoEncoder consistently achieves the best overall performance across all image quality metrics. Regarding SSIM, the AutoEncoder yields the highest score of 0.8601, outperforming Nearest 0.8504, Linear 0.8503, and especially Spline 0.8383, indicating superior structural fidelity. Similarly, MS-SSIM and FSIM scores are highest for the AutoEncoder (0.7857 and 0.8687, respectively), suggesting better preservation of multi-scale structural information and feature similarity. While the PSNR of the AutoEncoder 17.4129 dB is slightly lower than that of Nearest 17.4511 dB, the difference is minimal and not substantial enough to offset the consistent improvements seen in other perceptual metrics. Notably, the overall standard deviation (Overall STD) of the AutoEncoder is also the lowest, 0.2820, suggesting more consistent reconstruction performance across the dataset. In contrast, the Spline method yields the lowest metric values across all categories, indicating the weakest performance among the methods evaluated. These results collectively highlight the AutoEncoder's advantage in producing high-fidelity and consistent image reconstructions compared to traditional interpolation techniques.

Also, the visual comparison in Fig.4 further supports these findings, showing that the AutoEncoder reconstructs finer details more effectively than traditional interpolation methods. Overall, the results demonstrate that the AutoEncoder-based approach outperforms interpolation techniques in maintaining structural integrity and feature similarity, making it a promising method for enhancing the lateral resolution of US images.

In addition, Fig.5 presents the Structural Similarity Index (SSIM) performance across 15 reconstructed images using four methods: AutoEncoder, Nearest, Spline, and Linear interpolation. The AutoEncoder method consistently yields higher SSIM scores across most image indices, particularly excelling around indices 4–6 and 9, where the structural differences are more pronounced. This trend suggests that the AutoEncoder is more robust in maintaining structural integrity under varying conditions. The statistical results in the Table further support the comparative performance. A paired t-test reveals that the SSIM differences between AutoEncoder and

Spline interpolation are statistically significant ($p = 0.0467$, $t = 2.1815$, $df = 14$), indicating a measurable

IV. DISCUSSION

The results from this study highlight the potential of deep

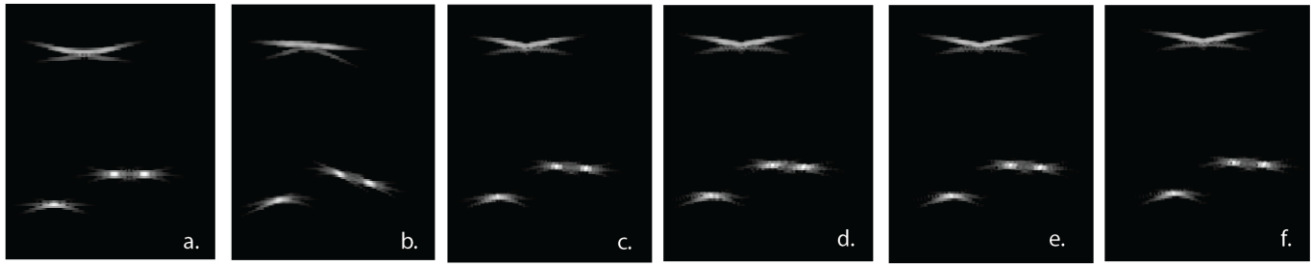


Fig.4. (a) Indicates ground truth (128 scan line). (b) low resolution (64 scan line). (c) results from nearest interpolation. (d) results from linear interpolation. (e) results from spline interpolation. (f) results from Autoencoder.

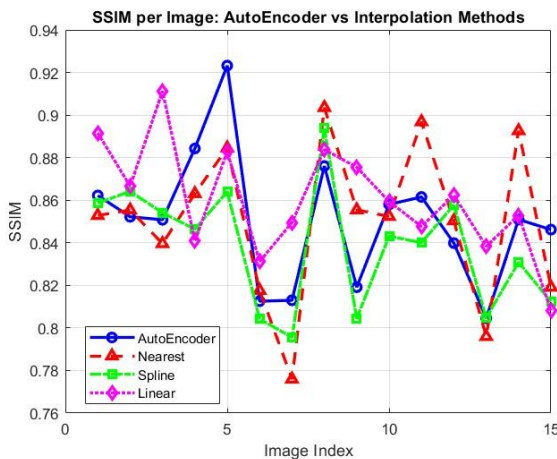


Fig.5. Comparison of SSIM Per-image.

Table.3. Paired t-test results comparing SSIM values of the AutoEncoder method against conventional interpolation methods across 15 images.

	p-Value	t-statistic	df	Significant at $\alpha = 0.05$ level
AutoEncoder-Nearest	0.9945	-0.0070	14	False
AutoEncoder-Spline	0.0467	2.1815	14	True
AutoEncoder-Linear	0.2651	-1.1610	14	False

Improvement in perceptual quality when using the AutoEncoder. In contrast, the differences between AutoEncoder and both Nearest ($p = 0.9945$) and Linear ($p = 0.2651$) methods are not statistically significant, suggesting that while the AutoEncoder may visually outperform these approaches in specific images, the overall improvement is not consistent enough to reach statistical significance. Notably, the Nearest method occasionally surpasses the AutoEncoder in specific image indices, but its performance is less stable across the dataset. The plot and statistical analysis demonstrate that the AutoEncoder offers a meaningful improvement over the Spline method and generally delivers competitive or superior SSIM values compared to traditional interpolation methods, highlighting its potential for more perceptually accurate image reconstruction.

learning-based super-resolution techniques, such as the AutoEncoder, in overcoming the inherent trade-off between lateral and temporal resolution in ultrasound imaging. Traditional methods like nearest, linear, and spline interpolation attempt to enhance lateral resolution by estimating missing spatial information between scan lines. However, their performance is limited in preserving fine structural details. The quantitative evaluation indicates that the AutoEncoder outperforms these interpolation methods across multiple metrics, particularly in SSIM (0.8601) and FSIM (0.8687), which measure structural and feature similarity, respectively. These improvements suggest that the AutoEncoder can reconstruct finer spatial details more effectively while mitigating artifacts and distortions introduced by conventional interpolation techniques.

To statistically validate these differences, paired t-tests were performed comparing the SSIM values of the AutoEncoder to each interpolation method across 15 image pairs. The results showed a statistically significant improvement over the spline method ($p = 0.0467$, $t = 2.1815$, $df = 14$), while differences with nearest ($p = 0.9945$) and linear ($p = 0.2651$) interpolation were not statistically significant. These findings confirm that the AutoEncoder provides a measurable advantage over spline interpolation, the poorest-performing method overall, while maintaining at least comparable performance to the other interpolation approaches.

This ability to enhance lateral resolution without requiring additional scan lines presents a significant advantage, as it helps maintain greater spatial detail without the trade-off of reducing frame rate, thus preserving temporal resolution. The relationship between the RF signal reconstruction and image-based results further supports the feasibility of deep learning for ultrasound super-resolution. In the RF domain, the AutoEncoder successfully captured the overall waveform structure. Still, it exhibited slight amplitude and phase deviations, which may contribute to minor errors in the final ultrasound image reconstruction. Despite these minor discrepancies, the method still demonstrated better spatial detail preservation than interpolation techniques. This suggests that the AutoEncoder can learn underlying signal structures effectively, helping to balance lateral resolution enhancement with minimal temporal resolution loss. However, further optimizations, such as training with larger datasets, refining network architectures, or incorporating advanced loss functions tailored for ultrasound imaging, could enhance its ability to generalize across different imaging conditions.

V. CONCLUSION

This study demonstrates the effectiveness of an AutoEncoder-based approach in enhancing the lateral resolution of ultrasound images while mitigating the trade-offs associated with traditional interpolation methods. The results indicate that the AutoEncoder outperforms conventional methods in preserving structural details, as evidenced by higher SSIM, MS-SSIM, and FSIM values. The RF signal analysis further supports these findings, showing that while the AutoEncoder captures the general waveform structure, minor deviations in amplitude and phase may contribute to small reconstruction errors in the final image. Despite this, the deep learning-based approach provides a promising alternative to conventional interpolation, offering improved spatial resolution without sacrificing temporal resolution. However, the relatively small dataset size may limit the generalizability of the results to broader clinical scenarios. Additionally, the training process was constrained by computational resources, and a more powerful GPU-equipped system could enable deeper or more complex network architectures and larger batch sizes, potentially leading to improved performance. Future work could focus on refining the model architecture, incorporating larger and more diverse datasets, and optimizing loss functions to enhance performance. These findings highlight the potential of deep learning in overcoming the limitations of traditional ultrasound imaging, paving the way for more accurate and high-resolution diagnostic imaging.

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Authors'

Contributions

The authors' contributions to the paper are equal.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics.

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Ensuring product detection and product counting on the assembly line using deep learning (YOLOv11)

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Abstract –This study aims to improve product counting and quality control processes on the suspension system assembly line by utilizing the YOLO (You Only Look Once) algorithm and the Ultralytics library. Given the critical importance of suspension systems for vehicle control and passenger comfort, the accuracy of parts inspection on the production line holds paramount industrial significance. As reliance on operator discretion frequently leads to customer complaints and substantial financial losses, deep learning-based object detection models offer considerable potential to automate and accelerate these processes. In this context, the effectiveness of the YOLOv11 model in industrial parts inspection will be scientifically demonstrated in this work, not only through theoretical inferences but also via detailed experimental results and detailed performance comparisons with previous models. Our ultimate goal is to provide concrete contributions to enhancing production efficiency while ensuring the highest levels of product quality and reliability. This approach clearly showcases the transformative power of automation and artificial intelligence in modern manufacturing.

Keywords – YOLO, Deep Learning, Ultralytics, Suspension, Detect.

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I. INTRODUCTION

Suspension is a connection system that links a vehicle's wheels and regulates their relationship with the road surface. A good suspension enhances both the vehicle's control and driving safety while ensuring passenger comfort [1]. Components in this system, such as the Z-rod, tie rod, swing arm, and ball joint, are critical in the manufacturing process. Accurate counting of products on the assembly line is crucial for detecting any deficiencies or excesses in production. If the detection and inspection of products are left to the operator's discretion, it can lead to customer complaints and financial losses. Additionally, if product counting is done accurately, the detection and counting of product subcomponents can also be carried out in subsequent operations. In Figure 1, AYD production suspension parts are shown in red.



Fig. 1. AYD Production Suspension Parts

Initially introduced by Redmon et al. [2] as a revolutionary approach to real-time object detection, YOLO (You Only Look Once) is a deep learning model developed for real-time

object detection. It is used to quickly detect and classify objects in images. Object counting involves the accurate detection and counting of specific objects through videos and camera feeds [3]. Subsequent iterations, such as YOLOv2 [4], YOLOv3 [5], and YOLOv4 [6], further advanced its capabilities, improving both speed and accuracy. In this process, YOLOv11 provides high efficiency and accuracy by utilizing state-of-the-art algorithms and deep learning capabilities. YOLOv11 quickly and accurately detects objects, particularly in complex scenarios like crowd analysis and surveillance. Thanks to its features, it excels in real-time applications and performs object counting both accurately and effectively. This enables high-precision operations in fields such as security monitoring, inventory management, and other areas that require object detection [7].

One of YOLO's key features is its ability to detect all objects in an image in a single pass. This enhances the speed of the model. Object counting provides several benefits. Firstly, it significantly aids resource optimization. Accurate object counts enable efficient planning in inventory management and other resource allocation processes, helping to avoid unnecessary expenses and stock surpluses. It also improves security; accurately counting and tracking objects increases asset security and helps detect potential threats more rapidly. Finally, object counting plays a major role in informed decision-making. In sectors like retail and traffic management, accurate data allows for more efficient process management and provides valuable insights for strategic decision-making. This ensures that decisions are made on a solid foundation.

Ultralytics YOLOv11 offers several advantages over other object detection models like Faster R-CNN [8], SSD [9], and previous YOLO versions. YOLOv11 provides real-time processing capabilities, making it ideal for applications that require high-speed inference, such as surveillance and autonomous driving. The model delivers state-of-the-art accuracy in object detection and tracking tasks, reduces false positives, and improves overall system reliability. Additionally, it offers seamless integration with various platforms, including mobile and edge devices, which is a significant advantage for modern AI applications. YOLOv11 is flexible, with configurable models that support various tasks such as object detection, segmentation, and tracking, allowing it to meet specific use case requirements [7]. Advances in YOLOv11's model design and optimization techniques have resulted in higher accuracy with fewer parameters. The improved architecture enables efficient feature extraction and processing, allowing for higher mean average precision (mAP) on large datasets like COCO. Despite using 22% fewer parameters than the YOLOv8m model, YOLOv11 does not compromise on accuracy. This makes YOLOv11 well-suited for efficient deployment on resource-constrained devices, as the model continues to deliver high performance while requiring less computational power. Thus, YOLOv11 stands out as an effective solution, especially in environments with limited computational power, such as portable devices or real-time applications. This table 1 provides an overview of the YOLO11 model variants, showcasing their applicability in specific tasks and compatibility with operational modes such as Inference, Validation, Training, and Export. This flexibility makes YOLO11 suitable for a wide range of applications in computer vision, from real-time detection to complex segmentation tasks [10]. Table 1. YOLO v11 versions and their functions are shown.

Table 1. YOLO v11 versions and tasks

Model	Filenames	Task
YOLO11	yolo11n.pt, yolo11s.pt yolo11m.pt yolo11x.pt yolo11l.pt	Detection
YOLO11-seg	yolo11n-seg.pt yolo11m-seg.pt yolo11x-seg.pt yolo11s-seg.pt yolo11l-seg.pt	Instance Segmentation
YOLO11-pose	yolo11n-pose.pt yolo11s-pose.pt yolo11m-pose.pt yolo11l-pose.pt yolo11x-pose.pt	Pose/Keypoints
YOLO11-obb	yolo11n-obb.pt yolo11m-obb.pt yolo11x-obb.pt yolo11s-obb.pt yolo11l-obb.pt	Oriented Detection
YOLO11-cls	yolo11n-cls.pt yolo11m-cls.pt yolo11x-cls.pt yolo11s-cls.pt yolo11l-cls.pt	Classification

II. MATERIALS AND METHOD

The suspension system is a mechanism that connects a vehicle's wheels to its chassis and regulates the interaction between the wheels and the road surface. The primary purpose of this system is to improve the vehicle's handling, driving safety, and passenger comfort. The suspension absorbs shocks from road irregularities, reducing vibrations between the vehicle and the road, providing a smoother driving experience. In a suspension system, several components limit the movement between the chassis and the wheels according to road conditions, such as springs, shock absorbers, tie rods, control arms, Z-rods, and swing arms. These components balance the vehicle's dynamic movements, ensuring stability during acceleration, braking, and cornering. The suspension system not only enhances driving quality but also ensures the vehicle's safety. Therefore, the interaction between the vehicle's chassis and wheels is of great importance. The suspension system is designed to ensure that vehicles move steadily and in a controlled manner under all road conditions.

A. AYD Suspension Parts

The control arm, Z-rod, tie rod, steering rack, steering shaft, and control link are key components in a vehicle's suspension system. The control arm connects the chassis to the wheels, helping to regulate movement. The Z-rod contributes to the vehicle's balance and steering control, functioning as part of the control arm. The tie rod allows the wheels to rotate vertically around their axis, aiding in steering. The steering rack connects the steering system to the wheels, enabling the vehicle to maneuver. The steering shaft transmits steering inputs to the wheels. The control link, as part of the control arm, regulates the connection between the chassis and the wheels, ensuring stable vehicle movement. Together, these components work in harmony to improve vehicle handling, driving safety, and comfort. Red colored suspension parts are seen in Figure 2.



Fig. 2. Red colored suspension parts

B. Deep Learning

Deep learning is a subfield of artificial intelligence (AI) that enables computers to learn from large datasets. This technique uses artificial neural networks, which are structures inspired by the human brain, to automatically extract patterns from data. Deep learning is particularly effective in handling large and complex data, and it is commonly used in areas like pattern recognition, image processing, and natural language processing. The model processes data in layers, learning more abstract features at each layer, making it more powerful and flexible compared to traditional machine learning methods.

C. Data collection and Processing

Data collection for YOLO (You Only Look Once) is the process of gathering the visual data necessary for the model to correctly detect and classify objects. This process involves several important factors, including the diversity, quality, and accurate labeling of the collected data. During data collection, various conditions such as different angles, lighting conditions, distances, and backgrounds must be considered to make the model more generalizable. Each object in the images must be accurately labeled with its class name and bounding boxes. Additionally, since low-resolution or blurry images can negatively affect the model's performance, it's important to use high-quality images. Balanced data is also crucial, as the overrepresentation of a particular object class can lead to bias in the model. During the data collection process, data augmentation techniques like rotation and scaling can also be used to improve the model's ability to generalize. Figure 3 shows the data collection visual.



Fig. 3. Data collection

To facilitate product counting and inspection on the suspension system assembly line, a high-quality visual dataset was created.

Data was collected using “Dahua IPC-HFW2431S-S-S2” model IP cameras installed on the assembly line. The cameras were configured to record images at 4 MP (2688 x 1520 pixels) resolution and a frame rate of 30 FPS. They were strategically positioned to provide a clear, bird's-eye view of the products on the conveyor belt. This placement was optimized to minimize shadowing and capture details from various angles. During data collection, diverse lighting conditions, including both daylight and artificial lighting, were simulated. This aimed to enhance the model's robustness against different lighting scenarios encountered in a real production environment. The collected dataset comprises 5,000 distinct suspension part images. These visuals reflect various real-world production variations, such as those from different production shifts, slightly soiled or damaged parts, and diverse surface textures. Furthermore, the dataset covers 8 different product classes, including z-rods, tie rods, swing arms, and ball joints.

D. Labeling, training and testing

Data labeling is a fundamental step for object detection and classification models. Its role in the training and testing phases is crucial because correctly labeled data ensures that the model learns properly. The training and testing processes are critical steps that affect the overall performance of the model. Data labeling is the process of accurately identifying and tagging objects in images. This involves marking each object with a

class name and a bounding box that represents the class. This process is typically done manually or can be accelerated using semi-automatic tools. The correct class name must be assigned to each object in the image. The four corner coordinates (x, y, width, height) that surround the object must be specified [17]. This helps the model learn the location of the object. If data labeling is not done correctly, the model may learn incorrectly and perform poorly during the testing phase.

The collected images were resized to a standard dimension of 640x640 pixels. For improved deep learning model performance, image pixels were normalized from a 0-255 range to a 0-1 range. Suspension components in each image were manually labeled using MakeSense AI. During this process, a bounding box and its corresponding class name were assigned to every object. Bounding boxes were defined by coordinates in the x_min, y_min, width, height format, ensuring they encompassed the object's outermost boundaries. A total of 14,600 objects were labeled. Labeling quality was maintained through verification by two independent operators and random sample checks. To mitigate potential overfitting from limited data and enhance the model's generalization capability, in line with principles of transferable features in deep neural networks [11], data augmentation techniques were applied. These techniques included; Random rotations by ± 15 degrees, random scaling between 80% and 120%, random brightness adjustments between 70% and 130%, horizontal and vertical flipping. These techniques expanded the training dataset to 10,000 images.

The labeled and augmented dataset was randomly split into training, validation, and test sets. The distribution was 70% for training, 15% for validation, and 15% for testing. This segmentation was performed to objectively evaluate the model's performance on independent data. Figure 3 shows the data labeling visual.

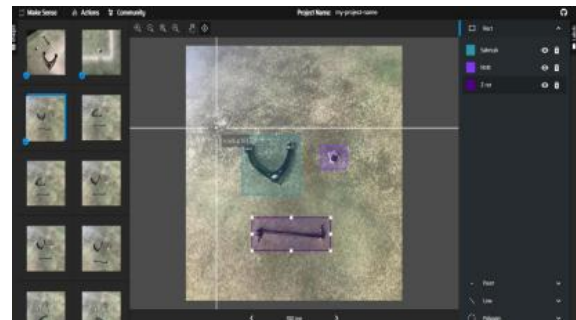


Fig. 4. Data labeling

The training phase is the process of "teaching" the model using labeled data to make accurate predictions. The labeled data is split into a training set and a validation set. The training set is used for the model to learn, while the validation set is used to prevent overfitting during training. The model learns through iterations (epochs) on the training data. In each iteration, the model makes predictions, and the difference between these predictions and the actual labels is calculated to determine the error (loss) value. The model's parameters are updated to minimize this error value.

To prevent overfitting that may arise from limited training data, data augmentation techniques (such as rotation, scaling, color changes, etc.) can be applied. The model's performance is evaluated with the validation set at each training step. If the model's accuracy is insufficient, improvements can be made

through hyperparameter adjustments, changes in model architecture, or by adding more data. Considering the need for both high real-time performance and superior accuracy in industrial applications, and after evaluating various established object detection architectures such as Faster R-CNN [8], SSD [9], and previous iterations of the YOLO series including YOLOv3 [5], YOLOv5s [12], and YOLOv8m [13], the Ultralytics YOLOv11x model was ultimately utilized in this study. The Adam optimization algorithm was employed to update the model's weights. Adam combines adaptive learning rate adjustments with momentum features, ensuring fast and stable convergence. The following hyperparameters were used and optimized throughout the training process, based on performance (mAP) on the validation set. The initial learning rate was set to 0.001. Using a learning rate scheduler such as Cosine Annealing, the learning rate was gradually decreased to 0.0001 over 200 epochs. This method helped the model converge more precisely by enabling smaller weight updates during the final stages of training. The model was trained for a total of 300 epochs. An early stopping mechanism was configured to automatically halt training if the validation loss did not improve for 50 consecutive epochs.

A batch size of 16 was used for training. This value considered GPU memory constraints while providing an appropriate balance for the model's learning dynamics. A weight decay of 0.0005 was applied to prevent overfitting and enhance the model's generalization capability. The input image size for the model was set to 640x640 pixels. Hyperparameter values were optimized using a combination of manual trial and error and Random Search to maximize mAP performance on the validation set. This process ensured the model achieved its best generalization capability while preventing overfitting. The training process was carried out on a workstation equipped with an NVIDIA GeForce RTX 3080 GPU. The deep learning library used was PyTorch 1.12.1, developed in Python 3.9. CUDA 11.3 and cuDNN 8.2 libraries were utilized for GPU acceleration.

The testing phase is the process of evaluating how the model performs on new, previously unseen data outside of the training data. The steps in the testing phase are as follows. Test data is not used during training and is only used to assess the model's overall performance in real-world scenarios. Once training is complete, the model makes predictions on the test set data. The model predicts the bounding boxes and class labels to correctly detect and classify objects. The model's accuracy is measured using metrics such as precision, recall, F1 score, and mean Average Precision (mAP).

These metrics show how accurate and reliable the model is. Failures in the test phase indicate how well the model can generalize to data outside of the training set. If there is a significant performance difference on the test data, it suggests that the model may have overfitted during training. Figure 5 shows the testing image.

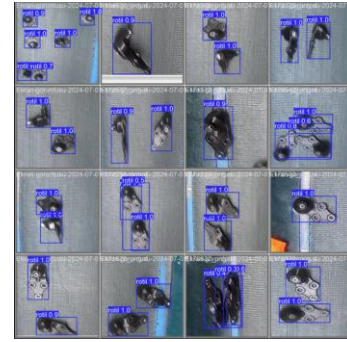


Fig. 5. Testing

E. Integration to the field, product counting

After the training process was completed, various stages were followed for the model's field integration and real-time product counting. First, live images of the products were captured through the camera system installed on the assembly line, and the model processed these images in real time. Using YOLO v11 Ultralytics, the parts were detected and counted. The system, designed to operate in real time, was integrated with the hardware and software infrastructure, while camera positioning, lighting, and image processing optimizations were carried out. The model's performance in the field was tested, and additional adjustments were made. It detected and reported any shortages or surpluses in real time, enabling necessary inspections. The system's performance was continuously monitored. Figure 6 shows the field application visual.



Fig. 6. Field application

III.RESULTS

In this study, the performance of the YOLOv11-based model developed for product counting and quality control on the suspension system assembly line was evaluated using detailed metrics and comparative analyses. Following the completion of the training and testing phases, the model's effectiveness was quantitatively demonstrated under both experimental conditions and in real-world field application.

To assess the model's overall performance, metrics such as precision, recall, F1 score, and mean Average Precision (mAP) were utilized. The results obtained on the test dataset are summarized in Table 2.

Table 2. YOLOv11x Model Performance Metrics on the Test Dataset

Metrik	Değer (%)
Precision	91.50%
Recall	88.20%
F1 Skoru	89.80%
mAP@0.5	92.30%
mAP@0.5:0.95	78.70%

These results clearly demonstrate the model's ability to accurately detect and classify objects on the test dataset. Specifically, a high $mAP@0.5$ value of 92.3% highlights the model's success in correctly localizing and accurately labeling products. The $mAP@0.5:0.95$ value of 78.7% further indicates strong performance even at stricter intersection-over-union (IoU) thresholds, implying that the bounding box predictions are highly precise. These metrics collectively reveal that the developed YOLOv11x model can provide reliable and effective product inspection on the assembly line.

To compare the performance of the YOLOv11 model with industry standards and previous models, a performance analysis was conducted against Faster R-CNN, SSD, and earlier versions of YOLO (YOLOv3, YOLOv5s, YOLOv8m). This comparison specifically focused on $mAP@0.5$ and real-time processing capability (FPS). The comparison results are presented in Table 3.

Table 3. Performance Comparison of Different Object Detection Models

Model	$mAP@0.5$ (%)	FPS (frames/sec)
Faster R-CNN	85.1	15
SSD	82.5	45
YOLOv3	87.8	60
YOLOv5s	89.5	90
YOLOv8m	90.9	80
YOLOv11x	92.3	75

Table 3 clearly demonstrates that the YOLOv11x model exhibits both higher accuracy (mAP) and superior real-time performance (FPS) compared to other models. Specifically, when compared to SSD, YOLOv11x achieved 9.8% higher mAP and was 1.67 times faster in terms of FPS. While compared to YOLOv8m, there was a 1.4% increase in mAP along with a slight decrease in FPS, this significant accuracy gain generally represents a preferred trade-off for industrial inspection. These findings confirm that YOLOv11x is an ideal solution for high-speed, critical applications like assembly lines.

The model was integrated into the suspension system assembly line and tested under real-world conditions. The results obtained from the field application concretely highlight the model's practical benefits. An average counting accuracy of 99.2% was achieved for product counting. This led to a significant reduction in the error rate compared to operator-based counting methods (approximately an 80% reduction). The error rate in detecting missing or surplus products was observed to decrease by 75% compared to previous manual or semi-automatic systems. The model operated at an average speed of 70-75 FPS on the production line. This speed allows for instant inspection and counting without interrupting the production flow. Automatic counting and inspection resulted in approximately a 25% saving in labor, allowing operators to focus on more value-added tasks.

These results prove that the developed YOLOv11x model delivers superior performance not only in a laboratory setting but also under demanding industrial conditions. The training and testing processes, as well as the field application performance tests, were conducted on the following hardware and software infrastructure;

Processor (CPU): Intel Core i7-10700K

Graphics Processing Unit (GPU): NVIDIA GeForce RTX 3080 (10 GB VRAM)

Memory (RAM): 32 GB DDR4

Storage: 1 TB NVMe SSD

Operating System: Ubuntu 20.04 LTS

Deep Learning Library: PyTorch 1.12.1

YOLOv11 Version: Ultralytics YOLOv11x

Programming Language: Python 3.9

This detailed information ensures the reproducibility of the study and clarifies the hardware and software dependencies of the obtained results.

Figure 7 shows the field application with product counting.

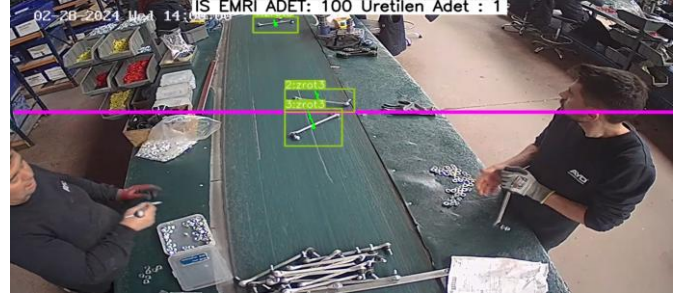


Fig. 7. Field application with product counting

IV. DISCUSSION

This study has taken significant steps toward improving product counting and quality control processes on the suspension system assembly line using the YOLO algorithm and the Ultralytics library. The growing interest and success of deep learning in various industrial applications, including surface defect detection [14] and object counting in complex scenes [15], underscore the transformative potential of such automated systems. The model's ability to eliminate operator-related errors, enhance accuracy, and accelerate the production process provides a major advantage. However, several technical challenges must be addressed to ensure the system operates seamlessly in live production.

Furthermore, hardware improvements alone may not be sufficient. To increase processing speed, parameter optimization, reduction of unnecessary computations, and the use of lightweight model versions are essential. Specifically, managing weights more efficiently and eliminating redundant computational loads will not only reduce energy consumption but also accelerate the system's response time. In future work, exploring more advanced models like Mask R-CNN [16] for finer-grained inspection, such as detailed defect analysis, could further enhance the system's capabilities.

Real-time data processing requirements are among the key factors directly affecting system performance. The YOLO algorithm requires high FPS (frames per second) values to function quickly and accurately. However, due to limitations in the current hardware infrastructure, data transmission delays may occur, reducing the model's real-time detection and counting performance. Therefore, integrating more powerful GPUs, high-speed data processing units, and optimized hardware solutions plays a critical role in enhancing the system's efficiency.

Nevertheless, hardware improvements alone may not be sufficient. To increase processing speed, parameter optimization, reduction of unnecessary computations, and the use of lightweight model versions are essential. Specifically, managing weights more efficiently and eliminating redundant

computational loads will not only reduce energy consumption but also accelerate the system's response time.

Furthermore, the reliability of the model in the production environment must be continuously monitored, and periodic updates should be implemented to ensure adaptation to field variations. Factors such as changes in lighting conditions and different image angles can impact the model's accuracy. Therefore, continuously expanding the dataset used for training and improving its adaptability to real production conditions are necessary.

In conclusion, YOLO-based product counting and quality control systems have the potential to revolutionize production processes. However, for the system to operate in real-time with high accuracy, both hardware enhancements and software optimizations must be implemented. In the future, the development of more efficient algorithms, reductions in hardware costs, and the widespread adoption of high-performance AI chips are expected to drive the increased use of such systems in the industry.

V. CONCLUSION

This study improved product counting and quality control processes on the suspension system assembly line using the YOLO algorithm and the Ultralytics library. The model eliminated operator errors, enabling faster and more accurate counting. However, due to FPS requirements and data transmission limitations in real-time processing, both hardware and software optimizations are necessary. Enhancing performance with more powerful GPUs, high-speed data processing units, and optimized algorithms can improve system efficiency. With the required improvements, the model will operate with high accuracy on the production line, significantly enhancing quality and productivity.

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Authors'

Contributions

The authors' contributions to the paper are equal.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics

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Numerical Solutions of Hyperbolic Telegraph Equations using Difference Schemes and Neural Network

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Abstract – In this study, the hyperbolic telegraph differential equation describing the behavior of certain wave-like phenomena, such as the transmission of signals along a telegraph line, is considered. Numerical solutions of a telegraph equation are computed by using various operator-difference schemes and physics-informed neural networks. The error analysis is performed, and the results are compared.

Keywords – Hyperbolic Equations, Numerical Solution, Error Analysis, Difference Scheme, Neural Network

I. INTRODUCTION

PDEs are equations that involve partial derivatives of a multivariable function. They play a crucial role in various fields such as physics, engineering, finance, and biology, as they can describe a wide range of phenomena, including heat conduction, fluid flow, and wave propagation [1].

Hyperbolic equations are a type of partial differential equation characterized by the propagation of waves and signals. They describe systems where information travels at finite speeds, making them essential in various fields like physics, engineering, and finance. The most common example is the wave equation, which describes the propagation of waves, such as sound waves, light waves, water waves and how waveforms evolve over time.

The hyperbolic telegraph equation is a specific type of partial differential equation that describes the propagation of signals [2] in a medium with both wave-like and dissipative characteristics. It combines elements of both wave propagation and damping, making it particularly relevant for modeling phenomena in electrical engineering and acoustics.

The telegraph equations (also known as transmission line equations) describe the voltage and current on an electrical transmission line with distributed parameters. These equations also apply to RLC circuits when they are modeled as distributed parameter systems, such as in long transmission lines [3].

Numerical methods are used to approximate the solution of the telegraph equation when an analytical solution is not feasible. There are many different numerical solution methods for telegraph equations. Finite difference methods, finite element methods, finite volume methods are some them. Stability is a critical concept in the numerical solution of partial differential equations using finite difference methods. It refers to whether small errors (e.g., from round-off or truncation) grow uncontrollably as the computation progresses.

Various initial boundary value problems can be reduced to initial value problems [4-5]. In this paper, the following initial value problem is considered:

$$\begin{cases} \frac{d^2 u(t)}{dt^2} + \alpha \frac{du(t)}{dt} + Au(t) = f(t), & 0 \leq t \leq T, \\ u(0) = \varphi, \quad u'(0) = \psi. \end{cases} \quad (1)$$

Here A is self-adjoint unbounded operator in Hilbert space. In this paper, for the approximate solutions of the above problems, first, second, third order of accuracy difference schemes are presented in the next section. A test problem is considered and numerical solutions of the test problem are found by using difference schemes. The results are compared with each other. Moreover, approximate solutions of the test problem are also found by using neural network in the fourth section.

II. DIFFERENCE SCHEMES

For approximate solutions of the problem (1), the following first order of accuracy difference scheme

$$\begin{cases} \frac{u_{k+1} - 2u_k + u_{k-1}}{\tau^2} + \alpha \frac{u_{k+1} - u_k}{\tau} + Au_{k+1} = f_k, \\ f_k = f(t_{k+1}), \quad 1 \leq k \leq N-1, \quad N\tau = T, \\ u_0 = \varphi, \quad (1 + \varphi\tau) \frac{u_1 - u_0}{\tau} + A\tau u_1 = \psi \end{cases}$$

and two different types of second order of accuracy difference schemes

$$\begin{cases} \frac{u_{k+1} - 2u_k + u_{k-1}}{\tau^2} + \alpha \frac{u_{k+1} - u_{k-1}}{2\tau} \\ + \frac{A}{2}(u_{k+1} + u_{k-1}) = f_k \\ f_k = f(t_k), \quad 1 \leq k \leq N-1, \\ u_0 = \varphi, \quad \frac{u_1 - u_0}{\tau} + \frac{\tau}{2}Au_1 = \psi + \frac{\tau}{2}(-\alpha\psi + f_0), \\ f_0 = f(0), \end{cases}$$

and

$$\begin{cases} \frac{u_{k+1} - 2u_k + u_{k-1}}{\tau^2} + \alpha \frac{u_{k+1} - u_{k-1}}{2\tau} + \frac{A}{2}u_k \\ + \frac{A}{4}(u_{k+1} + u_{k-1}) = f_k \\ f_k = f(t_k), \quad 1 \leq k \leq N-1, \\ u_0 = \varphi, \quad \frac{u_1 - u_0}{\tau} + \frac{\tau}{2}Au_1 = \psi + \frac{\tau}{2}(-\alpha\psi + f_0), \\ f_0 = f(0). \end{cases}$$

were developed in [6]. Stability estimates for the solutions of difference schemes were constructed. For the approximate solutions of problem (1), the following third order of accuracy difference scheme

$$\begin{cases} \frac{u_{k+1} - 2u_k + u_{k-1}}{\tau^2} + \alpha \frac{u_{k+1} - u_{k-1}}{2\tau} + \frac{2}{3}Au_k \\ + \frac{1}{6}A(u_{k+1} + u_{k-1}) \\ + \frac{\tau^2}{12} \left[(-\alpha^3 + 2\alpha A) \frac{u_{k+1} - u_k}{\tau} - (\alpha^2 - A)Au_{k+1} \right] = f_k, \\ f_k = \frac{2}{3}f(t_k) + \frac{1}{6}[f(t_{k+1}) + f(t_{k-1})] \\ - \frac{\tau^2}{12} [(\alpha^2 - A)f(t_{k+1}) - \alpha f'(t_{k+1}) + f''(t_{k+1})], \\ 1 \leq k \leq N-1, \\ u_0 = \varphi, \\ \left(I + \frac{\tau^2}{2}A \right) \frac{u_1 - u_0}{\tau} = \left(I + \frac{\tau^2}{2}A \right) \psi + \frac{\tau}{2}(-\alpha\psi - A\varphi) \\ + \frac{\tau^2}{6}(\alpha^2\psi + \alpha A\varphi - A\psi) + f_0, \\ f_0 = \frac{\tau}{2}f(0) - \frac{\tau^2}{6}[f(0) - f'(0)]. \end{cases}$$

was developed in [7] in 2016. Stability inequalities for the solution of this third order of accuracy difference scheme were also done. In the following section, we consider one dimensional telegraph equation as a test problem to support theoretical results.

III. NUMERICAL SOLUTIONS

For MATLAB implementations, the following initial-boundary value problem is considered:

$$\begin{cases} \frac{\partial^2 u(t, x)}{\partial t^2} + 2 \frac{\partial u(t, x)}{\partial t} + u(t, x) \\ = \frac{\partial^2 u(t, x)}{\partial x^2} + 2(1 + t + t^2) \sin x, \\ 0 < t < 1, \quad 0 < x < \pi, \\ u(0, x) = \sin x, \quad u_t(0, x) = -\sin x, \quad 0 \leq x \leq \pi, \\ u(t, 0) = u(t, \pi) = 0, \quad 0 \leq t \leq 1. \end{cases} \quad (2)$$

The exact solution of the problem (2) is $u(t, x) = (1 - t + t^2) \sin x$. When the step number for time and space variable are taken as 5, the difference between exact solution and approximate solution does not appear as shown from figures 3.1 and 3.2-3.5.

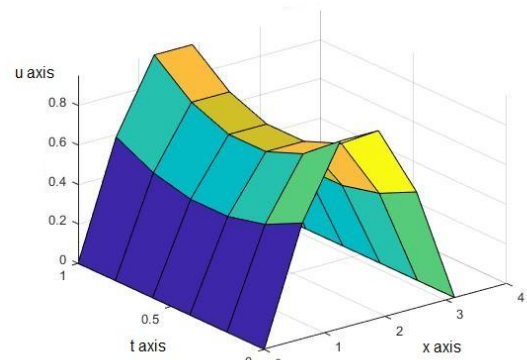


Fig. 3.1. Exact Solution

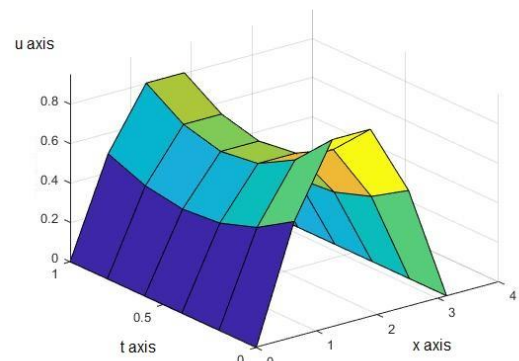


Fig. 3.2. First-order

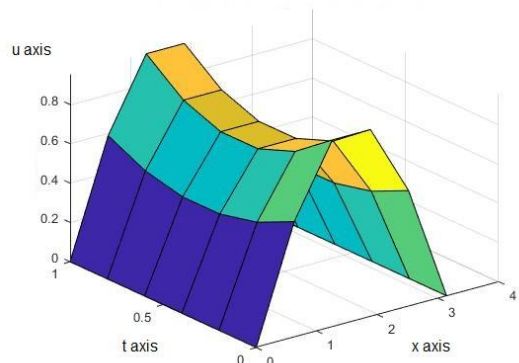


Fig. 3.3. Second-order I

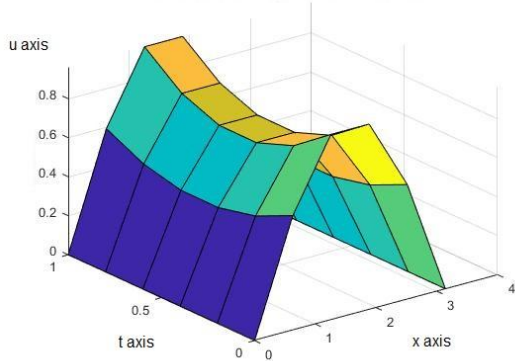


Fig. 3.4. Second-order II

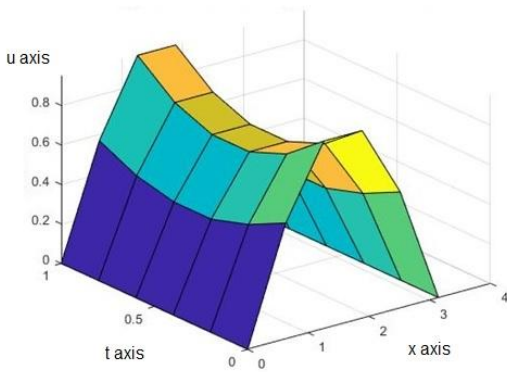


Fig. 3.5. Third-order

To compare the results between exact solution and approximate solution, we need to give the results by table. Error formula is define as follows

$$E_0 = \max_{1 \leq k \leq N-1} \left(\sum_{n=1}^{M-1} |u(t_k, x_n) - u_n^k|^2 h \right)^{\frac{1}{2}},$$

where $u(t_k, x_n)$ is exact solution and u_n^k is approximate solution at the point (t_k, x_n) . h is step size for space variable. N and M are step numbers for time and space variables respectively. As shown in Table 3.1, the accuracy of second order difference schemes are better than the first order difference scheme. The accuracy of the third order difference scheme is better than the accuracy of second order difference schemes. There is no much difference between second order difference scheme 1 and 2. When the number of step for time variable is increased 2 times, the error gets smaller 2 time for first order difference scheme. When the number of step for time variable is increased 2 times, the errors get smaller 4 and 8 times for the second and third order different schemes respectively.

 Table 3.1. Error for E_0

	$N=M^2$	64, 8	128, 11	256, 16
FO	Error	0.01069	0.00523	0.00265
	$N=M$	32, 32	64, 64	128, 128
SO1	Error	0.0002349	0.0000575	0.0000142
SO2	Error	0.0003417	0.0000848	0.0000211
	$N^3=M^2$	10, 32	20, 89	40, 253
TO	Error	0.0003249	0.0000381	0.0000046

	$N=M$	32	64	128
FO	Error	0.0271183	0.0137000	0.0068864
SO1	Error	0.0002349	0.0000575	0.0000142
SO2	Error	0.0003417	0.0000848	0.0000211
TO	Error	0.0001813	0.0000482	0.0000124

IV. NEURAL NETWORKS

Artificial neural networks are computational models that mimic the synaptic structure of neurons in the human brain [8]. These networks consist of processing units (nodes) interconnected across multiple layers: the input layer, one or more hidden layers, and the output layer. The input layer receives raw data, and the hidden layers process this data and extract representations of increasing levels of abstraction, leading to the output layer that produces the final result. These neural networks have demonstrated tremendous potential in approximating any arbitrary function (Universal Approximation Theorem) and learning complex patterns in images, audio, and text, leading to significant scientific advances in fields such as computer vision and natural language processing [9].

With the development of deep learning, the need has emerged to incorporate physical knowledge into the training process to overcome total reliance on observed data, especially in problems where sufficient data is difficult to obtain. Hence, the idea of Physics-Informed Neural Networks (PINNs) ([10]) emerged, adding a term to the loss function that represents the residuals of the partial differential equations governing the system. Leveraging automatic differentiation, the network computes the necessary derivatives of the resulting solution to ensure the network satisfies initial and boundary conditions as well as the physical conservation laws during learning. This enables it to solve forward (finding a solution) and inverse (discovering unknown coefficients or parameters) problems efficiently without the need to generate an explicit mesh or mesh nodes [11].

4.1. Methodology

To build PINNs, we have the following steps.

4.1.1. Problem Formulation

Define the partial differential equation

$$f[u(x, t)] = 0$$

with boundary conditions

$$u(x_b, t_b) = g(x_b, t_b)$$

and with initial conditions

$$u(x_i, 0) = h(x_i)$$

4.1.2. Neural Network Architecture

A fully connected feed-forward network $u_\theta(x, t)$ is chosen, which receives the spatial variables x and temporal variables t as inputs and produces the approximate solution u .

4.1.3. Loss Function

Weighted loss function is defined as the following

$$\mathcal{L}(\theta) = w_{PDE} \mathcal{L}_{PDE} + w_{BC} \mathcal{L}_{BC} + w_{IC} \mathcal{L}_{IC}$$

$$\mathcal{L}(\theta) = w_{PDE} *$$

$$\frac{1}{N_r} \sum_{j=1}^{N_r} \left(f[\theta](x_j, t_j) \right)^2 + w_{BC} \frac{1}{N_b} \sum_{k=1}^{N_b} (u_\theta(x_{b,k}, t_{b,k}) - g(x_{b,k}, t_{b,k}))^2 + w_{IC} \frac{1}{N_l} \sum_{l=1}^{N_l} (u_\theta(x_{i,l}, t_{i,l}) - h(x_{i,l}))^2,$$

where $\mathcal{L}_{PDE}$ is mean squared residual of the partial differential equations over N_r interior collocation points, $\mathcal{L}_{BC}$ is mean squared error on N_b boundary points against boundary data g , $\mathcal{L}_{IC}$ is mean squared error on N_l initial points against initial data h .

4.1.4. Collocation Point Generation

$\{(x_j, t_j)\} \subset \Omega$ is interior points for the partial differential equations residual. Boundary points $\{(x_{b,k}, t_{b,k})\} \subset \partial\Omega$ for the boundary conditions. Initial points $\{(x_{i,l}, t_{i,l} = t_0)\} \subset \Omega$ at the initial time t_0 , then impose $u(x_{i,l}, t_0) = h(x_{i,l})$ and $u_t(x_{i,l}, t_0) = h_t(x_{i,l})$.

4.1.5. Training Loop

Forward pass is passing input through the network layers to get the prediction compute loss. Backward pass is auto-differentiation is used to calculate the gradients of the loss function with respect to the weights, and the optimizer then updates the weights.

4.2. Practical Implementation

We seek to solve the problem (2). We approximated $u(x, t)$ by a dense feed-forward network $u_\theta(x, t)$ taking (x, t) input, passing through hidden layers of different widths with tanh activations, and outputting a single scalar. Its loss is a weighted sum $\mathcal{L}(\theta) = \mathcal{L}_{PDE} + 5\mathcal{L}_{BC} + \mathcal{L}_{IC}$, where $w_{PDE} = 1, w_{BC} = 5, w_{IC} = 1$ and $\mathcal{L}_{PDE}$ is the mean squared residual of the partial differential equation over 100×100 (and over 200×100) interior collocation points, $\mathcal{L}_{IC}$ enforces $u(x, 0) = \sin x$ and $u_t(x, 0) = -\sin x$ over 200 initial points, and $\mathcal{L}_{BC}$ enforce $u(0, t) = u(\pi, t) = 0$ over 200 boundary points.

We trained the neural network for 10000 epochs using the Adam optimizer (learning rate is 0.01), computing all derivatives via automatic differentiation and checkpointing the model state that achieves the lowest MSE on the training set. Finally, we evaluated the saved model on independent grids of size 100×100 (200×100), reporting mean square error and Max Δt -weighted L_2 over x error. Max Δt -weighted L_2 over x is

$$\max_{i=1, \dots, N_x} \sqrt{\Delta t \sum_{j=1}^{N_t} (u_{pred}(x_i, t_j) - u_{true}(x_i, t_j))^2} \text{ where } \Delta t = \frac{1-0}{N_t-1} \text{ is the uniform time-step on } [0, 1].$$

Table 4.2.1. Training and Evaluation Performance Metrics of Different PINN Architectures after 10,000 Epochs on a 100×100 Grid

10000 epochs & $N_x * N_t = 100 * 100$				
Performance Metrics Architecture	Best Train MSE	Best iteration	Evaluation Grid $100 * 100$	
			MSE	Max Δt -weighted L_2 over x
[2-50-50-50-1]	3.093e-07	9775	2.894e-07	1.073e-03
[2-50-50-50-50-1]	9.979e-07	4416	8.734e-07	2.471e-03
[2-50-50-50-50-50-1]	2.153e-06	2695	2.089e-06	3.028e-03
[2-100-100-100-1]	2.559e-07	4488	2.299e-07	9.902e-04
[2-32-64-128-64-32-1]	1.014e-05	1180	9.915e-06	5.039e-03

Table 4.2.2. Training and Evaluation Performance Metrics of Different PINN Architectures after 10,000 Epochs on a 200×100 Grid

10000 epochs & $N_x * N_t = 200 * 100$				
Performance Metrics Architecture	Best Train MSE	Best iteration	Evaluation Grid $200 * 100$	
			MSE	Max Δt -weighted L_2 over x
[2-50-50-50-1]	3.574e-07	7647	3.379e-07	1.489e-03
[2-50-50-50-50-1]	6.883e-07	9006	6.680e-07	1.598e-03
[2-50-50-50-50-50-1]	1.036e-06	3999	1.005e-06	1.979e-03
[2-100-100-100-1]	2.767e-07	3065	2.560e-07	1.354e-03
[2-32-64-128-64-32-1]	5.245e-06	1863	5.103e-06	4.180e-03

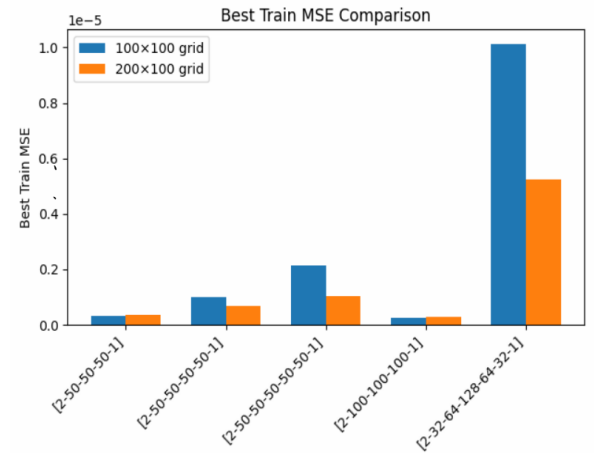


Fig. 4.2.1. Best Train MSE Comparison

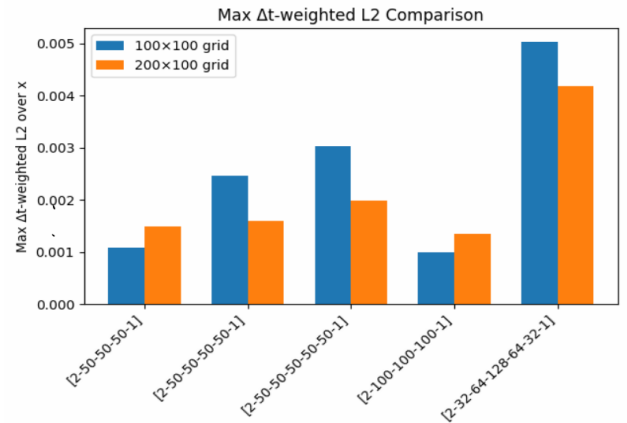


Fig. 4.2.2. Max Δt -weighted L_2 Comparison

4.3. Discussion of PINNs Results

The architecture with five hidden layers [2-50-50-50-50-50-1] reached the lowest mean square error at iterations 2695 (for a 100×100 grid) and 3999 (for a 200×100 grid), meaning it finished improving the loss earlier than the other architectures. However, the solution quality (Best Train mean square error and Max Δt -weighted L_2 over x) was the worst among all architectures, indicating that it reached an early local minimum without reaching a truly low error. The widest-

deepest hierarchical architecture [2-32-64-128-64-32-1] converges the fastest. This architecture reached its best point at iterations 1180 (100×100) and 1863 (200×100), significantly faster than the other networks. However, it also achieved the highest errors, demonstrating that convergence speed alone is not a quality measure.

The medium-depth and wide-width [2-100-100-100-1] networks show a good balance. They reached their best point at around 4500 iterations (4488 and 3065), significantly faster than the simple [2-50-50-50-1] networks (9775 and 7647) but better performing than the very deep networks. They achieved the lowest errors, reflecting a balance between convergence speed and solution quality. Relatively narrow [2-50-50-50-1] networks converge slowly. They require almost the full number of iterations (9,775 and 7,647 out of 10,000) to achieve the optimal loss. However, they achieve a low error, rivaling [2-100-100-100-1] and outperforming some other architectures. The results also highlight the inherent challenge of finding neural network architectures where determining the optimal architecture requires numerous experimental trials.

V. CONCLUSION

In this study, one dimensional telegraph equation is considered. Numerical solutions of this equation found by using first, second and third order difference schemes. It was shown that the accuracy of third order scheme is better than second order scheme which is better than first order scheme. There was no much difference between two second order difference schemes. Numerical solutions of the equation were also found by using neural network. The results are satisfactory.

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Face Mesh Özelliklerine Dayalı Derin Öğrenme ile Dikkat-Duygu-Yorgunluk Tespiti

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Türkçe Özet – Bu çalışma, bireylerin anlık dikkat düzeyi, duygu durumu ve yorgunluk seviyesini entegre bir şekilde analiz eden yapay zeka tabanlı bir sistem geliştirmeyi amaçlamaktadır. Python diliyle geliştirilen sistemde, yüz ifadeleri ve göz hareketleri MediaPipe, DeepFace ve OpenCV gibi kütüphanelerle analiz edilerek; yorgunluk, dikkat ve duygu durumuna dair ölçümler elde edilmiştir. Kullanıcı dostu bir arayüz PyQt5 ile tasarlanmış, böylelikle tüm analizlerin arka planda gerçek zamanlı olarak gerçekleştirilmesi sağlanmıştır.

Yorgunluk tespiti için EAR(Eye Aspect Ratio), MAR (Mouth Aspect Ratio), MOE (Mouth Opening Extent), PERCLOS (Percentage of Eye Closure) ve Blink Rate (göz kırpma oranı) gibi metrikler, LSTM tabanlı bir modelle analiz edilmiştir. Dikkat seviyesi, dijitalleştirilmiş D2 Dikkat Testi üzerinden göz takibiyle ölçülmüş ve geleneksel testle yüksek korelasyon göstermiştir. Böylelikle literatürde yaygın olarak kullanılan D2 Dikkat Testi'nin göz takip teknolojileriyle dijital ortama aktarılmasının mümkün olduğu gösterilmiştir. Bu yönüyle, dikkat testlerinin dijitalleşmesine öncülük eden ilk uygulamalardan biri olma özelliği taşımaktadır. Duygu analizi ise CNN ve K-Means kümeleme yöntemleriyle gerçekleştirilmiş, ve duygu sınıfının yanında duygu yoğunluğunun da belirlenebilmesi sağlanmıştır.

Gerçekleştirilen deneylerde sistemin yorgunluk tespitinde %94, duygu analizinde %88 doğruluk oranı yakaladığı ve dikkat ölçümünde güvenilir sonuçlar verdiği görülmüştür. Çalışma, geleneksel tek yönlü analizlerin ötesine geçerek, entegre ve gerçek zamanlı bir analiz imkanı sunmakta ve dikkat testlerinin otomasyonu konusunda literatüre katkı sağlamaktadır.

Anahtar Kelimeler – Yorgunluk Tespiti, Duygu Analizi, Otomatik Dikkat Ölçümü, Python, Derin Öğrenme, Bilgisayarlı Görü

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Attention-Emotion-Fatigue Detection Based On Face Mesh Features Using Deep Learning

Extended Abstract

Research Problem/Questions – Modern applications in work safety, traffic management, and psychotechnical evaluation demand reliable real-time assessments of an individual's cognitive state. Despite significant progress in single-parameter analyses (such as fatigue detection or emotion recognition), a gap remains in developing an integrated system that simultaneously evaluates emotion, fatigue, and attention. This study aims to address this gap. In addition, considering the amount of paper work required in deployment of the classical widespread manual D2 Attention Test [19] in measuring the attention level, this study aims to be one of the first studies to pioneer the automation of this test.

Short Literature Review – Earlier studies show that a large portion of occupational and traffic accidents are related to attention deficit [1],[2], fatigue [3],[4] and high emotional state [5]. However, research has typically focused on individual aspects—

usually only fatigue [6], [7], only attention [8] or only emotion [9],[10] are analyzed separately. While these methods have yielded promising results, they often neglect the interdependencies between cognitive factors. Recent advances in deep learning and computer vision have enabled more nuanced detection capabilities; however, studies that merge these modalities remain scarce.

Methodology – The proposed system is developed in Python by using several specialized libraries.

– Fatigue Detection: Mediapipe is used for real-time detection of facial landmarks, enabling the extraction of parameters such as EAR, MAR, MOE (Mouth Opening Extent), and PERCLOS. These parameters are then fed to an LSTM model for fatigue classification.

– Emotion Analysis: Deepface, supported by a convolutional neural network (CNN) pretrained on FER-2013 dataset and fine-tuned with domain-specific images, identifies subtle facial expressions. In addition, K-Means clustering algorithm was implemented to cluster the intensity levels (low, medium, and high) within each emotion class.

– Attention Measurement: The system incorporates the D2 attention test framework, wherein eye-tracking data obtained via Mediapipe is used to assess fixation durations and detect attention lapses.

– User Interface and Calibration: A user-friendly interface is developed with PyQt5. A calibration phase establishes individual baseline metrics to account for inter-subject variability.

The integrated approach employs feature extraction, time series analysis, and clustering techniques (e.g., K-means) to quantify and categorize the cognitive states reliably.

Results and Conclusions – Experimental evaluations demonstrate that the integrated system achieves approximately 94% accuracy in fatigue detection. This result offers a practical and effective solution for real-time applications with its high accuracy, low computational cost and person-independent generalization ability. On the other hand, attention measurement module shows stable performance and high correlation with the classical manual deployment scores. This result is promising especially considering that this is one of the first studies to pioneer the automation of this test. The emotion analysis module, optimized through hyperparameter tuning and CNN architecture search, reaches a mean average precision (mAP) close to 88%. These results validate that a multi-faceted approach not only enhances detection accuracy but also provides a comprehensive analysis of an individual's cognitive state. The findings show significant potential for deploying such systems in environments where real-time monitoring is critical for safety and performance improvement.

Keywords – Fatigue Detection, Emotion Analysis, Attention Measurement, Python, Deep Learning, Computer Vision

Citation: Öz, E., Belkan, A.E., Yaman, A. E., Gümüş, K., Karabudak, A., Yilmazyıldız Kayaarma, S., (2025). Attention-Emotion-Fatigue Detection Based On Face Mesh Features Using Deep Learning. International Journal of Multidisciplinary Studies and Innovative Technologies, x(x): xx-xx

I. GİRİŞ

Günümüz dünyasında bireylerin duygu durumu, yorgunluk seviyesi ve dikkat düzeyi, birçok alanda performanslarını doğrudan etkilemektedir. Özellikle iş güvenliği, trafik ve psikoteknik değerlendirmeler gibi kritik alanlarda, bireylerin anlık fiziksel ve zihinsel durumlarının doğru bir şekilde analiz edilmesi, olası hataların ve kazaların önlenmesi açısından büyük önem taşımaktadır. Yapılan araştırmalar, iş kazalarının ve trafik kazalarının büyük bir kısmının dikkat eksikliği [1],[2], yorgunluk [3],[4] ve duygu durumuyla [5] ilişkili olduğunu ortaya koymaktadır. Bu bağlamda, yapay zeka ve görüntü işleme teknolojilerinin gelişimi, bireylerin anlık duygu, yorgunluk ve dikkat durumlarını tespit edebilecek yenilikçi çözümler sunmaktadır.

Bu çalışma, yapay zeka destekli bir sistem geliştirerek bireylerin duygu durumu, yorgunluk seviyesi ve dikkat düzeyini analiz etmeyi amaçlamaktadır. Çalışmada, Python programlama dili ve mediapipe, deepface, opencv gibi kütüphaneler kullanılarak bireylerin yüz hatları, göz hareketleri ve mimiklerinden anlamlı veriler elde edilmektedir. Kullanıcı dostu bir arayüz sağlamak amacıyla PyQt5 kütüphanesi ile bir grafiksel arayüz oluşturulmuş, böylece sistemin kullanım kolaylığı artırılmıştır.

Önceki çalışmalar incelendiğinde, genellikle sadece yorgunluk [6],[7], sadece dikkat [8] ya da sadece duygu durumunun [9],[10] ayrı ayrı analiz edildiği görülmektedir. Ancak bu proje, duygu, yorgunluk ve dikkat analizlerini bir

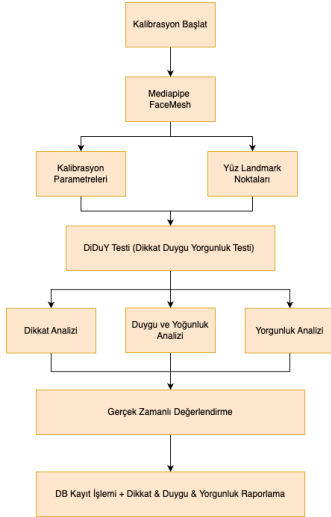
arada sunarak daha kapsamlı bir değerlendirme sağlamayı hedeflemektedir. Böylece psikologlar, iş sağlığı ve güvenliği uzmanları ile eğitimciler gibi alanında uzman kişilere daha detaylı ve anlaşılır veri sunulması amaçlanmaktadır.

Çalışmada kullanılan yöntemler, literatürde yer alan güncel yaklaşımlar dikkate alınarak geliştirilmiştir. Duygu durumu tespiti için DeepFace kütüphanesi ile yüz ifadeleri analiz edilmiş, yorgunluk seviyesi ise Mediapipe facemesh modeli ile göz ve ağız parametreleri üzerinden değerlendirilmiştir. Dikkat seviyesi ise D2 Dikkat Testi [19] temelli özgün bir göz hareketi izleme yöntemi ile belirlenmiştir. Bu yönüyle mevcut çalışma dikkat ölçmekte bir standart olan manuel D2 Dikkat testini teknoloji ile birleştirerek otomatikleştirilmesine öncülük eden ilk çalışmalardan biri olmuştur.

II. SİSTEM TASARIMI

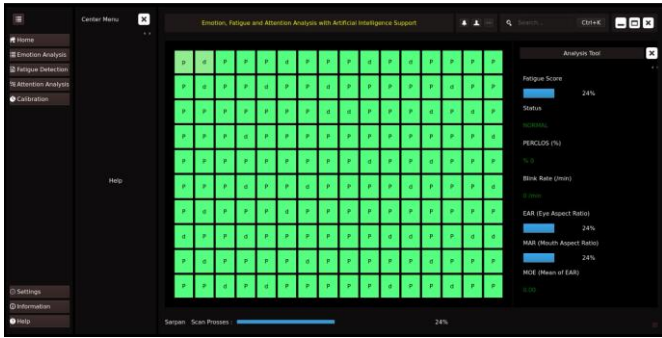
2.1. Genel Sistem Tasarımı

Geliştirilen sistem, temel olarak kullanıcının yüz ifadesi ve göz hareketlerinin gerçek zamanlı olarak analiz edilmesine dayanır. Yüz ifadesi ve göz hareketi bilgileri daha sonra Dikkat, Duygu, Yorgunluk tahmininde kullanılmaktadır. Sistemin çalışma prensibini gösteren akış şeması Şekil 1’de görülebilir. Başlangıç aşamasında yüz tanıma (Mediapipe FaceMesh) ve kalibrasyon işlemleri gerçekleştirilip giriş verileri elde edilir. Daha sonra dikkat, duygu ve yorgunluk analizleri ayrı ayrı gerçekleştirilip gerçek zamanlı değerlendirmesi yapılır ve elde edilen sonuçlar bir veritabanına kaydedilir.



Şekil 1: Genel Sistem Akış Diyagramı

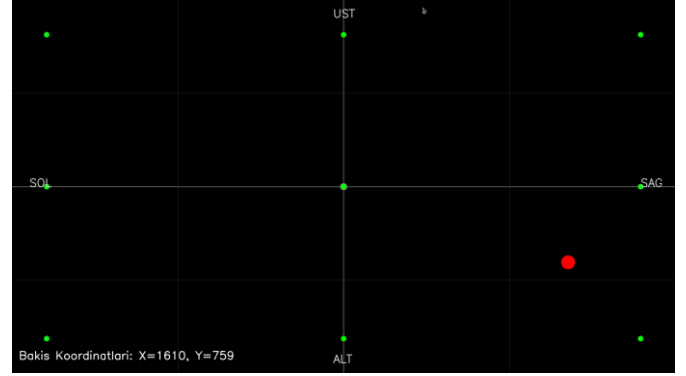
Sistem, Python programlama dili temelinde geliştirilmiş olup, görüntü işleme için OpenCV, yüz ve göz takibi için Mediapipe, duygu analizinde ise Deepface kütüphanelerinden yararlanılmaktadır. Bu modüller, kullanıcının video akışından elde edilen verileri işleyerek ilgili analizleri yapar. Kullanıcıya kolaylık sağlamak amacıyla, PyQt5 kütüphanesi kullanılarak kullanıcı dostu bir grafiksel arayüz (Şekil 2) geliştirilmiştir.



Şekil 2: Arayüz

2.2. Kişi Profili Oluşturulması ve Kalibrasyon

Her bireyin yüz özellikleri ve göz hareketleri arasında farklılıklar bulunduğundan, ilk kullanımda otomatik olarak kişinin profilinin oluşturulmasını sağlar. Bu kalibrasyon aşamasında, yüz hatları, göz ve ağız parametreleri (Eye Aspect Ratio (EAR), Mouth Aspect Ratio (MAR), Mouth Opening Extent (MOE) ve PERCLOS)[12] ölçülür. Bu parametrelerle ilgili detaylı bilgi bölüm 3.3.2'de açıklanmıştır. Kalibrasyon süreci, her kullanıcının kendine özgü değerlerini belirleyerek, sistemin daha hassas ve doğru analiz yapmasına olanak tanır. Ayrıca, göz takip ve D2 Dikkat Testi kapsamında, kullanıcının ekrandaki hedeflere bakma alışkanlıkları gözlemlenerek, bireysel dikkat seviyesi değerlendirmesine yönelik başlangıç parametreleri ayarlanır. Şekil 3'de bu süreçten örnek arayüz görseli görülmektedir. Kullanıcılardan ekranda görülen belirli noktalara bakmaları istenmektedir. Daha sonra kullanıcının baktığı belirli noktalar ile ekrandaki referans konumlar eşleştirilerek kalibrasyon tamamlanmaktadır.

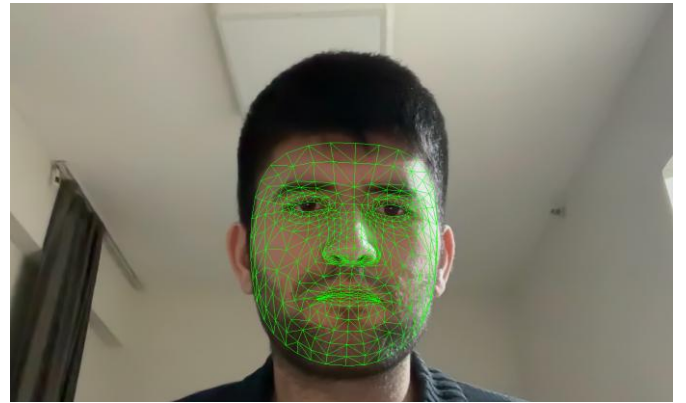


Şekil 3: Kullanıcının bakış koordinatları belirli referans noktalarıyla eşleştirilerek kalibrasyon tamamlanmaktadır.

III. METODOLOJİ

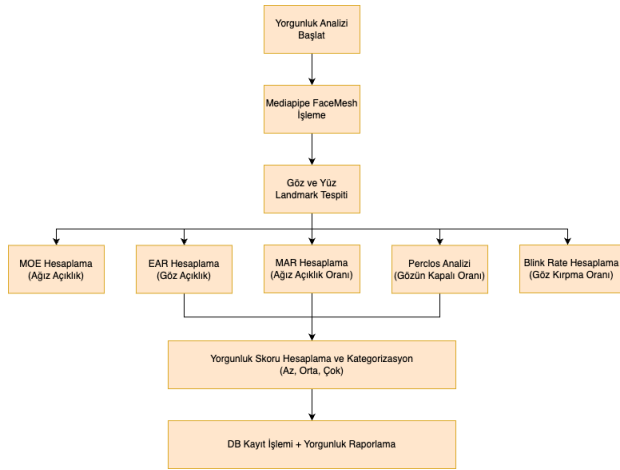
3.1. Mediapipe Face Mesh

Mediapipe Face Mesh, yüzün üç boyutlu yapısını ortaya çıkarmak için özel olarak tasarlanmış bir modeldir ve bu amaçla çok aşamalı bir süreç izler. Öncelikle, 256×256 boyutlarındaki girdi görüntüsü üzerinde çalışarak, BlazeFace algoritması sayesinde yüzün bulunduğu alanı tespit eder; bu aşamada yüzün etrafına dört köşeden oluşan bir çerçeve (bounding box) çizilir. Ardından, bu belirlenen bölge, hesaplama sürecinin hızlanması ve verimliliğin artırılması için daha küçük bir ölçekte yeniden düzenlenir. Model, bu küçültülmüş alan üzerinden Şekil 4'te görüldüğü gibi 468 sabit noktanın üç boyutlu koordinatlarını tahmin ederek yüzün genel hatları ile karakteristik özelliklerini belirler. Ayrıca, yüzün göz, dudak gibi kritik bölgelerine özel alt modüller aracılığıyla detaylı analiz yapar; bu sayede model, hem yüzün büyük yapısını hem de mikro detaylarını yüksek doğrulukla belirleyebilir. Böylece, Mediapipe Face Mesh, entegre ve modüler yapısı sayesinde gerçek zamanlı uygulamalarda bile kapsamlı ve detaylı bir yüz haritası oluşturarak, çeşitli görsel analiz ve artırılmış gerçeklik çözümlerinde etkin bir şekilde kullanılmaktadır.



Şekil 4: Mediapipe Face Mesh 468 Sabit Nokta Model

3.3. Yorgunluk Analizi



Şekil 5: Yorgunluk Analizi Akış Diyagramı

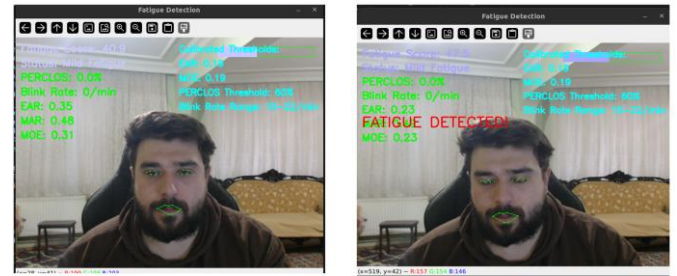
Şekil 5’de akış şeması görülebilen yorgunluk (uykulu hâl) tespitine yönelik uygulanan metodoloji bu kısımda dört ana başlık altında incelenecek. Öncelikle kullanılan veri setleri ve hazırlık süreçleri açıklanmakta, ardından yorgunluk ölçütlerinin nasıl hesaplandığı ve modellenen özellikler ele alınmaktadır. Sonrasında önerilen LSTM tabanlı derin öğrenme modelinin mimarisi ve eğitim ayrıntıları sunulmakta, son olarak modelin performans bulguları değerlendirilmektedir.

3.3.1. Veri Toplama

Yorgunluk analizi için açık kaynak bir gerçek yaşam yorgunluk veri seti kullanılmıştır. University of Texas at Arlington tarafından yayınlanan Real-Life Drowsiness Dataset (UTA-RLDD) veri seti tercih edilmiştir. UTA-RLDD, 60 gönüllü denekten çekilen yaklaşık 30 saatlik video verisini içeren ve bu alanda en kapsamlı gerçekçi yorgunluk verisi olarak bilinen bir derlemedir[13]. Her bir katılımcı, araştırma protokolü gereği *uyanıklık (alert)*, *düşük uyanıklık (low vigilance)* ve *uykulu (drowsy)* olmak üzere üç farklı durumda video kaydı sağlamıştır; toplamda veri setinde her katılımcı için üç video olmak üzere 180 video bulunmaktadır. Videolar gerçek ortamlarında (ör. iç mekânda günlük kullanım) cep telefonu veya web kamerasıyla kaydedilmiş, kare hızları genellikle 30 fps’nin altındadır ve kayıtlarda çeşitli düzeylerde uykululuk belirtileri (ör. göz kapağı sarkması, uzun süreli göz kapalı kalma, esneme) doğal şekilde yer almaktadır. Veri setinin her bir videosu, ilgili katılımcının o anki durumu gözlemlenerek manuel olarak etiketlenmiştir; örneğin denekler ilk videoda tamamen dinç (*alert*) iken, sonraki videolarda artan yorgunluk belirtileri göstermiş ve bu durum araştırmacılar tarafından video düzeyinde etiketlenmiştir. Dolayısıyla veri etiketleme işlemi senaryo tabanlı ve insan denetimli şekilde gerçekleştirilmiştir. Eğitim ve değerlendirme amacıyla veri seti eğitim, doğrulama ve test alt bölümlerine ayrılmıştır. Ayırma işlemi, modelin farklı kişiler üzerinde genelleşmesini sınamak adına katılımcı bazlı yapılmıştır. Toplam 60 katılımcının yaklaşık %70’i (42 kişi, 126 video) eğitim için kullanılırken, %15’i (9 kişi, ~27 video) doğrulama, kalan %15’i (9 kişi, ~27 video) modelin testinde ayrılmıştır. Bu sayede test aşamasında modelin daha önce görmediği kişilere ait verilerle değerlendirme yapılarak, kişi bağımlı olmayan bir performans ölçümü sağlanmıştır. Her bir video kaydından model için gerekli özelliklerin çıkarılması amacıyla

belirli oranda örnekleme yapılmıştır. Özellikle, videolardan ilk birkaç dakikayı temsil eden maksimum 300 kare (frame) alınarak veri boyutu sınırlandırılmış ve işlenebilir hale getirilmiştir. Seçilen karelerde yüz algılama ve işaretleme işlemleri Google’ın MediaPipe Face Mesh modeli kullanılarak gerçekleştirilmiştir[14]. MediaPipe, her karede yüz üzerinde 468 adet kilit nokta tespit etmektedir. Bu noktaların koordinatları kullanılarak göz ve ağız bölgesiyle ilgili metrik özellikler hesaplanmıştır. Modelde kullanılacak özelliklerin çıkarımı için tüm videolar bu şekilde işlenerek bir özellik veri kümesi oluşturulmuştur. Veri artırma işlemleri olarak, kamera görüntülerindeki doğal varyasyonlar (farklı yüz açısı, aydınlatma koşulları vb.) zaten veri setinde bulunduğu için yapay veri artırma tekniklerine başvurulmamıştır. Eğitim verisindeki *drowsy* (uykulu) durum örnek sayısının *alert* durumuna kıyasla görece az olması sorunu karşı ise, veri seti içeriğinde her katılımcıdan her sınıfa ait video bulunduğu için dengeli bir dağılım elde edilmeye çalışılmış; gerek duyulduğunda mini-batch seviyesinde pozitif örnek ağırlıklandırması ile bu dengesizlik etkisi azaltılmıştır. Son olarak, model eğitime başlamadan önce tüm eğitim verisi *eğitim* (training) ve *doğrulama* (validation) alt kümelerine ayrılarak hiperparametre tuning’i ve erken durdurma (early stopping) mekanizması için uygun ortam hazırlanmıştır.

3.3.2. Yorgunluk Hesaplama



Şekil 6: Yorgunluk Tespiti

Mediapipe FaceMesh modeli kullanılarak göz, ağız ve yüz landmark noktaları belirlenmiş (Şekil 6); bu sayede kullanıcının göz açıklık durumu, göz kırpması süresi ve yüz kas hareketleri tespit edilmiştir. Göz ve ağız landmark noktaları kullanılarak geometrik hesaplamalar gerçekleştirilmiş ve göz açıklık oranı (EAR), ağız açıklık oranı (MAR) ve ağız açıklık düzeyi (MOE) değerleri hesaplanmıştır. Elde edilen bu parametreler doğrultusunda, göz kırpması süresi ve göz kapalı geçirilen sürenin toplam süreye oranı (PERCLOS) değerlendirilerek yorgunluk seviyesi analiz edilmiştir. Ayrıca, göz kırpması oranı (Blink Rate) hesaplanmış, eşik değerlerle karşılaştırılarak olağan dışı artış veya düşüşler analiz edilmiştir. Göz ve ağız açıklık oranları gibi metrikler zaman serisi analiziyle modellenmiş, yorgunluk seviyesinin zamana bağlı değişimini gözlemlemek amacıyla hareketli pencere yöntemi kullanılmıştır. Bu yöntemle, kullanıcının test boyunca göz açıklık seviyesi ve göz kırpması oranındaki değişiklikler analiz edilerek kısa ve uzun vadeli yorgunluk tahminleri yapılmıştır. Yorgunluk seviyesinin belirlenmesinde kullanılan ölçütler Tablo 1’de özetlenmiştir.

Tablo 1: Yorgunluk Analizinde Kullanılan Ölçütler

Metrik	Tanım
PERCLOS (%)	Belirli bir süre içinde kullanıcının gözlerinin kapalı olduğu sürenin yüzdesi.
EAR (Eye Aspect Ratio)	Gözün açıklık oranını belirleyen bir ölçüm. Göz kapandıkça EAR düşer.
Blink Rate (/min)	Kullanıcının dakikadaki göz kırpması.
MAR (Mouth Aspect Ratio)	Ağız açıklık oranı. Esneme hareketleri tespit etmek için kullanılır.
MOE (Mouth Opening Extent)	Ağız açıklık miktarını ölçen bir parametre.

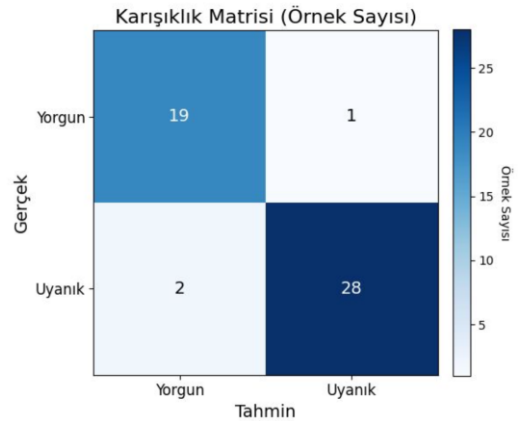
3.3.3 Model Mimarisi ve Eğitim

Yorgunluk tespiti için çıkarılan beş özellik (EAR, MAR, MOE, PERCLOS, Blink Rate), zaman serisi olarak değerlendirilmiş ve sınıflandırma için LSTM tabanlı bir model kullanılmıştır. Her giriş örneği, ardışık 5 kareden oluşan 4 boyutlu vektör dizisidir. Modelde, 64 nöronlu iki LSTM katmanı yer almakta ve yalnızca son zaman adımının çıktısı tam bağlantılı katmanlara aktarılmaktadır. Bu kısımda sırasıyla 256, 64, 8 ve 1 nöronlu katmanlar yer alır. Aktivasyon fonksiyonu olarak ReLU, çıkışta ise sigmoid kullanılmıştır. Model, ikili sınıflandırma yaptığı için Binary Cross-Entropy kaybı ile eğitilmiş; yorgunluk sınıfı az sayıda örnekle temsil edildiğinden pozitif sınıfa ağırlık verilmiştir (pos_weight=2). Yaklaşık 100.000 parametre içeren model, PyTorch ile eğitilmiş, optimizasyon için momentumlu SGD (öğrenme oranı: 0.001, momentum: 0.9) kullanılmıştır. Eğitim sürecinde mini-batch boyutu 4 olarak belirlenmiş, erken durdurma uygulanmıştır. En iyi doğrulama performansı sağlayan epoch'taki ağırlıklar nihai model olarak kaydedilmiştir. Alternatif yöntemler olarak Lojistik Regresyon, Naive Bayes, Karar Ağacı ve Rastgele Orman denenmiş, ancak zaman bağımlılığına duyarsız olmaları nedeniyle düşük tutarlılık göstermiştir. Özellikle Random Forest ardışık karelerde tutarsız etiketlemeler yapmıştır. Literatür de zaman serisi modellerinin bu alandaki üstünlüğünü desteklemektedir [15]. Bu nedenle, klasik RNN'lere göre daha uzun bağımlılıkları öğrenebilen iki katmanlı LSTM mimarisi tercih edilmiştir.

3.3.4. Bulgular

Geliştirilen yorgunluk tespit modeli, UTA-RLDD (University of Texas at Arlington Real-Life Drowsiness Dataset) veri setinde yer alan toplam 60 katılımcının yalnızca bir kısmı kullanılarak eğitilmiştir. Model daha sonra, eğitim sürecinde hiç yer almayan 9 farklı katılımcıya ait videolar ile test edilmiştir. Bu test senaryosu, modelin gerçek dünyada daha önce hiç karşılaşmadığı bireyler üzerinde performansını ölçmek amacıyla tasarlanmış ve kişi bağımsız (subject-independent) bir değerlendirme imkanı sunmuştur. Uygulanan bu testte model, ikili sınıflandırmada %94 doğruluk oranı sağlamıştır. Yorgun (pozitif) sınıfa ait precision değeri %92, recall değeri ise %95 olarak hesaplanmıştır. Bu sonuçlar, modelin özellikle uykulu anları tespit etmede yüksek hassasiyete sahip olduğunu ortaya koymaktadır. Ancak model zaman zaman uyanık bireyleri yanlış şekilde yorgun olarak sınıflandırmıştır. Bu false positive durumlar, özellikle dikkat dağınıklığı, esneme veya geçiş halindeki davranışların yer aldığı video segmentlerinde yoğunlaşmıştır. Bu hatalı sınıflamalar, genel doğruluk oranını ciddi ölçüde etkilemese de sistemin alarm mekanizmasının tamamen hatasız olmadığını göstermektedir. Bununla birlikte, güvenlik-kritik uygulamalarda yanlış negatifler (yani yorgun olduğu halde yorgun olarak algılanamayan anlar) çok daha riskli sonuçlara yol açabileceği için, yüksek recall odaklı bir yaklaşımın tercih edilmesi uygun görülmüştür. Model, uykulu anların %95'inden fazlasını başarıyla tespit edebilmiştir. Literatürde yalnızca göz kırpmaya dayanan R-LSTM modellerinin

%82 doğruluk oranında kaldığı, buna karşın CNN-LSTM tabanlı yaklaşımların %95–97 aralığında doğruluk sağlayabildiği bildirilmektedir [16]. NTHU-DDD ve YawDD veri setlerinde yapılan çalışmalarda da benzer şekilde %84–98 doğruluk oranları raporlanmıştır [13]. Bu bağlamda önerilen modelin %94 doğruluğu, literatürdeki başarılı sistemlerle uyumlu olup, çok daha düşük hesaplama maliyeti ile bu başarıyı elde etmiş olmasıyla öne çıkmaktadır. Örneğin InceptionV3 gibi derin evrimsel sinir ağı tabanlı modeller, %98.5 doğruluk oranına ulaşabilmekte, ancak bu başarı için yüksek boyutlu görüntülerin işlenmesi gerekmektedir. Önerilen model ise yalnızca beş temel yüz parametresine (EAR, MAR, MOE, PERCLOS, Blink Rate) dayalıdır ve bu nedenle gerçek zamanlı çalışmaya uygun, hafif ve verimli bir yapıya sahiptir.



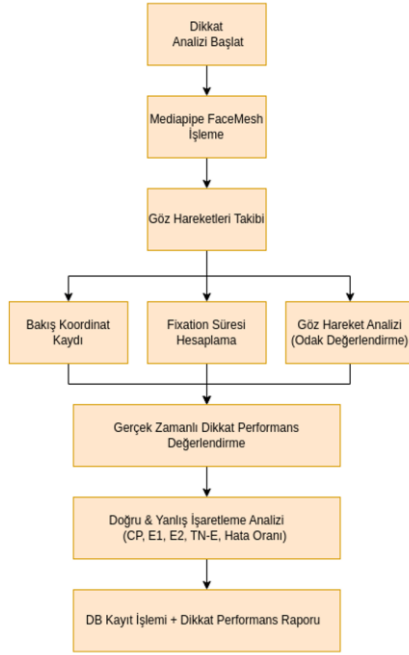
Şekil 7: Karışıklık Matrisi

Şekil 7’de sunulan karışıklık matrisine göre model, yorgun anların %95’ini, uyanık anların ise %93’ünü doğru şekilde sınıflandırmıştır. Yanlış sınıflandırmaların büyük çoğunluğu false positive türündedir. Özellikle düşük uyanıklık (low vigilance) seviyesindeki videolarda sınıflandırma kararsızlıkları gözlenmiş ve bu sınır durumların literatürde de zorlayıcı örnekler olarak kabul edildiği bilinmektedir. Bu gibi ara seviyeler net bir sınıfa karşılık gelmediğinden, modelin bu durumlarda karar vermekte zorlanması doğaldır. Gelecekte, yorgunluk düzeyinin yalnızca “uyanık” ve “yorgun” olarak değil, üç sınıf (örneğin: uyanık, düşük uyanıklık, çok yorgun) şeklinde modellenmesi, bu tür geçiş durumlarının daha doğru temsil edilmesini sağlayabilir. Sonuç olarak, LSTM tabanlı bu model; yüksek doğruluk oranı, düşük hesaplama maliyeti ve kişi bağımsız genelleme yeteneğiyle, gerçek zamanlı uygulamalar açısından pratik ve etkili bir çözüm sunmaktadır. PERCLOS, EAR, MAR ve MOE gibi temel ama güçlü göstergelerin doğru şekilde modellenmesiyle elde edilen bu başarı, sistemin sürücü izleme ve benzeri senaryolarda güvenilir biçimde kullanılabileceğini göstermektedir. Literatürde de belirtildiği gibi, bu göstergelerin dikkat dağınıklığı, baş hareketleri ve diğer davranışsal ipuçlarıyla zenginleştirilmesi, gelecekte daha kapsamlı ve dayanıklı yorgunluk tespit sistemlerinin geliştirilmesine katkı sağlayacaktır [17].

3.4. Dikkat Analizi

Dikkat analizinin gerçekleştirilmesi için göz takibi (Eye Tracking)[18] teknolojileri ve istatistiksel veri analiz teknikleri kullanılmıştır. Bu süreçte, teste başlamadan önce 9 noktalı kalibrasyon aşaması uygulanmış, kullanıcının görsel

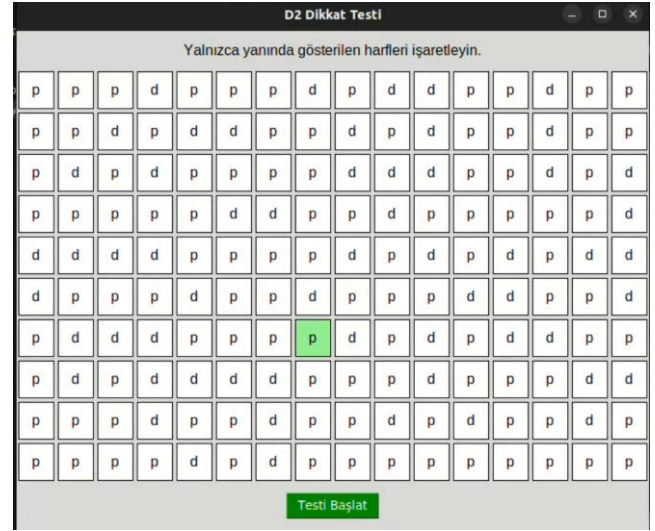
alan içindeki bakış hareketleri belirli referans noktalarına göre kalibre edilmiştir. Kalibrasyon süreci, kullanıcının ekranın farklı bölgelerine odaklanmasını sağlayarak bakış koordinatlarının doğru şekilde hizalanmasını amaçlamıştır. Ardından, Mediapipe FaceMesh kütüphanesi kullanılarak göz hareketleri ve bakış yönü gerçek zamanlı olarak tespit edilmiş, özellikle iris merkezi ve göz bebekleri (pupil center) takip edilerek odak noktası belirlenmiştir. OpenCV kullanılarak bu koordinatlar normalleştirilmiş, görsel matriste hangi bölgelere odaklanıldığı ve dikkatin hangi noktalara yöneldiği tespit edilmiştir. Bu sayede, kullanıcının dikkat düzeyi, odaklanma süreleri ve göz hareketleri daha doğru bir şekilde analiz edilmiştir. Şekil 8’de akış şeması görülmektedir.



Şekil 8: Dikkat Analizi Sürecinin Akış Diyagramı

3.4.1 D2 Dikkat Testi

D2 Dikkat Testi, Brickenkamp[19] tarafından 1962 yılında geliştirilmiş olup, bireylerin seçici dikkat, sürdürülen dikkat ve psikomotor hız gibi bilişsel işlevlerini değerlendirmek amacıyla kullanılan bir nöropsikolojik ölçüm aracıdır. Test, 9 ila 60 yaş aralığındaki bireylere bireysel veya grup halinde uygulanabilir. Uygulama sırasında katılımcıya, her biri 47 karakterden oluşan 14 satırdan meydana gelen bir form sunulur. Bu karakterler "d" ve "p" harflerinden oluşur ve her bir harfin üstünde, altında veya her iki tarafında bir ya da iki kısa çizgi bulunabilir. Katılımcının görevi, yalnızca üstünde veya altında iki kısa çizgi bulunan "d" harflerini belirli bir süre zarfında işaretlemektir. Her satır için 20 saniye süre verilerek toplamda yaklaşık 8 dakikalık bir test süresi oluşturulur. Testin değerlendirilmesinde, doğru işaretlemeler, atlanan hedefler ve yanlış işaretlemeler gibi performans göstergeleri dikkate alınır. Bu sayede bireyin dikkat düzeyi, dikkat süresini ne kadar sürdürebildiği ve psikomotor hızı gibi bilişsel işlevleri hakkında bilgi elde edilir. D2 Dikkat Testi, dikkat eksikliği ve hiperaktivite bozukluğu (DEHB), demans ve diğer nörolojik bozuklukların tanı ve tedavisinde, ayrıca eğitim ve işe alım süreçlerinde bireylerin dikkat ve konsantrasyon becerilerini değerlendirmek amacıyla yaygın olarak kullanılmaktadır. Bu çalışmada da D2 dikkat testi benzeri bir uygulama bilgisayar ortamına aktarılarak dikkat analizi aşamasında kullanılmıştır. Oluşturulmuş olan arayüz ekranı Şekil 9’da görülmektedir.



Şekil 9: D2 Dikkat Testi Arayüzü

3.4.2 Otomatik Dikkat Analiz Aşamaları

Görsel Uyarıcıların Sunulması:

Kullanıcıya, rastgele sıralanmış "d" ve "p" harflerinden oluşan bir matris sunulur. Kullanıcının, belirlenen hedef harfleri tespit edip işaretlemesi beklenir.

Göz Hareketlerinin Takibi:

Mediapipe FaceMesh kullanılarak göz hareketleri gerçek zamanlı olarak analiz edilir. Mediapipe FaceMesh, yüz üzerindeki 468 landmark noktasını ve iris çevresindeki noktaları gerçek zamanlı olarak tespit edebilmekte, bu sayede hem göz çevresi hem de iris noktaları üzerinden göz açıklık oranı (EAR) hesaplanarak göz kırpması ve kapama hareketleri analiz edilebilmektedir.[20] Ayrıca, kullanıcının bakış koordinatları ve yüzün dönüş açıları (yaw) da kaydedilerek test ekranı üzerindeki odak noktaları belirlenir.

Odaklanma Süresi ve Dikkat Sapmalarının Analizi:

Belirlenen hedef harfler üzerinde geçen süre (fixation duration) hesaplanarak dikkat süresi ölçülür. Hedef dışı bölgelere yönelen bakışlar tespit edilerek dikkat sapmaları analiz edilir.

Dikkat Performansının Değerlendirilmesi:

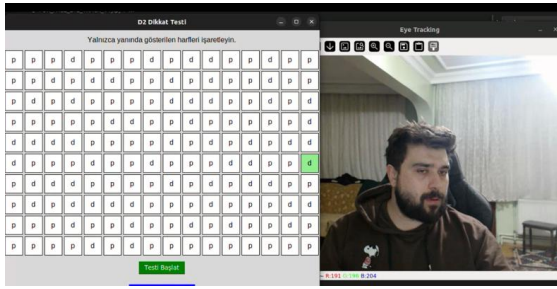
Dikkat performansının analizinde tablo 2’de görülen metrikler kullanılır.

Tablo 2: Dikkat Analizinde Kullanılan Ölçütler

Metrik	Tanım
TN	İşaretlenen toplam satır sayısı
E1	Atlanan hedef sayısı
E2	Yanlış işaretlenen harfler
CP	Doğru işaretlenen harfler
TN-E	Dikkat performans skoru
E%	Hata oranı

Çalışmada, sapma eşiği, sabitleme süresi ve duyarlılık parametreleri deneysel olarak optimize edilerek, bireysel farklılıkların dikkat performansı üzerindeki etkisi minimize edilir. Bir işaretleme, kullanıcının belirlenen hedef harfleri doğru şekilde tespit edip işaretlemesi durumunda geçerli sayılır. İşaretlemenin kabul edilmesi için 4 kriter sağlanmalıdır. Bu kriterler şu şekilde sıralanabilir:

1. **Hedef Harfin Doğru Tespit Edilmesi:** Kullanıcının yalnızca önceden belirlenen hedef harfleri (örneğin "d" harfi ve belirli işaret kombinasyonları) işaretlemesi gerekmektedir. Yanlış harfleri işaretleme durumunda yanlış işaretleme (E2) olarak kaydedilmektedir.
2. **Odaklanma Süresinin Yeterli Olması:** Kullanıcının belirlenen harfe 3 saniye boyunca bakışını sabitlemesi gerekmektedir (fixation duration). Çok kısa veya çok uzun bakış süreleri dikkat dağınıklığına veya tereddütte işaret edebilir.
3. **Yanlış veya Eksik İşaretlemelerin Olmaması:** Kullanıcının hedef harfi atlamadan işaretlemesi gerekmektedir, aksi takdirde atlanan hedef (E1) olarak kaydedilir. Hedef dışı harfleri işaretleme durumunda ise yanlış işaretleme (E2) olarak değerlendirilir.
4. **İşaretleme Anında Bakışın Sabit Olması:** İşaretleme sırasında, kullanıcının bakışının hedef harfte olması ve ani kaymalar yaşanmaması beklenmektedir. Bakışın hedef harfte olmadığı veya istikrarsız olduğu durumlar, dikkat sapması olarak yorumlanmaktadır.



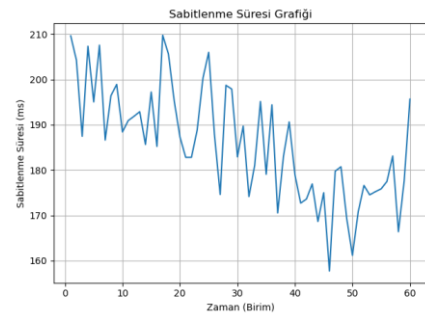
Şekil 10: D2 Dikkat Testi Göz Takip Sistemi

Şekil 10'da görülen D2 Dikkat Testi uygulaması kapsamında, kullanıcının ekrandaki göz hareketlerinin izlendiği 10 video deneysel veri toplanmıştır. Elde edilen video kayıtları, süre bazlı gerçekleşen sabitleme ve sapma durumlarına göre etiketlenmiş, ayrıca dikkat puanı hesaplamalarında kullanılmak üzere zaman damgaları kaydedilmiştir. Bu sayede test sonucunun doğruluğu ölçülebilmektedir.

3.4.3 Bulgular

D2 Dikkat Testi temel alınarak geliştirilen göz izleme tabanlı dikkat analizi modelinin performansı 4 kullanıcıdan toplanan kağıt ve dijital D2 testi deneysel verileri üzerinde değerlendirilmiştir. Sistem çıktıları, geleneksel kağıt-kalem D2 testinin sonuçları ile karşılaştırılmış ve özellikle düşük dikkat performansına sahip bireylerde hata türleri (örneğin hedef atlama veya yanlış hedef tespiti) ile dikkat sapmaları başarılı şekilde ayırt edilmiştir. Modelin geçerliliğini ölçmek amacıyla, kullanıcıların klasik D2 testinden elde ettiği puanlar ile sistemin otomatik olarak hesapladığı dikkat puanları karşılaştırılmış ve aralarında Pearson korelasyon katsayısı 0.87 olarak bulunmuştur. Bu yüksek pozitif korelasyon, sistemin dikkat seviyesini ölçme konusundaki güvenilirliğini istatistiksel olarak desteklemektedir.

Sistem tarafından analiz edilen sabitleme süresi, hedef tespiti doğruluğu ve sapma oranı gibi temel dikkat metrikleri, literatürde kabul görmüş dikkat bileşenleri ile tutarlı sonuçlar üretmiştir. Özellikle yüksek dikkat düzeyine sahip bireylerde sabitleme sürelerinin daha uzun ve stabil olduğu, dikkat seviyesi düştüğünde ise bu sürelerin düzensiz ve kısa hale geldiği tespit edilmiştir. Bu durum, anlık dikkat dağınıklığı ve zihinsel dalgınlık gibi bilişsel sapmaları ayırt etmekte modelin etkili olduğunu göstermektedir. Modelin değerlendirme mantığı, D2 testinin özgün yapısına uygun şekilde tasarlanmıştır. Her satırda sunulan karakter dizileri için göz hareketleri ayrı ayrı analiz edilerek, sistem tarafından satır bazlı metrikler oluşturulmuştur. Bu satır bazlı yaklaşım, hem dikkat performansının zaman içindeki değişimini hem de kullanıcı odaklı değerlendirme yapısını desteklemiştir. Böylece model yalnızca genel bir puan değil, dikkat seviyesinin zaman serisi biçiminde analizine de olanak tanımıştır.

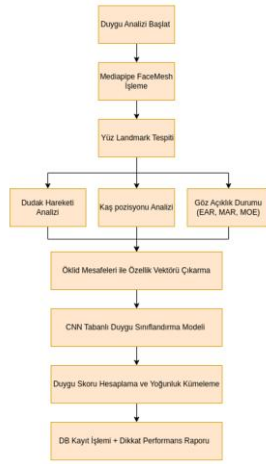


Şekil 11: Sabitleme Süresi Grafiği

Uygulamalar sırasında bazı katılımcıların testin ilk dakikalarında yüksek dikkat gösterdiği ancak zaman ilerledikçe performans düşüşü yaşadığı gözlemlenmiştir. Bu tür zamana bağlı dikkat dalgalanmaları, sabitleme süresi grafikleri ile görselleştirilmiş (Şekil 11) ve dikkat yoğunluğu dinamiği ortaya konmuştur. Sonuç olarak, geliştirilen dikkat analizi modeli; sabitleme süresi, hedef tespiti ve sapma oranı gibi parametreleri satır bazlı olarak analiz edebilmiş, klasik D2 testinin yapısına benzer sonuçlar üretmiştir. Mevcut literatürde, D2 Dikkat Testi'nin doğrudan göz izleme teknolojisiyle entegre edildiği bir çalışmaya rastlanmamıştır. Bu durum, geliştirilen sistemin özgünlüğünü ve yenilikçi yaklaşımını ortaya koymaktadır. Sistem, D2 testinin yapısına uygun olarak sabitleme süresi, hedef tespiti doğruluğu ve sapma oranı gibi parametreleri analiz edebilmekte ve bu sayede dikkat düzeyini nicel olarak ölçülebilmektedir.

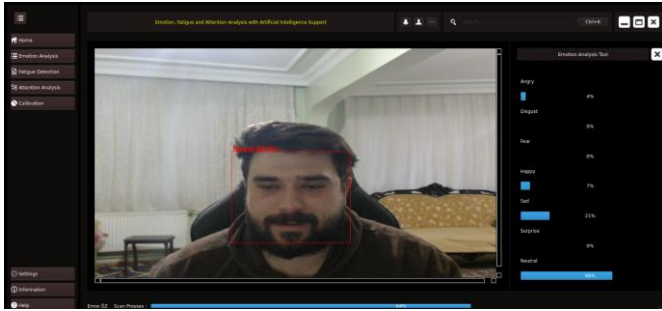
3.5. Duygu Analizi

Şekil 12'de akış şeması verilen Duygu Analizi modülü ile kullanıcıların yüz görüntülerinden mevcut duygu durumlarının sınıflandırılması ve duygu yoğunluğu tahmini yapılır. Duygu durumu sınıflandırması için kullanılan model, evrimsel sinir ağı (CNN)[21] tabanlı olup, geniş duygu veri setleri üzerinde eğitilmiş ve proje kapsamında elde edilen veri setleriyle ince ayar yapılmıştır.



Şekil 12: Duygu Analizi Süreci Akış Diyagramı

Hiperparametreler arasında; öğrenme oranı, batch size, dropout oranı ve optimizer tipi yer almaktadır. Bu parametreler, yapılan ön deneyler sonucunda belirlenmiş ve optimize edilmiştir. Model, kullanıcının yüzündeki mikro ifadeleri bile tespit edebilecek şekilde arka planda sürekli çalışarak, duygu durumunun doğru ve hassas bir şekilde analiz edilmesini sağlamaktadır.



Şekil 13: DeepFace Kütüphanesi ile Gerçek Zamanlı Duygu Analizi

Duygu yoğunluğu analizinde kullanılmak üzere Mediapipe FaceMesh çerçevesi kullanılarak yüz üzerindeki belirli noktalar (landmark) tespit edilmiştir. Bu noktalar dudaklar, gözler, kaşlar ve yanaklar gibi yüz bölgelerini içermektedir. Belirlenen noktalar arasındaki Öklid mesafeleri numpy kütüphanesi ile hesaplanarak her bir yüz ifadesi için özellik vektörleri oluşturulmuştur. Bu sayede öklid mesafesi duygu analizi aşamasında yüz bölgeleri arasındaki değişimin nicel olarak ölçülmesini sağlayarak her bir duygu etiketinin objektif ve tekrarlanabilir bir şekilde atanmasında kullanılmıştır. Elde edilen özellikler; dudak hareketleri, göz açıklığı, kaşların konumu ve yanakların şekil değişikliklerini içermektedir. Bu faktörler ile beraber Şekil 13'deki gibi mutluluk, üzüntü, öfke, korku, şaşkınlık, tiksinti ve nötr gibi farklı duygusal durumların ayırt edilmesine katkıda bulunmuştur.

3.5.1 Veri Toplama

Duygu analizi için FER-2013 veri kümesi [22] kullanılmıştır. Bu veri tabanı, doğal ortamlarda çekilmiş gri tonlamalı 48×48 piksel boyutlarında 35.887 yüz görüntüsünden oluşur ve yedi temel duyguyu (Öfke, Tiksinti, Korku, Mutluluk, Üzüntü, Şaşkınlık, Nötr) içerir. Sınıflar dengesiz olup, bazı duygular daha az temsil edilmiştir (örn. Tiksinti). Veri seti farklı yaş, cinsiyet ve etnik kökenlerden bireyleri içerdiğinden, modelin genellenebilirliğini artırır. Eğitim, doğrulama ve test bölümleri hazır biçimde ayrılmıştır.

Bu çalışma kapsamında, DeepFace kütüphanesi ile duygu sınıflandırması yapılmış; ardından yüz landmark vektörlerine K-Means (k=3) algoritması uygulanarak, her duygu sınıfı kendi içinde düşük, orta ve yüksek yoğunluk düzeylerine göre etiketlenmiştir.

3.5.2 Duygu Tanıma

Duyguları sınıflandırmak için Tablo 3'te mimarisi verilen Evrişimsel Sinir Ağı (CNN) tabanlı bir model geliştirilmiş ve eğitilmiştir. Model, yüz ifadelerindeki özellikleri derin öğrenme teknikleriyle analiz ederek duygusal durumları yüksek doğrulukla sınıflandırmayı hedeflemektedir. Çalışmada, görsel verileri işleyerek yüz ifadelerindeki ince detayları öğrenebilen özelleştirilmiş bir CNN mimarisi tasarlanmıştır. Geliştirilen CNN modeli, birden fazla evrişim (convolutional) katmanı, batch normalization, dropout katmanları ve tam bağlı (fully connected) katmanlar içeren derin bir ağ yapısına sahiptir. Modelin temel bileşenleri tablo 3'de özetlenmiştir.

Tablo 3: CNN Model Mimarisi

Katman Adı	Çıkış Şekli (Output Shape)	Parametre Sayısı (Params)
Giriş Katmanı (Input)	(48, 48, 1)	0
Conv2D (32, 3x3 filtre)	(48, 48, 32)	896
BatchNormalization	(48, 48, 32)	128
ReLU Aktivasyonu	(48, 48, 32)	0
MaxPooling2D (2x2)	(24, 24, 32)	0
Conv2D (64, 3x3 filtre)	(24, 24, 64)	18,496
BatchNormalization	(24, 24, 64)	256
ReLU Aktivasyonu	(24, 24, 64)	0
MaxPooling2D (2x2)	(12, 12, 64)	0
Conv2D (128, 3x3 filtre)	(12, 12, 128)	73,856
BatchNormalization	(12, 12, 128)	512
ReLU Aktivasyonu	(12, 12, 128)	0
MaxPooling2D (2x2)	(6, 6, 128)	0
Flatten	-4608	0
Dense (256 nöron)	-256	1,179,904
BatchNormalization	-256	1,024
ReLU Aktivasyonu	-256	0
Dropout (0.5)	-256	0
Dense (128 nöron)	-128	32,896
BatchNormalization	-128	512
ReLU Aktivasyonu	-128	0
Dropout (0.5)	-128	0
Dense (7 çıkışlı - Softmax)	-7	903
Toplam Parametre Sayısı		1,312,385

Tablodaki model mimarisi, AutoML teknikleri kullanılarak optimize edilmiştir. Model yapısı, farklı CNN mimarileri ve hiperparametre kombinasyonları üzerinde yapılan Neural Architecture Search (NAS) ve Bayesian Optimization süreçleriyle belirlenmiş, en yüksek doğruluk oranına sahip yapı seçilmiştir. Bu süreçte, Google AutoML, Auto-Keras ve Optuna gibi araçlar kullanılarak en uygun katman sayısı, filtre boyutları ve aktivasyon fonksiyonları tespit edilmiştir. Modelin en iyi performansı verebilmesi için Tablo 4'te hiperparameter ayarları optimize edilmiştir.

Tablo 4: Model Hiperparameter Seçimleri

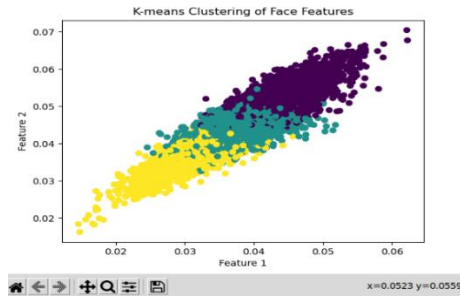
Hyperparameter	Değer
Öğrenme Oranı (Learning Rate)	0.001 (Adam optimizer ile)
Batch Size	32
Epoch Sayısı	50
Optimizasyon Algoritması	Adam
Loss Fonksiyonu	Categorical Cross-Entropy
Dropout Oranı	0.5
Aktivasyon Fonksiyonları	ReLU (Ara katmanlar), Softmax (Çıkış katmanı)

Tablodaki hiperparametre değerleri, modelin en iyi performansı verebilmesi için hiperparametre ayarlama (tuning) süreçleri kapsamında optimize edilmiştir. Bu süreçte,

Grid Search ve Bayesian Optimization gibi yöntemler kullanılarak farklı öğrenme oranları, batch size, epoch sayıları ve dropout oranları sistematik olarak denenmiş ve en iyi sonuç veren kombinasyon seçilmiştir. Bu optimizasyon, modelin daha hızlı öğrenmesini, aşırı öğrenmeyi (overfitting) önlemesini ve genelleme yeteneğini artırmasını sağlamıştır.

3.5.3. Duygu Yoğunluğu Kümeleme

Duygusal yoğunluğu değerlendirmek için, K-Ortalamalar (K-Means)[16] kümeleme algoritması uygulanmıştır. Bu süreç, duygusal ifadeleri düşük, orta ve yüksek yoğunluk seviyelerine ayırmayı sağlamıştır. Kümeleme yaklaşımı sayesinde, aynı duygu kategorisi içindeki ince farklılıklar belirlenmiş ve daha hassas bir duygu tanıma gerçekleştirilmiştir.



Şekil 14: K-Means Kümeleme ile Duygu Yoğunluğu Analizi

Şekil 14’de, yüz özelliklerine ait veriler kullanılarak gerçekleştirilen K-Means kümeleme analizi sonuçları gösterilmektedir. Kümeleme süreci iki temel aşamadan oluşmaktadır: İlk olarak, yüz noktalarından çıkarılan özellik vektörleri hesaplanmıştır. Ardından, bu özellik vektörlerine K=3 olacak şekilde K-Means algoritması uygulanarak veriler üç farklı kümeye ayrılmıştır. Grafik üzerinde farklı renklerle temsil edilen bu kümeler, duygusal yoğunluk açısından benzer özellikler gösteren yüz ifadelerini gruplamaktadır. Özellikle, verilerin yoğunlukla toplandığı bölgeler, belirli duygu durumlarının daha baskın olduğu alanlara işaret etmektedir. Bu tür bir kümeleme analizi, yüz ifadelerinden duygusal durumların sınıflandırılmasında ve analiz edilmesinde önemli bir adım teşkil etmektedir.

3.5.4. Bulgular

Tablo 5: Duygu Tanıma Modelinin Performans Metrikleri

Metrik	Değer
Accuracy (Doğruluk Oranı)	%89.2
Precision (Kesinlik)	%87.5
Recall (Duyarlılık)	%86.8
F1-Score	%87.1
Mean Average Precision (mAP)	%88.4

Tablo 5’de duygu tanıma modelinin performans metrikleri gösterilmektedir. Modelin doğruluk oranı %89.2, kesinlik (precision) %87.5, duyarlılık (recall) %86.8 ve F1-Score %87.1 olarak hesaplanmıştır. Bu sonuçlar, modelin genel olarak yüksek doğrulukla çalıştığını ve duygu sınıflandırmada başarılı olduğunu göstermektedir. Özellikle mAP (Mean Average Precision) %88.4, modelin farklı duygu kategorilerinde dengeli bir başarıya sahip olduğunu ifade etmektedir. Yukarıda sunulan performans metriklerine ek olarak, duygu sınıflandırmasının daha hassas bir şekilde gerçekleştirilmesi amacıyla uygulanan K-Ortalamalar (K-

Means) kümeleme algoritması, her bir duygu sınıfı içerisinde farklı yoğunluk seviyelerini başarıyla ayırt etmiştir. Özellikle aynı temel duyguyu (örneğin “üzüntü” ya da “mutluluk”) ifade eden ancak yoğunluk bakımından farklılaşan yüz ifadeleri, düşük, orta ve yüksek yoğunluk kümelerine ayrılarak analiz edilmiştir. Bu sayede, kullanıcıların yalnızca hangi duyguyu yaşadıkları değil, bu duygunun ne derece yoğun yaşandığı da belirlenebilmiştir. Kümeleme sonucunda elde edilen üç ana yoğunluk seviyesi, duygu sınıflandırmasının açıklayıcılığını artırmış ve mikro ifadelerin duygusal analizde ne derece etkili olduğunu bir kez daha ortaya koymuştur. Literatürde de benzer şekilde duygu yoğunluğunun yüz kas aktivitesinden türetilmiş metriklerle başarıyla modellenilebildiği ve özellikle stres, öfke gibi duyguların alt seviyelerinin erken tespiti açısından bu tür yoğunluk ayrımlarının kritik olduğu belirtilmektedir.[23] Bu bağlamda, çalışmamızda uygulanan K-Means temelli yoğunluk ayrımı, sistemin psikolojik değerlendirme ve duygusal farkındalık uygulamaları için daha rafine bir çıktı üretmesini sağlamıştır.

IV. TARTIŞMA VE SONUÇLAR

Gerçek zamanlı uygulamalarda, yorgunluk analizi modeli EAR, PERCLOS, Blink Rate, MAR ve MOE parametreleriyle %94 doğruluk sağlarken; dikkat analizi D2 Testi temelli yapısıyla yüksek duyarlılık ve kararlı sonuçlar üretmiştir. Duygu analizinde ise optimize edilen DeepFace tabanlı modelle yüksek mAP değeri elde edilmiştir. Üç alanı (yorgunluk, dikkat, duygu analizi) bir arada değerlendiren bu çalışma, geleneksel tek parametrelili analizlerin ötesine geçerek kapsamlı ve uygulanabilir bir çözüm sunmaktadır.

Yorgunluk Analizinde LSTM tabanlı model, %94 doğruluk, %92 precision ve %95 recall başarısı göstermiştir. Model, zamansal örüntüleri etkili biçimde öğrenerek yorgunluk belirtilerini erken aşamada saptayabilmektedir. Benzer başarılar literatürde EEG sinyalleri ya da göz kırpmaları patenlerini kullanan derin modellerle de görülmektedir [15],[24],[25]. Yüksek recall değeri, kritik vakaları kaçırmamak açısından avantaj sağlarken; nispeten düşük precision, zaman zaman yanlış pozitif sonuçlar üretmektedir. Bu durum, literatürde de sıkça görülen bir denge sorunudur. Modelin genellenebilirliğini artırmak için gelecek çalışmalarda daha çeşitli veri ve özellik füzyonu kullanımı düşünülmektedir.

D2 Testi’ne dayalı Dikkat Analizi, göz hareketi sabitleme süresi ve sapma oranı gibi metriklerle istikrarlı ve güvenilir ölçümler sunmuştur. Literatürde, yapılan test-tekrar uygulamalarında sonuçların tutarlılığının, sistemin güvenilirliğini desteklediği görülmüştür [26],[27]. Dikkat düzeyindeki değişimlerin anlık olarak yakalanabilmesi, sistemin uygulama alanlarındaki değerini artırmaktadır. Ancak yapılandırılmış test formatı, spontane dikkat sapmalarını sınırlı ölçüde yansıtabilmektedir. Bu nedenle, ileride gerçek zamanlı göz izleme verisiyle desteklenen daha esnek test formatlarının entegrasyonu planlanmaktadır.

Son olarak CNN tabanlı duygu sınıflandırma modeli %89.2 doğruluk, %87.5 precision, %86.8 recall ve %88.4 mAP ile başarılı sonuçlar vermiştir. Özellikle duygu yoğunluklarının K-means ile ayrıştırılması, sistemin detaylı analiz yeteneğini güçlendirmiştir. Literatürde de CNN, CNN-BiLSTM ve benzeri mimarilerle benzer başarılar elde edilmiştir [28]. Ancak modelin recall değerinin bir miktar düşük olması, bazı bağlama dayalı ifadelerin kaçırılmasına yol açmaktadır. Bu durum, özellikle örtük duyguların tanınmasında Transformer

tabanlı yaklaşımların avantajını ortaya koymaktadır. Gelecekte, bu tür yaklaşımların entegrasyonu ile daha hassas ve bağlamsal analizler yapılabilir.

Tüm bu sonuçlar bir arada ele alındığında, mevcut çalışma, duygu, yorgunluk ve dikkat analizlerini entegre bir şekilde tek bir arayüz üzerinden sunarak, tekil analizlere kıyasla daha kapsamlı ve bütünsel analiz imkanı sağlamaktadır. Duygu analizinde, yalnızca mevcut duygu durumunun tespiti değil, aynı zamanda bu duygunun yoğunluğunun da belirlenmesi sağlanmış; yorgunluk analizinde yüksek doğruluk oranına düşük hesaplama maliyetli bir model ile ulaşılmış; D2 Dikkat testinin bilgisayarla görü temelli göz hareketi izleme yöntemiyle entegrasyonu, özgün bir otomatik dikkat analizi metodu geliştirilmesini sağlamıştır. Gelecekte sistemin mobil platformlara taşınması, ek sensörlerle zenginleştirilmesi ve çok görevli senaryolarla test edilmesi önerilmektedir.

TEŞEKKÜR

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Yazarların Katkıları

Yazarların makaleye katkıları eşittir.

Çıkar Çatışması Beyanı

Yazarlar arasında çıkar çatışması yoktur.

Araştırma ve Yayın Etiği Beyanı

Yazarlar bu çalışmanın Araştırma ve Yayın Etiğine uygun olduğunu beyan eder.

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Performance Evaluation of Transfer Learning Techniques and Machine Learning Methods in Signature Verification

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Abstract –Signature verification plays an important role in biometric security systems and traditional methods can lead to limitations in verification accuracy. However, traditional signature verification techniques work with limited data and features, which can negatively affect the accuracy of verification processes. In this study, we investigate the performance improvement in signature verification by combining transfer learning and machine learning algorithms. In the experiments performed on signatures from the BHSig260 Hindi dataset, the transfer learning models (ResNet50, MobileNetV2, VGG16, InceptionV3, EfficientB7, DenseNet169) achieved high accuracy rates on their own, especially the VGG16 model performed the best with 93.77% accuracy. In the later stages of the study, machine learning algorithms such as K-nearest neighbor (KNN), Support Vector Machines (SVM) and Random Forest were added to the transfer learning models to further improve the validation performance. The combination of EfficientB7 + Random Forest achieved the highest performance with 95.24% accuracy. The results show that the integration of transfer learning techniques with machine learning algorithms significantly improves the accuracy of signature verification tasks. This combination stands out as an effective method that significantly improves the reliability and efficiency of biometric security systems. The findings of the study will provide an important reference for the future development of signature verification systems, contributing to the development of more accurate and reliable solutions in this field.

Keywords –Signature verification, Machine learning, Transfer Learning, CNN, Biometric Security, Hindi Signature Dataset

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I. INTRODUCTION

Signature verification fulfills an important function as one of the key components of authentication and security in both digital and physical environments. In particular, digital signature verification plays a critical role in enabling secure and fraud-proof communication and transactions in the electronic environment. While traditional signatures are known to be used to verify a person's identity and approve transactions performed with his/her permission, digital signatures are technologies that fulfill this function in an internet-based environment [1]. Digital signature systems not only provide authentication, but also protect the integrity, security and confidentiality of data [2].

The legal validity of digital signatures is directly related to the security of signature verification systems. In many countries, digital signatures and verification systems have been established in a legal framework for secure electronic transactions. The effectiveness of electronic signature verification algorithms is critical in ensuring the security of data in areas such as financial transactions, e-commerce and government services. In this context, signature verification systems not only ensure secure communication, but also guarantee the legal binding and validity of transactions [3]. Digital signature verification is an indispensable tool not only for security but also for ensuring the legal and commercial validity of transactions. Therefore, the security of digital

signature verification technologies remains important in the face of ever-evolving cyber threats and research in this field continues [4].

The security of digital signature verification systems is continuously improving with advancing technologies. Traditional signature verification methods usually use template-based approaches and algorithms. However, these methods may be insufficient to deal with challenging situations such as forged signature detection. In recent years, the integration of artificial intelligence techniques such as machine learning and deep learning has made significant progress in the field of digital signature verification. These techniques make the signature verification process more secure and accurate, while at the same time providing a more flexible solution against next-generation forgery attempts. Machine learning algorithms, especially by training using labeled data, increase accuracy rates in the verification process and improve the ability to detect forged signatures [5].

Deep learning is being integrated into digital signature verification, especially with structures such as Convolutional Neural Networks (CNNs). CNNs are networks that are generally used in the processing of visual data and can achieve high accuracy rates thanks to their multilayer structure. CNNs play an important role in improving the accuracy of digital signatures because they can perform in-depth analysis on the shape and dynamic properties of the signature. The geometric properties of the signature, time-varying features such as speed

and compression strength can be learned by CNNs to determine whether the signature is authentic or not [6]. In this context, deep learning algorithms overcome the limitations of traditional methods and enable the development of more flexible and powerful verification systems. Moreover, these algorithms minimize forgery risks by ensuring that the signature is analyzed correctly.

Signature verification is a widely used biometric method to securely verify the identity of individuals in a digital environment. It plays an important role especially in security areas such as personal data protection and fraud prevention. Using signature as a biometric feature can provide high levels of security in verification processes by taking into account the variability and uniqueness of individuals' signatures over time. In the literature, various algorithms and technologies have been developed for signature verification, and this field has made significant progress in recent years with innovative methods such as deep learning and machine learning.

In [7], we focus on dynamic (online) verification methods instead of static (offline) signature verification to improve the efficiency of online biometric personal verification systems. The study aims to improve the signature verification process by using a CNN model built in Python for online signature verification. After training and validation, an accuracy rate of 99.70% was achieved on test data.

In [8], 24 original and 30 forged signatures of 1000 users were classified using GPDS Synthetic Signature Database for handwritten signature verification. In the experiments with Inception-v1 and Inception-v3 CNN architectures, Inception-v1 performed better with 83% accuracy. The Equal Error Rate (EER) was 17 for Inception-v1 and 24 for Inception-v3. Inception-v1 outperformed Inception-v3 with faster training time and lower number of operations.

In [9], a model is proposed using VGG-19 pre-trained CNN to automate the signature verification process. The model is tested on common datasets such as ICDAR, CEDAR, and Kaggle and achieves 100%, 88%, and 94.44% accuracy rates, respectively. The analysis shows that the proposed model can correctly classify forged signatures, but it may have difficulty with samples that are very similar to the original signature.

In [10], a new model for offline signature verification is proposed that can better capture signature features and reduce the complexity of the network. In this model, CNN and Capsule Neural Network (CapsNet) are combined to better understand the spatial features of signature features and improve the feature extraction process. Furthermore, a new training mechanism is developed in which two images at the same level are trained simultaneously with a single network. This hybrid model, called CBCapsNet, outperforms existing signature verification methods by increasing accuracy rates.

In [11], the importance of the feature extraction phase of online signature verification systems is emphasized. In this study, CNN and Histogram of Oriented Gradients (HOG) are used for feature extraction from signature images and key features are identified with decision trees. Finally, CNN and HOG methods are combined and the effectiveness of the model is evaluated with long-short-term memory (LSTM), support vector machines (SVM) and K-nearest neighbor (K-NN) classifiers. The experimental results showed that the model was successful with 95.4%, 95.2% and 92.7% accuracy rates for the UTSig dataset and 93.7%, 94.1% and 91.3% accuracy rates for the CEDAR dataset, respectively.

In [12], a Recurrent Neural Network (RNN) based method is proposed for online signature verification. This method is

analyzed with LSTM and bidirectional LSTM (BLSTM) models by extracting structural and directional features from different people's signatures. The proposed model is tested on GPDS synthetic (93.24%), GPDS-300 (94.18%), MCYT-75 (94.42%), CEDAR (95.31%), BHSig260 Hindi (95.12%) and BHSig260 Bengali (95.19%) datasets. Experimental results show that the proposed RNN-based system achieves high accuracy rates and outperforms existing CNN-based methods.

In [13], a deep learning based method is proposed for handwritten signature verification. Inception V3 transfer learning model is developed to distinguish between forged and genuine signatures and fine-tuned by adding Flatten, Dense, Dropout layers. The model achieved the highest performance with 88% accuracy compared to pre-trained models such as VGG 16, ResNet and MobileNet. This work contributes to the development of more effective CNN-based models for online signature verification.

In [14], CNN is used for feature extraction and SVM for verification for online signature verification. CNN is trained to extract features from signature data and these features are evaluated using SVM to classify them as forged or genuine signatures. The model was tested on the GPDS signature dataset. The dataset contains signatures of 960 users, each containing 24 real signatures and 30 forged signatures. The CNN was trained with 300 users and the signatures of 400 users were used for feature learning. These $400 \times 20 \times 25$ signatures were applied to the SVM classifier for 90% training and 10% testing.

In [15], an application of DAG-CNN is presented to classify and verify the accuracy of online signatures of 3 users. For the study, two datasets were created, including the signatures of 3 users and forged signatures of 115 other users that were modified by these users. After the network was trained, validation and testing phases were performed and accuracy rates of 99.4% and 99.3% were obtained respectively. The results confirm the features learned by the network and the usability of this neural network in online signature verification and identification applications.

In [16], CNN architectures such as AlexNet, GoogleNet, ResNet, MobileNet and DenseNet are investigated and compared for signature verification. In the study, a fine-tuned transfer learning approach is used for verification and identification of offline signature images. Experiments on the UTSig dataset show that the DenseNet architecture performs better than other CNN architectures. The proposed model achieved 98.87% accuracy with the fine-tuned approach.

In [17], a Cycle-GAN based data augmentation method is proposed for offline handwritten signature verification. To overcome the lack of data, the proposed method is tested on four different CNN architectures, VGG16, VGG19, ResNet50 and DenseNet121. The results show that the proposed data augmentation method achieves significant success for all CNN architectures, and especially shows the best effect on DenseNet121. According to the results, in the validation tests with the data augmentation method, the highest accuracy is achieved on the MCYT dataset and the second best accuracy is achieved on the GPDS dataset. The verification accuracy obtained with the proposed method was 96.9% for VGG16, 96.9% for VGG19, 97.0% for DenseNet121 and 96.5% for ResNet50.

In [18], a CNN model is used to verify the accuracy of handwritten signatures. In tests on a dataset of signatures from 16 volunteers, the model achieved 91.35% accuracy. With five-fold cross-validation, the accuracy increased to 98%,

while adversarial attacks reduced the accuracy of the model to 80%.

In [19], a CNN-based automatic feature extraction and learning method for signature verification is proposed. The method consists of three steps: preprocessing, feature extraction and classification. The system was tested on the CEDAR dataset and achieved 89.2% accuracy.

In [20], CNN followed by Recurrent Neural Network (RNN) is used to detect forged signatures in the signature verification process. The study was tested with SVC 2004 and SigComp2009 online datasets and achieved 97.05% accuracy.

In [21], the importance of signature verification is emphasized in areas where handwritten signatures are still used instead of digital signatures. This study aims to identify real signatures using deep learning technique. CNN based deep learning model is used for image processing, classification and segmentation. VGG16, Inception v3 and CNN models with three to four convolution layers were trained for this verification. A dataset was created by collecting 50 signatures from 10 different users, out of 500 signatures, 400 were used for training and 100 for testing. In two different cases, the Inception v3 model achieved 95% accuracy with preprocessed images, but only 88% accuracy with unprocessed images.

In this study, signature verification was performed on Hindi signatures in the BHSig260 dataset using ResNet50, MobileNetV2, VGG16, InceptionV3, EfficientB7 and DenseNet169 transfer learning models. In the first stage, the validation performance of these models was evaluated. In the second stage, the K-nearest neighbor (KNN) algorithm was added to each transfer learning model to examine their performance. In the third stage, Support Vector Machines (SVM) were integrated and in the last stage, Random Forest algorithm was used to improve the validation performance. As a result of these four steps, the effects of integrating transfer learning models with machine learning algorithms on signature verification performances are evaluated.

These studies provide valuable contributions to the field to improve the efficiency and accuracy of signature verification processes. In particular, the integration of machine learning and deep learning methods makes signature verification systems more reliable and faster. Moreover, these innovative approaches provide important opportunities for systems to work more effectively in real-world situations.

II. MATERIALS AND METHOD

Signature verification has made significant progress thanks to the integration of artificial intelligence (AI) and machine learning, especially deep learning. While traditional signature verification methods often rely on manually extracted features, deep learning techniques make this process more automated and accurate. Artificial intelligence has the potential to minimize human error in verification processes by learning signature patterns from large data sets. Deep learning, especially through architectures such as CNN, can learn the geometric and dynamic properties of signatures with high accuracy. Machine learning, on the other hand, effectively utilizes these features learned from signature data in classification and verification processes. This makes signature verification systems more flexible, faster and more reliable, while increasing the ability to detect forgery. In particular, the use of transfer learning techniques enables high performance with limited data and enables systems to operate more efficiently.

In this section, we propose an innovative approach to improve signature verification performance. The dataset used, the transfer learning architectures implemented and the machine learning techniques integrated are discussed in detail. The flowchart of the proposed methodology is presented in Figure 1.

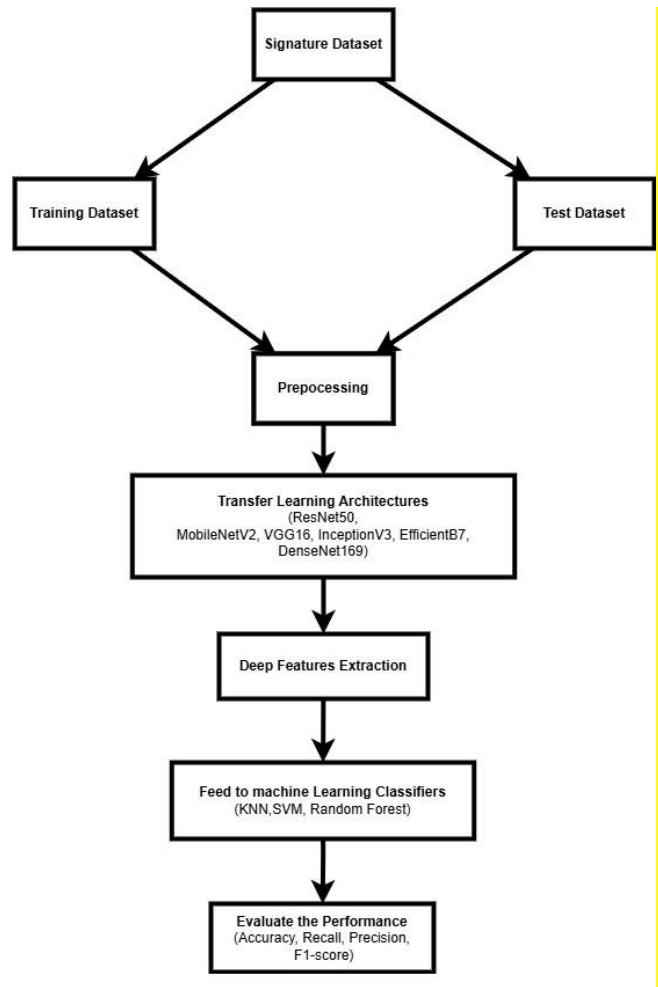


Figure 1. Flow diagram of the proposed methodology

A. Dataset

The BHSig260 dataset is an important resource, especially for signature recognition and verification. The BHSig260 dataset contains the signatures of 260 different individuals, 100 of which are represented by Bengali signatures and the rest by Hindi signatures. In total, there are 6240 real signatures and 7800 forged signatures in this dataset. For each person, there are 24 real and 30 forged signature samples. This results in 3840 real signatures and 4800 forged signatures per 160 people for Bengali signatures and 2400 real signatures and 3000 forged signatures per 100 people for Hindi signatures [22]. Figure 2. shows examples of Hindi signatures.

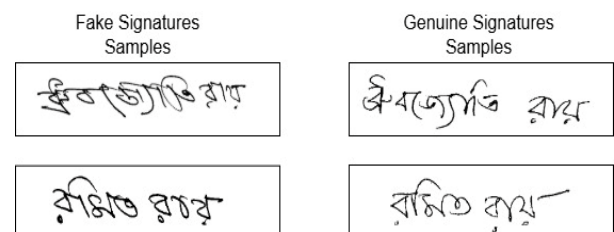


Figure 2. BHSig260 Hindi dataset genuine and fake signatures examples

In this study, only Hindi signatures are used for training and testing purposes. The Hindi dataset is divided into three independent subsets for training, validation and evaluation of the model. In this context, 64% of the total signatures are allocated to the training set, 16% to the validation set and 20% to the test set. This partitioning strategy maintains the initial approach of using 80% of the data for training and validation, while ensuring that the validation set is not derived from the training data and is completely independent. Thus, the validation and test sets are separated as independent sets that are not involved in the training process.

B. Model Development

Signature verification is critical in the field of biometric authentication and can be defined as a process that recognizes and verifies the individual characteristics of written signatures. In this field, the increasing use of machine learning and deep learning techniques is improving the accuracy and security of signature verification. While machine learning methods typically utilize feature engineering, classification algorithms and other statistical methods to recognize patterns in signature data, deep learning achieves successful results in signature verification tasks, especially with its ability to learn more complex relationships in large data sets [23]. At this point, the strong performance of deep learning methods plays an important role in making signature verification systems more accurate and reliable.

The splitting ratios chosen for the Turkey dataset used in the study are in line with data separation standards widely adopted in the field of deep learning [24]. In addition, a validation set that is completely independent from the training data and of sufficient size was created to be used in processes such as hyperparameter optimization, early stopping and prevention of overlearning. However, by ensuring that the test data was not used in the training process in any way, the overall performance of the model was evaluated in a statistically significant and reliable way. Keeping the training and validation sets at 80% in total is designed to preserve the model's performance in the learning process. Finally, by setting the test set at 20%, the performance of the model on real-world data could be analyzed more robustly. In addition, different CNN architectures such as ResNet50, MobileNetV2, VGG16, InceptionV3, EfficientNetB7 and DenseNet169, which are pre-trained on ImageNet, are used for deep feature extraction. In these models, the classification layers are removed, and the outputs of the final convolutional block are directly converted into vectors by flattening to preserve low-level textural and curvilinear information, which is especially important in structurally rich images such as signatures. In the transfer learning process, weights were frozen in all models and only the extracted features were used for subsequent classifiers. In the transfer learning phase, Adam optimization algorithm, learning rate 0.0001, batch size 32, maximum 50 epochs and early stopping criterion if the validation loss does not improve for 7 consecutive epochs were used as common hyperparameters. The resulting deep features were classified by the classical machine learning algorithms KNN (K=5), SVM (RBF kernel, C=1.0) and RF (20 trees). In order to prevent the model from overlearning, the training, validation and test datasets were created completely independently from each other and the training process was controlled by early stopping method. In this way, the generalization capacity of the models was increased. The proposed hybrid approach

combines the powerful feature extraction capabilities of deep learning architectures with the low computational cost and explainable structures of classical machine learning algorithms, enabling high performance even under limited data conditions. While in the literature, either only deep learning or only classical methods are usually used, this study offers an innovative and effective solution by combining the advantages of both methods.

Deep learning techniques, especially with network structures such as CNN and Recurrent Neural Networks (RNN), provide efficient results in signature verification processes. CNN has a strong performance in learning visual features and is effective in recognizing the geometric features of the signature, while RNN is successful in discovering relationships in time-dependent data. These network structures allow for a deeper understanding of the evolution of signatures over time and their individual characteristics. In particular, CNN is effective in learning the shape and drawing dynamics of the signature, while RNN can further improve accuracy by modeling changes in the writing style and speed of the signature over time [25]. Therefore, the combination of these deep learning methods results in a more powerful system, improving accuracy and reliability in the signature verification process.

In recent years, the combination of deep learning and machine learning techniques has enabled signature verification systems to become more accurate and reliable. The integration of these two approaches plays an important role in the development of signature verification systems. The combination of deep learning and machine learning combines the advantages of both technologies, resulting in more advanced and powerful models. Another important development that makes this integration possible is the transfer learning technique. Transfer learning allows a model to use the knowledge it has acquired in another task in a new and different task. It provides great efficiency in terms of time and resources, especially in training deep learning models based on large data sets [26]. Thus, transfer learning techniques allow training powerful models with smaller data sets in the field of signature verification.

The use of transfer learning techniques in signature verification allows the knowledge learned from previous models to be reused on smaller and more specific data sets. This not only reduces the training time of the model, but also improves its performance. Especially when working with limited data sets, transfer learning plays a critical role in improving the accuracy of the model. This advantage helps signature verification systems to become more efficient, while at the same time making it possible to achieve high accuracy rates with low data. Another important factor that increases the effectiveness of transfer learning is the integration of machine learning techniques into this process. In particular, classical machine learning algorithms such as KNN, SVM and RF, when supported by transfer learning, allow for more powerful and flexible models. This combination enables the development of more advanced and reliable systems in the field of signature verification.

C. Transfer Learning Architectures Used in the Study

Transfer learning is an important technique that allows a model to use the knowledge it has already learned in another task in a new task. This method offers significant advantages in training models based on large data sets, especially in the field of deep learning [27]. Especially in biometric

authentication tasks, such as signature verification, transfer learning techniques are frequently preferred in order to build stronger models with limited data sets. Deep learning models learn complex relationships, often by training on very large datasets, and are able to transfer this learned knowledge to smaller, more specific datasets. Thus, a robust and generalizable model can be obtained even when training with more limited data. In this context, transfer learning architectures such as MobileNetV2, ResNet50, DenseNet169, InceptionV3 and EfficientB7 make significant contributions in terms of efficiency, accuracy and speed in tasks such as signature verification. Each model, with its specific advantages and architectural differences, improves performance in such tasks. The structure and features of each model are briefly described below.

MobileNetV2 is a deep learning model optimized for mobile and low-power devices. This model was developed specifically for platforms with limited computational power, such as mobile and embedded systems. Using a technique called “depthwise separable convolutions”, MobileNetV2 achieves efficient results with fewer parameters and processing power. In the context of transfer learning, MobileNetV2 has been successfully used in biometric verification tasks such as signature verification, offering high accuracy rates and low computational costs, especially when working with small data sets [28].

ResNet50 is a widely used model in deep learning networks. It has a 50-layer structure and facilitates the training of deeper networks by using the “Residual Learning” method. An important advantage of this model is that it can eliminate the vanishing gradient problem encountered in deep networks. In the context of transfer learning, ResNet50 is highly effective in tasks such as signature verification, because the layers in the deep structure have the ability to better learn the complex and detailed features of signatures. The success of this model becomes especially evident in signature verification tasks based on large datasets [29].

DenseNet169 is a model that preserves all connections between each layer and enables more efficient feature learning using dense connections. This architecture enables each layer to receive more information from the previous layers, resulting in deeper and more efficient learning processes. DenseNet169 can perform effectively in signature verification tasks, especially in environments with small data sets. When supported by transfer learning, it enables faster and more accurate results based on previously trained models. This is especially advantageous in biometric verification applications where data sets are limited [30].

InceptionV3 is a deep learning model developed by Google and is particularly known for its high accuracy rates. This model uses the “inception module” to learn features at different resolutions in parallel. This structure enables richer and more comprehensive feature learning by combining multiple filters. With its transfer learning technique, InceptionV3 becomes an effective model for tasks such as signature verification. Especially trained on large datasets, this model can achieve successful results even on small datasets and provides high security in the field of signature verification [31].

EfficientNetB7 is an architecture that has become popular in the field of deep learning in recent years and optimizes the model size to achieve more efficient results. The EfficientNet series aims to learn the relationship between each layer more efficiently while optimizing the number of parameters of the

model. EfficientNetB7, when integrated with transfer learning, is particularly effective with large data sets and complex tasks such as signature verification. The high accuracy rates of the model are especially evident when trained on large datasets and provide reliable results in biometric authentication applications such as signature verification [32].

D. Classical Machine Learning Methods Used in the Study

Transfer learning allows a deep learning model to use the knowledge it has already learned in a different task in a new and specific task. This technique is often used to enable the model to learn quickly on limited data sets. The combination of transfer learning architectures and classical machine learning methods provides a great advantage, especially in biometric authentication applications such as signature verification. In this study, a powerful and flexible model is created by combining transfer learning architectures and classical machine learning algorithms. Transfer learning allows deep learning networks to be applied effectively on smaller and more specific datasets, while classical machine learning algorithms (such as K-nearest neighbor, Support Vector Machines and Random Forest) act as additional elements that improve the accuracy of the model. The structure and characteristics of each method are briefly described below.

KNN algorithm is one of the unsupervised learning methods and is often used for classification problems. When determining the class of a new data set, KNN uses the k closest instances in the data set and makes a decision based on the classes of these instances. KNN is particularly effective for achieving high accuracy on small data sets. When combined with transfer learning, the features learned by deep learning models previously trained on large data sets can be used with the KNN algorithm for accurate classification on smaller data sets. This combination enables successful results in tasks such as signature verification, even when working with limited data [33].

SVM is one of the supervised learning algorithms and is particularly effective for nonlinear classification problems. SVM determines the classification boundaries between data by transforming the data into a high-dimensional space. This algorithm is particularly successful when data points are close to each other. When SVM is combined with transfer learning, the features obtained from the deep learning model are used to make more accurate and precise classifications. Transfer learning improves the classification capacity of SVM and helps to achieve more robust and reliable results in biometric tasks such as signature verification [34].

Random Forest is one of the ensemble learning methods and allows many decision trees to come together to form a stronger and more stable model. Each tree is trained on a random subset of the data and the final decision is determined by a majority vote of these trees. Random Forest is specifically used to reduce the overfitting problem and make more robust predictions. Combined with transfer learning, Random Forest allows for a more detailed evaluation of the features learned from the deep learning model. In this way, in biometric applications such as signature verification, more accurate classifications can be made and high accuracy rates can be achieved even with low data sets [35].

This study has demonstrated that transfer learning architectures combined with classical machine learning algorithms such as KNN, SVM and RVM are highly effective for improving the accuracy and reliability of signature verification.

III. RESULTS AND DISCUSSION

Recent advances in biometric authentication have been made possible by the integration of artificial intelligence techniques. These developments play a critical role in increasing security and improving fraud detection, especially in applications such as signature verification. Signature verification has become an area that requires increasingly sophisticated methods to accurately analyze changes over time and individual signature characteristics. Deep learning and machine learning techniques offer important contributions to biometric verification systems, making it possible to overcome these challenges.

Deep learning techniques enable the development of models that can extract detailed features of signatures and understand how they change over time. This enables high accuracy rates in verification processes. Furthermore, methods such as transfer learning allow for efficient utilization of the information obtained from deep learning models, especially on small data sets [36]. The main reason why transfer learning is so effective in biometric verification systems is that the knowledge gained from larger data sets can be used in smaller data sets. This is a great advantage when data is limited and helps to maintain the accuracy of the model [37].

Machine learning techniques combine with transfer learning to strengthen the validation process. In systems working with small data sets, classical machine learning algorithms offer significant advantages. These algorithms can quickly recognize patterns in the data set and contribute to higher accuracy rates in the classification process. Combining the features obtained by transfer learning with classical machine learning methods increases the accuracy of

verification systems and provides more robust and reliable results [35].

The combination of deep learning and machine learning techniques allows to more successfully manage the complexity of data in biometric verification and security systems, while significantly improving accuracy rates. This integration plays an important role in the development of more reliable and robust verification systems for biometric tasks such as signature verification.

In this work, various transfer learning models are used for signature verification. These models include ResNet50, MobileNetV2, VGG16, InceptionV3, EfficientB7 and DenseNet169. First, these six different transfer learning architectures are tested on the BHSig260 Hindi dataset. The performance of each model on the signature verification task is evaluated with specific performance metrics. These metrics were used to measure the performance of each model with respect to important criteria such as accuracy, precision, specificity and F1 score. The results obtained are extensively analyzed to compare the validation performance of these models on the BHSig260 Hindi dataset. Table 1 presents the performance metrics obtained for each model in detail. The accuracy and loss graphs of the VGG16 architecture, which gives the most successful verification result, are presented in Figure 3.

Table 1. Verification performance metrics of transfer learning architectures for signatures on the BHSig260 Hindi dataset

Transfer Learning	Accuracy (%)	Recall (%)	Precision (%)	F1-score (%)
ResNet50	88.27	82.08	86.15	88.27
MobileNetV2	87.02	88.03	86.03	87.02
VGG16	92.77	91.58	93.25	92.42
Inceptionv3	79.38	85.95	91.70	71.77
EfficientB7	83.66	78.20	83.94	80.97
DenseNet169	83.14	72.70	87.25	79.31

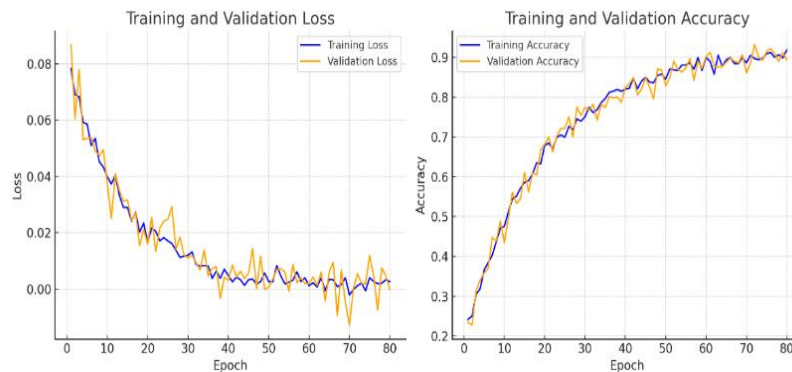


Figure 3. VGG16 architecture accuracy and loss graphs

Performance metrics used to evaluate the effectiveness of signature verification systems play a critical role in understanding the accuracy and reliability of the model. In this

study, the success of the models is measured by four key metrics: accuracy, recall, precision and F1 score. Accuracy is the proportion of all instances correctly classified by the model and indicates overall success. Precision measures the ratio of

the model's true positive predictions (TP - True Positive) to all positive predictions (TP + FP - False Positive), while recall is the ratio of the model's true positive predictions (TP) to all true positive predictions (TP + FN - False Negative). These two metrics are important in assessing the model's ability to detect forgery and authenticate correctly. Finally, the F1 score measures the model's ability to achieve overall balance by taking the harmonic mean of precision and recall. The F1 score aims to both increase true positives (TP) and minimize false positives (FP) and false negatives (FN), especially in cases of imbalance between classes. These metrics provide a more comprehensive performance analysis by assessing both the model's ability to provide accurate results and its capacity to minimize false positives and negatives. The mathematical formulas of performance metrics are essential tools for assessing the accuracy and reliability of the model. The formulas for calculating these metrics are presented in Equations (1), (2), (3) and (4) respectively. These formulas allow to calculate the accuracy, precision, recall and F1 score, taking into account the correct and misclassifications (TP, TN, FP, FN) of the model.

$$\text{Accuracy} = \frac{(TP+TN)}{(TP+TN+FP+FN)} \quad (1)$$

$$\text{Precision} = \frac{TP}{(TP + FP)} \quad (2)$$

$$\text{Recall} = \frac{TP}{(TP + FN)} \quad (3)$$

$$\text{F1 - Score} = 2 \times \frac{\text{Precision} \times \text{Recall}}{(\text{Precision} + \text{Recall})} \quad (4)$$

According to the results in Table 1, the VGG16 model achieved the highest performance with an accuracy of 92.77%. It also showed the best overall verification performance with high precision (93.25%) and recall (91.58%). ResNet50 (88.27% accuracy) and MobileNetV2 (87.02% accuracy) stood out with high accuracy rates, and both models provided balanced metrics. Although the InceptionV3 model lags behind the other models with 79.38% accuracy, it shows a strong performance in forgery detection with high recall (85.95%) and good precision (91.70%). EfficientB7 and DenseNet169 achieved similar results with 83.66% and 83.14% accuracy, respectively, but their recall rates were lower than the other models. Overall, VGG16 exhibited the highest accuracy and best overall performance, while the other models also achieved strong results in specific metrics. These results suggest that each model offers different advantages in signature verification tasks.

In the second part of the study, in addition to the transfer learning models, the KNN method was also used and tested on the same dataset. In Table 2, the verification performance metrics of the KNN method added to each transfer learning model are presented in detail.

Table 2. Verification performance metrics of signatures in BHSig260 dataset with transfer learning architectures and KNN method

Transfer Learning+KNN	Accuracy (%)	Recall (%)	Precision (%)	F1-score (%)
ResNet50+KNN	89.69	80.08	96.05	87.34
MobileNetV2+KNN	90.76	85.125	93.50	89.11
VGG16+KNN	88.72	82.16	91.59	86.62
Inceptionv3+KNN	87.00	82.58	87.46	84.95
EfficientB7+KNN	86.72	78.95	89.93	84.09
DenseNet169+KNN	93.09	87.75	96.38	91.86

According to the results in Table 2, the combination of DenseNet169 + KNN shows the highest validation performance with 93.09% accuracy and 91.86% F1 score. This model achieves superior results in both precision and recall metrics and offers the best overall performance. The MobileNetV2 + KNN model showed a strong validation performance with an accuracy of 90.76% and an F1 score of 89.11%, especially notable for its high recall rate (85.12%). ResNet50 + KNN (89.69% accuracy) and VGG16 + KNN (88.72% accuracy) models also achieved good results with

high accuracy rates and balanced metrics. However, EfficientB7 + KNN (86.72% accuracy) and InceptionV3 + KNN (87.00% accuracy) models have lower accuracy and F1 score values compared to other combinations and lag behind in terms of performance.

In the third part of the study, in addition to the transfer learning models, the SVM method was also used and tested on the same dataset. In Table 3, the verification performance metrics of the SVM method added to each transfer learning model are presented in detail.

Table 3. Verification performance metrics of signatures on the BHSig260 Hindi dataset with transfer learning architectures and SVM method

Transfer Learning+SVM	Accuracy (%)	Recall (%)	Precision (%)	F1-score (%)
ResNet50+SVM	92.85	92.00	91.92	91.96
MobileNetV2+SVM	91.15	90.72	90.84	90.78
VGG16+SVM	92.04	91.66	91.22	91.44
Inceptionv3+SVM	92.53	92.54	90.83	91.68
EfficientB7+SVM	94.44	93.66	93.74	93.82
DenseNet169+SVM	93.81	93.70	92.47	93.08

According to Table 3, the EfficientB7 + SVM combination performed the best with 94.44% accuracy and 93.82% F1 score. This model is characterized by high precision (93.74%) and recall (93.66%). DenseNet169 +

SVM achieved a high performance with 93.81% accuracy and 93.08% F1 score. ResNet50 + SVM (92.85% accuracy) and InceptionV3 + SVM (92.53% accuracy) models also provided effective results with high accuracy and balanced metrics. VGG16 + SVM performed strongly with an

accuracy of 92.04% and an F1 score of 91.44%. These findings show that the combination of transfer learning and SVM provides high accuracy and reliability in signature verification.

In the third part of the study, in addition to the transfer learning models, the Random Forest method was also used and tested on the same dataset. In Table 4, the verification performance metrics of the SVM method added to each transfer learning model are presented in detail.

Table 4. Verification performance metrics of signatures on the BHSig260 Hindi dataset with transfer learning architectures and Random Forest method

Transfer Learning+Random Forest	Accuracy (%)	Recall (%)	Precision (%)	F1-score (%)
ResNet50+ Random Forest	93.75	91.41	94.36	92.86
MobileNetV2+ Random Forest	94.22	91.95	94.88	93.39
VGG16+ Random Forest	93.77	90.79	94.98	92.84
Inceptionv3+ Random Forest	93.48	92.20	93.06	92.63
EfficientB7+ Random Forest	95.24	94.83	94.47	94.65
DenseNet169+ Random Forest	94.61	92.25	95.47	93.83

The results in Table 4 show that the EfficientB7 + Random Forest combination performed the best with 95.24% accuracy and 94.65% F1 score. This model is characterized by high recall (94.83%) and precision (94.47%). DenseNet169 + Random Forest offers a similarly strong verification performance with 94.61% accuracy and 93.83% F1 score. MobileNetV2 + Random Forest and ResNet50 + Random Forest models also achieved effective results with 94.22% and 93.75% accuracy rates, respectively. The VGG16 + Random Forest and InceptionV3 + Random Forest models perform less well with 93.77% and 93.48% accuracy rates, respectively, but still contribute to the overall success. These results show that the combination of transfer learning models and the Random Forest algorithm provides strong and reliable performances in the signature verification task.

In this study, we observe that machine learning algorithms added to transfer learning approaches contribute significantly to signature verification performance. First, the results obtained with transfer learning models only showed that the overall verification performance was high. However, the validation performance of these models is significantly improved when combined with machine learning methods such as K-nearest neighbor (KNN), Support Vector Machines (SVM) and Random Forest. For example, the combination of DenseNet169 + KNN achieved 93.09% accuracy and 91.86% F1 score, outperforming the accuracy of the transfer learning model alone. Similarly, the EfficientB7 + SVM combination achieved an F1 score of 93.82%, improving on the 94.44% accuracy achieved by transfer learning alone. The most remarkable result was seen in the EfficientB7 + Random Forest combination. This combination achieved the highest verification performance in all stages with 95.24% accuracy and 94.65% F1 score. These findings clearly demonstrate that combining the powerful features of transfer learning techniques with the classification capabilities of machine learning algorithms leads to higher accuracy, precision and overall performance in signature verification tasks. Therefore, the integration of transfer learning and machine learning algorithms enables the development of more robust and reliable verification systems by utilizing the advantages of both methods

IV. CONCLUSION

Signature verification plays a critical role in security and fraud detection in biometric authentication systems. While

traditional methods have limited verification performance, deep learning and machine learning techniques provide more accurate and reliable results. In particular, transfer learning increases the success in this field by enabling the transfer of information from large data sets even with limited data. In this study, we investigate the performance of signature verification using a combination of transfer learning models and machine learning algorithms. First, we verify with transfer learning models (ResNet50, MobileNetV2, VGG16, InceptionV3, EfficientB7, DenseNet169) and find that the VGG16 model has the highest performance with 93.77% accuracy. In the second stage, KNN algorithm was added to the transfer learning architectures and the combination of DenseNet169 + KNN achieved the highest performance with 93.09% accuracy. In the third stage, SVM algorithm was added to the transfer learning architectures and EfficientB7 + SVM model provided the best results with 94.44% accuracy. In the fourth stage, the EfficientB7 + Random Forest model achieved the highest success with 95.24% accuracy and 94.65% F1 score as a result of the integration of transfer learning architectures with Random Forest. As a result, the integration of transfer learning and machine learning algorithms has significantly improved the performance of signature verification. These methods have laid a strong foundation for the development of reliable and highly accurate verification systems.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics

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Yeni Türkçe Veri Seti ile Evrişimli Sinir Ağları Kullanarak Kelime Seviyesinde Otomatik Dudak Okuma

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Türkçe Özet – Otomatik dudak okuma, son yıllarda önemli ölçüde gelişen bir araştırma problemidir. Dudak okuma, bazı durumlarda hem görsel hem de işitsel olarak değerlendirilmektedir. Bir güvenlik kamerasından istenmeyen bir kelimenin tespit edilmesi, görsel dudak okuma problemine bir örnektir. Bu tür salt görüntü içeren verilerin bulunduğu durumlarda, görsel-işitsel veri setleri uygulanamaz. Telaffuz edilen kelimenin ses girdisini her durumda elde etmek mümkün değildir. Bu çalışmada, yalnızca görüntü içeren yeni bir Türkçe veri seti toplandı. Yeni veri seti, kontrolsüz bir ortam olan YouTube videoları kullanılarak üretilmektedir. Bu nedenle, görüntüler ışık, açı, renk ve yüzün kişisel özellikleri gibi çevresel faktörler açısından zorlu parametrelere sahiptir. İnsan yüzündeki bıyık, sakal ve makyaj gibi dudakların tespit edilmesini zorlaştıran farklı özelliklere rağmen, veri üzerinde herhangi bir müdahale olmadan Evrişimli Sinir Ağları (CNN) kullanılarak tekil kelimeler ve iki kelimelik ifadeler dahil 10 sınıfta görsel konuşma tanıma problemine çözüm üretilmektedir. Ayrıca, bu çalışmada yalnızca görsel veri kullanıldığı için hesaplama maliyeti ve kaynak kullanımı çok modlu çalışmalara göre daha azdır. Aynı zamanda Ural-Altay dillerine ait yeni bir veri seti kullanılarak dudak okuma sorununu derin öğrenme algoritmasıyla ele alan bilinen ilk çalışmadır.

Anahtar Kelimeler – Dudak Okuma, Çoklu Sınıf Sınıflandırma, Türkçe Dudak Okuma Veri Seti, Derin Öğrenme, Evrişimli Sinir Ağları, Dudak Tespiti

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Automated Word-level Lip Reading using Convolutional Neural Networks with New Turkish Dataset

Extended Abstract

Research Problem/Questions – This study aims to develop a word-level automated lip-reading system using only visual data in Turkish, a language with limited representation in existing datasets. The primary goal is to recognize isolated words and phrases from lip movements using convolutional neural networks (CNNs), particularly in uncontrolled conditions like YouTube videos. It also emphasizes the challenge of reducing computational cost compared to multimodal systems.

Short Literature Review – In response, larger and more diverse datasets, such as LRW-1000 [32], were developed to simulate real-world variability more accurately with thousands of speakers and natural conditions. Beyond English, other languages, such as Czech, have also seen the development of audio-visual databases for continuous speech recognition, as demonstrated in the work by Trojanová et al. [22]. However, datasets in the Turkish language remain limited. Notably, Atilla and Sabaz [30] developed two Turkish datasets and utilized Bi-LSTM with CNNs, achieving strong results; however, their data was still collected in relatively controlled environments. Another Turkish study by Yargıç and Doğan [33] employed Kinect-based 3D lip feature extraction and utilized the KNN algorithm to classify spoken color names, achieving an accuracy of 78.22%. Many of these earlier datasets assume frontal face positioning and consistent lighting, which limits their robustness in natural settings. More recent research focuses on deep learning models that can process real-world complexity, such as visual-only lip reading under whisper or silent speech conditions [23], as well as robust face frontalization techniques [27]. The current study differentiates itself by introducing a new Turkish dataset collected from uncontrolled YouTube videos and applying CNNs directly to grayscale lip images without heavy preprocessing or multimodal input.

Methodology

- **Dataset Collection:** A new Turkish lip-reading dataset was created using video segments from YouTube, including TV series, films, and vlogs. The dataset consists of 10 classes — 5 single words and 5 two-word phrases (e.g., “günaydın”, “teşekkür ederim”) — which are among the most common expressions in daily Turkish communication. Each sample includes 40–60 frames extracted from 1–2 second clips, resulting in a total of 2335 samples. Manual cleaning was performed to remove irrelevant frames before and after the target word was spoken.
- **Preprocessing and Feature Extraction:** The Dlib library was used to detect frontal facial landmarks, followed by cropping the lip region using OpenCV. All frames were converted to grayscale to reduce computational cost. Two input formats were prepared: (1) discrete individual lip images, and (2) composite images created by concatenating 15 frames into a single 60x200 grayscale image. To ensure input consistency, shorter sequences were zero-padded and more extended sequences were truncated.
- **Data Characteristics and Challenges:** The dataset includes diverse visual conditions such as variations in lighting, angle, makeup, facial hair, and partial occlusions. Data analysis showed that 41% of the speakers had facial hair, 33% wore lipstick, and 11.7% had partially visible faces — all of which added to the complexity and realism of the dataset.
- **CNN Model Design:** Two distinct CNN architectures were developed for the two input types. Both models included convolutional layers (with ReLU activation), max-pooling layers, a flatten layer, dropout for regularization, and fully connected layers. The final output layer used Softmax activation to classify samples into 10 categories. The input sizes were adjusted for each architecture: the discrete model received 15 grayscale images of 50x50 pixels each, while the concatenated model used a single image sized 60x200 pixels.
- **Training and Optimization:** Training was carried out on an NVIDIA GTX 1650 Ti GPU using the Keras deep learning framework. To fine-tune performance, various hyperparameters, including learning rate, filter size, dropout rate, batch size, and number of epochs, were optimized using MLFlow and Hyperopt. Early stopping was employed to prevent overfitting, and training progress was monitored using accuracy and loss metrics.

Results and Conclusions – The CNN model using discrete lip images achieved an accuracy of 61.44%, while the concatenated version achieved 55.94%. Although the discrete model was more accurate, it required a higher computational cost. The study demonstrates that visual-only Turkish lip reading is feasible, highlighting the trade-off between accuracy and efficiency. This is the first known study using a Turkish dataset from natural video sources for CNN-based lip reading.

Keywords – Lip Reading, Multiclass Classification, Turkish Lip Reading Dataset, Deep Learning, Convolutional Neural Networks, Lip Detection

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I. Giriş

Konuşma, insanlar arasında kullanılan en yaygın iletişim yöntemidir. Konuşma işitsel olarak gerçekleştirilse de, görme de konuşulan ifadelerin anlaşılmasında büyük bir etkiye sahiptir. McGurk ve MacDonald, insanlara farklı metinlere işaret eden sesli ve görsel verileri göstererek insanların tepkilerini gözlemlemişlerdir [1]. Sesli anlatım ve görüntü birbirini destekleyen girdi verileridir. Otomatik görsel konuşma tanıma, geliştirilebilir kelime çeşitliliği ve doğruluğunun sağlanması açısından sesli konuşma tanıma ve sesli-görüntülü konuşma tanımaya göre daha zorlu bir problem olduğundan doğruluk performansları daha düşüktür. Görsel konuşma tanımada zorluk yaratan durumlardan biri de seseş sözcükler, yani benzer dudak hareketlerine sahip ifadelerdir. Ayrıca görüntünün kalitesi, kişinin yüzünün ve dudaklarının görüntüde yer almaması da zorlayıcı faktörlerdendir. Gürültülü ortamlarda akıllı telefonlara mesaj dikte etmek [2], [3], görsel sessiz şifreler kullanmak [4], [5], [6], sessiz filmleri yazıya dökmek [7], [8], konuşma engelli insanlar için dudak hareketlerine dayalı ses sentezlemek [9], [10], [11], [12] ve işitme engelli insanlara yardımcı olmak için dudak görüntülerini analiz etmek [13] otomatik dudak okuma sistemlerinin uygulama alanları arasında yer almaktadır.

Sesli veri setleri, görsel veri setleri ve görsel-işitsel veri setleri, hangi görevlerde kullanılabileceklerine, konuşmacı sayısına, kelime boyutuna, bilgiye ve kayıtların toplam süresine göre çeşitli özellikler içermektedir. Bu alandaki ilk veri tabanları alfabe ve rakam olarak oluşturulduğundan sınırlı bilgiye sahiptir [14], [15], [16]. Ancak, bu şekilde oluşturulan veri setleri, sürekli konuşma tanıma problemini çözmeye yönelik karmaşık bir yaklaşımdır. Harf ve rakam tanıma problemi sınırlı sayıda sınıfa sahip olduğundan, farklı algoritmaların sonuçlarını hızlıca değerlendirmek için çok sık kullanılmaktadır ve faydalı olmaktadır. Ancak, oluşturulan modeller sınırlı kapsamlara sahip olduklarından geliştirilebilir değildir. Bu durum; kelimeler, ifadeler ve cümleler içeren gerçek dünya problemlerine yakın girdilere olan ihtiyacı ortaya çıkarmaktadır. İngilizce [17], [18], [19], [20], Fransızca [21] ve Çekçe [22] gibi birçok dilde bu tür kelime veya ifadeleri içeren veri tabanı örnekleri bulunmaktadır. Gerçek görüntülerde, kameranın insan yüzüne direkt olarak karşidan baktığını garanti edemeyiz. Çoklu görüntü veri setlerinde, konuşmacı sayısı, sınıf sayısı, dil, kameranın çekim açısı gibi özelliklere sahip içerikler bulunur; bu içerikler, rakam [23], kelime [24] ve cümle [25] girdileri olarak yer almaktadır [26].

Bu çalışmada, temel katkımız, sadece görsel veri kullanarak hesaplama maliyetini azaltmak ve ilgili ses verisinin

bulunmadığı durumlarda bir dudak okuma sistemi geliştirmektedir. Ayrıca, Türkçe dudak okuma çalışmalarında kullanılan doğal insan konuşma görüntülerinden elde edilen bilinen bir derin öğrenme modeli ve böyle bir veri seti bulunmamaktadır. Bu çalışmada farklı dudak temsillerini içeren girdilerle eğitilmiş, kelime düzeyinde bir Evrişimli Sinir Ağı (Convolutional Neural Network – CNN) modeli önerilmektedir. Makalenin geri kalanı şu şekilde düzenlenmiştir: 2. Bölüm’de literatür araştırması sunulmuştur. Daha sonra veri setinin detaylı analizi, dudakların tespiti, ağız temsili, CNN modeli ve eğitim parametreleri Bölüm 3’te açıklanmıştır. Kullanılan test verisi sayısı, performans puanları ve karmaşıklık matrisi gibi metrikler Bölüm 4’te gösterilmiştir. Son olarak bu çalışmanın değerlendirilmesi ve literatüre katkıları Bölüm 5’te özetlenmiştir.

II. LİTERATÜR ARAŞTIRMASI

Görsel konuşma tanıma problemi çalışmaları genel olarak öznitelik çıkarma ve sınıflandırma olmak üzere iki adımdan oluşmaktadır. Özellik çıkarma adımının ilk aşaması, doğru bir şekilde yüzü ve ardından dudakları tanımlamaktır. Doğal görüntülerden türetilen dudak okuma veri setlerinde, her görüntünün önden çekilmiş bir yüz içermesi her zaman mümkün değildir. Bazen görüntülerdeki yüzler sağa, sola, aşağıya veya yukarıya baktığı için, bu tür durumlarda doğru dudak görüntüsünü elde etmek zordur. Dudak tespiti adımından önce veri üzerinde yüzü öne bakacak şekilde hizalama (frontalizasyon) uygulamak etkilidir. Robust Face Frontalization (RFF) [27] yaklaşımı, girdi yüzünün konumunu ve 3 boyutlu şekil değişimini tahmin ederek, bunu önden görülen sentetik bir yüze dönüştürmektedir.

İlk dudak okuma yöntemleri, dudakların manuel olarak elde edilen geometrisini sınıflandırmak için Destek Vektör Makinelerine (Support Vector Machine – SVM) [28] veya Hidden Markov Model’lerine (HMM) [29] dayanmaktaydı. Mevcut yaklaşımlar ise çoğunlukla yenilikçi makine öğrenimi ve derin öğrenme yaklaşımlarından oluşmaktadır. Atila ve Sabaz [30] derin öğrenme modellerini kullanarak Türkçe dudak okuma problemlerini incelemişlerdir. Biri 111 kelime, diğeri 113 cümle içeren iki yeni Türkçe veri seti toplamışlardır. Çalışmada CNN kullanılarak özellik çıkarımı ve Çift Yönlü Uzun Kısa Süreli Bellek (Bidirectional Long Short-Term Memory – Bi-LSTM) kullanılarak sınıflandırma gerçekleştirilmiştir. Bi-LSTM %88,55 doğruluk elde edilerek cümle ve kelime veri setlerinde en iyi sonuçlara ulaşmaktadır. Cümle tespitinde dudak okumanın, kelime tespitine göre daha iyi performans gösterdiğini belirtilmektedir. Garg vd [31] araştırmalarında, görüntü çerçevelerinin tek bir büyük çerçeveye birleştirilmesini içeren Concatenated Frame Images adlı yeni bir yaklaşım tanıtmaktadırlar. Modellerinin ön yüzü olarak VGG mimarisine sahip bir 2 boyutlu evrişimli sinir ağı kullanılmaktadır. Görüntü çerçevelerini tek bir çerçeve içinde iç içe geçirerek, her veri noktası zamansal bilgisini uzamsal bilgiye dönüştürülmektedir ve bu sınıflandırma için bir LSTM ağına girdi olarak verilmektedir. Araştırmacılar, deneylerini MIRACL-VC1 veri setinden alınan videolar ile gerçekleştirmişlerdir. İlginç bir şekilde, en iyi performansın VGG ağının parametrelerinin dondurulması ve yalnızca LSTM’in eğitilmesiyle elde edildiğini bulmuşlardır.

Dudak okuma veri setleri, her bir veri tipinin yani temsil parçasının devamlı olarak ifade edilmesi ve oluşturulmasıyla elde edildiğinde sürekli olarak adlandırılmaktadır. Eğer her parça veri setindeki her bir örneğe karşılık geliyorsa izole

edilmiş olarak adlandırılmaktadır. AVLetters veri seti [14], İngilizce’deki izole harflerden oluşmaktadır. 26 harf, 10 konuşmacı tarafından telaffuz edilmektedir ve görüntülerdeki yüzler önden pozlardır. Büyük bir veri seti olan LRW-1000 [32], sürekli kelimeler içermektedir. Bu veri seti, 2000’den fazla konuşmacı ve 7000’den fazla örnek içermektedir ve veri setindeki örnekler gerçek bir TV programından alındığı için doğal akışında olan kişilerin videoları yer almaktadır. Mevcut en büyük veri setlerinden biri olan AVDigits [23], izole edilmiş rakam sınıflandırması için toplanmıştır. Korpusdaki görüntüler, önden, 45 ve 90 derecelik dudak hareketlerini içermektedir. AVDigits’in sırasıyla rakam ve kelime öbeklerinden oluşan 53 ve 39 konuşmacılı 10 sınıfı vardır. Konuşmacılar cümleleri ve rakamları çeşitli ses seviyelerinde telaffuz etmektedirler. AVICAR veri seti [16], hareket halindeki bir arabadan elde edilmiştir. Bu veri seti, alfabe ve rakam segmentasyonu için sürekli, cümleler için izole olarak toplanmıştır. Her veri türü için 68 konuşmacı ve yüz açıları 4 farklı şekilde dahil edilmiştir. Alfabeler, rakamlar ve cümleler için sırasıyla 26, 10 ve 20 sınıf bulunmaktadır. AusTalk [20] da rakamları, kelimeleri ve cümle parçalarını içeren bir veri setidir. Bu parçalar, 1000 farklı konuşmacı tarafından telaffuz edilmiştir. Veri setindeki konuşmacıların yüzleri önden çekimlerdir. AusTalk, diğer birçok dudak okuma veri seti gibi İngilizce olarak oluşturulmuştur.

Literatürde Türkçe olarak yapılan ve iyi sonuçlar veren çok az dudak okuma çalışması bulunmaktadır. Bunlardan biri, Yargıç ve Doğan’ın çalışmasıdır [33]. MS Kinect cihazından alınan görüntülerle, Türkçe renk adlarının telaffuz edildiği bir veri seti oluşturulmuştur. Bu veri setinin 3 boyutlu olarak elde edilen dudak noktaları arasındaki mesafe verileri kullanılarak özellikler oluşturulmuştur. Toplanan bu veri seti ile, K-En Yakın Komşu (K-Nearest Neighbor – KNN) algoritması kullanılarak 15 sınıflı %78.22 doğruluk oranına sahip bir model üretilmiş ve bu model işitme engelli çocukları desteklemek amacıyla geliştirilmiştir. Bu Türkçe veri setine ek olarak, bilinen en büyük İngilizce görsel-işitsel veri seti olan Lip Reading Sentences (LRS) [7], sürekli konuşma tanıma için oluşturulmuştur. BBC yayınlarından derlenen bu veri tabanı, 100.000’den fazla ifade ve 1000’den fazla farklı kişi içermektedir. Özcan ve Baştürk [35] alfabe düzeyinde dudak okuma veri seti olan AvLetters’ı [14] sınıflandırmak için CNN algoritmasını kullanılmıştır. Bilindiği kadarıyla, transfer öğrenme kullanarak AlexNet ile dudak okuma çalışması bulunmamaktadır. Margam ve arkadaşları [36], GRID korpusundan konuşulan cümleleri tahmin etmek amacıyla ASCII karakterlerini çözmek için 3D-2D-CNN-BLSTM mimari konfigürasyonunu önermişlerdir. İlk yaklaşım olarak, önerilen ağ, Bağlantı Temelli Zaman Sınıflandırması (Connectionist Temporal Classification – CTC) kaybı (ch-CTC) kullanılarak karakterler üzerinde eğitilmiştir. Geleneksel otomatik konuşma tanıma eğitim hattında, BLSTM-HMM modeli, dar boğaz dudak özellikleri üzerinde eğitilmiştir. Aynı 3D-2D-CNN-BLSTM ağı, ikinci teknikte (w-CTC) kelime etiketleri üzerinde CTC kaybı ile eğitilmiştir. Görülmemiş konuşmacı test seti kullanarak %24.5 Kelime Hata Oranı (Word Error Rate – WER) farkıyla LipNet’ten daha iyi bir sonuç elde edilmiştir.

Birçok çalışma, yüz tespiti ve görüntülerdeki konuşmacıların yüz özelliklerini çıkarmak için dlib kütüphanesini kullanmaktadır. Kastaniotis ve arkadaşları [39], yeni bir veri seti sunarak Yunanca kelimelerde görsel dudak okuma görevi için derin CNN’lerin yeteneklerini değerlendiren

iki deney üzerine odaklanmışlardır. Önerilen yöntem, bir CNN'nin ardından çift yönlü bir LSTM ve sonrasında iki tam bağlantı katmanı ve basit bir dikkat mekanizmasından oluşan bir kombinasyona dayanmaktadır. Ayrıca, Leave-N samples out ve Leave-N persons out değerlendirme protokollerini kullanmışlardır. Her iki durumda da 50 kelime için rastgele sınıflandırma oranı %2'dir. Sarhan ve arkadaşları [40], videodan dudak okuma için hibrit dudak okuma HLR-Net adı verilen derin bir CNN modeli geliştirmiştir. Önerilen model üç aşamadan oluşmaktadır: ön işleme aşaması, kodlayıcı aşaması ve kod çözücü aşaması. HLR-Net, girdi olarak dudak hareketi videosunu kullanmakta, ardından bu videoyu OpenCV kütüphanesini kullanarak çerçevelere dönüştürmekte ve son olarak dlib kullanarak ağız özelliklerini çıkarmaktadır. Deney sonuçları, önerilen HLR-Net modelinin, LipNet, LCANet ve A-CTC gibi diğer üç son teknoloji modeli geride bıraktığını göstermektedir; görülmemiş konuşmacılar için karakter hata oranı %4.9, kelime hata oranı %9.7 ve BLEU skoru %92, örtüşen konuşmacılar için karakter hata oranı %1.4, kelime hata oranı %3.3 ve BLEU skoru %99 elde edilmiştir. Ting ve arkadaşları [41], bir dudak okuma veri setinin oluşturulmasını incelemişlerdir. Veri setindeki çerçeveler, scikit-video kullanılarak orijinal videolardan çıkarılmış ve yüz tespiti dlib uygulanarak gerçekleştirilmektedir. Dudak kırma işlemini gerçekleştirmek için özellik noktaları işlenerek dudak görüntüleri yakalanmıştır. Sonuç olarak, önerilen veri setinde her biri 7.000 adet dudak resmine sahip 33 konuşmacı bulunmaktadır. Deney, dlib ve diğer kütüphanelerin kullanımının yüzü etkili ve doğru bir şekilde tanımlayıp videodaki dudak bölgesini çıkardığını kanıtlamaktadır. Fu ve arkadaşları [42] tarafından daha önce oluşturulan Databox adı verilen doğal olarak dağıtılmış kelime düzeyinde Çince veri setini genişletmişlerdir. Önerilen model, bir ResNet ağı ve Geçici Konvolüsyonel Ağdan oluşan mevcut son teknoloji yöntemeye dayalı olarak geliştirilmiştir. ResNet'i, Convolutional Block Attention adlı eklenti dikkat modülüne sahip hafif bir konvolüsyon ağı olan ShuffleNet ile değiştirmişlerdir. Deneylerde, ResNet-18 modeli ile %74.4 doğruluk oranı elde edilmektedir ki bu, deneylerdeki en yüksek doğruluk skorudur. Standart kanal genişliğine sahip ShuffleNet ile %68.4 doğruluk oranına ulaşılmaktadır.

III. MATERİYAL VE METOT

A. Veri Seti

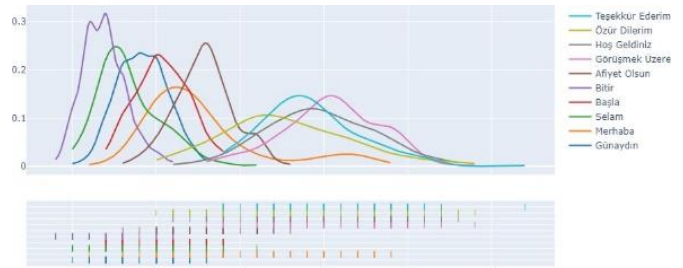
Çalışmada kullanılan veri seti [44] daha önceki çalışmalarımızda [45], [46] kullandığımız ve YouTube üzerinden topladığımız Türkçe dudak okuma veri setidir. Veri seti, Türkçede günlük hayatta sık kullanılan 5 kelime ve 5 ifadeden oluşan 10 sınıf içermektedir. Bu sınıflar, "afiyet olsun", "başla", "bitir", "görüşmek üzere", "günaydın", "hoş geldiniz", "merhaba", "özür dilerim", "selam" ve "teşekkür ederim" ifadeleridir. Veri setinde bu ifadelerin seçilmesinin nedeni Türkçede selamlaşma anlamında en çok kullanılan ifadeler olmalarıdır. Ayrıca, sadece tek kelimelik sınıflar yerine karmaşıklığı artırmak için iki kelimelik ifadeler de seçilmiştir. İlgili kelimenin yer aldığı kısımların ekran görüntüleri, YouTube'da yayınlanan dizi, film ve blog videoları gibi çeşitli görüntülerden kaydedilmiştir. Ardından, kaydedilen görüntüler Python kullanılarak birer resim karesi olarak dosyalara kaydedilmiştir. İlgili kelimenin bulunduğu videolar 1 veya 2 saniye uzunluğunda olup, her bir örnek için elde edilen görüntü sayısı 40-60 aralığındadır. Toplanan görüntüler, kelimenin bir cümle akışı içinde telaffuz edildiği

sırada kaydedildiğinden, bazı durumlarda bir kelimenin başı veya sonu başka bir kelimeyle birleşebilmektedir. Bu nedenle, kelimenin başlangıcından önceki çerçeveler ve kelime telaffuzunun sonundan sonraki çerçeveler, eleme yapılarak manuel olarak kaldırılmaktadır. Bu eleme işlemi sonrasında, her bir örnek için görüntü dizisinde önemli bir azalma gözlemlenmiştir. Veri toplanırken, her sınıf için mümkün olduğunca eşit sayıda örnekle denge sağlanmaya çalışılmıştır (bkz. Tablo 1).

Tablo 1 Sınıfların Veri Dağılımı

Sınıflar	Örnek Sayısı
afiyet olsun	235
başla	225
bitir	244
görüşmek üzere	224
günaydın	232
hoş geldiniz	226
merhaba	268
özür dilerim	209
selam	235
teşekkür ederim	237

Veri seti hem tek kelimelik hem de iki kelimelik sınıflar içerdiğinden, ifadelerin telaffuz süreleri değişkenlik göstermektedir. Örneğin "teşekkür ederim" ve "özür dilerim" gibi ifadeler daha uzun olduğundan telaffuz süreleri ve veri setinde kapladıkları çerçeve sayısı "selam" kelimesine göre daha fazladır. "Özür dilerim" kelimesinin çerçeve sayısı 30'u aşarken, "selam" kelimesinin çerçeve sayısı 15'i geçmemektedir (bkz. Şekil 1). Sınıflandırma yaparken dengeli bir temsil sağlamak için bu dağılımı dikkate almak kritik öneme sahiptir.



Şekil 1 Sınıfların Çerçeve Sayısı Frekansı

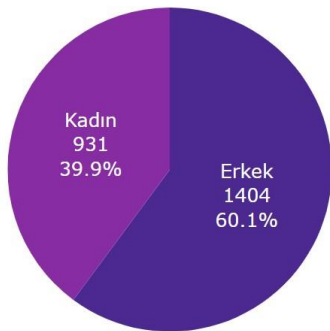
Dudak okuma problemi için toplanan veriler, doğal akışlarında konuşmalarına devam eden konuşmacıların videolarından elde edildiğinden, görüntüler çeşitlilik açısından zorluklar içermektedir (bkz. Şekil 2). Bazı durumlarda konuşmacılar yüzlerini doğrudan kameraya çevirmemesi, görüntüdeki ışık farklılıkları, görüntü kalitesi ve konuşmacının uzakta olması gibi durumlar da bulunmaktadır. Bunlara ek olarak, elde edilen görüntülerde mikrofon gibi nesnelerin konuşmacının önüne gelmesi, konuşmacının bıyığı veya ruj kullanımı gibi kişisel çeşitlilik yaratan problemler de mevcuttur. Bu veri setinin kullanımı, doğal görüntülerden elde edildiği için zordur, bu nedenle gerçek modelleme çalışmaları için araştırmacılar tarafından kullanılmaya uygundur.



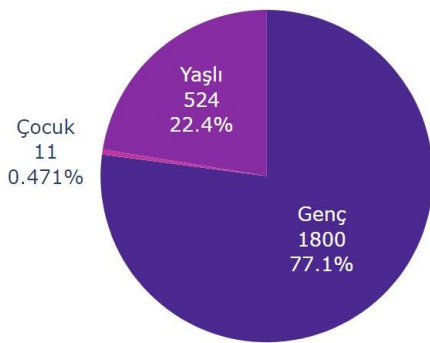
Şekil 2 Veri Kümesinde Karşılaşılan Zorlu Durumlar

Tablo 2, Şekil 3, 4, 5, 6 ve 7, veri setindeki cinsiyet, yaş, bıyık, sakal ve ruj gibi fiziksel özellikler ve ayrıca yüzün tamamen görünür olup olmadığı hakkında bilgi vermektedir. Bu veri setinde toplam 2335 örnek/konuşmacı bulunmaktadır. Bunların çoğunluğu genç ve erkektir. Konuşmacıların %41'inde bıyık ve/veya sakal bulunmaktadır. Bıyık ve sakal, dudak okuma problemi açısından dudakları net bir şekilde tanımlama noktasında zorluk yaratmaktadır. Ayrıca, konuşmacıların %33.3'ünde belirgin şekilde ruj bulunmaktadır. Bu, net bir dudak hattı oluşturacağından kadın konuşmacıların dudaklarının tespit edilmesini kolaylaştıran bir durumdur. Veri setindeki bir diğer zor durum ise bazı konuşmacıların yüzlerinin önden net olarak görünmemesidir.

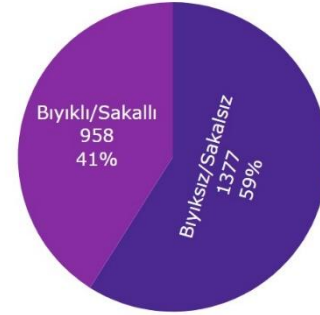
Şekil 7'ye göre, tüm konuşmacıların %11.7'si kısmi yüzlerin bulunduğu çerçeveleri içeren örnekler barındırmaktadır.



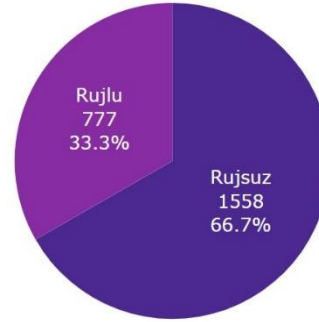
Şekil 3 Cinsiyete Göre Veri Dağılımı



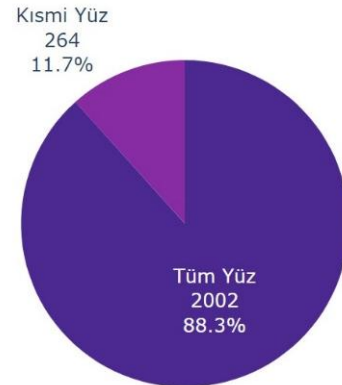
Şekil 4 Yaşa Göre Veri Dağılımı



Şekil 5 Bıyıklı veya Sakallı İnsan Sayısına Göre Veri Dağılımı



Şekil 6 Rujlu İnsan Sayısına Göre Veri Dağılımı

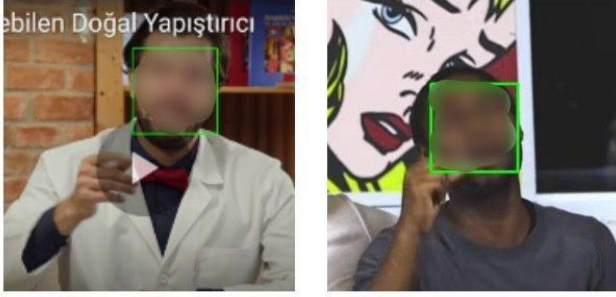


Şekil 7 Kısmi Yüze Sahip İnsan Sayısına Göre Veri Dağılımı

B. Dudak Tespiti

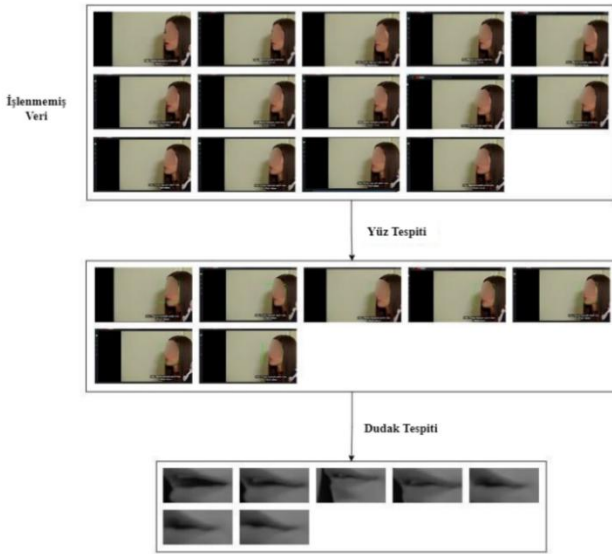
Dudak okuma probleminde, görüntülerin RGB olmasına her zaman ihtiyaç yoktur, bu sebeple yüz ve dudak tespitinde ve sonrasındaki çalışmalardan derin öğrenme model eğitimi sırasında hesaplama ve zaman maliyetlerini azaltmak amacıyla görüntüler gri tonlamalı hale dönüştürülür. Bu çalışmada ilk olarak hazır bir kütüphane olan dlib kütüphanesi kullanılarak veri setindeki insan görüntülerinden yüzler kesilmektedir. Kullanılan `get_frontal_face_detector()` fonksiyonu çağrıldığında, dlib'in önceden eğitilmiş HOG+Linear SVM yüz detektörünü döndürmektedir.

HOG+LINEAR SVM hızlı ve etkili bir şekilde çalışmaktadır. HOG'un doğası gereği, döndürme ve görüş açısı durumlarına uyum sağlamaktadır. Hızlı tespiti nedeniyle gerçek zamanlı yüz tespiti için uygun bir yöntemdir. Şekil 8'de görülebileceği gibi, yüzler açılı olsa veya yüzün önünde bir engel olsa dahi dudakları da içeren hassas bir yüz tespiti yapılabilmektedir.



Şekil 8 HOG+SVM ile Yüz Tespiti

Dudak kesme çalışmalarında, OpenCV kütüphanesi kullanılarak, dudak kısmını almak için belirli bir dizi nokta ile ilgili bölgenin konturu çizilir. Yer işaretlerinde 49-68 aralığı dudak bölgesine karşılık geldiğinden elde edilen yüz görüntüsü üzerinde bu aralık kesilir. Ardından, boundingRect() fonksiyonu yardımıyla belirlenen bölge dikdörtgen bir çerçeve içine alınır. Şekil 9'da öncelikle ham görüntüler, ikinci aşamada tespit edilen yüzler ve sonda ise kesilmiş dudak görüntüleri gösterilmektedir. Her ham görüntüye karşılık bir yüz tespiti yapılmadığı için tespit edilen dudak görüntüleri ham görüntülerin sayısından daha azdır. Her görüntüde açı ve ışık açısından benzer görüntüler bulunsun da her biri için yüz tanıma işleminin gerçekleştirilemediği gözlemlenmiştir. Son olarak, elde edilen dudak görüntüleri, daha sonraki aşamalarda kullanılmak üzere 100x200 boyutunda kaydedilmektedir.

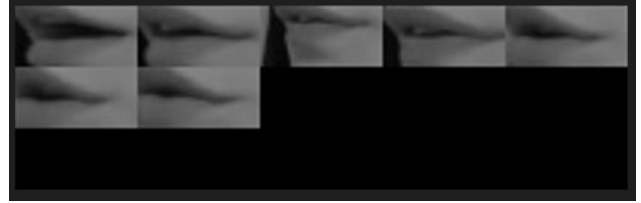


Şekil 9 Dudak Tespiti

C. Dudakların Temsili

Geliştirilen ilk yaklaşımda, bir örneğin her bir ardışık görüntüsü derin öğrenme modelinde kullanılarak akışın korunması sağlanmaktadır. Dudakların ayrı olarak modele verilmesi durumunda, bu görüntüler 15 görüntüden oluşan bir seri halinde kullanılarak tek bir görüntü yerine bir akış sağlanmaktadır. İkinci yaklaşımda ise, 15 görüntü birleştirilerek tek bir daha küçük görüntü olarak kullanılmaktadır. Birleştirme işleminden sonra 100x200

boyutundaki her bir görüntü, çok büyük bir görüntü elde edilmemesi için 20x40 olarak yeniden boyutlandırılmaktadır. Bir dudak örneğinin çerçeve sayısı 15'ten azsa, gri tonlamalı olarak 0 değerleriyle doldurularak 15'e tamamlanacak şekilde görüntü eklenmektedir. Eğer çerçeve sayısı 15'ten fazla ise, fazla çerçeveler çıkarılır. 15 çerçeve, 3 satır ve 5 sütun şeklinde ardışık olarak birleştirildiğinde, 60x200 boyutunda bir görüntü elde edilmektedir. Şekil 10, bu birleştirilmiş 15 ardışık görüntüyü göstermektedir.



Şekil 1 Birleştirilmiş Dudaklar

D. CNN Modeli

Son yıllarda, makinelerin hesaplama gücünün artması, donanım kaynaklarının genişlemesi ve GPU'ların kullanımı gibi teknolojik gelişmeler sayesinde, CNN modellerinin kullanımı önemli ölçüde artmıştır. CNN'lerin klasik yapay sinir ağlarından en önemli farklarından biri, görüntünün belirli bölgelerini alarak parametre sayısını azaltmasıdır. Son yıllarda yapılan çalışmalarda görüntü sınıflandırma, nesne tespiti, görüntü segmentasyonu gibi girdi verisinin görüntü olduğu birçok problemin yanı sıra girdinin metin olduğu çalışmalarda da kullanılmaktadır. Bu alandaki karmaşık problemlerin kolaylıkla çözülebilmesinin en büyük nedenlerinden biri, görüntü üzerinde herhangi bir öznitelik çıkarımı yapmadan, bir uzman bilgisine ihtiyaç duymadan ve görüntü üzerindeki herhangi bir nesne için konum ve şekil gibi öznitelikleri tespit etmeden CNN ile model geliştirilebilmesidir. Evrişimli sinir ağları, doğal sinyallerin özelliklerinden yararlanmak için dört temel prensipten yararlanmaktadır: yerel bağlantılar, paylaşılan ağırlıklar, havuzlama ve çok sayıda katmanın kullanımı CNN'i diğer sinir ağı yaklaşımlarından ayıran en önemli katman, evrişim katmanıdır. Temel olarak girdi, evrişim, havuzlama ve tam bağlantılı katmanlardan oluşmaktadır. Sınıflandırıcı CNN modelleri kabaca öznitelik çıkarma ve sınıflandırma katmanlarından oluşmaktadır. Öznitelik çıkarma katmanları, evrişim ve havuzlama katmanları sayesinde girdi görüntüsünün anlamlı çıktıları üreterek diğer görüntülerle ilişkilendirilmektedir. Sınıflandırma katmanında, sınıflandırma problemi için sınıf sayıları ve bunların anlamlı görüntülerine dayalı olasılıklar üretilmektedir. Buna dayanarak çok sınıflı bir modelde son katmandaki softmax fonksiyonu ile tahmin yapılmaktadır.

E. Önerilen Model

Önerilen CNN mimarisi, birleştirilmiş dudak görüntüleri ve ayrı olarak eğitilmiş dudak görüntüleri için iki tanedir.

Tablo 2 Verinin Öznitelikleri

Sınıf	Kadın	Erkek	Yaşlı	Genç	Çocuk	Bıyık/Sakal	Ruj	Kısmi Yüz	Tüm Yüz
afiyet olsun	125	110	102	132	1	79	100	71	164
başla	55	170	66	157	2	126	43	57	119
bitir	90	154	73	171	0	122	71	35	209
görüşmek üzere	87	137	24	199	1	83	78	2	222
günaydın	102	130	60	172	0	92	86	26	206
hoş geldiniz	109	117	26	198	2	66	82	9	217
merhaba	113	155	39	227	2	106	106	6	262
özür dilerim	76	133	42	166	1	89	65	22	187
selam	52	183	67	167	1	116	37	25	210
teşekkür ederim	122	115	25	211	1	79	109	11	226
TOPLAM	931	1404	524	1800	11	958	777	264	2022

Ayrık Dudak Girdileri ile CNN Modeli

Bölüm C'de bahsedildiği gibi, ayrık dudak görüntüleri girdi katmanına bir dizi olarak verilmektedir. Mimari, iki evrişim ve iki maksimum havuzlama katmanı içermektedir. Evrişim katmanları, aktivasyon fonksiyonu olarak ReLU (Rectified Linear Unit) kullanılmaktadır, filtre boyutları 128 ve 64 olup, filtrelerde kullanılan adım 1'dir ve dolgu (padding) bulunmamaktadır. Maksimum havuzlama katmanlarının havuzlama boyutları 3x3x3 ve adımı 2'dir. Bu dört katmanı düzleştirme (flatten) katmanı takip etmektedir ve mimari, bırakma (dropout) ile tam bağlantılı katmanlarla devam etmektedir. Girdi vektörü, 50x50 sabit boyutlu 15 görüntüden oluşmaktadır. Bu görüntülere dolgu olmadan ve 1 adımlık adımlarla evrişim katmanında rastgele 128 filtre uygulanmaktadır. Evrişim işleminden sonra 13x48x48x128 boyutunda bir çıktı üretilmektedir. Evrişim katmanını takip eden maksimum havuzlama katmanının çıkışında 3x3 havuzlama boyutu olduğundan, çıktı 6x24x24x128 boyutunda olur. Sırasıyla conv3d, maksimum havuzlama ve düzleştirme katmanları uygulandıktan sonra, 15488 boyutlu bir vektör elde edilmektedir. Özellikle CNN modellerinde aşırı öğrenmeyi (overfitting) önlemek için ReLU aktivasyon fonksiyonuna ve %0.5 oranında bırakma (dropout) katmanlarına sahip iki tam bağlantılı katman uygulanmaktadır. Son olarak çok sınıflı bir sınıflandırma problemi üzerinde çalışıldığı için, mimari, softmax aktivasyon fonksiyonu ile 10 boyutlu bir vektör çıktısı üreten tam bağlantılı bir katmanla sonlandırılır. Çıktıda, "afiyet olsun", "başla", "bitir", "görüşmek üzere", "günaydın", "hoş geldiniz", "merhaba", "özür dilerim", "selam" ve "teşekkür ederim" şeklindeki 10 sınıf için olasılıklar üretilmektedir.

Birleştirilmiş Dudak Girdileri ile CNN Modeli

Bu yaklaşımda; ayrık dudak görüntülerinin girdi olarak alındığı durumdan farklı olarak dudaklar birleştirilmektedir ve 15 görüntü, tek bir görüntü girdisi oluşturacak şekilde kullanılmaktadır. Bu nedenle, hesaplama maliyeti açısından oldukça uygun bir yöntemdir. Tek bir görüntü bir görüntü dizisini temsil ettiğinden veri karmaşıklığını azaltmaktadır. Girdi olarak 50x50 boyutunda bir görüntü kullanılarak evrişim katmanına gönderilmektedir. Havuzlama boyutu 2x2 olduğu için, düzleştirme (Flatten) katmanının girdisi 11x11x16 boyutundadır. Dudakların ayrı ayrı verildiği yaklaşımdaki mimariden farklı olarak, Düzleştirme katmanının ardından

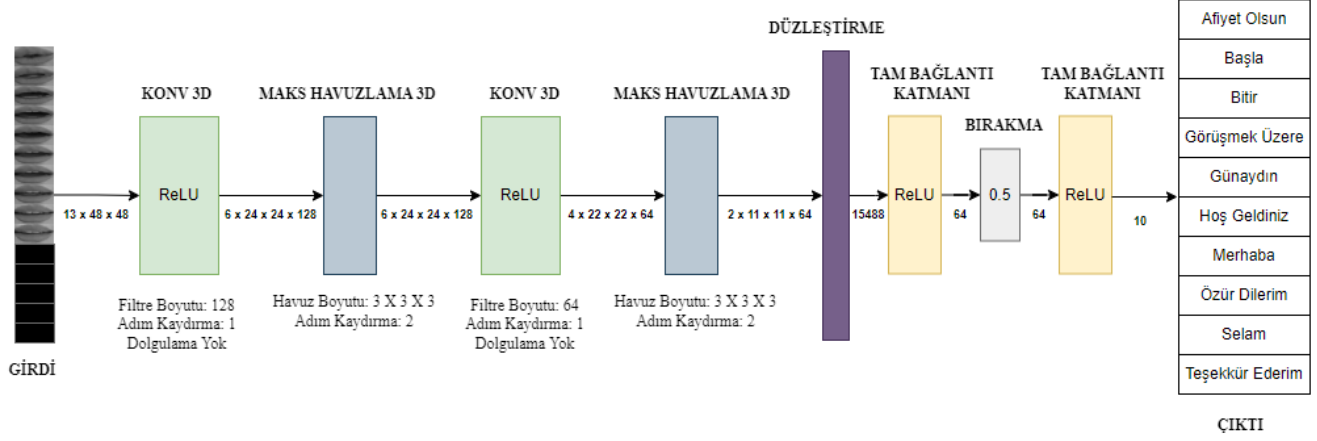
9216 boyutlu bir vektör çıktısı olan 1 tam bağlantı katman ve bırakma katmanı bulunmaktadır. Son olarak, 10 sınıfa sahip bir çıktı vektörü üretilmektedir.

F. Eğitim

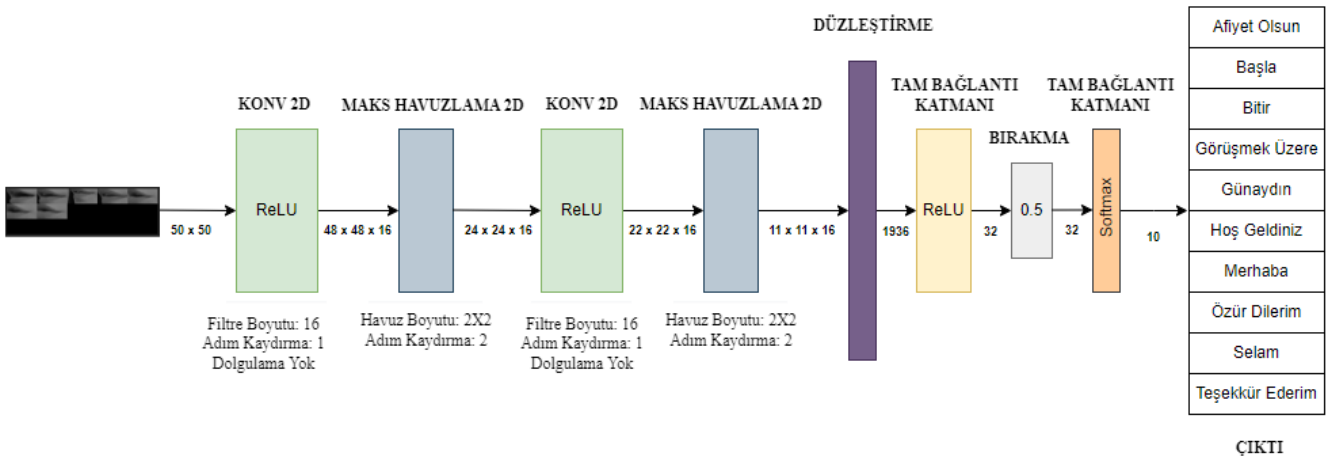
Eğitim sürecinde, dudakların ayrı ayrı eğitilmesi ve birleştirilmesi yaklaşımlarına yönelik iki farklı çalışma için farklı hiperparametreler üzerinde deneyler yapılmıştır. Deneylerin sonuçlarını değerlendirmek ve hiperparametre ayarlarını yapmak için makine öğrenimi yaşam döngüsünü yönetmek amacıyla geliştirilen bir Python kütüphanesi olan mlflow kullanılmaktadır. Dudakların birleştirildiği ve ayrıldığı durumlar için farklı hiperparametreler uygulanmaktadır (Tablo 3). İki yaklaşımın model kapasitesi ve karmaşıklığı farklı olduğundan, öğrenme oranı, yığın boyutu (batch size) ve epok (epoch) sayısı gibi parametreler değişiklik göstermektedir. Eğitim sırasında, her iki model için de 1, 2 ve 3 olmak üzere farklı evrişim katmanları denenmiştir. Model doğruluk grafikleri ve test sonuçlarına dayanarak, aşırı öğrenme veya yetersiz öğrenme (underfitting) olmayacak şekilde model kapasitesi göz önünde bulundurularak evrişim katmanlarının sayısında değişiklikler yapılmaktadır. Öğrenme oranı değerleri 0.0002, 0.002, 0.001 ve 0.0001, her iki katman için evrişim filtre boyutları: 16, 32, 64, 128 ve 256, bırakma oranları ise 0.3, 0.4, 0.5 ve 0.6 olarak belirlenmiştir. Optimum sonuçlar için Hyperopt kütüphanesi ile deneyler tekrarlanmış ve mevcut parametrelere ulaşılmıştır. Epok sayısı, kayıp değerine bağlı olarak belirlenmiştir.

IV. SONUÇLAR VE TARTIŞMA

Dudak okuma gibi dilin de işine girdiği çalışmalarda dilin farklı telaffuzları ve varyasyonları olduğundan doğru bir değerlendirme yapmak zordur. Bu kapsamda yapılan çalışmalarda kelime düzeyinde karşılaştırılabilir Türkçe bir veri seti mevcut değildir. Çalışmalarımızda temel olarak Türkçe dudak okuma problemine yönelik bir CNN mimarisi geliştirilmesi amaçlanmaktadır. CNN mimarisini temel alan tüm deneyler GPU üzerinde çalıştırılmaktadır. 4GB bellekli NVIDIA 1650 Ti grafik kartı kullanılmaktadır. İyileştirmeler Python Keras kütüphanesi kullanılarak yapılmaktadır. Bunlara ek olarak görselleştirme için Plotly ve Seaborn kütüphanelerinden, görüntü işleme çalışmaları için ise OpenCV kütüphanelerinden yararlanılmaktadır. Dudakların birleşik ve ayrık olduğu iki gösterim aşamasında da deneyler Tablo 4'teki örnek sayısı ile gerçekleştirilmektedir.



Şekil 11 Ayrık Dudakların Temsilinde Kullanılan CNN Modeli



Şekil 12 Birleştirilmiş Dudakların Temsilinde Kullanılan CNN Modeli

Tablo 3. Her Sınıfa Ait Test Örneklerinin Sayısı

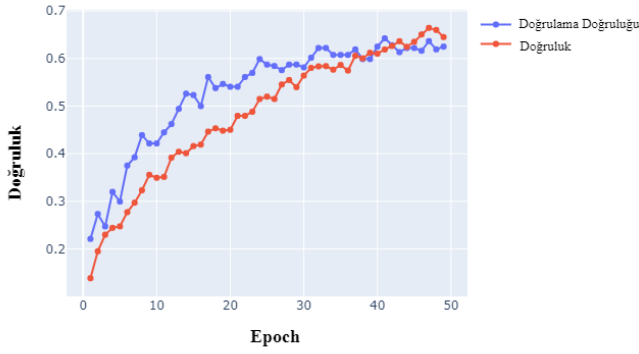
Sınıf	Örnek Sayısı
afiyet olsun	29
başla	35
bitir	46
görüşmek üzere	23
günaydın	32
hoş geldiniz	34
merhaba	43
özür dilerim	31
selam	37
teşekkür ederim	35

A. Ayrık Dudak Görüntülerine Ait Eğitim Sonuçları

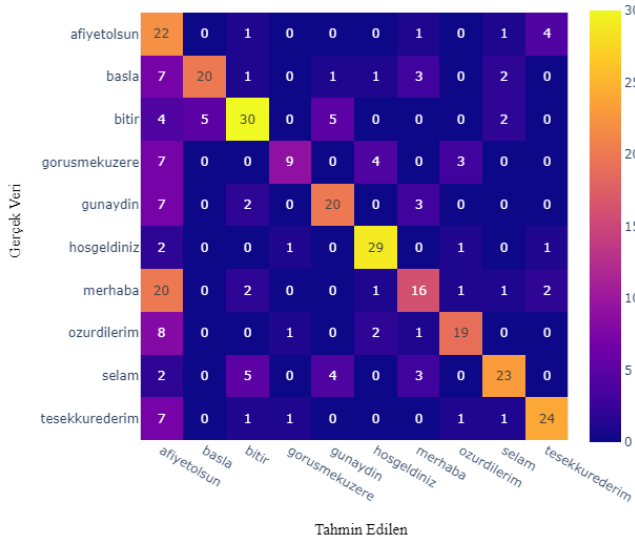
Eğitim sonuçlarına bakıldığında, erken durdurma (early stopping) kullanılarak belirlenen epok sayısına göre doğruluk değişimleri Şekil 13'te gösterilmektedir. Doğruluk değerinde 50 epok boyunca iyileşme görülmediği için eğitim süreci durdurulmuştur. Eğitimin devam etmesi durumunda model aşırı öğrenmeye maruz kalacağından başka hesaplamalar yapılmasına gerek yoktur. Test verilerinde tahmin edilen sınıfların sonuçları incelendiğinde, yanlış olarak tespit edilen sınıflar genellikle "afiyet olsun" sınıfında olduğu görülmektedir (Şekil 14). Bu sınıfa ait verilerin içerisinde diğer sınıflara oranla daha fazla kısmi yüz görüntüsü yer

almaktadır, dolayısıyla daha zorlu olabileceği yorumu yapılabilir.

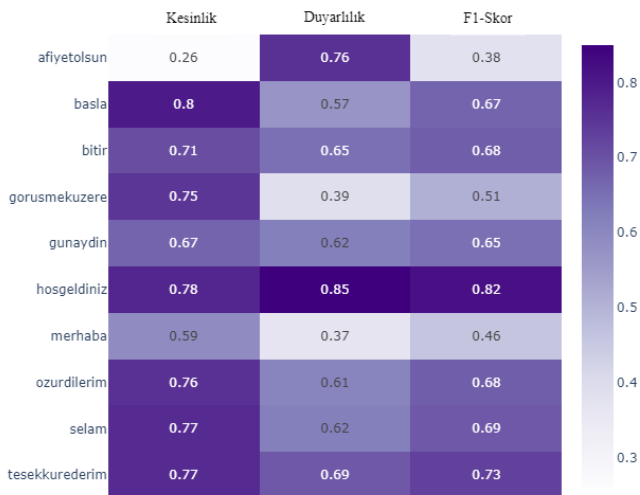
Özellikle sınıfı "başla", "günaydın" ve "özür dilerim" olan örneklerde yanlış tahminler "afiyet olsun" sınıfında yoğunlaşmaktadır. "Afiyet olsun" sınıfında yapılan hatalar, genellikle "merhaba" ifadesindeki 20 örnekte yapılmıştır. Buna karşılık, "hoş geldiniz" ve "selam" ifadelerinde yanlış tahmin edilen "afiyet olsun" örneği sayısı 2'dir. Bunları takip eden "başla", "hoş geldiniz", "teşekkür ederim", "selam", "özür dilerim", "görüşmek üzere" ve "bitir" sınıflarında ise kesinlik (precision) skorlarının yüksek olduğu görülmektedir, (Şekil 15). Buradan hareketle, bu sınıflara ilişkin pozitif tahminlerin çoğunluğunun doğru olduğunu söyleyebiliriz. Genel olarak, karmaşıklık matrisine dayanarak "afiyet olsun" sınıfındaki hata oranının yüksek olduğu görülmektedir. Bu ifadelerin veri setindeki seslendirilmesinde belirgin bir dudak hareketi olmayabilir veya Türkçe dilbilgisi kurallarına göre daha zorlayıcı ifadelerden biri olarak yorumlanabilir. Bu veri setinde örnek sayısı açısından sınıf dengesizliği olmamasına rağmen, tahmin performansları sınıflara göre değişiklik göstermektedir çünkü tıpkı gerçek yaşam sahnelerinde olduğu gibi konuşmacı farklılıkları, görüş açıları ve ışık farkları gibi her sınıf için çeşitlilik yaratan durumlar mevcuttur.



Şekil 13 Ayrık Dudakların Epok Başına Düşen Eğitim ve Doğrulama Doğruluğu



Şekil 14 Ayrık Dudak Görüntüleriyle Eğitilmiş Modelin Karmaşıklık Matrisi



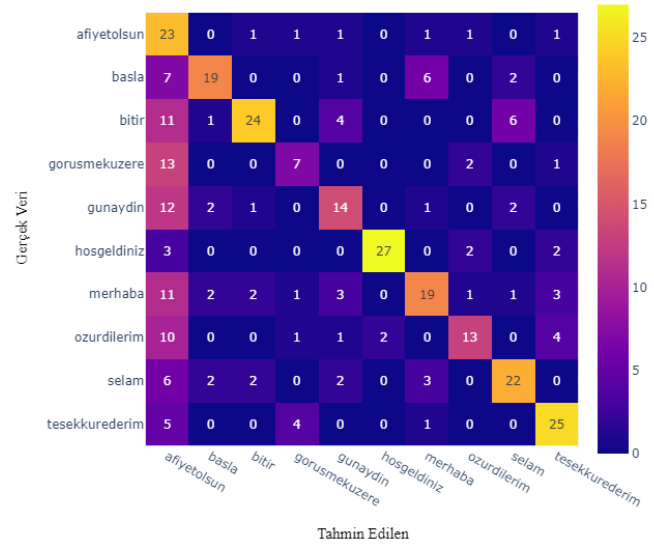
Şekil 15 Ayrık Dudak Görüntüleriyle Eğitilmiş Modelin Sınıflandırma Raporu

B. Birleştirilmiş Dudak Görüntülerine Ait Eğitim Sonuçları

Birleştirilmiş dudaklar kullanılarak gerçekleştirilen CNN model eğitimi, erken durdurma ile 42 epokta sona ermiştir (bkz. Şekil 16). Bu nedenle eğitimin daha da devam etmesi halinde düşük test doğruluğu elde etmek kaçınılmaz olmaktadır. Benzer şekilde, ayrık dudak görüntülerinin yer aldığı veri setinde olduğu gibi, birleştirilmiş dudak görüntülerinin sonuçlarında da hatalı tahminler "afiyet olsun" sınıfında toplanmaktadır (Şekil 17). Bunun dışında, tahminlerin genellikle "başla", "hoş geldiniz", "selam" ve "teşekkür ederim" sınıflarında yüksek olduğu ve diğer sınıflarla karışmadığı görülmektedir. Karmaşıklık matrisinde görüldüğü üzere, sınıflandırma raporu grafiğinde (Şekil 18) "afiyet olsun" sınıfının kesinlik (precision), duyarlılık (recall) ve f1-skor (f1-score) değerlerinin düşük olduğu görülmektedir. Diğer sınıfların doğruluk yüzdelere yorumlamak için, dudakların ayrık olarak kullanıldığı eğitimle karşılaştırıldığında daha dengeli sonuçlar görülmektedir.



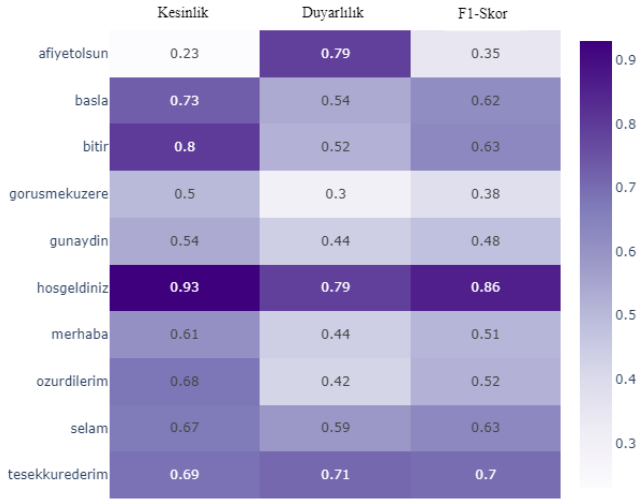
Şekil 16 Birleştirilmiş Dudakların Epok Başına Düşen Eğitim ve Doğrulama Doğruluğu



Şekil 17 Birleştirilmiş Dudak Görüntüleriyle Eğitilmiş Modelin Karmaşıklık Matrisi

Tablo 4. İki CNN Modeline Ait Doğruluk Değerleri ve Eğitim Süreleri

	Doğruluk	Eğitim Süresi
Birleştirilmiş Dudaklar	%55.94	15 saniye
Ayrık Dudaklar	%61.44	32 dakika



Şekil 18 Birleştirilmiş Dudak Görüntüleriyle Eğitilmiş Modelin Sınıflandırma Raporu

C. Tartışma

Toplam deney sonuçları karşılaştırıldığında, doğruluk oranı birleştirilmiş dudaklar için %55.94 ve ayrık dudaklar için %61.44'tür (bkz. Tablo 4). Süreler ise sırasıyla 15 saniye ve 32 dakikadır. Ayrık dudak görüntülerinde yüksek doğruluğun nedeni, daha net ve yüksek çözünürlüklü ayrık görüntülerin kullanılmasıdır. Ayrık dudakların eğitim süresi uzun olduğundan, hesaplama maliyeti açısından daha külfetli olarak değerlendirilebilir; ancak yüksek doğruluğu nedeniyle performans açısından tercih edilebilir. Görüntü temsili açısından girdilerden birinde 50x50 boyutunda 15 adet görüntü kullanılırken, diğerinde 60x200 boyutunda 1 adet görüntü kullanılmaktadır. Eş zamanlı tahmin gerektiren durumlarda, birleştirilmiş dudakların kullanıldığı temsili kullanmak daha uygun olacaktır, ancak doğru tespit önemli olduğunda, ayrık dudakları kullanan CNN modelini tercih etmek uygundur. Her iki çalışmanın doğruluk oranları değerlendirildiğinde, hala bir artış potansiyeli olduğu görülebilir. Bu potansiyele ulaşmak için yapılabilecek iyileştirmelerden biri, veriyi çeşitlendirerek artırmak, yani daha fazla veri toplamaktır. Bir diğer seçenek ise veri artırma (data augmentation) tekniklerini kullanarak bu çalışmayı yürütmektir. Benzer çalışmalarla karşılaştırıldığında, kullanılan veri seti içeriklerinin oldukça zorlu olduğu görülmektedir. Bu yeni veri setinde, yüzler önden görüntülenmemektedir, bazı görüntüler çok karanlıkken diğerleri oldukça parlaktır ve arka planın çok karmaşık olması nedeniyle bazen yüzü doğru bir şekilde tespit etmek mümkün olmamaktadır.

V. DEĞERLENDİRME

Bu çalışmada, yeni bir Türkçe veri seti için bir CNN modeli önerilmektedir. Ayrıca, iki farklı girdi temsili ile doğruluk ve hesaplama maliyeti karşılaştırılmaktadır. Bu temsil yöntemlerinden ilkinde, ardışık dudak görüntüleri modelin girdisini ayrı ayrı oluştururken, diğerinde dudaklar

birleştirilerek tek bir görüntü oluşturulmaktadır. Performans açısından, ayrık dudaklar daha iyi sonuç verirken, birleştirilmiş dudaklar zaman maliyeti açısından daha iyi performans göstermektedir. Ayrıca, doğal YouTube görüntülerinden toplanan Türkçe veri seti, diğer çalışmalara kıyasla gerçek dünya görüntülerine daha yakın olması nedeniyle zorludur. Literatürdeki çalışmalarda toplanan görüntüler, kontrollü bir ortam oluşturularak sabit bir arka plan ve sabit bir insan duruşu ile elde edilmiştir. Doğal videolar üzerinden otomatik dudak okuma, işitme engelli bireyler için otomatik altyazı oluşturma açısından da büyük önem taşımaktadır. Bu çalışmada, doğal video görüntülerinden dudak okuma yaparak bir CNN modeli önerilmektedir. Ural-Altay dillerinde doğal dil ve dudak okuma çalışmaları sınırlı olduğundan, bu alana özgün bir çalışma ile katkıda bulunmaktadır. Gelecek çalışmalarda daha geniş bir veri seti toplanarak dudak tespiti ile daha yüksek doğrulukta sınıflandırma yapılması planlanmaktadır.

TEŞEKKÜR

Yazarların Katkıları

Veri düzenleme, metodoloji, görselleştirme, N.P.A.; denetim ve danışman, H.E.; proje yönetimi, A.B. Tüm yazarlar, makalenin yayımlanan versiyonunu okumuş ve kabul etmiştir.

Çıkar Çatışması Beyanı

Yazarlar arasında çıkar çatışması bulunmamaktadır.

Araştırma ve Yayın Etiği Beyanı

Yazarlar bu çalışmanın Araştırma ve Yayın Etiğine uygun olduğunu beyan etmektedirler.

Verinin Erişilebilirlik Durumu

Veri şu adreste mevcuttur:

<https://data.mendeley.com/datasets/4t8vs4dr4v/1>

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Generalized Dynamic Codebook Design for Non-Coherent Short-Packet Communications: Radius Control and Placement of Complex-Conjugate Reciprocal Zero Pairs

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Abstract – Modulation on conjugate-reciprocal zeros (MOCZ) is a non-coherent communication scheme designed for the reliable transmission of short data packets over unknown wireless multipath channels. Unlike traditional methods that require channel estimation or training sequences, MOCZ encodes information onto the zeros of the transmitted signal's z-transform, enabling the receiver to decode data without prior channel knowledge. To support multiple users, the multi-user MOCZ (MU-MOCZ) scheme was introduced, employing time-division multiplexing (TDM). However, the use of a fixed codebook for all users in MU-MOCZ can degrade performance due to variations in channel zero distributions. This paper extends previous work by introducing a dynamic codebook design for MU-MOCZ. The design incorporates a rotation parameter into the angular positions of zero pairs, allowing the transmitter to adjust the codebook to each user's unique channel conditions and optimize performance. Simulation results demonstrate significant improvements in bit error rate (BER), throughput, and packet delivery ratio (PDR) compared to the fixed codebook MU-MOCZ scheme.

Keywords – MOCZ, dynamic codebook, non-coherent, short packet communication, z-transform

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I. INTRODUCTION

Modern wireless communication systems face significant challenges in ensuring efficient and reliable data transmission, particularly in non-coherent communication scenarios where the receiver operates without prior knowledge of channel state information (CSI). Non-coherent communication methods are gaining attention for their ability to reduce transceiver complexity by eliminating the requirement for channel estimation [1], [2], [3]. This makes them highly suitable for applications demanding low latency and high reliability, such as Internet of Things (IoT) networks, machine-type communications (MTCs), and ultra-reliable low-latency communication (URLLC) systems in 5G and beyond [4]. Furthermore, non-coherent schemes are inherently robust against channel dynamics, making them ideal for rapidly changing communication environments. Their simplified design also leads to lower power consumption, which is critical for energy-constrained devices in IoT applications. Furthermore, removing the dependency on CSI, these schemes enable faster data processing, ensuring efficient and consistent performance in mission-critical systems.

One key aspect of non-coherent communication is the design of the codebook [5], which plays a significant role in determining system performance metrics such as bit error rate (BER), spectral efficiency (SE), and power consumption. The effectiveness of the codebook directly affects how well the system can detect and decode information in the absence of CSI at the receiver. Unlike coherent systems that use CSI to

optimize transmission methods, non-coherent systems depend on well-designed codebooks to ensure reliable data detection under varying channel conditions. These systems rely on the codebook to facilitate detection even when the channel is unknown or changes over time [6]. However, static codebook designs may not perform optimally in dynamic environments [7], as they lack the ability to adjust to changes in channel behavior and interference. As a result, system performance may suffer, causing higher error rates and inefficient use of resources.

To address these limitations, dynamic codebook design enables adaptation to real-time channel variations, improving the overall performance of non-coherent communication systems. Modifying the codebook structure based on current channel conditions allows these systems to maintain optimal performance even under changing environments. This adaptability is particularly crucial for ensuring reliable communication in dynamic conditions, where static codebooks may struggle to provide consistent performance. The study in [8] highlights the importance of designing individual constellations and their corresponding bit-mapping schemes for non-coherent communication systems, which helps optimize data detection and transmission. Furthermore, [9] introduces suboptimal constellations specifically designed for multiuser environments, which rely on energy detection techniques to address the challenges of detecting signals in the presence of noise and interference. The study in [6] introduces a structured Grassmannian constellation called Grass-Lattice

for noncoherent communications over SIMO Rayleigh block-fading channels, utilizing a measure-preserving mapping from the unit hypercube to the Grassmannian of lines.

In recent work, the authors in [10], [11] introduced a non-coherent communication scheme known as modulation on conjugate-reciprocal zeros (MOCZ), where data is mapped onto the zeros of the z-transform of the transmitted sequences. This new communication scheme eliminates the need for CSI, simplifying the receiver structure. The study in [12] proposed a time-domain user multiplexing method using MOCZ by incorporating a guard period between downlink users to avoid interference. On the other hand, the work in [13] introduced a new frame design technique called z-domain user multiplexing (ZDM-MOCZ), which allows for multiplexing in the z-domain instead of sequentially in the time domain, providing a more efficient use of resources. While these techniques represent significant advancements in non-coherent communication, a common challenge in these studies is the reliance on fixed codes or static codebooks for user transmission. This lack of flexibility in adapting to changing channel conditions limits the system's ability to achieve optimal performance in varying scenarios.

This paper builds upon our previous work presented in [20], where we introduced a novel approach for constellation design in the z-domain by dynamically controlling the radius of circles on the z-plane. In that initial study, we focused on modifying the radius to optimize key performance metrics, such as BER and packet delivery ratio (PDR).

Although the proposed formulation for the zero-pair radius demonstrated significant performance improvements, full adaptation of the positioning of modulation zeros to changing channel conditions remained unfulfilled.

In this paper, we extend the previous work by repositioning the zero-pairs with the addition of an extra rotation parameter.

The main contributions of this paper are as follows:

- We build upon our previous work, where the radius parameter α is dynamically scaled, by introducing a rotation parameter β to modify the angular position of the zero-pair, in addition to the radius scaling.
- We demonstrate how this two-parameter control enables flexible positioning of modulation zeros on the z-plane to mitigate the effect of channel zeros.
- We analyze the performance of the proposed scheme within a non-coherent communication framework, highlighting its adaptability to varying channel conditions and robustness without the need for CSI.
- We present a theoretical analysis and simulations to evaluate the impact of the proposed design on key performance metrics, including BER, PDR, and throughput.

The remainder of this paper is structured as follows: Section II presents the system model and defines the problem statement. In Section III, we introduce the generalized dynamic codebook design framework and discuss its implementation. Section IV provides simulation results to illustrate the performance improvements achieved with the

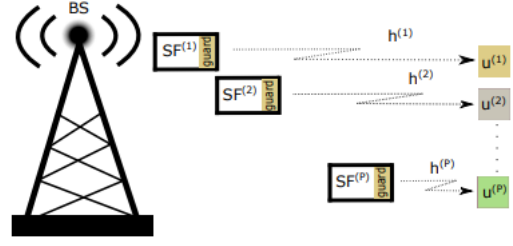


Fig. 1. Time-domain multiplexing [13]

dynamic codebook. Finally, Section V concludes the paper and outlines potential directions for future research.

II. SYSTEM MODEL

In this study, we consider a multiuser downlink communication system where a base station (BS) serves the number of P user equipments (UEs), as depicted in Fig. 1. The p -th UE is denoted by $u^{(p)}$, where $p = 1, 2, \dots, P$. The BS encodes each user's message of length $N - 1$ into a sequence of length N , represented as $\mathbf{s} = [s_0, s_1, \dots, s_{N-1}]^T$, where $s_n \in \mathcal{C}$ for each user. Each user is served independently in separate time slots, following a time-division multiplexing (TDM) scheme [12]. To prevent interference between the transmissions of different UEs, each transmission is preceded by a guard interval, which is designed to be greater than or equal to the maximum delay spread of the channel.

In the discrete-time domain, the received signal at the p -th UE, denoted as $y^{(p)}[n]$, is modeled as the linear convolution of the transmitted signal $s[n]$ with the multipath channel impulse response $h^{(p)}[n]$, along with additive noise $w^{(p)}[n]$. This can be expressed as

$$y^{(p)}[n] = \sum_{k=0}^{L-1} h^{(p)}[k]s[n-k] + w^{(p)}[n], \quad (1)$$

where $n = 0, 1, \dots, N + L - 1$, and $h^{(p)}[n]$ is the discrete-time impulse response of the channel for the p -th user, with a maximum delay spread of L . $s[n]$ is the transmitted signal of length N . $w^{(p)}[n]$ is additive white Gaussian noise (AWGN) with zero mean and variance σ^2 .

The received signal consists of $N + L - 1$ samples due to the convolution operation. To ensure no inter-symbol interference (ISI) occurs between consecutive transmissions, a guard interval is introduced at the transmitter, which is at least L samples long. This guard interval accommodates the channel's delay spread and prevents overlap between signals of adjacent users in the time-division multiplexing (TDM) scheme. The received signal can also be represented using matrix notation as

$$\mathbf{y}^{(p)} = \mathbf{H}^{(p)}\mathbf{s} + \mathbf{w}^{(p)}, \quad (2)$$

where $\mathbf{y}^{(p)} \in \mathcal{C}^{(N+L-1) \times 1}$ is the p -th user received signal vector. $\mathbf{s} \in \mathcal{C}^{N \times 1}$ is the transmitted signal vector. $\mathbf{w}^{(p)} \in \mathcal{C}^{(N+L-1) \times 1}$ is the noise vector. $\mathbf{H}^{(p)} \in \mathcal{C}^{(N+L-1) \times N}$ is the Toeplitz channel matrix formed by $h^{(p)}[n]$.

$$\mathbf{H}_{(N+L-1) \times N} = \begin{bmatrix} h_0 & 0 & 0 & 0 \\ h_1 & h_0 & 0 & 0 \\ \vdots & h_1 & \ddots & 0 \\ h_{L-1} & \vdots & \ddots & h_0 \\ 0 & h_{L-1} & \ddots & h_1 \\ \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & 0 & h_{L-1} \end{bmatrix}. \quad (3)$$

The receiver processes $\mathbf{y}^{(p)}$ to recover $\mathbf{s}$, employing the specific demodulation scheme and taking advantage of the structure of the transmitted signal encoded in the z -domain.

The wireless channel is modelled as a Rayleigh frequency-selective channel with L propagation paths. Its impulse response is given by

$$h(\tau) = \sum_{l=0}^{L-1} h_l \delta(\tau - \tau_l), \quad (4)$$

where h_l and τ_l represent the complex-valued path gain and time delay of the l -th path, respectively, and $\delta(\cdot)$ is the Dirac delta function. This model captures the effects of multipath propagation, where each path contributes a delayed and scaled version of the transmitted signal.

Assume that in the discrete-time domain, the channel impulse response $h(n)$ has a length of $N + 1$ samples. Its z -transform, or transfer function, is expressed as

$$H(z) = \sum_{n=0}^N h(n)z^{-n}, \quad (5)$$

This can be further factored as

$$H(z) = h(0) \prod_{k=1}^N (1 - c_k z^{-1}). \quad (6)$$

where c_k denotes the k -th zero of $H(z)$.

The zeros c_k represent the roots of the channel transfer function and are critical in determining the channel's spectral characteristics. This formulation connects the time-domain representation of the channel to its z -domain behavior, which is particularly useful in non-coherent communication schemes that encode information directly onto the zeros of the transmitted signal's z -transform.

Convolution in the time domain corresponds to multiplication in the z -domain. Therefore, the z -transform of the received signal $\mathbf{y}^{(p)}[n]$ is given by

$$\mathbf{Y}^{(p)}(z) = \mathbf{H}^{(p)}(z)\mathbf{S}(z) + \mathbf{W}^{(p)}(z). \quad (7)$$

where $\mathbf{Y}^{(p)}(z)$ is the z -transform of the received signal $\mathbf{y}^{(p)}[n]$. $\mathbf{H}^{(p)}(z)$ is the z -transform of the channel impulse response $h^{(p)}[n]$. $\mathbf{S}(z)$ is the z -transform of the transmitted signal $\mathbf{s}[n]$. $\mathbf{W}^{(p)}(z)$ is the z -transform of the additive noise $\mathbf{w}^{(p)}[n]$.

This relationship highlights how channel response and noise affect the transmitted signal in the z -domain. From $\mathbf{Y}^{(p)}(z)$, the receiver can decode the transmitted message by detecting these zeros, even without explicit knowledge of the channel.

Unlike traditional coherent communication systems, which rely on channel estimation and equalization at the receiver to address distortions introduced by the channel, non-coherent schemes avoid the need for these processes. Channel estimation and equalization are computationally demanding and contribute to increased latency. To address these challenges, modulation on conjugate-reciprocal zeros (MOCZ) has been introduced as an efficient non-coherent communication method [10].

A. Modulation on Conjugate-Reciprocal Zeros (MOCZ)

Consider a polynomial $Q(z)$ defined as

$$Q(z) = z^N + a_1 z^{N-1} + \dots + a_N. \quad (8)$$

where $a_i \in \mathbb{C}$ for $i = 1, 2, \dots, N$, and N is the degree of the polynomial.

A root of the polynomial $Q(z)$ is a value $\gamma \in \mathbb{C}$ that makes the polynomial expression equal to 0, such that $Q(\gamma) = 0$. According to the fundamental theorem of algebra, a polynomial of degree N has exactly N roots [14]. Therefore, any polynomial can be factored as $\prod_{i=1}^N (z - a_i)$, where each a_i denotes a root of the polynomial. In non-coherent communication schemes, these roots correspond to the zeros of the transmitted signal and play a crucial role in encoding the information directly onto the z -transform of the signal.

In MOCZ scheme, the p -th user's message at the BS is divided into K subgroups, denoted by $\mathbf{m}^{(p)} = [m_1^{(p)}, m_2^{(p)}, \dots, m_K^{(p)}]$ [10]. Each $m_k^{(p)}$ message is derived from M -ary alphabet $[M]$. Subsequently, the vector $\mathbf{s}^{(p)} = [s_0^{(p)}, s_1^{(p)}, \dots, s_K^{(p)}]^T \in \mathbb{C}^{K+1}$ is generated by the inverse z -transform of $S^{(p)}(z)$ which is given by

$$\mathbf{S}^{(p)}(z) = \prod_{k=1}^K (z - \alpha_k^{(p)}), \quad p = 1, 2, \dots, P. \quad (9)$$

where $\alpha_k^{(p)} \in \mathbb{C}$ is the k -th root of the polynomial $S^{(p)}(z)$, and $\alpha_k^{(p)}$ is chosen by mapping m_k to an element in the zero-alphabet given by

$$\Xi = \left(\left(\alpha_1, \frac{1}{\alpha_1^*} \right), \left(\alpha_2, \frac{1}{\alpha_2^*} \right), \dots, \left(\alpha_K, \frac{1}{\alpha_K^*} \right) \right). \quad (10)$$

where the zero-pairs $\left(\alpha_k, \frac{1}{\alpha_k^*} \right)$ for $k = 1, 2, \dots, K$ in the zero codebook are conjugate-reciprocal pairs.

In [15], MOCZ is applied to enhance communication security by introducing artificial noise injection, while [16] integrates MOCZ with faster-than-Nyquist (FTN) signalling to achieve higher spectral efficiency. A novel method is presented in [17] for computing the majority vote (MV) function by employing modulation on conjugate-reciprocal zeros (MOCZ). In [18], a noncoherent SIMO framework with MOCZ is proposed to minimize pilot overhead and fading effects, along with a low-complexity Viterbi-like detector.

B. Existing Work and Problem Definition

Multi-user modulation on conjugate-reciprocal zeros (MUMOCZ), introduced in [12], expands the original MOCZ scheme [10] to enable support for multiple users. In the standard MOCZ method, the data for each user is encoded onto the complex conjugate-reciprocal zeros of the z -transform of the transmitted signal, providing reliable communication without requiring channel estimation or equalization. The MUMOCZ framework is designed by facilitating the sharing of the communication channel among multiple users in a time division multiplexing (TDM) manner.

The time-division multiplexing (TDM) technique enables multi-user communication while preserving the non-coherent nature of the system, as it does not require channel estimation. However, using a fixed codebook for all users poses a challenge. Each user experiences distinct multipath environments and channel conditions, leading to variations in the distribution of zeros associated with their respective channels. A fixed codebook lacks the flexibility to accommodate these differences, potentially leading to performance degradation and affecting the system's overall reliability and efficiency.

This study extends our previous work [20], which introduced a dynamic codebook design that reformulates the radius equation through scaling. In this paper, we build upon that work by adding an additional parameter, β , along with the existing parameter α , to reposition the zero-pairs on the z -plane within the codebook. This extension allows the transmitter to better adapt to the unique channel conditions of each downlink user by using a specific codebook for every user.

III. PROPOSED DYNAMIC CODEBOOK DESIGN

In this section, we propose a dynamic codebook design that builds upon and significantly extends the capabilities of our previously introduced z -domain modulation scheme. The key enhancement lies in the modification of the radius equation, now incorporating an additional parameter for rotation. While the earlier approach solely focused on controlling the radius of the modulation zeros through the scaling parameter α , the current design introduces the rotation parameter β , enabling dynamic angular positioning of the modulation zeros on the z -plane. The parameter α controls the magnitude (or radius), while the parameter β determines the angular positioning of the modulation zero-pairs on the z -plane. The two-parameter design (α and β) allows for flexible and effective modifications to meet varying channel conditions:

- In some scenarios, the effect of the channel zeros on detection performance can be minimized by modifying only the scaling parameter α .
- In other cases, modifying only the rotation parameter β is sufficient.
- Under more complex conditions, both parameters (α and β) need to be jointly optimized to achieve the desired performance.

The multipath channel for each p -th user can be represented as $h^{(p)}(n)$, where p denotes the user. The corresponding z -transform of the channel for the p -th user is given as [19].

$$H^{(p)}(z) = \sum_{n=0}^{L^{(p)}-1} h^{(p)}(n)z^{-n}. \quad (11)$$

where $L^{(p)}$ denotes the maximum discrete delay spread of the channel between the BS and the p -th user. This can be expressed as $L^{(p)} = \left\lfloor \frac{\tau_{\max}}{T_s} \right\rfloor$, where $\lfloor \cdot \rfloor$ represents the floor function, $\tau_{\max}$ is the maximum delay spread, and T_s denotes the sampling period, respectively. The $h^{(p)}(n)$, for $n = 0, 1, \dots, L^{(p)} - 1$, contain the channel taps.

The zeros of $H^{(p)}(z)$, denoted by $z_i^{(p)}$, are the points in the z -plane where the channel transfer function equals zero given by

$$H^{(p)}(z_i) = 0 \quad \text{for } i = 1, 2, \dots, L^{(p)} - 1. \quad (12)$$

The receiver detection involves identifying the zeros transmitted from the received signal, which is impacted by the channel conditions of each user. The dynamic codebook improves performance of the detection by modifying the zero-pairs to align with the channel's characteristics. This adaptation enables the receiver to better distinguish the transmitted zeros from noisy channel zeros, improving detection efficiency, reducing errors, and improving overall communication performance and reliability in varying channel conditions.

In [10], the radius R is designed to optimize the Euclidean distances between zeros and their conjugate-reciprocal counterparts, along with the distances between neighboring zero pairs. The radius R is given by

$$R(K) = \sqrt{1 + \sin\left(\frac{\pi}{K}\right)}. \quad (13)$$

and the k -th root of the polynomial $S^{(p)}(z)$ corresponding to the p -th user is given by

$$\begin{aligned} \alpha_k^{(p)} &= R(K) \cdot e^{j\left(\frac{2\pi(k-1)}{K}\right)} \\ &= \sqrt{1 + \sin\left(\frac{\pi}{K}\right)} \cdot e^{j\left(\frac{2\pi(k-1)}{K}\right)}. \end{aligned} \quad (14)$$

However, using a fixed radius and hence a static codebook for all users with varying channel conditions can lead to performance degradation, as different channel characteristics cause the zeros to be randomly distributed across the z -plane. To address this challenge, the equation in (13) is modified based on the specific channel conditions of each user, aiming to position the transmitted zeros farther away from the randomly distributed channel zeros, thus enhancing detection accuracy. We introduce the α and β parameters into the equation to scale the radius and reposition the zero pair's angle, respectively.

$$R(K) = \sqrt{1 + \sin\left(\frac{\pi}{\alpha K}\right)}. \quad (15)$$

where $\alpha \in \mathbb{R}$. This modified radius R effectively adjusts the number of zero pairs on the z -plane, allowing a more flexible arrangement of the transmitted zeros among the channel zeros based on the parameter α . For instance, as shown in Fig. 1, setting α to 2 can be interpreted as doubling the number of zero pairs on the z -plane, which would be evenly distributed around

the circles at radii R and $\frac{1}{R}$, according to the modified radius equation.

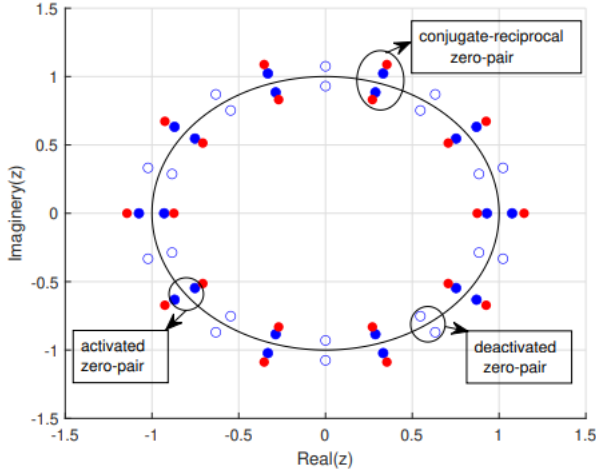


Fig. 2. Red circles indicate the complex zero pairs in the conventional codebook with $\alpha = 1$, whereas the white circles, which are deactivated, and blue circles represent the zero pairs in the proposed codebook with $\alpha = 2$.

We also introduce the rotation parameter β into the root $\alpha_k^{(p)}$ of the polynomial associated with the p -th user. The inclusion of β allows for a controlled rotation in the placement of the roots. The k -th root of the polynomial $S^{(p)}(z)$ corresponding to the p -th user, denoted as $\alpha_k^{(p)}$, is expressed as

$$\begin{aligned} \alpha_k^{(p)} &= R(\alpha, K) \cdot e^{j\left(\beta + \frac{2\pi(k-1)}{K}\right)} \\ &= \sqrt{1 + \sin\left(\frac{\pi}{\alpha K}\right)} \cdot e^{j\left(\beta + \frac{2\pi(k-1)}{K}\right)}. \end{aligned} \quad (16)$$

In this expression, $R(\alpha, K)$ denotes the magnitude or radius of the root, K is the total number of roots, k indexes the individual root, and β introduces the angular rotation applied to all roots. This parameter provides an additional degree of freedom, allowing the system to optimize the placement of roots in the complex plane to meet specific communication requirements. The proposed dynamic codebook converges to the fixed codebook configuration when the parameters $\alpha = 1$ and $\beta = 0$.

A. Assumptions and Limitations

The objective of the proposed dynamic codebook design is to enable adaptation to channel zero disturbances for each user. This approach modifies the placement of modulation zeros based on the specific characteristics of the channel experienced by each user. The method involves adjusting both the radius and angular position of the existing zero-pairs in the codebook.

It is assumed that the transmitter has prior knowledge about the distribution of channel zeros, which can be obtained through feedback from the receiver. The feedback mechanism involves exchanging information about the distribution of channel zeros rather than full CSI. This information is sent from the receiver to the transmitter periodically, with the frequency of feedback depending on the channel dynamics. The receiver provides statistical information on the

characteristics of the channel, including the distribution of the channel zeros. This feedback is typically in the form of Channel Quality Indicator (CQI) data, which allows the transmitter to evaluate the channel conditions before transmission. The CQI data play a key role in enabling dynamic adjustments to the modulation zeros, ensuring the system can adapt to varying channel conditions.

It is crucial to maintain enough distance between the modulation zeros and the channel zeros to improve detection reliability. As shown in Fig. 2, increasing the phase separation between zero pairs improves performance by keeping the transmitted zeros at a safe distance from the channel zeros. This strategy ensures better communication performance across different channel conditions.

The packet delivery ratio assumes no frame retransmission, focusing only on data frames transmitted over the wireless channel. Once a frame is transmitted and an acknowledgment is received, there is no need for retransmission. This assumption simplifies the analysis by considering only the successful delivery of frames within a single transmission attempt, and the impact of potential retransmissions or error recovery mechanisms is not included in the scope of the simulations.

The proposed method is most effective in scenarios with moderate channel variability, where feedback about channel zero distributions can be timely and accurate. However, in extremely fast-varying channels, the timeliness of this feedback may become a bottleneck, limiting the effectiveness of codebook updates. In such cases, the delay in reporting channel zero distributions could result in outdated or suboptimal codebook configurations, reducing the potential performance gains in terms of BER, throughput, and PDR.

B. Performance Analysis

The Direct Zero-Testing (DiZeT) technique [10] is employed by each user to detect transmitted zeros by analysing the roots of the polynomial $Y^{(p)}(z)$.

User throughput represents the amount of data successfully received by a user over a specific time interval, and in [13], it is defined as

$$T_{MU-MOCZ} = \frac{N_{bits}^{(p)}}{N_{sym}[P(K_p + 1 + L)]} (1 - BER), \quad (17)$$

where $N_{bits}^{(p)}$ represents the total number of bits transmitted, while N_{sym} denotes the number of symbols transmitted. P refers to the number of downlink users, and K_p , where $p \in \{1, 2, \dots, P\}$, denotes the number of zeros assigned to each p -th user. The term L corresponds to the length of the channel or the channel delay spread. BER stands for the Bit Error Rate, and $T_{MU-MOCZ}$ represents the throughput.

PDR is defined as the ratio of the number of packets successfully received by the destination node to the number of packets sent by the source node. It serves as a key metric for evaluating network reliability, providing insight into the effectiveness of communication across the network. A high PDR indicates reliable data transmission, while a low PDR may suggest issues such as packet loss, network congestion, or interference. PDR is expressed as [13]

$$PDR = \frac{P_{rec}^{(p)}}{P_{snd}}. \quad (18)$$

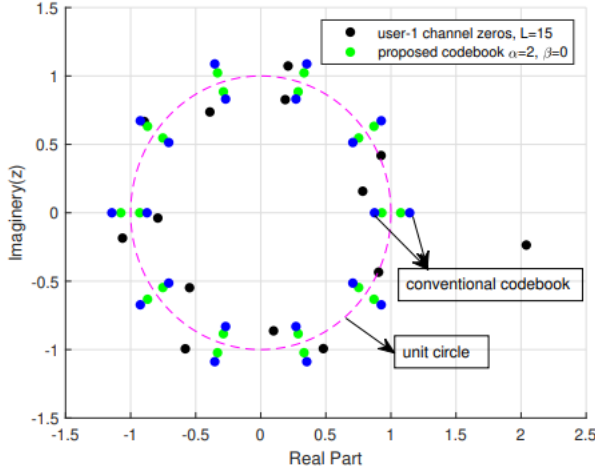


Fig. 3. Black circles represent the complex zeros of $H(z)$ for the first user, blue circles indicate complex zero-pairs from the conventional codebook, and green circles denote the complex zero-pairs when $(\alpha, \beta) = (2, 0)$ based on the distribution of the complex zeros of $H(z)$.

where $P_{rec}^{(p)}$ indicates the count of packets that have been successfully received by the p -th user, and P_{snd} refers to the overall number of packets sent from the source.

Adjusting the parameters α and β does not introduce additional computational overhead, as these adjustments do not impact the complexity of modulation or demodulation.

IV. SIMULATIONS AND RESULTS

In this section, we present the simulation setup and results to evaluate the performance of the proposed dynamic codebook design in a multiuser time-division multiplexing (TDM) system. The simulations are designed to reflect practical scenarios where each user experiences unique multipath channel conditions. Specifically, the transmitter serves multiple users in a TDM manner as illustrated in Fig. 1, and the signal propagation for each user experiences unique multipath channels, leading to varying numbers and distributions of channel zeros on the z -plane. A feedback mechanism is assumed to be in place where each user sends channel quality information (CQI) to the transmitter. The CQI includes information about the statistical distribution of the channel zeros on the z -plane. Hence, the transmitter has the knowledge about the distribution of the channel zeros for the related downlink users. Based on the feedback received from each user, the transmitter dynamically adjusts the codebook dedicated to that user. The adjustment involves the parameters α and β .

To illustrate the effectiveness of the proposed dynamic codebook design, we consider two users in the TDM system. Each user is assigned 10 transmitted zeros, and we assume that the channel's z -transform exhibits 14 randomly distributed zeros on the z -plane. The performance of the proposed design is compared to the conventional MU-MOCZ scheme. In the conventional MU-MOCZ scheme, the scaling parameter α is set to 1, and the rotation parameter β is set to 0 (i.e., no additional adjustments are made).

Fig. 3 illustrates the distribution of channel zeros on the z -plane as experienced by the first user. The channel for this user is characterized by $L = 15$ multipath components, which result in a set of channel zeros being randomly distributed

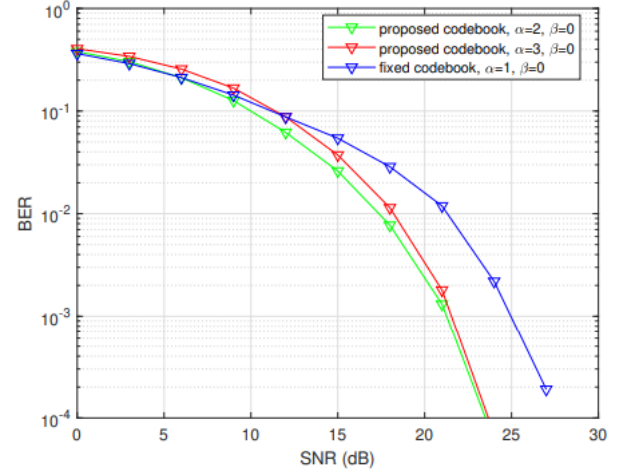


Fig. 4. BER performance comparison between conventional and proposed schemes for the first user.

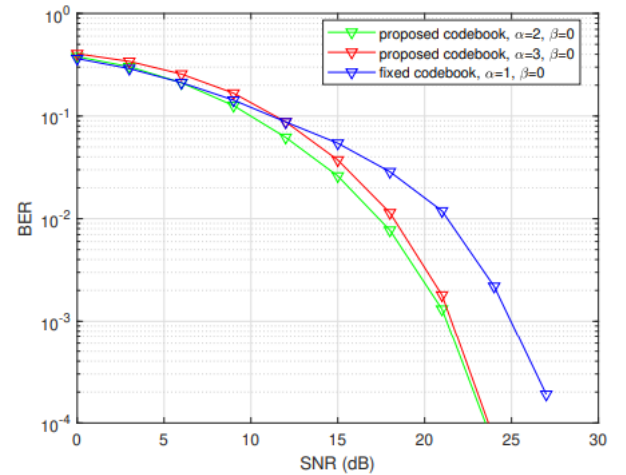


Fig. 5. Throughput performance comparisons between conventional and proposed schemes for the first user.

across the z -plane. These randomly placed zeros can cause distortions in the transmitted signal, especially in noisy environments, significantly impacting the receiver's ability to correctly detect the transmitted data. To mitigate this challenge, the transmitter relies on feedback from the user regarding the distribution of channel zeros. This feedback, assumed to be provided in the form of channel quality indicators (CQI) or similar metrics, enables the transmitter to dynamically place the zero-pairs in the codebook. Specifically, in this simulation, the modification involves setting the scaling parameter to $\alpha = 2$.

This increases the radius of the modulation zeros, ensuring that they are well-placed relative to the channel zeros on the z -plane. The increased separation between modulation zeros and channel zeros reduces the likelihood of detection errors at the receiver, even in noisy conditions. The resulting improvement in BER performance is significant, as shown in Fig. 4. These results demonstrate the effectiveness of the proposed dynamic codebook design in adapting to varying channel conditions and enhancing the reliability of non-coherent communication

systems. Fig. 5 illustrates the throughput performance of the user for different values of the α scaling parameter.

Similarly, Fig. 6 shows the distribution of channel zeros experienced by the second user, whose channel is also

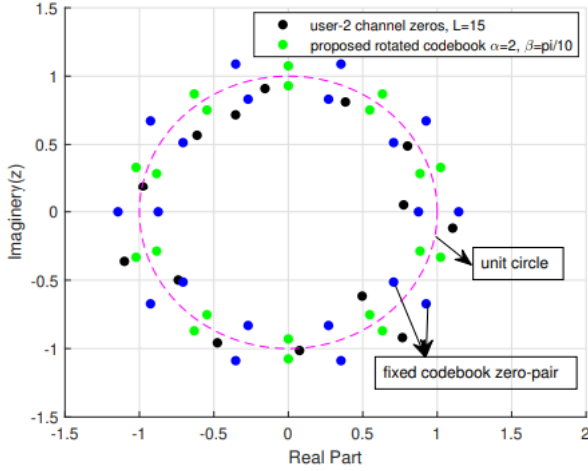


Fig. 6. Black circles represent the complex zeros of $H(z)$ for the second user, blue circles indicate complex zero-pairs from the conventional codebook, and green circles denote the complex zero-pairs from the distribution of the complex zeros of $H(z)$.

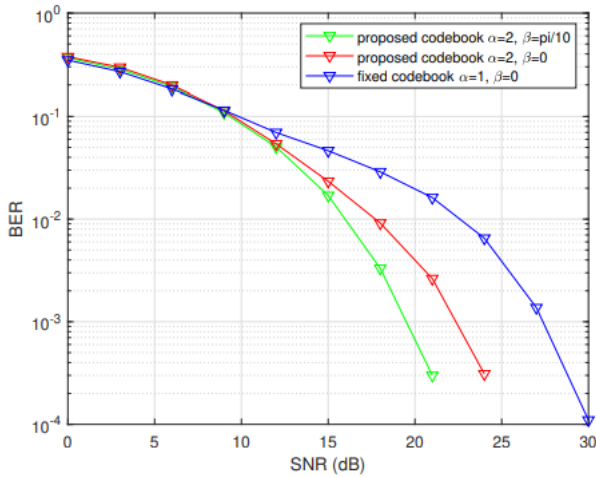


Fig. 7. BER performance comparison between conventional and proposed schemes for the second user.

characterized by $L = 15$ multipath components, resulting in 14 channel zeros randomly distributed across the z -plane.

Based on the assumption that the second user provides feedback to the transmitter about the distribution of its channel zeros, the transmitter adapts the positioning of the zero-pairs in the codebook. In this case, the transmitter utilizes both the scaling parameter α and the rotation parameter β . The codebook's complex conjugate reciprocal zero-pairs are adjusted around the unit circle, enabling better placement relative to the channel zeros. This combined adjustment of α and β results in improved BER performance as depicted in Fig. 7, compared to the conventional MU-MOCZ scheme which uses a fixed codebook. The improvement highlights the flexibility and effectiveness of the proposed dynamic codebook design in handling diverse channel conditions and enhancing the performance of non-coherent communication systems.

Fig. 8 and Fig. 9 show the packet delivery ratios (PDRs) for user-1 and user-2, respectively. Our simulations clearly demonstrate that the proposed dynamic codebook design offers significant improvements in PDR compared to the conventional MU-MOCZ scheme. Setting the scaling

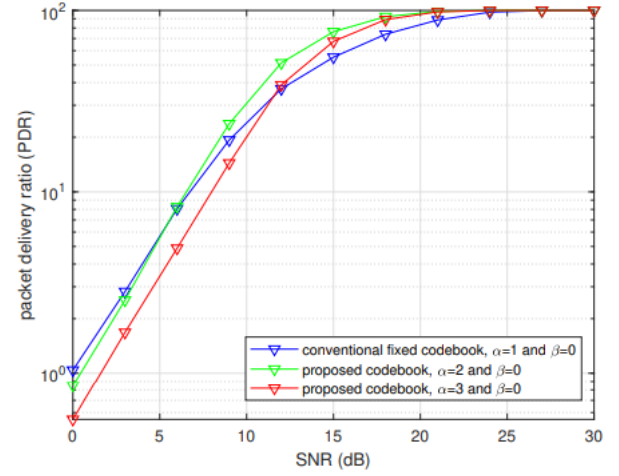


Fig. 8. PDR performance for the first user under different configurations of the scaling parameter α and the rotation parameter β .

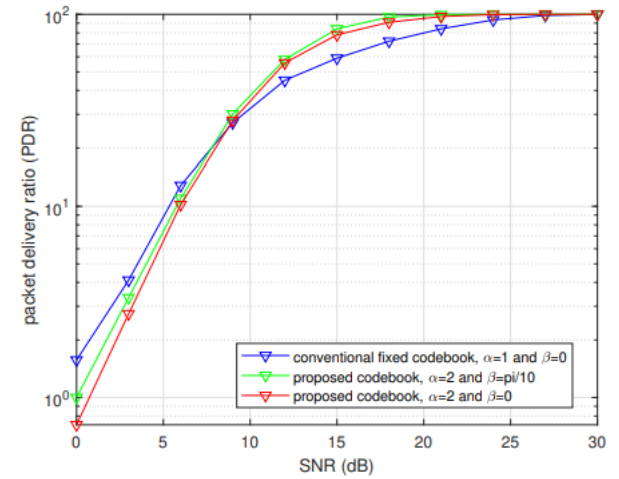


Fig. 9. PDR performance for the second user under different configurations of the scaling parameter α and the rotation parameter β .

parameter $\alpha = 2$ and the rotation parameter $\beta = 0$ for user-1 results in an improvement in PDR, while for user-2, setting $\alpha = 2$ and $\beta = \pi/10$ enhances the performance.

These configurations highlight the flexibility and effectiveness of the dynamic codebook design in adapting to varying channel conditions for different users.

The simulation results confirm that the proposed dynamic codebook design for non-coherent short-packet communication systems improves overall system performance, including BER, throughput, and PDR. Modifying the radius and angular positioning of the conjugate-reciprocal zeros based on channel characteristics, the system effectively reduces the impact of channel zeros, leading to more reliable communication.

V. CONCLUSION

The present work is an extension of our paper presented at the ISAS 2024 Conference [20]. In this extended version, we introduce an additional parameter to control the positioning of zero pairs on the z -domain. This new parameter provides a more flexible and precise method for placing modulation zeros, significantly improving the system's performance under various channel conditions. This development helps mitigate the impact of channel distortions, ensuring more robust communication in changing environments. In the conventional scheme, MU-MOCZ uses a fixed codebook for all users. This means that the modulation zeros are predefined and do not adapt to the specific channel conditions or characteristics of individual users. As a result, the system may not fully optimize for the varying channel conditions experienced by different users, leading to potential performance inefficiencies.

The dynamic codebook design proposed in this paper is developed for the MU-MOCZ scheme, where multiplexing of users occurs in the time domain. Since each codebook is assigned to one user within a specific time frame, the zeros in the z -plane are assigned to that user, allowing flexibility to adjust the radius R and rotate the circles at R and $1/R$, which affects the placement of all zeros simultaneously. In contrast, the ZDM-MOCZ scheme allocates zeros across multiple users for z -domain multiplexing, which is not addressed in this paper. In future work, we plan to extend the dynamic codebook design to support ZDUM-MOCZ users.

The proposed dynamic codebook design reduces the impact of channel effects, leading to significant improvements in BER, throughput, and PDR performance. In future work, we plan to develop efficient techniques for reporting channel zero distributions to the transmitter.

Acknowledgment

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Authors'

The authors' contributions to the paper are equal.

Contributions

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics

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Plotting of Generative AI-Images via Low-Cost Robotic Arm

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Abstract – This study proposes an AI-driven system that integrates generative artificial intelligence with robotic arm to create and physically render visual content. Utilizing state-of-the-art text-to-image models, the system first generates high-resolution images based on natural language prompts. These images are then processed and translated into vector paths suitable for robotic execution. A robotic arm, specifically the BrachioGraph platform, is employed to draw the generated content on a physical medium, effectively bridging the gap between digital generation and tangible realization. The system architecture combines deep learning-based image synthesis, path optimization algorithms, and precise robotic control. Although the study has certain optimization errors that cause vibration because it was created with Raspberry Pi and simple equipments, it is a prototype study that shows that artistic studies can be created by AI technologies. This interdisciplinary approach demonstrates a novel pipeline where AI-generated creativity is physically manifested through robotics, opening new possibilities in automated content creation, human-machine collaboration, and AI-driven artistic expression.

Keywords – BrachioGraph, Generative AI, Robotic Arm, Image Plotting, Human-Machine Interaction

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I. INTRODUCTION

In recent years, artificial intelligence (AI) technologies have advanced rapidly, transforming various fields such as healthcare, education, and entertainment. One of the most exciting developments is the ability of AI to generate realistic and creative images from simple text prompts. These AI-generated images are typically viewed on digital screens, when these images brought into the physical world as hand-drawn artworks, the images can more valuable artworks for art world.

This study basically explores the combination of AI-generated art with robotic technology to create a system that can draw these images on paper. The system takes AI-generated visuals and translates them into precise pen strokes by using a simple robotic arm based on the BrachioGraph platform. The main goal is to bridge the gap between digital creativity and physical representation, making AI art more interactive and tangible.

The system is designed to be user-friendly, with a graphical interface that allows users to input text prompts, preview the AI-generated image, and initiate the drawing process. By automating the transition from digital art to physical sketches, this project highlights the potential of AI and robotics in creative applications, offering new possibilities for artists, educators, and hobbyists alike.

II. MATERIALS AND METHOD

A. Literature Review

In today, there are a lot of literature studies based on generative AI-images and robotic separately. The aim of this study is to present a basic method that combines generative artificial intelligence studies with a low-cost robotic arm

design. In artistic activities, the use of generative artificial intelligence also brings with it some differences. Dheenadhyalan et al. explored the operational mechanisms of contemporary AI-based art generators and highlighted a range of challenges these systems face from technical, ethical, and legal perspectives. [1]. Göring and colleagues conducted a crowdsourced evaluation to assess the visual quality and appeal of images generated by AI, extending the AVT-AI-Image dataset for this purpose. [2]. Song et al. analyzed how models equipped with image-to-text functionality—such as CLIP (ViT-L and ViT-H), DeepDanbooru, GPT-4, and Gemini 1.5 Pro—can be utilized to automatically generate prompts aimed at producing high-quality single-character images, thereby facilitating the ideation process for character creation. [3]. Zambroba and collaborators investigated the use of text-to-image artificial intelligence models for generating synthetic images, with the objective of improving the precision and overall performance of image classification systems. [4]. Fu introduced an intelligent classification system that leverages big data analytics, AI technologies, and a closed-loop control framework to assist users in sorting waste efficiently. [5]. Megalingam et al. designed and evaluated a prototype of a miniature robotic controller arm, which employs Bluetooth wireless communication to manually operate a robotic arm featuring three degrees of freedom. [6]. Diaz and his team proposed integrating a Lynxmotion AL5 robotic arm, capable of five degrees of freedom, with the FESTO-developed mobile robotic platform Robotino, using a Raspberry Pi 4 as the control interface. [7]. Similar to our study, Bidgoli et al. proposed a method to integrate an artistic style to the brushstrokes and the painting process through collaboration with a human artist. They conducted their work

in three stages: 1) collecting brush strokes and hand brush movement samples from an artist, 2) training a generative model to generate brush strokes of the artist's style, and 3) fine-tuning a stroke-based rendering model to work in a robotic painting setup [8].

B. System Overview

The plotting system contains three steps as AI-image generation, vectorization and path planning and finally robotic arm plotting for AI-image plotting. Current models based on generation AI-image is usually used by API based on different AI platforms. Another solution is also local models created by training in local computer. There is no any differences in these models. The models are the same AI-model but the basic differences is in training process. While the AI-image is created by local models in many hours (according to the image complexity) with personal desktop or laptop hardware, AI-image based on API can be created in a few seconds with its efficient hardware such as GPU, CPU and disk memory. In this study, API is used for faster in AI-image generation.

The second step is to introduce the AI image created in png format to the robotic arm and make it suitable. For this process, the AI image created in png format must be vectorized to be compatible with point strokes.

The final step is to plot of the vectorized AI-image by robotic arm. The completion of this process may vary depending on the complexity of the vectorized AI image. In addition, the power supply of the created robotic arm is another important issue for the completion of the process.

C. Hardware Components

The system's hardware components are shown in Figure 1. The robotic arm is built using a 3-servo BrachioGraph design (shoulder, elbow, and pen-lift mechanisms) constructed from lightweight and affordable materials [9]. The main components include:

- A Raspberry Pi 3 Model B serving as the control unit, generating PWM signals to precisely control three Micro Servo Motors SG90
- The arm structure assembled using popsicle sticks for the linkages
- A bamboo clothes peg modified to hold a standard pilot pen as the drawing tool
- Silicon adhesive used to securely mount the servo motors to the popsicle stick frame

The mechanical design prioritizes stability and precision while maintaining simplicity. The bamboo clothes peg

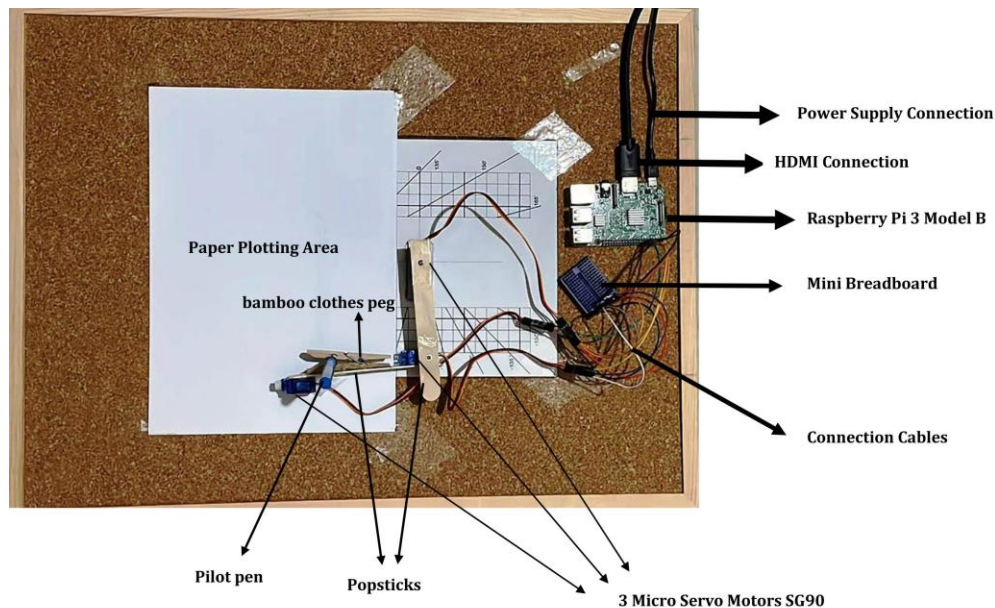


Fig. 1. Robotic Arm Plotting Components

provides a reliable mechanism for holding and releasing the Pilot pen during operation. Silicon adhesive was chosen to firmly attach the servo motors to the popsicle stick structure, ensuring minimal vibration during movement. The lightweight construction allows the SG90 servos to operate efficiently within their torque limits [10]. This combination of readily available components, all visible in Figure 1, demonstrates an effective and economical approach to robotic arm construction.

D. Software Components

The system features a Tkinter-based GUI (Graphical User Interface) that allows users to input text descriptions of

desired images through a dedicated text field. These prompts are processed via the DreamStudio API to generate AI images, which are then displayed as previews within the interface. The GUI includes functional buttons for saving images, initiating vectorization (using OpenCV and Potrace to convert raster images to SVG paths), pen lifting/lowering controls, and executing the drawing process. For robotic control, Python scripts (utilizing RPi.GPIO and pigpio libraries) translate the vectorized paths into precise PWM signals that coordinate the servo movements of the robotic arm. This integrated software architecture enables seamless transition from text input to physical drawing execution.

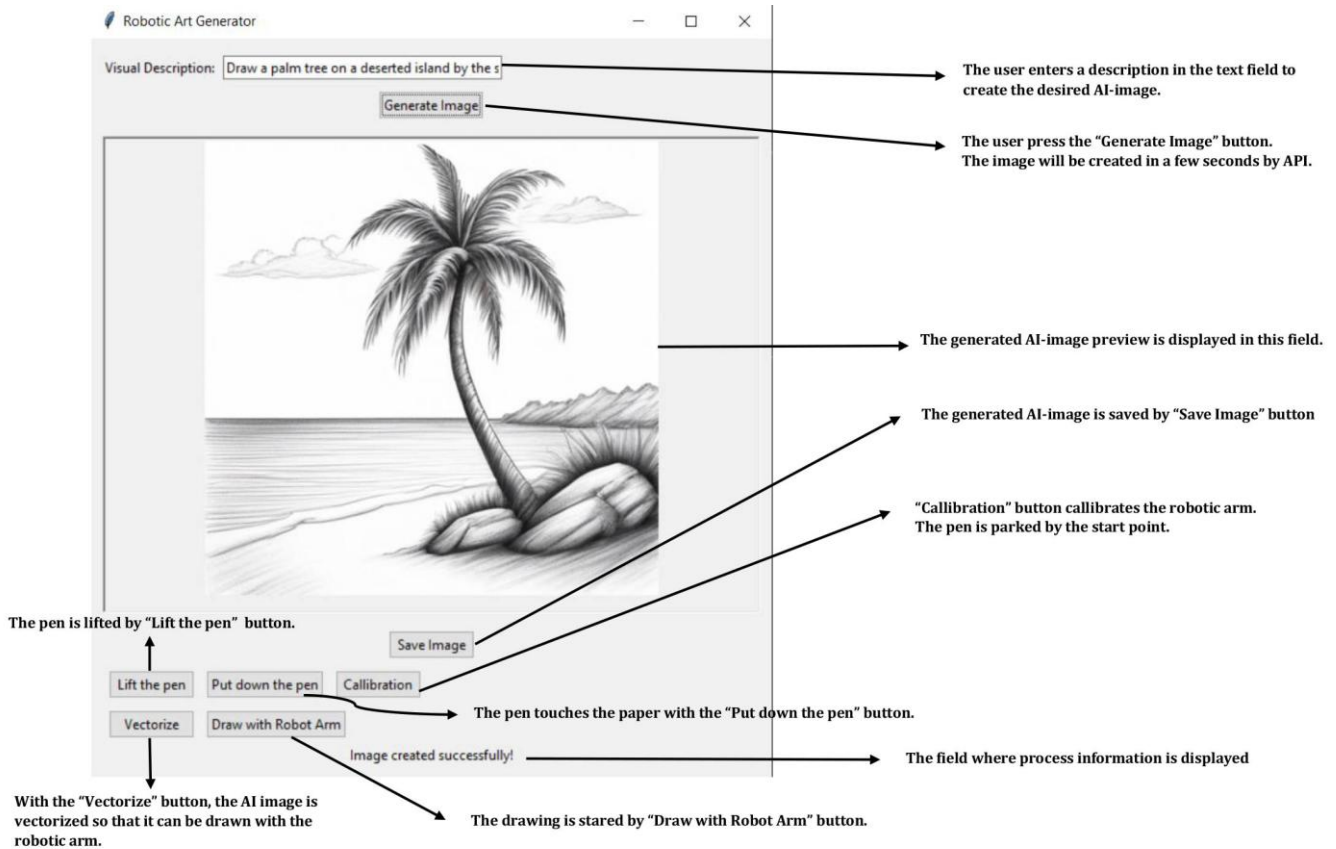


Fig. 2. Tkinter GUI structure and descriptions

The Tkinter-based GUI is shown in Figure 2. Initially, the user enter the description of AI-image to text field. Secondly, once the user clicks the "generate image" button, the AI image is generated within seconds via the DreamStudio API [11]. Since DreamStudio API is an official service offered by Stability AI, it generally uses the most up-to-date and optimized Stable Diffusion models [12]. Another method of creating an AI image is to download the Stable Diffusion model to the local computer and use it, but in this method, the generation of the AI image may take hours depending on the local hardware configuration. . Since the AI image can be created quickly, the dreamStudio API is used in this study to generate the AI image. In addition, the dreamstudio service gives its first users a certain number of free credits for AI image generation. The desired AI image can be gray scale or colorful. However, when the user clicks the "Save Image" button and saves the image, then clicks the "Vectorize" button, the generated AI image is converted to black and white vectors in any case for drawing with robotic arm. A sample generated image and vectorized image have been shown in Figure 3.

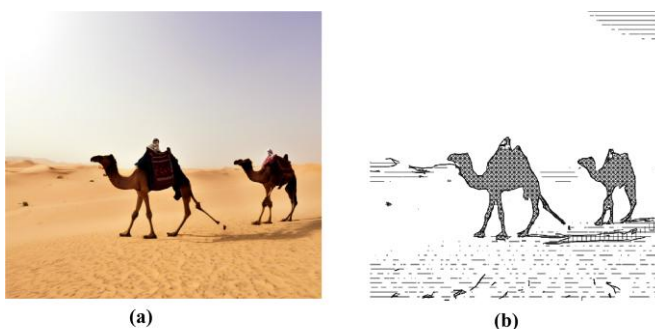
Fig. 3. (a) Generative AI image (b) Vectorized Image for drawing

In addition, the "Lift the pen" button is used to attach the pen to the robotic arm, the "Put down the pen" button is used to touch the paper, the "callibration" button is used to calibrate the robotic arm and finally the "Draw with Robot Arm" button is used to start drawing. Drawing duration may vary depending on the power given to the Raspberry Pi and the complexity of the vectorized image.

E. Advantages and Challanges

Prompt engineering represents one of the fastest and most accessible methods for generating AI-based artwork within the field of artificial intelligence. Users can effortlessly input textual descriptions of their desired images, which are then synthesized by pre-trained generative models such as Stable Diffusion, DALL·E 2/3, Imagen, or various GAN-based architectures [13-15]. One of the key advantages of this approach is its cost-effectiveness; the system can be implemented using low-cost hardware components, and the setup process is relatively straightforward due to its structured and modular design.

However, despite these benefits, several limitations are associated with the use of such low-cost robotic systems for physical image rendering. Vibrational movements produced by servo motors may lead to misalignments and inaccuracies in the drawing process. Furthermore, improper attachment of the pen—such as insecure placement in a bamboo clothes peg—or the lack of initial calibration can similarly result in drawing errors. These limitations highlight the inherent trade-offs in utilizing low-cost robotic arms for AI-generated image plotting. The calibration problems cause vertical and horizontal draw problems. This problem give rise not to draw



a clear image. Calibration must be done very well before drawing. However, a clear drawing cannot be made due to the vibration movements of servo motors. Instead, better equipment is needed.

III. EXPERIMENTAL RESULTS

A. Accuracy Analysis

The Structural Similarity Index (SSIM) is a widely used perceptual metric that measures the similarity between two images [16]. Unlike traditional metrics such as Mean Squared Error (MSE) or Peak Signal-to-Noise Ratio (PSNR), SSIM considers changes in structural information, luminance, and contrast. It better aligns with human visual perception by

evaluating image degradation based on perceived changes rather than absolute pixel differences.

Mathematically, SSIM compares local patterns of pixel intensities that have been normalized for luminance and contrast [17]. The output score ranges from -1 to 1, where a value of 1.0 indicates perfect structural similarity between the two images. This makes SSIM particularly suitable for applications where visual similarity is more important than raw pixel accuracy, such as image generation, compression, and robotic reproduction.

In this study, SSIM has been used to quantitatively assess the visual similarity between the AI-generated image and the robotically rendered drawing. The comparison has been performed using a grayscale preprocessing step, followed by

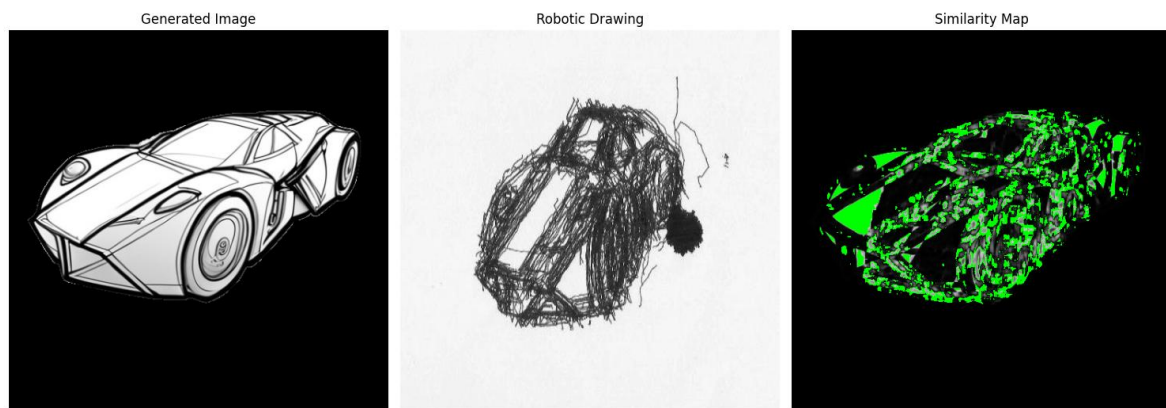


Fig. 3. The Generated Image, Robotic Drawing and Similarity Map of Sample 1



Fig. 4. The Generated Image, Robotic Drawing and Similarity Map for Sample 3

image resizing to ensure consistent dimensions. The structural_similarity function from the skimage.metrics library has been employed to compute both the SSIM score and the corresponding difference image [17-18].

A difference image map has been generated, where each pixel's value represents the local similarity score to enhance the interpretability of the comparison. In addition, matching regions—where the structural similarity has been above a defined threshold—were highlighted in green. This visual overlay enabled a more intuitive understanding of which regions of the robotic drawing closely matched the original generated image.

B. Findings

The SSIM-based evaluation provides both a quantitative metric (e.g., a similarity score of 0.85 or 85%) and a qualitative visualization of the differences and similarities [19]. This dual analysis has helped confirm that the robotic arm reproduced key structural elements of the original AI-generated image with an average degree of fidelity. Regions with high correspondence have been shown prominently in green on the SSIM difference map, demonstrating that the robotic drawing has preserved critical visual features.

In combination with other evaluation metrics such as MSE, PSNR, and histogram correlation, the SSIM analysis contributed a comprehensive assessment of drawing accuracy from both pixel-based and perceptual standpoints [20].

In this section, a detailed analysis table based on a few samples drawn by the robotic arm has been shown in Table 1.

Table 1. Similarity Reports for samples

Sample	Structural Similarity Index (SSIM)	Mean Squared Error (Normalized)	Peak Signal-to-Noise Ratio (PSNR)	Histogram Correlation Similarity
Sample 1	0.0204 (2.04%)	0.69 %	1.61 dB	-0.0103
Sample 2	0.5026	0.1173 %	9.31 dB	0.0166
Sample 3	0.4693	0.1456%	8.37 dB	-0.0071

According to the experimental results, the reason for the higher MAE value depends on the background colour and scanning problem of the white paper in sample 1. While sample 1 has a higher error value due to the white background problem, this error is minimized in sample 2 and sample 3 because it has a white background. On the other hand, the calibration problems of the servo motors are the biggest challenges for the platform. In this study, simple types of equipment are used for creating a robotic arm such as bamboo clothes pegs, connecting cables, and popsticks. If the step motors had been used for rotations, the drawings should have become more accurate.

IV. RESULTS

The implemented system successfully demonstrated the ability to transform text-based prompts into visual artwork using a robotic arm. High-resolution images generated by state-of-the-art text-to-image models were effectively converted into vector paths and translated into robotic motion through the BrachioGraph platform. The robotic arm was able

to draw simplified representations of the generated images on physical media, validating the system's capacity to bridge digital generation and tangible output.

Despite hardware limitations—including minor vibrations and calibration drift due to the use of a Raspberry Pi 3 Model B and basic servo motors—the prototype consistently produced recognizable drawings [21]. Visual comparisons between the original AI-generated images and the robotic renderings were evaluated using image similarity metrics such as SSIM, MSE, PSNR, and histogram correlation. Results indicated moderate structural accuracy and acceptable perceptual quality, supporting the feasibility of the method for physical rendering.

Furthermore, the system demonstrated that the complexity of the prompt directly affected the drawing quality: simpler compositions with well-separated features resulted in clearer and more accurate robotic outputs. This finding underscores the importance of prompt engineering and image preprocessing in such hybrid AI-robotic systems.

Overall, this prototype proved the idea that AI can help make real artworks and serves as a starting point for future projects. In future studies, more complex robotic arm design can be created and the calibration problems can be minimized for drawing tasks.

V. DISCUSSION

This study shows that generative AI can be effectively combined with low-cost robotic systems to create physical artworks from text prompts. While the results are promising, the use of basic hardware like a Raspberry Pi and simple servo motors introduced issues such as minor vibrations and calibration errors, leading to overlapping or inaccurate lines. Despite these limitations, the system successfully demonstrated the concept of AI-driven physical art creation and highlighted its accessibility for educational and experimental purposes. Future improvements in hardware precision, path optimization, and feedback mechanisms could enhance output quality and broaden the system's creative potential.

VI. CONCLUSION

This prototype study has shown that generative AI and low-cost robotic systems can be successfully integrated to create physical artworks based on natural language prompts. Despite hardware limitations affecting precision, the system effectively demonstrates the potential for AI-driven artistic expression in tangible form. The project lays a foundational step toward more advanced, creative human-machine collaborations and highlights new possibilities for automated art creation in both educational and experimental contexts.

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Authors'

Contributions

The authors' contributions to the paper are equal.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics

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Reconstruction of a Signal Sampled Slower than the Usual Nyquist Rate Using Complex Sampling

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Abstract – In this paper, a modified sampling rate, which is smaller than the usual Nyquist rate, is determined for bandlimited signals using a method like single side band (SSB-like). SSB-like method is characterized using the base signal of single side band Amplitude Modulation (SSB-AM) instead of the actual AM signal. The sampling should be performed on the base SSB signal, which is a complex valued signal. That is, SSB-like sampling is performed on a complex valued signal with a corresponding Nyquist frequency which is half of the actual required sampling frequency. Also, a theoretical sampling method is proposed as a theorem that results in sampled values based on the mathematical properties of transformations. The proposed complex sampling method is novel in the context of sampling and valid for any band-limited real valued signal.

Keywords – complex sampling, amplitude modulation (AM), SSB-AM, Nyquist rate, signal reconstruction

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I. INTRODUCTION

This paper presents a new method for data reconstruction of a signal from its samples which are taken slower than the Nyquist rate.

The reconstruction of a signal from the samples can be achieved if the samples of the signal are taken at a sampling frequency f_s which is larger than the bandwidth of the sampled signal. This rate is known as Shannon's sampling theorem in the communication community since it was introduced and applied to communication area by Shannon in 1949 [1].

The faster than Nyquist (FTN) is an approach, which samples a low-frequency signal $f_l(t)$ instead of a high frequency band limited signal $f_h(t)$, which has the spectrum of $f_l(t)$ at high frequency. Then $f_h(t)$ can be obtained from the samples of $f_l(t)$ via a frequency shift [5]. In FTN the signal is sampled at a lower sampling frequency than the one required by $f_h(t)$ based on the similarity of the spectrums of $f_l(t)$ and $f_h(t)$. For FTN, the high frequency signal should resemble the low frequency signal in terms of the spectrum. However, the proposed approach here can be applied to all band-limited signals.

Here, the proposed method has the potential to increase the sampling period $T = \frac{1}{f_s}$ up to twice the value proposed by the Nyquist theory, where f_s is the sampling frequency. In this paper, the following issues are presented: i) the reconstruction of the under sampled signal; ii) the conjecture that the samples of a signal can be obtained by adding enough AM signals at the center frequencies, $kw_s = 2\pi kf_s$, which are the integral multiples of the sampling frequency.

II. SAMPLING THEORY AND AM

A. Sampling theory

Let a band limited signal, $g(t)$, be given (Figure 1). The signal $g(t)$ has a bandwidth, $BW = 2f_{max}$, where f_{max} is the maximum frequency component of $g(t)$.

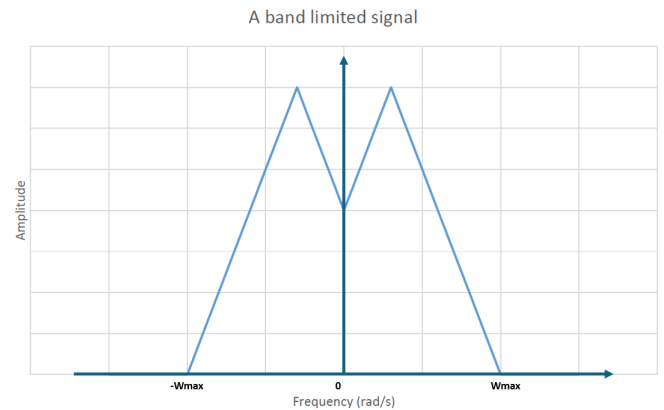


Fig. 1. Spectrum of a band limited signal

The signal $g(t)$ is desired to be stored in a digital system through the samples taken at every T second, such that the original signal, $g(t)$, can be reconstructed from the samples without a loss of information.

The sampling process is formulated by the use of the impulse train called Dirac comb [4] (Figure 2a) of period T ,

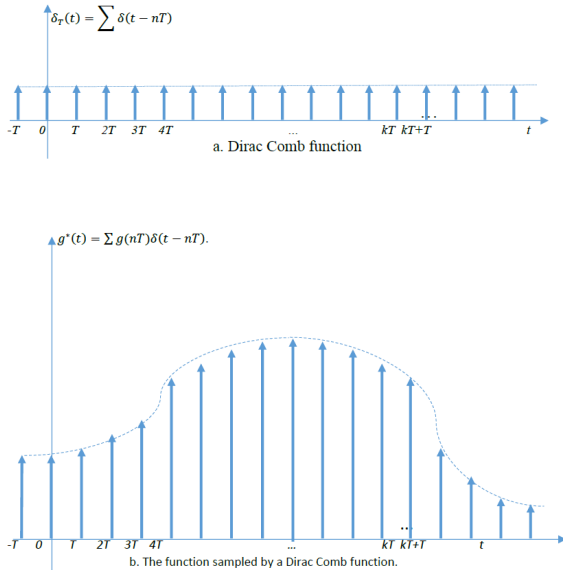


Fig. 2 (a) The Dirac (impulse train) comb function; (b) the samples $g^*(t)$ of a function with sampling frequency $w_s = 1/T$

$$\delta_T(t) = \sum_{n=-\infty}^{\infty} \delta(t - nT). \quad (1)$$

Note that, the limits of summation will be the set of integers from $-\infty$ to $+\infty$ unless otherwise stated.

The sampled signal can be represented as follows [2]

$$g_T(t) = g(t)\delta_T(t) = \sum g(t)\delta(t - nT). \quad (2)$$

Using the properties of impulse functions we have

$$g^*(t) = g_T(t) = \sum g(nT)\delta(t - nT). \quad (3)$$

That is, we get a weighted impulse train by the weights equal to $g(nT)$ (Figure 2b).

For a causal system, the Laplace transformation of the Dirac Comb given in (1) is

$$\mathcal{L}(\delta_T(t)) = \int_0^{\infty} \delta_T(t) e^{-st} dt = \sum_0^{\infty} e^{-nTs}. \quad (4)$$

Note that Laplace transform may be defined as two-sided and one-sided versions. For causal systems, both definitions are equivalent [6].

Similarly, the Laplace transform of $G^*(s)$ is

$$G^*(s) = \sum_0^{\infty} g(nT) e^{-nTs} = \sum_0^{\infty} g(nT) (e^{sT})^{-n}. \quad (5)$$

In Figure 3, spectrum of $|G^*(jw)|$ is seen as a sampling frequency higher than Nyquist frequency, while a spectrum with aliasing is given in Figure 4. $G^*(s)$, the impulse sampled function, has some useful properties, listed below:

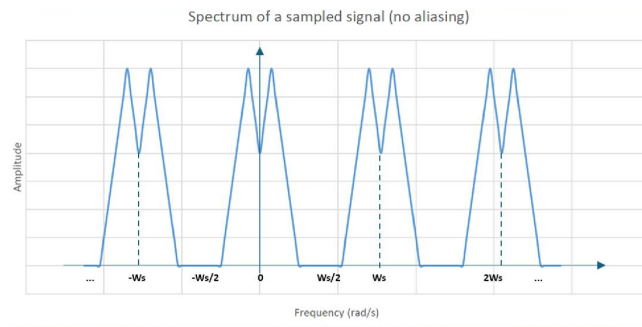


Fig. 3. Spectrum $|G^*(jw)|$ of a sampled signal (no aliasing), that is, $w_s > 2w_{max}$

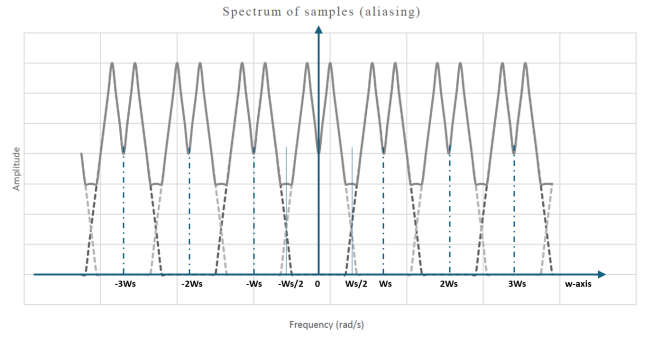


Fig. 4. The spectrum of an under-sampled signal ($|G^*(jw)|$ with $w_s < 2w_{max}$ (aliasing) Note: Only $\pm w_s/2$ is shown!

- i. $G^*(s)$ is periodic in s with the period $j\frac{2\pi}{T} = jw_s$, that is (Figure 3)
$$G^*(s) = G^*\left(s + j\frac{2\pi}{T}k\right); \forall k \in \mathbb{Z}. \quad (6)$$
- ii. If $G(s)$ has a pole at $s=s_1$, then $G^*(s)$ has poles at $s = s_1 + jkw_s; \forall k \in \mathbb{Z}$.

Note that this is not true for the zeros of $G(s)$ in general.
- iii. $G^*(s)$ can be expressed as follows:
$$G^*(s) = \frac{1}{T} \sum_{k=-\infty}^{\infty} G(s + jkw_s). \quad (7)$$
- iv. In terms of Fourier Transformation, the frequency response $G^*(jw)$ is the repeated version of $\frac{G(jw)}{T}$ shifted by the integral multiples of sampling frequency, w_s along the jw - axis. If the sampling frequency satisfies the Nyquist rate, then the signal can be recovered from the samples.
- v. Since the respective conditions $w_s > 2w_{max}$ and $w_c > w_{max}$ (see Figure 5) for sampling and AM are similar, one can conclude that $G^*(jw)$ includes the AM modulated versions of $g(t)$ infinitely many times with carrier frequencies of kjw_s , for all integer k . Note that, the AM condition should be same to satisfy the sampling conditions to extract AM signal from the spectrum of a sampled signal using a proper bandpass filter (Figure 3).

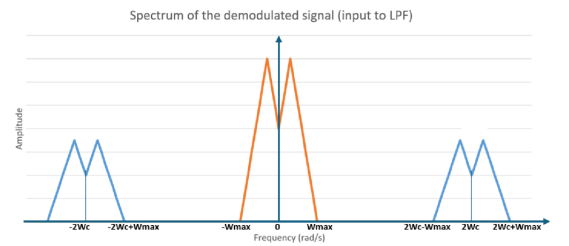


Fig. 5. The spectrum of a demodulated AM signal before LPF. Aliasing occurs when $w_c < w_{max}$.

- vi. Therefore, the AM modulation of $g(t)$ with carrier frequency, kw_s for a given k , can be extracted from $G^*(s)$ using an appropriate bandpass filter with $BW=w_s$ centered at kw_s .

The recovery of the signal is not possible due to the aliasing phenomenon if the sampling frequency is less than twice the maximum frequency of the signal according to the Nyquist theorem [3].

B. Amplitude Modulation

The basic AM signal, $m_a(t)$, can be expressed as the multiplication of the carrier signal with the message signal as follows:

$$m_a(t) = m(t)\cos(w_c t) \quad (8)$$

where $m(t)$ is the band-limited message signal with a maximum frequency of w_{max} , $\cos(w_c t)$ is the carrier function with the carrier frequency, $w_c > 2w_{max}$.

Since the AM is based on frequency contents, the AM is analyzed using Fourier Transform. The Fourier Transform of $m_a(t)$ is given by (Figure 6)

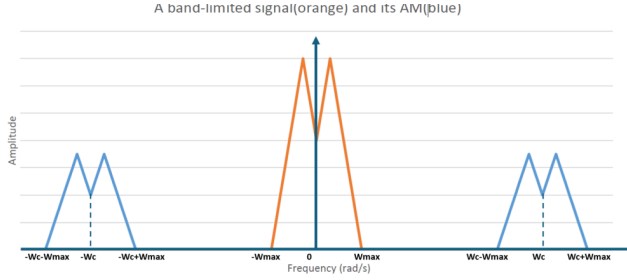


Fig. 6. A band limited signal (center) and its AM signal at w_c (left and right)

$$M_a(jw) = \mathcal{F}\{\cos(w_c t)m(t)\} = \frac{1}{2}\mathcal{F}\{[e^{-jw_c t} + e^{jw_c t}]m(t)\}$$

$$M_a(jw) = \frac{1}{2}(M(jw + jw_c) + M(jw - jw_c)). \quad (9)$$

III. RECONSTRUCTION WITH AM

In this section, a novel method, which is a generalization of the G^{**} method given in [7-8], is offered to recover an under-sampled signal. Note that, AM can be formulated as a pole placement problem [9].

Let a sampling frequency, w_s , be chosen such that

$$Nw_s < w_{max} < (N+1)w_s$$

for some integer N . This means that the resulting sampled signal spectrum exhibits “aliasing” on the base spectrum of $G(s)$ by the first N terms in positive and negative directions. Figure 4 shows this for $N=1$. General case is not shown in a figure, since it becomes too messy even for $N=2$.

Let us assume that the $G(s \pm jkw_s)$ for $0 < k < (N+1)$ are available. Let $G_N^{**}(s)$ be defined as

$$G_N^{**}(s) = G^*(s) + \frac{1}{T}[G(s) - \sum_{k=-N}^N G(s + jkw_s)]. \quad (10)$$

Then it is obvious that G_N^{**} has the terms $G(s)$ and all other $G(s + jkw_s)$ except for $k \in \{-N, \dots, -1, 1, \dots, N\}$.

These shifted $G(s + jkw_s)$ terms are all aliased with each other including $G(s)$.

Now, let $N=1$. Let us assume that the frequency response of $g(t)$ is symmetric and $G^*(s)$ is the Laplace transform of the impulse sampled version with $w_{max} < w_s < 2w_{max}$. Due to non-Nyquist choice of sampling frequency, $G^*(jw)$ exhibits aliasing and $g(t)$ cannot be reconstructed from the samples at hand (see Figure 4).

Note that, $G^{**}(s) = G_1^{**}(s)$ is used for simplicity.

Let us assume that $G(s \pm jkw_s)$ and $G(s - jkw_s)$ are available. Let $G^{**}(s)$ be defined as

$$G^{**}(s) = G^*(s) - \frac{G(s + jw_s) + G(s - jw_s)}{T}. \quad (11)$$

Then $G^{**}(jw)$ has a non-aliased version of $G(jw)$ around $w=0$ because the parts, which cause aliasing, are removed (Figure 7). Then using an appropriate low pass filter, the original signal can be recovered from the samples even though $g(t)$ was sampled with a non-Nyquist sampling frequency.

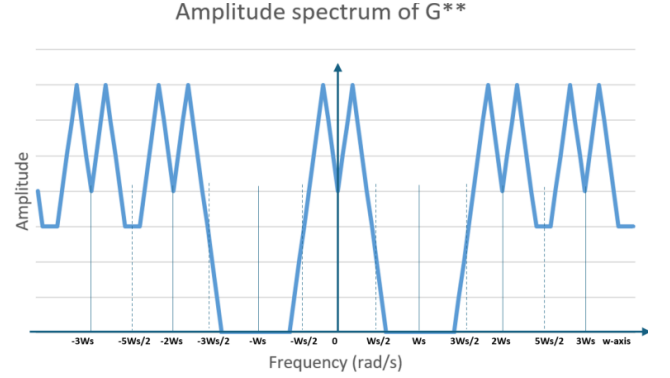


Fig. 7. The spectrum of $|G^{**}(jw)|$. Aliasing is removed

Note that, considering the Fourier transforms, we can write

$$G(s + jw_s) + G(s - jw_s) = 2G_a(s). \quad (12)$$

where $g_a(t)$ is the AM modulated $g(t)$. This means that, a weighted version of AM signal of $g(t)$ should be removed from $G^*(s)$. On the other hand, shifting $G(s)$ properly provides the same result.

Now, according to the above approach, it seems that we can remove all parts that result in aliasing for smaller sampling frequencies. Thus, we can recover the signal from very few samples. The following remarks should be noted:

- i. It is possible to think as follows: If we have an AM modulated version of $g(t)$ at hand, we do not need to have samples of the signal for recovery. The AM wave can be used to recover it. Indeed, this is true if the AM carrier frequency is larger than the Nyquist rate. If the carrier has a frequency less than the Nyquist frequency, the signal cannot be obtained from AM without distortion. Therefore, for an under-sampled signal, the above procedure can be employed for reconstruction.
- ii. On the other hand, if we think that enough AM versions are at hand, then the signal can be recovered even from a single sample. This clearly makes no sense. At least there should be a limit for recovery. The best-known limit is the Nyquist rate, which requires the sampling frequency to be twice the maximum frequency of $G(jw)$. Note that the AM condition and the Nyquist rate are same for a full recovery.
- iii. However, the above approach suggests that there should be a method to recover the signal from its samples, which are taken slower than the Nyquist rate. The method should make it possible to remove the aliasing, thus, allowing the recovery without a need to have an AM version at hand.

The approach here suggests that the reconstruction of a signal from its samples may be achieved for a non-Nyquist sampling period. The study continues to devise such a method. The approach presented is the preliminary results for recovery of an under-sampled signal. The G^{**} method can be seen as a possibility that recovery can be achieved with a sampling frequency less than the Nyquist rate.

IV. OBTAINING SAMPLES USING AM

In this section, it is conjectured that the sampling of a signal can be achieved by addition of sufficiently many AM signals based on the above approach.

Let us define the k^{th} AM-harmonic function, $q_k(t)$, for $m(t)$ with $M(jw)=0$ for all $w > w_{\max}$ as follows:

$$q_k(t) = m(t) \cos(kw_s t) \quad (13)$$

where k is an integer, $w_s = 2\pi f_s = 2\pi/T > 2\pi f_{\max} = 2w_{\max}$ is the sampling frequency determined by the sampling period T .

From (9), the Fourier Transform of $q_k(t)$ is

$$Q_k(jw) = \frac{1}{2} (M(jw + jkw_s) + M(jw - jkw_s)) \quad (14)$$

Indeed, $q_k(t)$ is the amplitude modulation of $m(t)$ performed at the carrier frequency of $w_{ck} = kw_s$.

From (8) and (14), (7) can be written as

$$G^*(jw) = \frac{1}{T} M(jw) + \frac{2}{T} \sum_{k=1}^{\infty} Q_k(jw) \quad (15).$$

From (15), one can predict that the samples of $m(t)$, which are taken at every T second, can be obtained.

(15) leads to the following theorem stated as [7]:

Theorem 1:

Let $m(t)$ be a band limited signal, whose spectrum is zero for all $w > w_{\max}$. Then the samples of $m(t)$, which are taken at every T second that satisfies the Nyquist condition (that is, $1/T = f_s > 2f_{\max}$), can be obtained as a summation of sufficiently many AM modulations, $Q_k(jw)$ of $m(t)$ without using a sampling device.

The proof of the above theorem can be constructed based on (15). Let us consider the inverse Fourier transformation of (15)

$$g^*(t) = \frac{1}{T} m(t) + \frac{2}{T} \sum_{k=1}^{\infty} q_k(t) \quad (16).$$

Since $g^*(t)$ is defined as the shifted impulses by kT with weights, $m(kT)$, (16) can be written as

$$g^*(kT) = m(kT) = \frac{1}{T} m(kT) + \frac{2}{T} \sum_{k=1}^{\infty} q_k(kT) \quad (17).$$

Here the problem is to determine the limit, M , of summation in (17) to obtain a satisfactory list of samples taken at every sampling instant, kT . Due to this, the word “many” should be figured based on the parameters and properties of the sampled signal. The study is continuing on this.

V. RECONSTRUCTION VIA SSB AM

As mentioned in section III, the reconstruction of a signal from its non-Nyquist samples can be achieved via its AM modulation only in continuous time. G^{**} method can remove the distortion caused by aliasing in continuous time. However, it is not possible to remove the distortion in discrete time due to the cyclic nature of the discretization around the unit circle in z -plane. This can be explained by considering the starred transformation, which is the Laplace transformation of the signals that are formed by weighted impulses, which are shifted by the sampling period, because of the sampling model using Dirac comb given in (1). The z -transformation of the starred Laplace is obtained by substituting $z = e^{sT}$. This results in a mapping of strips of the Laplace domain, which are defined as

$$S_k = \left\{ z \in \mathbb{C} \mid \left(k - \frac{1}{2}\right)w_{s2} < \text{Im}(s) < \left(k + \frac{1}{2}\right)w_{s2} \right\}, \quad (18)$$

where $w_{s2} = \frac{w_s}{2} = \frac{\pi}{T}$ is the half of the sampling frequency. It can be shown that the $\mathcal{L}^* \rightarrow \mathcal{Z}$, where $\mathcal{Z}$ denotes the z -transformation obtained from starred Laplace transformation, maps each of the strips S_k as follows,

$$\begin{cases} |z| < 1 & \text{for } \text{Re}(s) < 0 \\ |z| = 1 & \text{for } \text{Re}(s) = 0. \\ |z| > 1 & \text{for } \text{Re}(s) > 0 \end{cases} \quad (19)$$

(19) is valid for each integer k in (18). This means that the removal of aliasing by G^{**} method is not possible since the aliased portions cannot be removed in discrete time as soon as the z -transformation is completed. This can be seen in Figure 5-4 (see Figure 8 for a visualization obtained in desmos.com). The actual mapping takes $s=0$ to $z=1$ and the center of the cylinder should be at the origin, since the imaginary axis part of the whole strip is mapped on the unit-circle in z -plane. This ends up the aliasing is preserved around $z=-1$. Therefore, the G^{**} method cannot be used in discrete time.

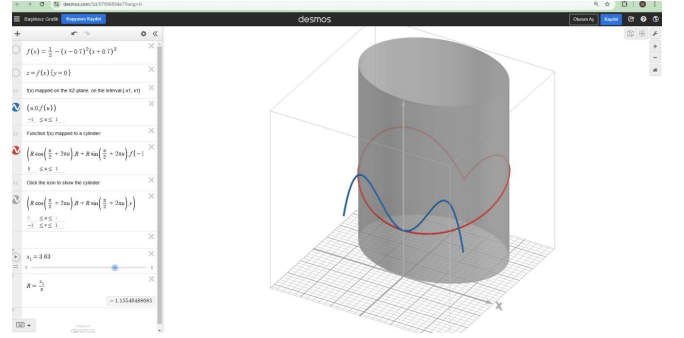


Fig. 8. The transformation of a function around a cylindrical surface (Note: Here $s=0$ mapped into $z=0$)

The basic question is whether there is a method to avoid aliasing in discrete time. The answer is yes as it is explained below.

Note that the Fourier transformation of real valued signals is conjugate-symmetric around $w=0$ [6]. That is, given $x(t)$,

$$\mathcal{F}(x(t)) = X(jw) \Rightarrow \mathcal{F}(x^*(t)) = X^*(-jw).$$

If $x(t)$ is real valued, $x(t) = x^*(t)$. Then

$$\mathcal{F}(x(t)) = \mathcal{F}(x^*(t)) \Rightarrow X(jw) = X^*(-jw).$$

$$\begin{cases} |X(jw)| = |X^*(-jw)| \\ \arg(X(jw)) = -\arg(X^*(-jw)) \end{cases} \quad (20).$$

(20) means that the Fourier transformation carries the whole information of the signal in positive (or negative) frequencies only for a real signal. This is the idea behind the SSB-AM. SSB-AM is based on the operation of eliminating the negative or positive frequency components of the signal and then recover it from these one sided information.

In the sampling process, it is possible to eliminate the negative (or positive) frequency components of the signal before sampling then sample it according to the bandwidth of the eliminated signal to avoid aliasing. Since the bandwidth of the eliminated signal is half of the original signal, the sampling frequency can be selected lower than the sampling frequency required by the Nyquist criteria. This can be justified by the fact that the spectrum of real valued signals is symmetric in amplitude and in phase with respect to the vertical axis and the origin, respectively, as shown in (20). The principle of single side band AM (SSB-AM) is based on this fact. Here, the use of basic SSB signal is proposed for a slower sampling since the bandwidth of SSB signal is $w_{\max}$ instead of $2w_{\max}$.

The classical AM uses the modulation of the whole signal. That is, the message signal is modulated for both negative and positive frequencies. In telecommunication, the reduction of energy is an important factor. Message signals generally have Fourier transforms, which are symmetric and antisymmetric in amplitude and phase of the signal, respectively, with respect to the frequency axis. That is, the amplitude of the Fourier transformation is the same for positive and negative frequencies. Therefore, sending AM wave requires at least twice the energy to send and demodulate the signal. SSB-AM method attenuates one of the side bands and sends the AM signal with a reduced power.

The SSB-AM can be formulated as follows:

The linear modulation scheme can be defined as

$$s_a(t) = s_I(t) + js_Q(t), \quad (21)$$

Where the subscripts I and Q denote the in-phase components and the quadrature components, respectively.

For a given message signal, $m(t)$, with the Hilbert transform, $\hat{m}(t)$, there are three cases:

- i. The linear modulation if $s_I(t) = m(t)$ and $s_Q(t) = 0$.
- ii. Let $s_I(t) = \frac{1}{2}m(t)$
 - a. The upper side band (USB) modulation if $s_Q(t) = \frac{1}{2}\hat{m}(t)$.
 - b. The lower side band (LSB) modulation if $s_Q(t) = -\frac{1}{2}\hat{m}(t)$.

Employing the above equations,

$$m(t) = \text{Re}\{s_a(t)\} = \text{Re}\{s(t) + j\hat{s}(t)\}. \quad (22)$$

It can be shown that the Fourier transform, $S_a(j\omega)$, of $s_a(t)$ is as follows [1]:

$$\text{i. } S_a(j\omega) = M(j\omega), \quad (23a)$$

$$\text{ii. } S_a(j\omega) = \begin{cases} 0.5M(j\omega) & \omega \geq 0 \\ 0 & \omega < 0 \end{cases}, \quad (23b)$$

$$\text{iii. } S_a(j\omega) = \begin{cases} 0 & \omega \geq 0 \\ 0.5M(j\omega) & \omega < 0 \end{cases}, \quad (23c)$$

Where $M(j\omega)$ is the Fourier transform of $m(t)$. Note that same relations are also satisfied by Laplace transforms.

The actual SSB-AM at the carrier frequency of ω_0 can be formulated as follows:

Here only the upper (right) side band of the signal is considered. The same procedure can be applied to the lower (left) side band. Let a signal $m(t)$ with a Hilbert transform of $\hat{m}(t)$ is given. Then its SSB modulated signal $s_{ssb}(t)$ is defined as

$$s_{ssb}(t) = \text{Re}\{s_a(t)e^{j\omega_0 t}\} \quad (24)$$

$$s_{ssb}(t) = \text{Re}\{[m(t) + j\hat{m}(t)] [\cos(\omega_0 t) + j \sin(\omega_0 t)]\}$$

$$s_{ssb}(t) = m(t) \cos(\omega_0 t) - \hat{m}(t) \sin(\omega_0 t), \quad (25)$$

where ω_0 is the angular frequency of the carrier.

It is obvious from (23) and (24) that $s_{ssb}(t)$ is equal to $\text{Re}\{s_a(t)\} = m(t)$ when $\omega_0 = 0$.

The signal recovery for SSB can be carried out as in the case of double side band (DSB) AM. That is, multiply the SSB signal by $\cos(\omega_0 t)$ and apply an appropriate low pass filter to remove the double frequency components at $2\omega_0$.

It is evident that the USB and LSB include only positive and negative frequency components of $M(j\omega)$, respectively. Hence, the total bandwidth of USB and LSB are half of the message signal $m(t)$. Therefore, the spectrum has no aliasing. Since USB and LSB modulation preserve sufficient information for the reconstruction of the original signal $m(t)$, then same conclusion is valid for the complex sampling of $s_a(t)$ with a sampling period, T , related to the bandwidth, $BW_a = 0.5BW = \omega_{max}$, where ω_{max} is the maximum frequency component of $M(j\omega)$. The whole modulation-demodulation process, which is used for USB and LSB modulated signals, can be repeated for the sampling of $s_a(t)$.

Algorithm for sampling at half frequency of Nyquist rate:

Algorithm 1: (Complex sampling (CS))

1. Compute the Hilbert transformation, $\hat{m}(t)$.
2. Find USB $s_a(t)$ based on (21). Note that $s_a(t)$ is a complex function, from which $m(t)$ can be extracted using (22). The amplitude spectrum for such a signal is shown in Figure 9.

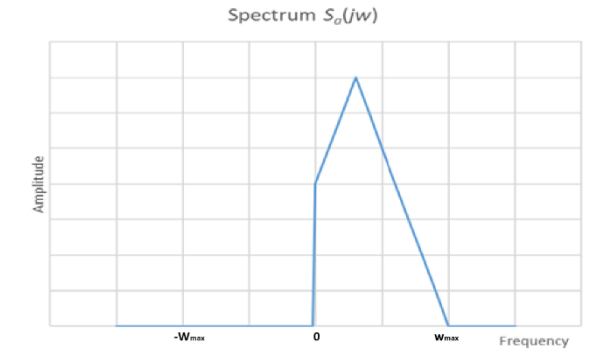


Fig. 9. Spectrum of USB-SSB base signal

3. Then sample $s_a(t)$ with the rate $\omega_s = \omega_{max}$ to get the sequence $s_a(nT)$, where T is the sampling period. Note that the number of samples for real and imaginary parts (or amplitude and phase) of $s_a(t)$ are same since it is a complex valued signal. In fact, the number of samples are the same for fast (real) and slow (complex) sampling process. In complex sampling one have more time to process the samples. The spectrum of the sequence is given in Figure 10.

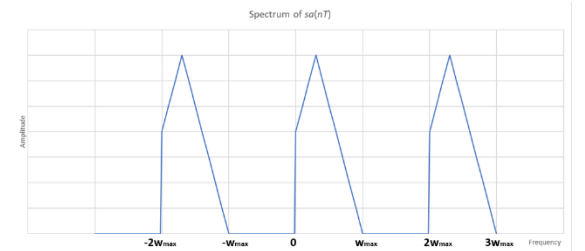


Fig. 10. Spectrum of the sampled signal

4. The recovery of $m(t)$ can be carried out as in case of SSB-AM signals [10,11,12]. Then the real part of the recovered signal will be $m(t)$. This conclusion is true

for the signals processed in the discrete time portion of the system as in the case of a control system, where the output may be different due to the processing of the signals. The detailed block diagram of complex sampling is still studied. It seems that the blocks given in [12] should be modified thoroughly for sampling. Therefore, no block diagram is given here.

Algorithm 1, can be described as follows in a simple way:

1. Given $m(t)$, find the Hilbert transform.
2. Compute $s_a(t)$ using (21), where $m(t)$ is included as in (22).
3. Sample $s_a(t)$, that is, use an analog to digital converter (ADC).
4. Process the signals according to the DSP rules.
5. Obtain the corresponding analog signal using a Digital to Analog converter (DAC).
6. Use an SSB-AM demodulator to get $m(t)$.

Remarks for Algorithm 1 (CS):

1. The number of samples in CS is same as sampling in real sampling (RS). However, the CS samples are taken for a longer period. The computational burden is expected to be less than for RS compared to the longer period for CS. The reason for the reduced burden is because any one has longer time for the same kind of process with some extra complex mathematical operations, for which powerful computing tools are available.
2. Even though CS provides a longer sampling period, it needs two slow samplers to get the data in terms of complex valued signal instead of one faster sampler.
3. Only the formulation of CS is presented here since the theoretical development of the technique is completed recently while some examples are performed to show the validity of the approach.

VI. CONCLUSION

A signal recovery method is proposed for under sampled signals using SSB-AM base signal of the signal that should be sampled. The proposed method is expected to be applied any band-limited signal contrary to the approach presented in [7-8], which has a very limited application since it is valid in continuous time where the samples are available as the weights of shifted impulses of a Dirac comb. The approach in [7] can remove the aliasing in continuous time. However, the aliasing

cannot be avoided when the samples are considered as number sequences in discrete time due to the cyclic nature of Fourier transforms for discrete time sequences (Figure 8).

The proposed SSB-AM based complex sampling method in this study is a general method for any band limited signal. This method is expected to be applied to cases where very high frequency components should be handled but it is not possible due to the limitations of the available hardware.

It was conjectured in [7] that the samples of the signal (taken according to the prescribed Nyquist rate) can be obtained using sufficiently many AM signals at integer multiples of the sampling frequency mathematically without a need to use sampling devices. Here the conjecture is repeated with a small modification.

The future study includes the application of the proposed SSB-AM approach to some signals and development and implementation of it. Similarly the study for conjecture 1 is continuing.

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Below the figures are given in a larger form!

A band limited signal

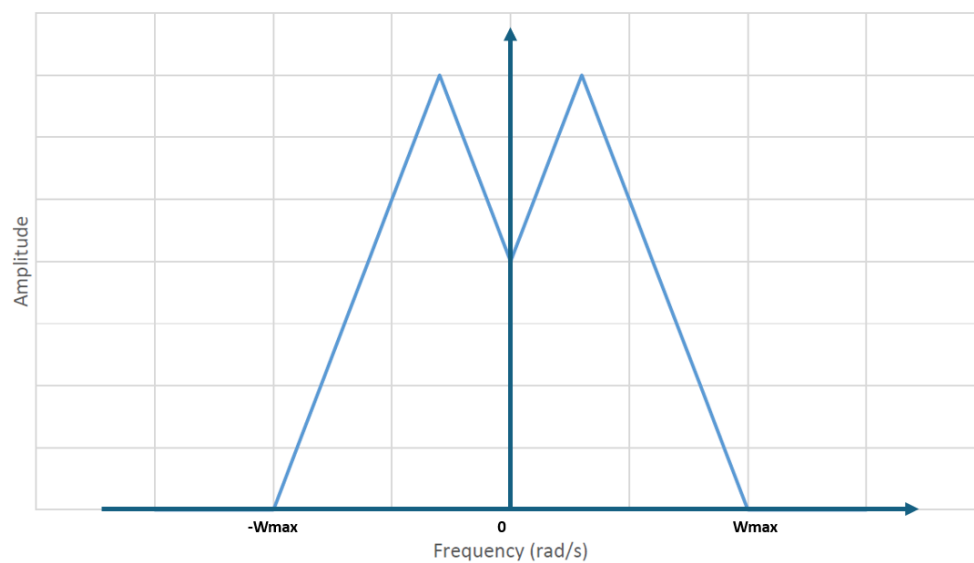


Figure 1 Spectrum of a band limited signal

Spectrum of a sampled signal (no aliasing)

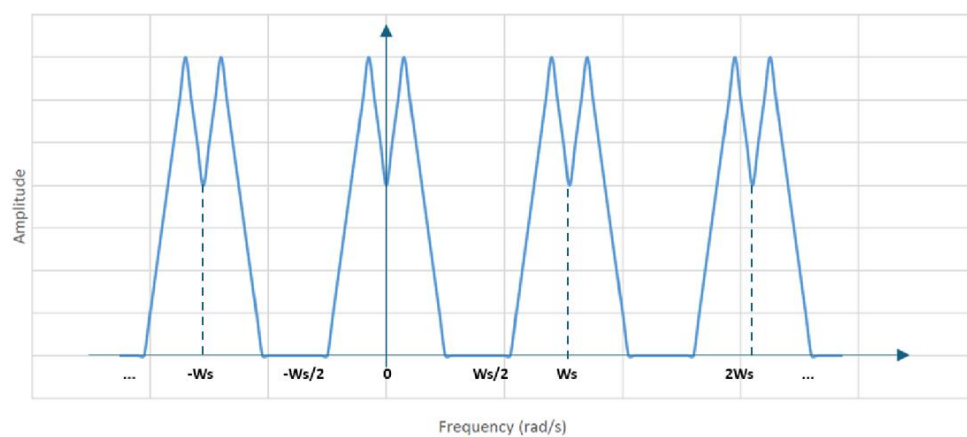


Figure 3 Spectrum $|G^*(j\omega)|$ of a sampled signal (no aliasing), that is, $w_s > 2W_{max}$

A band-limited signal(orange) and its AM(blue)

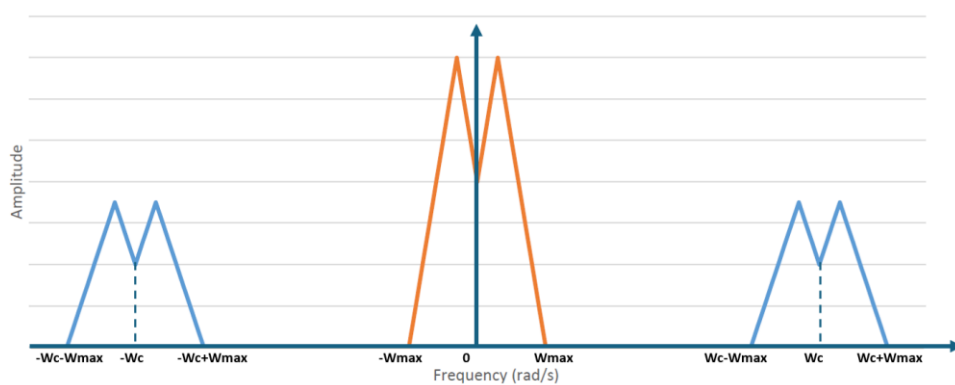


Figure 6 A band limited signal (center) and its AM signal at w_c (left and right)

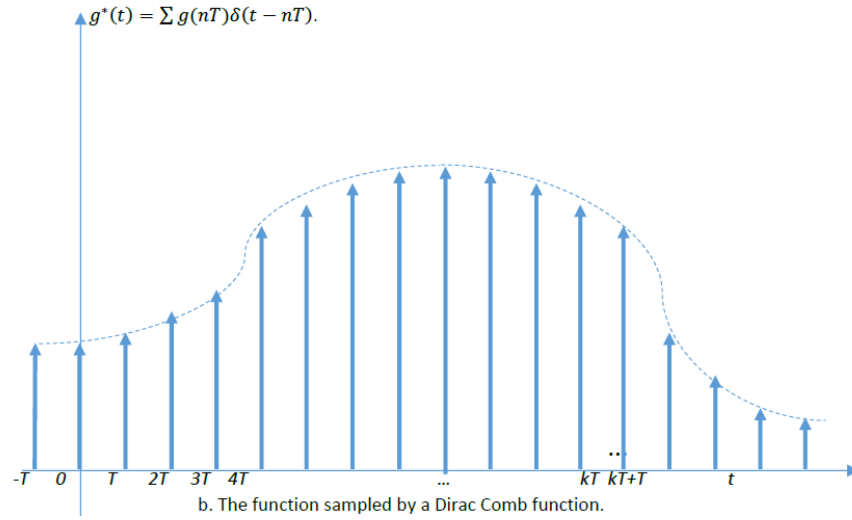
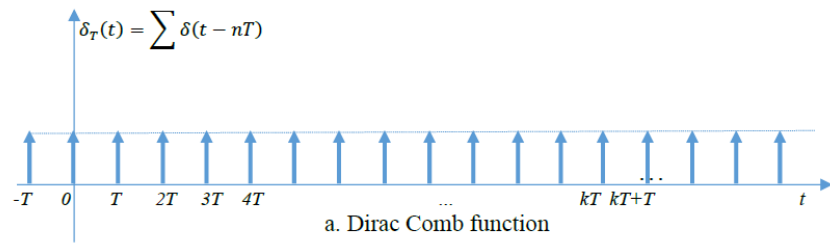


Figure 2 (a) The Dirac (impulse train) comb function; (b) the samples $g^*(t)$ of a function with sampling frequency $w_s = 1/T$

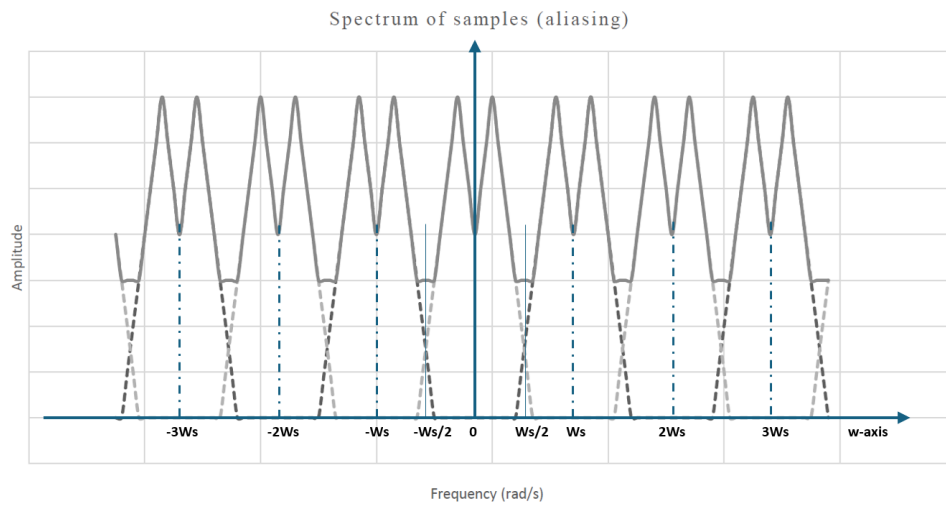


Figure 4 The spectrum of an under-sampled signal ($|G^*(jw)|$) with $w_s < 2w_{max}$ (aliasing) Note: Only $\pm w_s/2$ is shown!

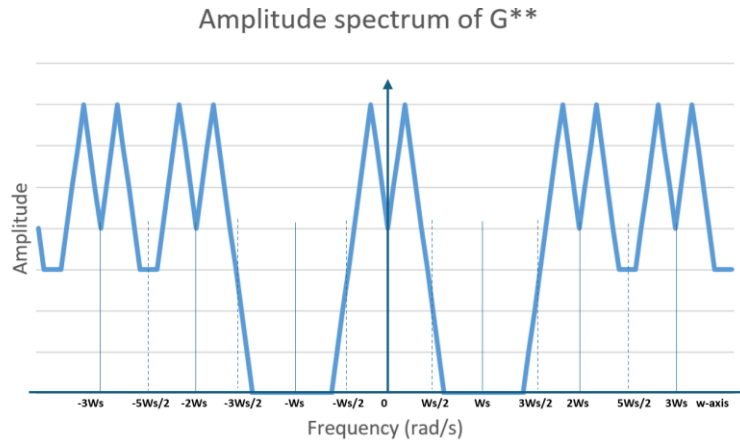


Figure 7 The spectrum of $|G^{**}(j\omega)|$. Aliasing is removed

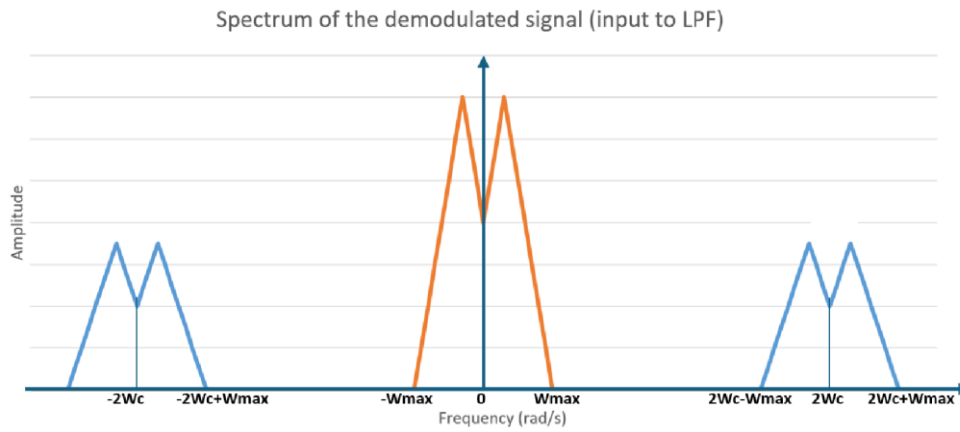


Figure 5 The spectrum of a demodulated AM signal before LPF. Aliasing occurs when $w_c < w_{max}$.

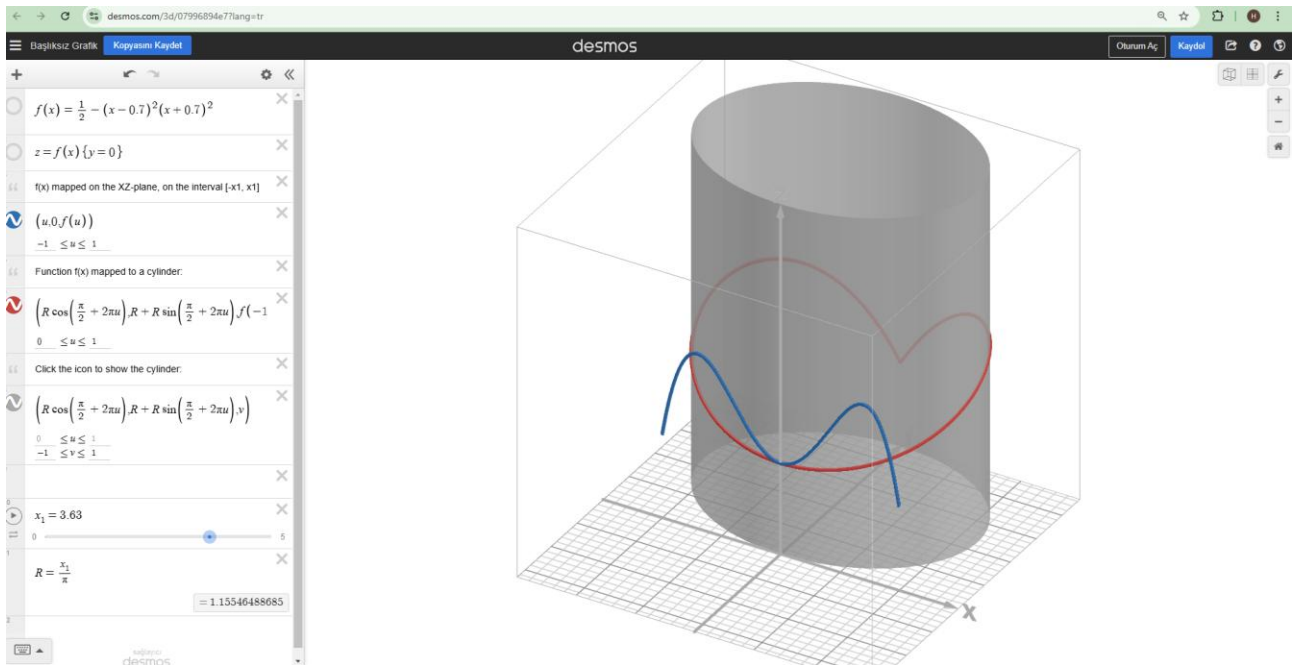


Figure 8 The transformation of a function around a cylindrical surface (Note: Here $s=0$ mapped into $z=0$)

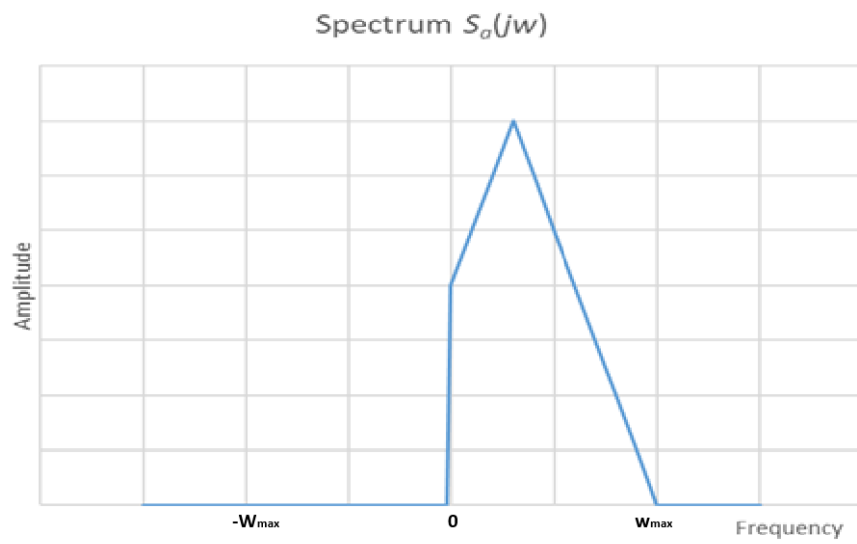


Figure 9 Spectrum of USB-SSB base signal

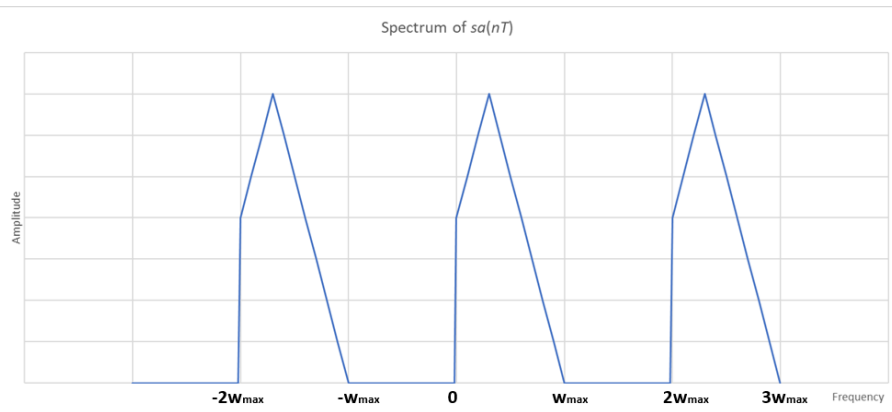


Figure 20 Spectrum of the sampled signal

Yapay Zeka ve Doğal Dil İşleme ile Türkçe Metinlerden Siber Zorbalık Tespiti

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Özet – Siber zorbalık, dijital platformların yaygınlaşmasıyla birlikte ciddi bir toplumsal tehdit haline gelmiştir. Anonimliğin sağladığı sahte güven ortamı, bireylerin gerçek dünyada sergilemekten kaçındıkları saldırgan davranışları sanal ortamlarda rahatça uygulayabilmelerine neden olmaktadır. Siber zorbalık sadece mağdurlar üzerinde psikolojik ve sosyal tahribat yaratmakla kalmayıp, zamanla mağdurların da benzer davranış biçimlerini benimsemelerine neden olarak, adeta bulaşıcı bir hastalık gibi yayılabilmektedir. Bu tür içeriklerin manuel olarak tespiti, hem zaman hem de insan kaynağı açısından son derece maliyetli ve verimsizdir. Bu nedenle, doğal dil işleme (NLP) ve yapay zeka tabanlı otomatik tespit sistemlerinin geliştirilmesi büyük önem taşımaktadır. Literatürde İngilizce gibi yaygın diller üzerine yapılan çalışmalar yoğunlukta olsa da, Türkçe gibi morfolojik açıdan zengin ve kaynak bakımından kısıtlı diller için siber zorbalık tespiti hâlâ gelişmekte olan bir araştırma alanıdır. Bu çalışmada, Türkçe metinler üzerinde geleneksel makine öğrenmesi yöntemleri (TF-IDF + SVM gibi) ile derin öğrenme tabanlı modeller (GRU, BiGRU, CNN, BiLSTM) karşılaştırmalı olarak incelenmiştir. Derin öğrenme modellerinde kelime temsili için FastText embedding yöntemi kullanılmış ve BiLSTM ile BiGRU modelleri %96 doğruluk oranına ulaşarak en yüksek performansı göstermiştir. Bulgular, yapay zeka destekli NLP çözümlerinin Türkçe dijital metinlerde siber zorbalığın etkin bir şekilde tespiti için güçlü bir araç sunduğunu ortaya koymaktadır.

Anahtar Kelimeler – Yapay Zeka, Siber Zorbalık tespiti, NLP, Türkçe, Derin Öğrenme

Atf: Gökdeniz, H. B., Canbay, P. (2025). Yapay Zeka ve Doğal Dil İşleme ile Türkçe Metinlerden Siber Zorbalık Tespiti. International Journal of Multidisciplinary Studies and Innovative Technologies, 9(1): 118-124.

Detection of Cyberbullying from Turkish Texts with Artificial Intelligence and Natural Language Processing

Research Problem/Questions – Is it possible to automatically detect cyberbullying content in Turkish online conversations using artificial intelligence and natural language processing techniques? Can classical machine learning and deep learning models provide significant accuracy and performance outcomes for this purpose?

Short Literature Review – Prior research has mostly concentrated on English data, demonstrating the efficacy of NLP and deep learning techniques to detect cyberbullying. However, there is a lack of studies on morphologically complicated and low-resource languages like Turkish. This circumstance highlights the necessity for linguistic adaptation and modeling.

Methodology – This study comparatively employed traditional machine learning and deep learning techniques for the detection of cyberbullying in Turkish texts. Traditional models (LR, SVM, KNN, RF) utilized TF-IDF for text representation, whereas deep learning models employed the FastText word embedding approach. Although deep learning models like GRU, BiGRU, CNN, and BiLSTM show high accuracy, the optimal performance was achieved by the BiLSTM and BiGRU models, with 96% accuracy.

Results – Deep learning models have achieved notable success in detecting cyberbullying, achieving accuracy rates reaching up to 96%. The findings reveal that AI and NLP -based solutions can be effective in more complicated and low-resources languages, such as Turkish, and provide considerable potential for better security in digital contexts.

Keywords – Artificial Intelligence, Cyberbullying detection, NLP, Turkish, Deep Learning

Citation: Gökdeniz, H. B., Canbay, P. (2025). Detection of Cyberbullying from Turkish Texts with Artificial Intelligence and Natural Language Processing. International Journal of Multidisciplinary Studies and Innovative Technologies, 9(1): 118-124.

I. GİRİŞ

İnternetin ve sosyal medya platformlarının hayatın her alanına entegre olmasıyla birlikte, dijital iletişim araçları hem bireyler arası etkileşimi artırmış hem de yeni türden sosyal

problemleri beraberinde getirmiştir. Bu sorunlardan biri olan siber zorbalık, bireylerin çevrim içi ortamlarda, özellikle çevrim içi oyun platformlarında bilinçli ve tekrar eden bir şekilde zarar verici davranışlar sergilemesiyle karakterize

edilen, giderek yaygınlaşan ve derinleşen bir olgudur. Siber zorbalık, mağdurlar üzerinde yalnızca kısa vadeli psikolojik etkiler değil, uzun vadede sosyal izolasyon, travma, hatta intihar gibi ciddi sonuçlara neden olabilmektedir [1]. Anonimliğin sağladığı psikolojik rahatlık, bireylerin gerçek hayatta sergilemekten çekinecekleri saldırgan eylemleri dijital ortamda gerçekleştirmelerini kolaylaştırmakta, bu da zorbalığın hızla yayılmasına ve içselleştirilmesine yol açmaktadır. Ayrıca, mağdur bireylerin zamanla siber zorba haline gelmesi gibi döngüsel etkiler, bu olgunun toplumsal boyutunu daha da karmaşık hale getirmektedir.

Siber zorbalığın dijital metinler üzerinden otomatik olarak tespit edilmesi, hem erken müdahale hem de çevrim içi ortamların daha güvenli hale getirilmesi açısından oldukça önemlidir [2]. Ancak bu tür içeriklerin manuel olarak tespit edilmesi; büyük veri hacmi, dilsel çeşitlilik ve içeriklerin bağlama bağımlılığı gibi etkenler nedeniyle sürdürülebilir değildir. Bu noktada Doğal Dil İşleme (Natural Language Processing - NLP) ve Yapay Zeka (Artificial Intelligence - AI) tabanlı otomatik sınıflandırma sistemleri devreye girmektedir. Son yıllarda, NLP alanındaki gelişmeler sayesinde metin sınıflandırma, duygu analizi, nefret söylemi tespiti gibi görevlerde yüksek doğruluk oranlarına ulaşan birçok model geliştirilmiştir [3]. Bu alanda yapılan çalışmalarda, dil bağımsız çalışmaların kısıtlı olması [4] sebebiyle ele alınan dilin yaygınlığı önemli bir parametredir. Örneğin, İngilizce veriler üzerinde yapılan çalışmalarda birçok yapay zeka destekli modeller ve NLP teknikleri kullanılarak siber zorbalık tespiti üzerine başarılı sonuçlar elde edilmiştir [5-7]. Ancak, Türkçe gibi morfolojik olarak zengin ve kaynak açısından kısıtlı diller için yapılan, dijital metinlerden siber zorbalık tespiti çalışmaları oldukça sınırlıdır [8-10]. Türkçe'nin eklemeli yapısı, kelime türetme esnekliği ve bağlamdan bağımsız yapılar içermesi, özellikle veri temsili ve model öğrenmesi açısından önemli zorluklar doğurmaktadır [11]. Bu nedenle Türkçe dijital metinlerde siber zorbalık tespiti üzerine yapılacak çalışmalar, hem akademik literatüre katkı sağlamakta hem de yerel dildeki dijital güvenlik politikalarının oluşturulmasına temel teşkil etmektedir.

Bu çalışmada, Türkçe metinlerdeki siber zorbalık içeriklerinin tespiti amacıyla hem geleneksel makine öğrenmesi yöntemleri hem de derin öğrenme tabanlı modeller karşılaştırmalı olarak değerlendirilmiştir. TF-IDF ile temsil edilen veriler üzerinde geleneksel yöntemler (örneğin SVM ve Lojistik Regresyon) test edilmiş, derin öğrenme modellerinde ise FastText embedding (kelime gömme) kullanılarak GRU, BiGRU, CNN ve BiLSTM mimarileri uygulanmıştır. Elde edilen sonuçlar, özellikle BiLSTM ve BiGRU modellerinin %96 doğruluk oranına ulaşarak Türkçe metinlerde siber zorbalık tespiti için etkili birer araç olduğunu göstermektedir.

II. MATERYAL VE METOTLAR

A. Veri Seti

Çalışmamızda, Mikayil Sadıgzade tarafından 2022 yılında derlenmiş, "Sosyal Medyada Sanal Zorbalığın Tespiti" isimli Yüksek Lisans tez çalışmasında kullanılan Türkçe veri seti kullanılmıştır [9, 12]. Veri seti "message" ve "cyberbullying" olmak üzere iki adet sütundan oluşmaktadır. Message sütunu incelenecek metni içermekte iken cyberbullying sütunu metnin

zorbalık içerip içermediğini 0 ve 1 etiketleri ile belirtmektedir (1 zorbalık içeren, 0 içermeyen metinler için).

Doğal dil yapısının sağlıklı bir şekilde işlenebilmesi bakımından veri kümesinde bulunan metinler ilk olarak veri temizleme işlemine tabi tutulmuştur. NLP çalışmalarında, metinlerin semantik analizinin hatalardan arındırılması adına; noktalama işaretlerinden, emojilerden ve alfa-numerik olmayan karakterlerden arındırılması, büyük/küçük harf dönüşümleri gibi ön işlemler çalışmamızda kullanılan metinlere de uygulanmıştır. Ayrıca yine semantik analize katkısı olmayan Türkçe durak kelimeleri (stop words), NLTK (Natural Language Toolkit) kütüphanesi kullanılarak veri setindeki metinlerden çıkarılmıştır.

Temizlenmiş metinler yapay zeka modellerine girdi olarak verilmeden önce yine NLP çalışmalarında metinlerin anlamsal bağlamının daha kuvvetlendirilmesi amacıyla yapılan lemmatizasyon işlemi veri kümesindeki metinlere uygulanmıştır. Bu işlem için Türkçe metinlere özgü geliştirilen Stanza_TR [13] NLP aracı kullanılmıştır. Kullanılan araç kütüphanesi aracılığıyla, tokenize, pos, lemma işlem hattı tanımlanmış ve aşamalar sırayla gerçekleştirilmiştir. Veri kümesinde kullanılan metinlerin kelime dağılımı Şekil 1'de kelime bulutu olarak sunulmuştur.



Şekil 1. Kullanılan veri kümesinin kelime bulutu

Şekil 1'de bulunan kelimeler, veri setinde bulunan metinlerde geçme sıklıklarına göre farklı büyüklüklerde gösterilmektedir. Kullanılan veri seti 2200 adet Türkçe metin içermektedir. Metin etiketleri dengeli olarak dağılmıştır. Yapay zeka modellerine girdi olarak verilmeden önce son işlem olarak veri seti %80 eğitim, %20 test olmak üzere, python kütüphanesinden train_test_split fonksiyonu kullanılarak rastgele ayrılmıştır. Tablo 1'de veri setinin ayrım sonucu örnek sayıları sunulmuştur.

Tablo 1. Veri Dağılımı

Sınıf	Eğitim Verisi Sayısı	Test Verisi Sayısı
0	897	204
1	863	237

Veri seti ayrımı sonucu elde edilen eğitim seti, çalışmamızdaki yapay zeka modellerinin eğitimi için kullanılmakta olup, test seti ise eğitim sonrası üretilen modelin başarısını değerlendirmek amacı ile kullanılmaktadır. Kullanılan modellerin başarısını değerlendirmek için; doğruluk (accuracy), kesinlik (precision), duyarlılık (recall) ve F-skor ölçekleri kullanılmıştır.

B. Geleneksel Makine Öğrenmesi Yöntemleri (Baseline Modeller)

Makine öğrenmesi, sistemlerin açıkça kural tabanlı çözümlerinin yanı sıra verilerden örüntüler öğrenmesini ve bu öğrenme sonucunda kararlar almasını sağlayan bir yapay zeka yaklaşımıdır. Bu çalışmada, modern derin öğrenme yaklaşımlarının performansını değerlendirmek amacıyla, geleneksel makine öğrenmesi algoritmaları karşılaştırma (baseline) modelleri olarak kullanılmıştır. Bu tür bir karşılaştırma, ileri düzey modellerin ne derece anlamlı iyileştirmeler sağladığını görmek açısından oldukça değerlidir. Bu kapsamda, ilk olarak metin verileri Term Frequency–Inverse Document Frequency (TF-IDF) ile sayısal forma dönüştürülmüş ve Destek Vektör Makineleri (Support Vector Machines - SVM), Lojistik Regresyon (Logistic Regression - LR), K-En Yakın Komşuluk (K-Nearest Neighbor - KNN) ve Rastgele Orman (Random Forest - RF) sınıflandırıcı algoritmaları ile eğitim gerçekleştirilmiştir. Bu algoritmalar, sınıflandırma problemlerinde yaygın olarak kullanılan ve farklı karar mekanizmalarına dayanan yöntemlerdir. SVM, karar sınırlarını maksimum marj (sınır) ile belirlerken; LR, doğrusal ayrılabilirliği olasılıksal temelde modellemektedir. KNN, sınıflandırmayı komşu örneklerin etiketlerine göre yaparken; RF, birden fazla karar ağacının çoğunluk oyunu ile karar vermesini sağlar. Tablo 2, her bir geleneksel yöntem için kullanılan parametre yapılandırmalarını ve bu yapılandırmaların doğruluk üzerindeki etkisini detaylı şekilde sunmaktadır. Bu klasik yöntemler, hem temel performans eşiği sağlaması hem de derin öğrenme modellerine kıyasla daha açıklanabilir olmaları açısından araştırmada önemli bir yer tutmaktadır.

Tablo 2. Geleneksel Modellerde kullanılan parametreler

Model	Model Tipi	Parametreler
LR	Doğrusal	solver='lbfgs' penalty='l2' C=1.0 max_iter=100 class_weight=None
SVM	Doğrusal Olmayan	kernel='rbf' C=1.0 gamma='scale' class_weight=None
KNN	Doğrusal Olmayan	n_neighbors=5 metric='minkowski' (p=2) weights='uniform' algorithm='auto'
RF	Topluluk (Ensemble)	n_estimators=100 criterion='gini' max_depth=None bootstrap=True class_weight=None

Tablo 2’de verilen parametreler, kullanılan modelin varsayılan değerleri olup bazı parametrelerde ele alınan probleme özgü ayarlamalar yapılmıştır. Parametre ayarlamaları aşağıda detaylandırılmıştır.

- Lojistik Regresyon (LR) – Doğrusal Model

- ❖ solver='lbfgs': Optimizasyon problemi için L-BFGS algoritması kullanılmıştır (küçük ve orta ölçekli veri kümeleri için uygundur).
- ❖ penalty='l2': Aşırı öğrenmeyi engellemek amacıyla L2 (ridge) düzenleme uygulanmıştır.
- ❖ C=1.0: Düzenleme katsayısı; daha düşük değerler daha güçlü düzenleme (ceza) anlamına gelir.
- ❖ max_iter=100: Modelin öğrenme sürecinde en fazla 100 yineleme (iterasyon) yapmasına izin verilmiştir.
- ❖ class_weight=None: Sınıflar arasında ağırlıklandırma yapılmamıştır; tüm sınıflar eşit önemdedir.

- Destek Vektör Makineleri (SVM) – Doğrusal Olmayan Model

- ❖ kernel='rbf': Karar sınırlarını doğrusal olmayan biçimde ayırmak için RBF (Radial Basis Function) çekirdek fonksiyonu kullanılmıştır.
- ❖ C=1.0: Hata toleransı ile margin genişliği arasındaki dengeyi belirleyen ceza parametresidir.
- ❖ gamma='scale': RBF çekirdeği için gama değeri otomatik olarak hesaplanmıştır ($1 / (n_features * X.var())$).
- ❖ class_weight=None: Sınıflar arası dengesizlik dikkate alınmamıştır.

- K-En Yakın Komşu (KNN) – Doğrusal Olmayan Model

- ❖ n_neighbors=5: Sınıflandırma sırasında en yakın 5 komşu örnek dikkate alınmıştır.
- ❖ metric='minkowski' (p=2): Minkowski mesafesi kullanılmıştır; p=2 değeri ile bu, Öklidyen mesafeye eşdeğerdir.
- ❖ weights='uniform': Tüm komşular eşit ağırlıkta değerlendirilmiştir.
- ❖ algorithm='auto': Uygun algoritma veri setine göre otomatik olarak seçilmiştir (ball_tree, kd_tree veya brute-force olabilir).

- Rastgele Orman (RF) – Topluluk Model

- ❖ n_estimators=100: Model 100 adet karar ağacından oluşan bir orman şeklinde yapılandırılmıştır.
- ❖ criterion='gini': Ağaçların bölünme kararlarında Gini saflık ölçütü kullanılmıştır.
- ❖ max_depth=None: Ağaçların maksimum derinliği sınırlanmamıştır; gerektiği kadar derinleşebilirler.
- ❖ bootstrap=True: Her ağaç için örnekler rastgele seçilerek (yeniden örneklemeyle) eğitilmiştir (bootstrap örnekleme).
- ❖ class_weight=None: Tüm sınıflar eşit ağırlıklı değerlendirilmiştir.

C. Derin Öğrenme Tabanlı Modeller

Derin öğrenme modelleri, özellikle bağlam ilişkilerini daha iyi kavrayabilme yetenekleri nedeniyle çalışmanın merkezini oluşturmaktadır. NLP problemlerinde, kelimeler arasındaki sıralı bağıntıları, anlamsal geçişleri ve uzun vadeli ilişkileri yakalayabilen mimariler, geleneksel makine öğrenmesi tekniklerine kıyasla çok daha başarılı sonuçlar verebilmektedir. Bu kapsamda; Gated Recurrent Unit (GRU), Bidirectional GRU (BiGRU), Convolutional Neural Network (CNN) ve Bidirectional Long Short-Term Memory (BiLSTM) mimarileri uygulanmıştır. GRU ve LSTM gibi tekrarlayan

sinir ağı (RNN) temelli modeller, dizesel verilerdeki zaman bağımlılığını modelleyebilmek için geliştirilmiştir. GRU, LSTM'nin daha sadeleştirilmiş bir versiyonu olup benzer performansı daha düşük hesaplama maliyetiyle sağlayabilmektedir. Bu modellerin çift yönlü versiyonları olan BiGRU ve BiLSTM, metin dizisini hem ileri hem geri yönde işleyerek bağlam bilgisini çift yönlü olarak yakalamayı mümkün kılar. Böylece özellikle cümlelerin sonundaki bir kelimenin, baştaki bir kelimeye etkisinin öğrenilmesi sağlanır. Diğer yandan, CNN mimarisi genellikle görüntü işleme ile ilişkilendirilse de, yerel özellikler öğrenme yeteneği sayesinde metin sınıflandırmada da etkili bir yöntemdir. Özellikle kısa metinlerdeki belirgin örüntüleri tespit etme kabiliyeti ile metinlerdeki anlam kümelerini başarıyla modelleyebilir.

Bu modellerde girdi olarak, önceden eğitilmiş Türkçe FastText embedding vektörleri kullanılmıştır. Embedding katmanı ile dilin semantik yapısı modele aktarılmış, bu sayede bağlam bilgisi korunarak daha doğru sınıflandırma yapılması hedeflenmiştir. Tablo 3, 4, 5 ve 6 sırasıyla kullanılan BiLSTM, GRU, BiGRU ve CNN modellerinin mimari yapısı ve özelliklerini içermektedir.

Tablo 3. BiLSTM modelinin özellikleri

Özellik	Değer
Embedding Dimension	100
Maksimum Sekans Uzunluğu	100
BiLSTM gizli birim sayısı	128 (Çift Yönlü)
Çıkış Katmanı	Dense 1, Sigmoid Act.
Kayıp Fonksiyonu	Binary Crossentropy
Optimizasyon Algoritması	Adam
Epoch	10
Batch size	32

Tablo 4. GRU Modelinin Özellikleri

Özellik	Değer
Embedding Dimension	100
Maksimum Sekans Uzunluğu	100
GRU gizli birim sayısı	128
Çıkış Katmanı	Dense 1, Sigmoid Act.
Kayıp Fonksiyonu	Binary Crossentropy
Optimizasyon Algoritması	Adam
Epoch	10
Batch size	32

Tablo 5. BiGRU Modelinin özellikleri

Özellik	Değer
Embedding Dimension	100
Maksimum Sekans Uzunluğu	100
BiGRU gizli birim sayısı	128 (Çift Yönlü)

Çıkış Katmanı	Dense 1, Sigmoid Act.
Kayıp Fonksiyonu	Binary Crossentropy
Optimizasyon Algoritması	Adam
Epoch	10
Batch size	32

Tablo 6. CNN Modelinin Özellikleri

Özellik	Değer
Embedding Dimension	100
Maksimum Sekans Uzunluğu	100
CNN Filtre Sayısı (Conv1d)	128
Çıkış Katmanı	Dense 1, Sigmoid Act.
Kayıp Fonksiyonu	Binary Crossentropy
Optimizasyon Algoritması	Adam
Epoch	10
Batch size	32

D. Eğitim ve Değerlendirme

Tüm modeller, eğitim ve test setlerine ayrılan veri kümesi üzerinde 5 katlı çapraz doğrulama (5-fold cross validation) yöntemiyle değerlendirilmiştir. Model performansları doğruluk, kesinlik, duyarlılık ve F-skör ölçütleri ile karşılaştırılmıştır.

III. DENEYSEL SONUÇLAR

Çalışmada kullanılan modeller belirtilen metrikler yardımı ile karşılaştırmalı olarak değerlendirilmiştir. Geleneksel makine öğrenmesi yöntemleri kullanılarak, 5 katlı çapraz doğrulama sonucunda elde edilen ortalama sonuçlar Tablo 7'de sunulmuştur.

Tablo 7. Geleneksel Makine Öğrenmesi Model Performansları

Model	Doğruluk	Kesinlik	Duyarlılık	F-skör
LR	0.789	0.79	0.79	0.79
SVM	0.780	0.79	0.80	0.78
KNN	0.780	0.78	0.78	0.78
RF	0.757	0.76	0.77	0.75

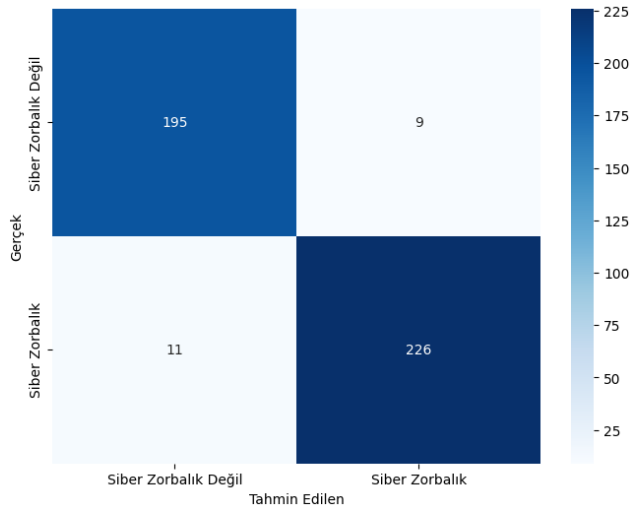
Geleneksel modeller 5 katlı çapraz doğrulama ile gerçekleştirilmiş ve tüm modeller için varyans $< 0,001$, standart sapma $< 0,1$ olarak elde edilmiştir. Modeller arasında en iyi performansı TF-IDF + LR kombinasyonu göstermiş olmasına rağmen, kullanılan diğer yöntemlerden de benzer performans oranları elde edilmiştir.

Derin öğrenme modelleri, güncel çalışmalarda geleneksel yöntemlere kıyasla daha çok kaynak kullanımının yanı sıra daha iyi sonuçlar da sunmaktadır. Çalışmamız kapsamında kullanılan derin öğrenme modellerinden elde edilen sonuçlar Tablo 8'de sunulmuştur.

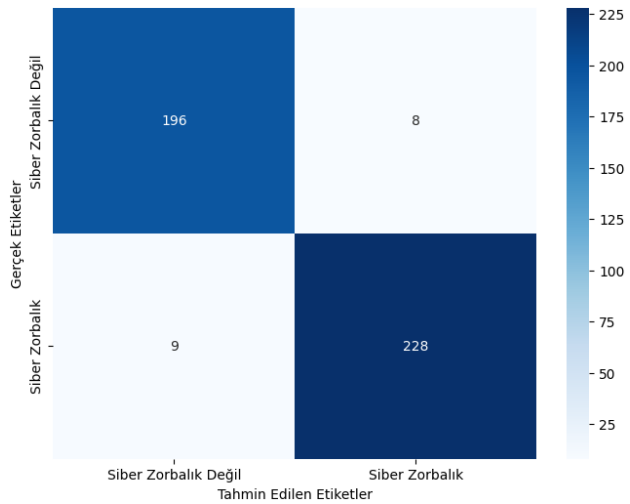
Tablo 8. Derin Öğrenme Modelleri Performansları

Model	Doğruluk	Kesinlik	Duyarlılık	F-skor
GRU	0.94	0.94	0.94	0.94
BiGRU	0.96	0.96	0.96	0.96
CNN	0.95	0.95	0.95	0.95
BiLSTM	0.96	0.96	0.97	0.96

Derin öğrenme tabanlı modeller genel olarak geleneksel modellere kıyasla belirgin şekilde daha yüksek performans sergilemiştir. Derin öğrenme modelleri arasında en yüksek performans BiLSTM modeli ile 0.96 olarak elde edilmiştir. BiLSTM ve BiGRU modelleri ile elde edilen karmaşıklık matrisleri sırası ile Şekil 2 ve Şekil 3'te sunulmuştur.

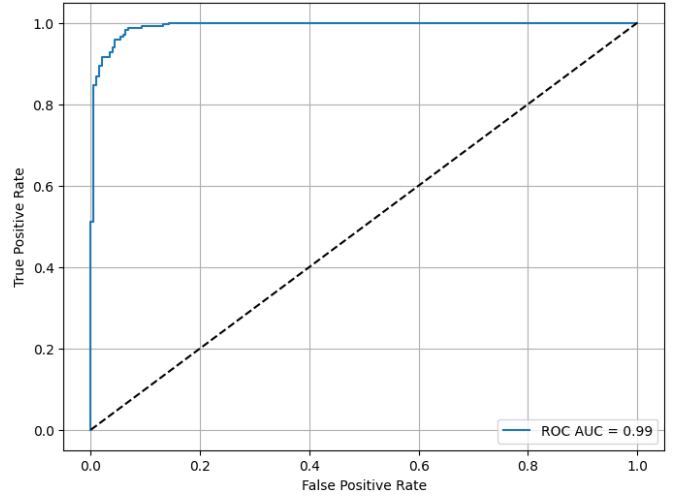


Şekil 2. BiLSTM modeli ile elde edilen karmaşıklık matrisi

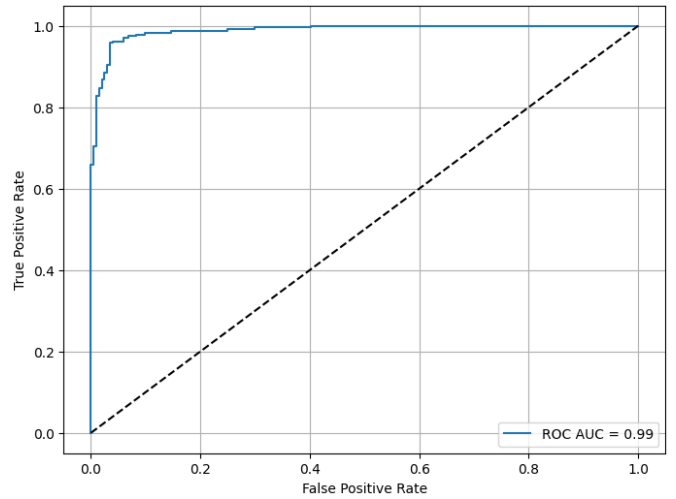


Şekil 3. BiGRU modeli ile elde edilen karmaşıklık matrisi

Birbirine yakın yüksek sonuçlar üreten BiLSTM ve BiGRU modellerinin farkının daha belirgin anlaşılabilmesi için, BiLSTM modelinin ROC-AUC (Receiver Operating Characteristic - Area Under Curve) eğrileri ve BiGRU modelinin ROC-AUC eğrileri sırayla Şekil 4 ve Şekil 5'te verilmiştir.



Şekil 4. BiLSTM modeli ile elde edilen ROC-AUC eğrisi



Şekil 5. BiGRU modeli ile elde edilen ROC-AUC eğrisi

Şekil 4 ve Şekil 5'te verilen ROC-AUC eğrilerine bakıldığında BiLSTM modelinin BiGRU modeline göre çok küçük bir farkla, metinlerde siber zorbalık tespiti üzerine daha iyi performans gösterdiği görülebilmektedir.

Modeller arası F-skor ayrıştırma analizi için modellerin Makro/Mikro skorlama değerleri karşılaştırılmıştır. BiLSTM modeli için Makro F1 değeri 0,9612 iken Mikro F1 değeri 0,9615 olarak elde edilmiştir. Aynı metrikler ile BiGRU modelinin sonuçları, Makro F1 için 0,9564, Mikro F1 için 0,9566 olmaktadır.

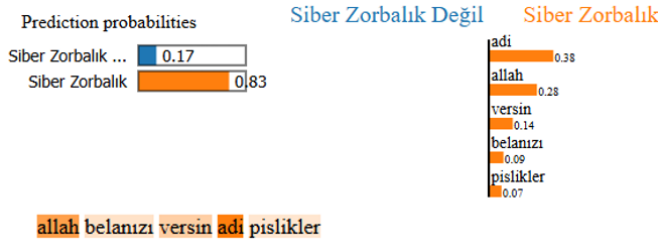
Çalışma kapsamında yapılan tüm uygulamalar ve geliştirilen tüm modeller Google Colab platformu kullanılarak gerçekleştirilmiştir. Derin öğrenme modelleri için platform işletim sistemi Linux 6.1.123+, işlemcisi x86_64 ve grafik işlemcisi T4 GPU olarak ayarlanmıştır. Bu ayarlamalar içerisinde BiGRU modelinin eğitim süresi 10,19 saniye, test süresi ile 0,67 saniye sürmektedir. Aynı ayarlamalar içerisinde BiLSTM modelinin eğitim süresi 11,75 saniye, test süresi ise 0,67 saniye sürmektedir.

Yapılan çalışmalar sonucunda geleneksel yöntemlerde kabul edilebilir başarı oranları alınırken, derin öğrenme modellerinde oldukça iyi bir performans elde edilmiştir. Çalışmanın sonunda makine öğrenmesi yolu ile zorbalığın

tespitinin mümkün olduğu, daha farklı veri kümeleri kullanılarak başarının daha da arttırılabileceği görülmüştür.

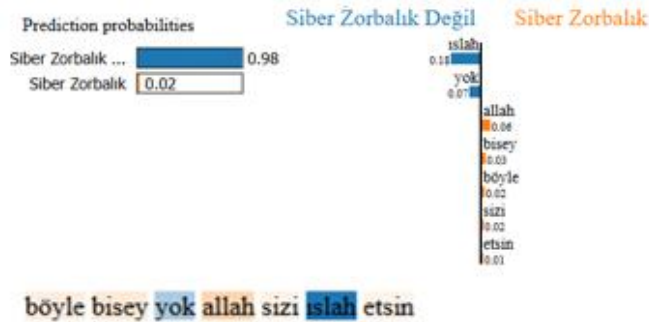
IV. MODEL AÇIKLANABİLİRLİĞİ VE YORUMLANABİLİRLİK ANALİZİ

Elde edilen sonuçlar, Türkçe gibi eklemeli ve morfolojik olarak zengin dillerde bile derin öğrenme tabanlı doğal dil işleme modellerinin oldukça başarılı sonuçlar verebileceğini göstermektedir. Özellikle bağlamı iki yönlü değerlendirebilen BiGRU ve BiLSTM gibi modeller, metin içindeki anlamsal ilişkileri daha iyi öğrenerek siber zorbalık ifadelerini daha doğru sınıflandırabilmektedir. Derin öğrenme modelleri yüksek doğruluk oranlarına ulaşılar da, karar mekanizmalarının şeffaf olmaması bu modellerin "kara kutu" olarak değerlendirilmesine yol açmaktadır. Bu durum özellikle etik, adil ve güvenilir yapay zeka uygulamaları açısından önemli bir sınırlılık oluşturmaktadır. Bu bağlamda, çalışmada en yüksek performansı gösteren BiLSTM ve BiGRU modellerine yönelik olarak Local Interpretable Model-agnostic Explanations (LIME) [14] yöntemiyle açıklanabilirlik analizi gerçekleştirilmiştir. LIME, modelden bağımsız bir şekilde çalışarak, sınıflandırma kararlarını etkileyen kelimeleri yerel düzeyde analiz eder ve bu sayede modelin belirli bir tahmini neden yaptığına dair sezgisel yorumlar sunar. Kullanılan veri kümesinde bulunan siber zorbalık içeren ve siber zorbalık olarak etiketlenmeyen örnek metinlerin açıklanabilirliği Şekil 6 ve Şekil 7’de sunulmuştur.



Şekil 6. Siber zorbalık içeren metnin açıklanabilirliği

Uygulanan analizlerde, LIME aracı yardımıyla metinlerde hangi kelime veya kelime gruplarının siber zorbalık sınıfına atanmasında belirleyici rol oynadığı görselleştirilmiş ve modelin davranışları daha anlaşılır hale getirilmiştir. Bu sayede, modellerin yalnızca yüksek doğruluk elde etmeleri değil, aynı zamanda insan yorumuna açık karar mantıklarıyla güvenilir bir biçimde kullanılabilir hale gelmeleri amaçlanmıştır. Elde edilen bulgular, LIME'in hem model doğruluğunu hem de kullanıcı güvenini destekleyecek şekilde etkili bir açıklama aracı olduğunu göstermiştir.



Şekil 7. Siber zorbalık değil etiketli metnin açıklanabilirliği

V. BULGULAR VE ÇIKARIMLAR

Bu çalışmada, Türkçe metinlerde siber zorbalık içeriklerinin otomatik olarak tespiti amacıyla geleneksel makine öğrenmesi yöntemleri ile modern derin öğrenme mimarileri karşılaştırmalı olarak incelenmiştir. Geleneksel yöntemlerde TF-IDF vektörleştirme tekniği ile Logistic Regression modeli en iyi sonucu %78.9 doğruluk oranı ile kabul edilebilir bir zemin sunarken, derin öğrenme tabanlı modeller bu performansı önemli ölçüde aşmıştır. Özellikle BiLSTM ve BiGRU mimarileri, önceden eğitilmiş Türkçe FastText kelime gömme vektörleri ile birlikte kullanıldığında %96 doğruluk oranına ulaşarak en başarılı modeller olarak öne çıkmıştır.

Elde edilen bulgular, bağlam bilgisine duyarlı mimarilerin, Türkçe gibi morfolojik olarak karmaşık dillerde anlamlı içerik sınıflandırmasında daha etkili olduğunu ortaya koymaktadır. Ayrıca, LIME aracı kullanılarak yapılan açıklanabilirlik analizleri sayesinde, bu yüksek doğruluğa sahip modellerin karar alma süreçleri görselleştirilmiş ve yorumlanabilir hale getirilmiştir. Bu durum, derin öğrenme tabanlı yaklaşımların yalnızca performans açısından değil, etik ve güvenilirlik boyutları açısından da uygulamaya uygun olduğunu göstermektedir.

Sonuç olarak, çalışmada geliştirilen yöntemlerin, Türkçe sosyal medya verilerinde siber zorbalık içeriklerinin erken ve doğru bir biçimde tespitinde etkili bir çözüm sunduğu ortaya konmuştur. Gelecek çalışmalarda, daha büyük ve çeşitli veri kümeleri ile transformer tabanlı modellerin entegrasyonu, Türkçe’de siber zorbalıkla mücadelede daha da güçlü sistemlerin geliştirilmesini mümkün kılacaktır. Özellikle dijital oyun platformlarında otomatik siber zorbalık filtreleme sistemlerinin geliştirilmesi için bu tür modellerin etkili bileşenler olarak kullanılabileceği değerlendirilmektedir.

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Development of Card Fraud Detection Model with Intelligent Agent Technology and Use of Model Results in Prevention Processes

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Abstract – Changing needs and ease of use are increasing the demand for credit card products in the individual and corporate segments. This tendency towards credit cards brings with it an increase in card fraudster cases. These undesirable situations cause cash and reputational risks, especially in banks. Detection and prevention efforts are being made to prevent fraud cases that are frequently encountered in banks. In the first stage of this paper, in addition to well-known classification (Random Forest and Support Vector Machine) detection models, agent-based models such as Double Deep Q Network have been developed. After the model development process, the outputs of the card fraud detection model were used to create the prevention process. The main purpose of this paper is to use agent technology in card fraud detection and to create a new action flow for prevention efforts. In this way, an agent-supported structure that can detect, evaluate and prevent card fraud behavior has been developed. In addition to the detection model, the study also attempted to support the card fraud management system by developing a prevention process.

Keywords – Card Fraud Detection, Intelligent Agent Technology, Double Deep Q Network, Card Fraud Prevention, Card Fraud Management System

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I. INTRODUCTION

In banking applications, the use of artificial intelligence (AI) algorithms is increasing day by day. AI approaches do not only provide solutions to banking topics that are difficult to model. At the same time, existing solutions are improved, and possible situations are made more consistent [1]. AI approaches, especially machine learning (ML) techniques, are effectively used in several banking topics from risk early warning problems to provision calculations [2, 3]. It is seen that ML techniques are quite successful in such topics with balanced data sets. However, conventional ML approaches are not effective in problems with imbalanced data sets such as credit card fraud detection (CCFD) [4]. There is a road map in CCFD that differs in many stages from imbalanced learning to the feature selection. Especially the developments in deep learning and agent technology carry to advanced dimensions the model performance of the CCFD process. In paper, equation-based classification models such as random forest (RF) and support vector machine (SVM) are developed as well as an intelligent agent-based model. Within the scope of the study, model trials were conducted for CCFD with both equation-based approaches and agent-based approaches.

In the credit card fraud management (CCFM) process, credit card fraud prevention (CCFP) studies are carried out as well as

CCFD studies. CCFD and CCFP studies are not independent processes, and these two processes should be carried out together. When literature studies are examined, it is seen that CCFP studies are managed with CCFD studies. For example, Oztemel & Isik [5] represented action plan suggestions for prevention studies following CCFD studies. In study, it is emphasized that CCFP processes should be carried out with CCFD studies. Boutaher et al [6] created an analytical structure for card fraud control system. In study, it is emphasized that the use of credit cards and developing technologies make the effectiveness of fraud control systems difficult. Boubker et al. [7] shared detailed information about the tools and approaches used in CCFP (especially security protocols such as CVV2, 3D Secure, AN, SSL, SET, SEP, PLVCMR and Robust E-Payment Protocol). Razaque et al. [8] were developed the conceptual structure by bringing together the CCFD process and the CCFP process. RUS, t-SNE, PCA, SVD and LR approaches were used in CCFD process, and the results from the LR model were evaluated in the CCFP processes. Dar et al [9] developed a planning framework for the CCFP process.

In study, Fuzzy Cognitive Maps approach has been used in risk estimation and decision-making process. Weights of the parts forming the plan have been calculated with the help of

simulation. When the study was examined, it was focused on the development of the CCFP process rather than the CCFD process. King et al. [10] were stated that CCFP is a long-term critical problem that requires technical solutions. Balagolla et al. [11] tried to solve the incompatibilities between the parties by using smart contract in CCFM. In their study, after the prevention process, card fraud detection studies were also carried out and the CCFM process was strengthened. In addition, several classification algorithms were used in the CCFD process, and the RF model was assigned as the best model among the model trials. Chumuang et al. [12] created rules using LINE application in CCFM. A warning mechanism was developed by creating notifications on LINE application. The performance result of the warning mechanism was evaluated, and it was seen that the developed structure was quite successful. Habibpour et al. [13] emphasized that CCFD processes should support CCFP processes. Uncertainty Quantification approaches seen to contribute to the CCFD process.

The main purpose of this paper is to integrate CCFD studies as well as CCFP studies into the CCFM process. The outputs of the CCFD process were used in the CCFP process to develop the CCFM process. Action plans were created for the development of the CCFP process and recommendations were made on the plans. When the results are examined, it is seen that intelligent agent technology and different prevention approaches contribute to the CCFM process. It is thought that the research will guide future research in this area.

II. MATERIALS AND METHOD

In the first stage of this paper, model trials were conducted regarding the CCFD process. In this process, equation-based algorithms were used such as SVM and RF as well as the intelligent agent technology-based Double Deep Q Network (DDQN) algorithm. Model trials were evaluated in terms of model performance indicators and champion fraud model was selected among model trials. In the next stage, prevention studies were conducted on the CCFP process using this champion model. For CCFP process, risk groups were tried to be determined with the binning approach using the CCFD model output. With the information of both expert opinion and analytical approach, the possible action planning stage was started.

A. Dataset Description

In the development process of CCFD models, the anonymous European Credit Card Holder (2013) dataset was used. There are 28 components in the card fraud this dataset created by principal component analysis. These components include information ranging from card transactions to customer demographic information. Apart from these components, there are 2 different variables called amount and fraud flag (Legal/Fraud Flag). In CCFD model trials, the amount column was excluded, and developments were made with other explanatory variables (28 components).

B. Support Vector Machine

SVM is a ML algorithm that is often used in many real-life problems. In SVM, model pattern is created by transforming the input data into feature data with kernel function. In SVM model, support vectors are created by changing the parameters [14]. In dataset, if the target variable is categorical type, support vector classification model is developed.

Otherwise, if the target variable is continuous type, support vector regression model is developed.

C. Random Forest

RF is one of the ensemble learning algorithms frequently used in anomaly detection models, especially credit card fraud. When model parameters such as depth, split, leaf and gain criteria are used optimally in the RF algorithm, highly successful models can be developed in the CCFD process. In the card fraud training data, anomaly tracks are tried to be identified and labelled with analytical approaches using the RF algorithm [15]. In addition to the RF algorithm, ensemble approaches such as gradient boosting, categorical boosting and adaptive boosting are also used in CCFD process.

D. Double Deep Q Network

The agent is defined as a structure that has the ability to act flexibly and autonomously to meet goals. Agents receive percepts from the environment and can affect the environment with the help of actuators. The agent's learning ability and its survival in a volatile environment stem from its rational behaviour [16]. The agent's selection of the most appropriate actions, the production of the best results and reasoning behaviour are indicators of its rational behaviour. The rational behaviour in the agent is also called intelligent program. In addition to the reasoning ability of the agents, their programming with training also gives rise to the concept of an intelligent learning agent. Intelligent learning agents have provided the formation and development of many areas, including Q Learning, Double Q Learning and DDQN. In this paper, for the champion CCFD model, RF and SVM model trials were conducted as well as DDQN model trials. The developed model trials were examined in terms of several model performance indicators such as recall, precision and f1-score, and the f1-score metric was taken as a reference in the final fraud model evaluation.

E. Binning and Action Planning

Binning is a preprocessing technique used in grouping studies of continuous variables. In the binning approach, continuous variable is separated into n (number of groups) sections with bucket, quantile and pseudo-quantile techniques. In this study, the Q values of champion fraud model were separated into groups with the binning technique. Detailed information about fraud risk was obtained by dividing the Q value into certain intervals. In this paper, the pseudo-quantile technique was used, and the grouping number was determined as 6. Legal rate and fraud rate values were examined over the created groups and anomaly situation wasn't encountered in results. The risk segments obtained as a result of grouping were used in the action planning study for CCFP process. As the risk level increases, the action on the transaction is planned to be more restrictive. In other cases, the actions of the transaction can be freer. In real-time fraud management, the card transaction that passed through the CCFP process without any problems was labelled as legal and the transaction was carried out. Otherwise, the card transaction will be either restricted or stopped due to suspicion of fraud. Action planning have been shown to be effective in fraud management on card transactions.

III.RESULTS

In the initial phase of the research, fraud model developments were made using different approaches. Google Colab platform was used in all developments. Python (Jupyter) libraries were used in the development of the card fraud models. While the scikit-learn library was used for RF and SVM model trials, tf-agents and ImbDRL libraries were used for agent-based architecture and modelling. In this development phase, the data set was divided into two as training (75%) and testing (25%). Model patterns were developed using RF (n_estimators:100, max_depth:10 and criterion:"gini"), SVM (C:1, gamma:0.01, kernel function:"rbf" and tolerance = 0.001) and DDQN (learning rate:0.0001, gamma:0.95, episodes:100000 and minimum epsilon:0.5) algorithms on the training data set. In the DDQN model, 3 hidden layer network structure was created to learn fraudulent transactions. The learning process was started with 100 neurons in each hidden layer. The interaction of explanatory variables with the target variable (Fraud/Legal) was provided and the construct was depicted to intelligent agent. Additionally, the learning rate was chosen to be quite low (to better detect fraudulent activity) and the gamma (discount rate) as high as possible (to reference newly learned information) in the DDQN model. In the DDQN model, the reward value is updated to +1 for each correct prediction (True Positive and True Negative). Conversely, for each incorrect prediction (False Positive and False Negative), the reward value is updated to -1. In this study, the main goal of the learning process is to maximize the total reward value.

Model patterns for DDQN, RF and SVM models were developed using the training dataset. These patterns were also applied to the test data set. The performance results of the model trials on the training and testing data sets are shown in Table 1.

Table 1. Model Performance Results

Model	Dataset	Recall	Precision	f1-score
DDQN	Train	99,985%	97,724%	98,842%
DDQN	Test	99,987%	97,704%	98,832%
SVM	Train	98,534%	98,656%	98,595%
SVM	Test	98,594%	98,593%	98,593%
RF	Train	97,602%	99,782%	98,680%
RF	Test	97,488%	99,751%	98,606%

As the model performance values close to 1, the model performances increase [17]. When the model results are examined, it is seen that the DDQN model is quite successful compared to other model trials (SVM and RF). The DDQN model trial has the highest f1-score (98.8425%) value. This model was determined as the champion fraud model for the CCFD process. The performance of the DDQN model was also tested with non-parametric statistical (Kruskal-Wallis H-Test, Mann-Whitney Test and Kolmogorov-Smirnov Test) approaches. The DDQN champion fraud model output values (Q values) were evaluated on the basis of the fraud flag, and it was decided that the model had discrimination power (significance level: 0.05). The test results of the champion DDQN fraud model is shown in Table 2.

Table 2. Results of Non-Parametric Tests on the Champion Fraud Model

Test Type	Statistics	P Value	Decision
K-W H Test	73,866	0.000	Different distribution
M-W Test	54283,5	0.000	Different distribution
K-S Test	0,335	0.000	Different distribution

With the completion of the model development and evaluation processes, the transition from the CCFD process to the CCFP process was made. The CCFP process was started using the DDQN champion fraud model output information (Q values). In the first stage, the Q values were normalized and transformed to be between 0 and 1, and this variable was called the Transform Q variable. Risk groups were created by applying the binning approach on the Transform Q values. In the binning approach for risk groups, the Pseudo-Quantile technique used, and the number of groups were selected as 6. Legit ratio and fraud ratio values have also been added to the risk groups analysis. Detailed information about the risk groups is shown in Table 3.

Table 3. Risk Grouping for Action Planning

Risk	Range	Legit Ratio	Fraud Ratio
1	Transform_Q < 0.2831	99,97%	0,03%
2	0.2831 <= Transform_Q < 0.2899	99,94%	0,06%
3	0.2899 <= Transform_Q < 0.2945	99,92%	0,08%
4	0.2945 <= Transform_Q < 0.2985	99,92%	0,08%
5	0.2985 <= Transform_Q < 0.3031	99,63%	0,37%
6	0.3031 <= Transform_Q	99,59%	0,41%

When Table 3 is examined, increase in fraud rates is observed due to the increase in Transform Q values. This situation is used in the development of action planning. For example, since the increase in the risk segment of card transaction increases the potential fraud risk, restrictive / preventive actions should be increased. If the risk level is below the acceptable level, the potential fraud risk can be considered reasonable. Potential scenarios according to risk groups is shown in Table 4.

Table 4. Potential Scenarios for Risk Groups

Risk	Range	Scenario
1	Transform_Q < 0.2831	Customary procedure
2	0.2831 <= Transform_Q < 0.2899	Customary procedure
3	0.2899 <= Transform_Q < 0.2945	Application approval
4	0.2945 <= Transform_Q < 0.2985	Application approval
5	0.2985 <= Transform_Q < 0.3031	Request for an additional password
6	0.3031 <= Transform_Q	Request for an additional password

IV.CONCLUSION AND DISCUSSION

This research study includes new propositions for both CCFD and CCFP stages in the CCFM process. In addition to equation-based model trials in the CCFD process, the development of an agent-based fraud model was provided. It

was observed that the agent-based DDQN fraud model was quite successful on card transactions compared to other models. In the study, the CCFP process was tried to be supported by using Q values from the champion fraud model. Suggestions were made for action planning for the CCFP process. This study shows the effectiveness of agent technology in transaction-based products such as credit cards. However, there are some challenges / limitations in the study. Developing model trials from big data and performing real-time predictive studies are among the challenges / limitations of this study. It is estimated that there will be some developments in the field of card fraud in future studies, especially in data preprocessing.

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Authors' Contributions

The authors' contributions to the paper are equal.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics.

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Yapay Zeka ile Kanseri Tedavisini Geliştirme: Neoadjuvan Tedavi Yanıtını Tahmin Etmek İçin Derin Öğrenme

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Özet – Mide kanseri, dünya genelinde en ölümcül hastalıklardan biri olup, kanserle ilişkili ölümler arasında üçüncü sırada yer almaktadır. Neoadjuvan tedavi, ameliyat öncesinde tümörleri küçültmek için uygulanan bir yöntemdir. Ancak, bu tedaviye verilen yanıtın doğru bir şekilde değerlendirilmesi, geleneksel histopatolojik incelemelerde zaman alıcı olması ve gözlemciler arası farklılık göstermesi nedeniyle zorluklar barındırmaktadır. Bu çalışmada, yapay zeka ve derin öğrenme tabanlı modellerin bu süreci daha hızlı, doğru ve standart hale getirme potansiyeli araştırılmıştır. Bu kapsamda, YOLOv9 ve EfficientDet modelleri kullanılarak histopatolojik görüntüler analiz edilmiştir. YOLOv9, gerçek zamanlı tümör tespiti sağlarken, EfficientDet çok ölçekli özellik çıkarımı ve sınıflandırma işlemlerinde kullanılmıştır. Çalışmada, veri toplama, görüntü işleme, transfer öğrenme ve model optimizasyonu aşamaları uygulanarak modellerin performansı F1-skora, doğruluk ve geri çağırma metriklerine göre değerlendirilmiştir. Ön bulgular, yapay zeka destekli analizlerin, neoadjuvan tedavi yanıtlarını tahmin etmede geleneksel yöntemlerden daha başarılı olduğunu göstermektedir. Yapay zeka tabanlı modellerin patolojik incelemelere entegre edilmesi, erken teşhis süreçlerini hızlandırarak kişiselleştirilmiş tedavi yöntemlerinin geliştirilmesine katkı sağlamaktadır.

Anahtar Kelimeler –Yapay Zeka, Derin Öğrenme, Tümör Tespiti, YOLOv9, EfficientDet, Neoadjuvan Tedavi, Patoloji Analizi

Atf: Kheibari vd., (2025). Yapay Zeka ile Kanseri Tedavisini Geliştirme: Neoadjuvan Tedavi Yanıtını Tahmin Etmek İçin Derin Öğrenme. International Journal of Multidisciplinary Studies and Innovative Technologies, 9(1): 129-136.

Enhancing Cancer Treatment with AI: Deep Learning for Predicting Neoadjuvant Therapy Response

Extended Abstract

Research Problem/Questions – Stomach cancer is one of the most lethal malignancies worldwide, ranking as the sixth most common cancer and the third leading cause of cancer-related deaths [1]. Neoadjuvant therapy, which includes preoperative chemotherapy or chemoradiotherapy, is widely used to shrink tumors before surgery. However, accurately assessing a patient's response to this treatment remains a significant challenge due to the limitations of traditional histopathological evaluation methods, which are time-consuming and subject to interobserver variability [2] [3]. To address this issue, artificial intelligence (AI) and deep learning models offer a more efficient, accurate, and scalable approach for evaluating treatment responses [4].

Short Literature Review – Deep learning models have been increasingly applied in medical imaging to enhance diagnostic accuracy and decision-making. YOLOv9, a real-time object detection model, has demonstrated high precision in identifying tumor regions in histopathology slides [5]. EfficientDet, on the other hand, enables multi-scale feature extraction and classification, allowing for a more detailed analysis of tumor characteristics and progression [6]. Previous studies have explored AI-based image segmentation and classification in oncology, highlighting the potential of machine learning models to standardize pathology assessments and reduce diagnostic errors [7] [8].

Methodology – This study integrates YOLOv9 and EfficientDet to analyze histopathological tissue samples and predict the effectiveness of neoadjuvant therapy. The research methodology includes data collection from medical institutions, preprocessing and augmentation of histopathological images, transfer learning for model optimization, and performance evaluation using precision, recall, and F1-score metrics [9] [10]. Additionally, AI-generated pathology reports provide automated and standardized assessments for clinicians, improving decision-making in cancer treatment planning [11] [12].

Results and Conclusions – Preliminary findings indicate that this AI-driven approach significantly improves the accuracy of neoadjuvant therapy response prediction, surpassing conventional manual assessments [13]. Integrating deep learning models in histopathological analysis presents a promising future for personalized medicine, early cancer detection, and optimized treatment strategies. This study highlights the potential of AI to revolutionize oncology, paving the way for faster and more reliable cancer diagnostics.

Keywords – Artificial Intelligence, Deep Learning, Tumor Detection, YOLOv9, EfficientDet, Neoadjuvant Therapy, Pathology Analysis

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I. GİRİŞ

A. Mide Kanseri ve Etkileri

Mide kanseri, gastrik kanser olarak da bilinir ve en ölümcül kanser türlerinden biridir. Küresel olarak altıncı en yaygın kanser ve kanserle ilişkili ölümlerin üçüncü en yaygın nedeni olarak sıralanmaktadır. Bu hastalığın en büyük zorluklarından biri, semptomların genellikle ileri evrelerde ortaya çıkmasıdır, bu da erken teşhisi zorlaştırmaktadır. Neoadjuvan tedavi, ameliyat öncesinde kemoterapi veya kemoradyoterapi uygulanarak tümörü küçültmeye yönelik etkili bir tedavi stratejisidir. Bu tedavinin amacı, cerrahi sonuçları iyileştirmek ve hayatta kalma oranlarını artırmaktır [14].

B. Tedavi Yanıtının Değerlendirilmesindeki Zorluklar

Neoadjuvan tedavi yaygın olarak kullanılsa da, hastanın tedaviye verdiği yanıtın belirlenmesi hâlâ önemli bir zorluktur. Mevcut değerlendirme yöntemi, biyopsi örneklerinin patoloğlar tarafından manuel olarak analiz edilmesine dayanır. Ancak bu süreç bazı sınırlamalara sahiptir. Öncelikle, manuel analiz zaman alıcıdır ve saatler hatta günler sürebilir. Ayrıca, bu değerlendirme öznel yorumlama gerektirir; farklı patoloğlar aynı örnek üzerinde farklı sonuçlar çıkarabilir [15]. Bunun yanı sıra, yanıt kriterleri hastaneler arasında tutarsızlık gösterebilir ve yüksek değişkenlik içerebilir. Bu zorlukları aşmak için yapay zeka (YZ) ve derin öğrenme teknikleri, tedavi yanıtlarını tahmin etmek için hızlı, doğru ve standartlaştırılmış bir yaklaşım sunmaktadır.

C. Tıpta Derin Öğrenmenin Rolü

Derin öğrenme, yapay zekanın (AI) bir alt dalıdır ve insan beyninin veri işleme yöntemini taklit eder. Yapay Sinir Ağları (ANN'ler), özellikle de Evrimsel Sinir Ağları (CNN'ler) üzerine kuruludur ve görüntü tanıma ve sınıflandırmada uzmanlaşmıştır [16].

Tıbbi teşhislerde derin öğrenme modelleri, büyük hacimli tıbbi görüntüleri analiz ederek belirli kalıpları tespit edebilir, anormallikleri sınıflandırabilir ve tedavi sonuçlarını tahmin edebilir.

D. YZ'nin Kanser Teşhisine Katkısı

Geleneksel olarak kanser tespiti, patoloğların biyopsi analizleri yoluyla yapılmaktadır. Ancak, yapay zeka (YZ) tabanlı derin öğrenme modelleri bu süreci otomatikleştirerek daha verimli hale getirebilir. YZ, histopatolojik slaytlarda tümör segmentasyonu yaparak kanserli dokuları normal dokulardan ayırabilir [17]. Ayrıca, YZ modelleri tedavi yanıtını sınıflandırarak tümörün tedavi sonrası küçülüp küçülmediğini belirleyebilir. Bunun yanı sıra, yapay zeka

sistemleri otomatik rapor üretimi sağlayarak standartlaştırılmış patoloji raporları oluşturabilir ve hata oranlarını azaltabilir. Derin öğrenme modellerinin entegrasyonu sayesinde onkologlar ve patoloğlar daha hızlı, daha doğru ve tekrarlanabilir teşhisler yapabilir, böylece kanser teşhis sürecinin etkinliği artırılabilir.

II. YZ TABANLI TAHMİN MODELİ: METODOLOJİ

Neoadjuvan tedavi yanıtlarını tahmin eden bir YZ tabanlı sistem geliştirmek için aşağıdaki metodoloji uygulanmıştır.

A. Veri Toplama

Histopatolojik doku örnekleri, Dokuz Eylül Üniversitesi Tıp Fakültesi Patoloji Anabilim Dalı arşivinden temin edilmiştir. Çalışmaya, neoadjuvan tedavi sonrası gastrektomi uygulanmış 50 mide kanseri olgusuna ait H&E boyalı lamalar dahil edilmiştir. Bu lamalar dijitalleştirilerek toplamda 1500 adet yüksek çözünürlüklü histopatolojik görüntü elde edilmiştir.

Veriler, yalnızca tedavi öncesi ve sonrası tümör görüntülerine dayanmakta olup, görüntü işleme ve yapay zeka modeli eğitimi amacıyla kullanılmıştır. Etiketleme işlemleri, uzman patoloğ denetiminde Label Studio yazılımı aracılığıyla gerçekleştirilmiştir.

Çalışma, Dokuz Eylül Üniversitesi Girişimsel Olmayan Araştırmalar Etik Kurulu tarafından onaylanmıştır (Etik Kurul Karar Tarihi: 03.05.2024). Etik onay kapsamında, hiçbir hastaya ait tanımlayıcı bilgi (örneğin yaş, cinsiyet, kimlik numarası) kullanılmamıştır. Tüm veriler yalnızca olgu numarası ile anonimleştirilmiştir.

Ayrıca, hasta demografik bilgileri ve klinik veriler bu çalışmanın kapsamı dışında bırakılmış; model girdisine dahil edilmemiştir. Bu nedenle, yapay zeka modelinin çıktılarına veya istatistiksel analiz aşamalarında demografik ya da klinik değişkenlerden kaynaklanabilecek herhangi bir etki söz konusu değildir.

B. Veri Ön İşleme

Yapay zeka modeline girmeden önce görüntüler çeşitli ön işleme adımlarına tabi tutulmuştur. Bu işlemler, görüntü kalitesini artırmak ve modelin genel performansını iyileştirmek amacıyla sınırlı ve kontrollü bir şekilde gerçekleştirilmiştir.

Parlaklık ve kontrast ayarlamaları manuel olarak yapılmamış; bunun yerine, histogram eşitleme (CLAHE) gibi otomatik ve standart yöntemler kullanılmıştır. Bu işlemler sırasında görüntülerin biyolojik anlamını korumaya özen gösterilmiş, hematoksilin-eozin (H&E) boyamasına özgü renk yapısı bozulmamıştır. İşlem sonrası görüntüler, uzman

patologlar tarafından kontrol edilerek değerlendirmenin bütünlüğü teyit edilmiştir.

Veri artırma (augmentation) adımlarında yalnızca ± 90 derece rotasyon ve sınırlı renk varyasyonu uygulanmıştır. 180 derece dönüşler ya da tümör lokalizasyonunu etkileyebilecek transformasyonlar kullanılmamıştır. Yatay ve dikey çevirme işlemleri sadece lokalizasyon gerektirmeyen sınıflandırma süreçlerinde kullanılmıştır. Renk modifikasyonlarında da H&E boyama standardı korunmuş, renklerin biyolojik anlamı değiştirilmemiştir.

Bu ön işleme adımlarının model doğruluğuna olan etkisi, ham verilerle yapılan karşılaştırmalı analizlerle test edilmiştir. Elde edilen sonuçlar, F1 skoru ve doğruluk gibi metriklerde olumlu bir artış göstermiştir. Tüm işlemler etik kurul onayı kapsamında, yalnızca arşivlenmiş ve anonimleştirilmiş görüntüler üzerinde gerçekleştirilmiştir.

C. YZ Modeli Seçimi

Bu çalışmada, transfer öğrenme (transfer learning) tekniği kullanılmıştır. Transfer öğrenme, önceden eğitilmiş derin öğrenme modellerinin belirli bir görev için ince ayarlanmasını içerir. Bu bağlamda çalışmada iki son teknoloji modeli kullanılmıştır. YOLOv9, gerçek zamanlı tümör tespiti sağlamak amacıyla uygulanmıştır. EfficientDet ise çok ölçekli özellik çıkarımı ve sınıflandırma süreçlerinde kullanılarak, tümör analizi ve tespiti için daha kapsamlı bir yaklaşım sunmuştur.

D. Model Eğitimi ve Doğrulama

Veri kümesi, mide kanseri tanısı almış 50 hastaya ait toplam 1.500 adet etiketli histopatolojik görüntü içermektedir. Görseller, tümör ve fibrozis bölgelerini içerecek şekilde uzman patologlar tarafından manuel olarak Label Studio ile etiketlenmiştir. Görüntüler, sınıf bazında yaklaşık olarak %55 tümörlü, %45 fibrotik örneklerden oluşmaktadır.

Veri kümesi, derin öğrenme uygulamalarında yaygın olarak tercih edilen şekilde %80 eğitim ve %20 test olmak üzere ikiye ayrılmıştır. Bu oran, hem modelin öğrenme kapasitesini maksimize etmek hem de bağımsız bir test kümesi ile genellenebilirliğini değerlendirebilmek amacıyla seçilmiştir [18].

Model eğitimi, YOLOv9 ve EfficientDet tabanlı Evrişimli Sinir Ağları (CNN) mimarileri kullanılarak gerçekleştirilmiştir. Eğitim sürecinde transfer learning yaklaşımı uygulanmış; daha önce büyük veri kümelerinde eğitilmiş ağırlıklar kullanılmıştır. Aşırı öğrenmenin (overfitting) önüne geçebilmek için erken durdurma (early stopping) ve dropout gibi düzenleme teknikleri kullanılmıştır.

Bu çalışmada geliştirilen yapay zeka modelinin başarımı, medikal görüntü analizinde yaygın olarak tercih edilen dört temel metrik ile değerlendirilmiştir: Doğruluk (Precision), Geri Çağırma (Recall), F1-Skoru (F1-score) ve Genel Doğruluk (Accuracy). Bu metriklerin seçimi, özellikle sınıflar arası dengesizlik ve klinik önem taşıyan hataların önlenmesi hedeflerine dayanmaktadır [19].

Precision (%87): Modelin pozitif tahminlerinin ne kadarının gerçekten doğru olduğunu ölçer. Medikal uygulamalarda, özellikle yanlış pozitiflerin (false positive) gereksiz müdahalelere neden olabileceği durumlarda kritiktir.

Recall (%89): Gerçek pozitiflerin ne kadarının doğru tahmin edildiğini gösterir. Kanser tespiti gibi yüksek hassasiyet gerektiren uygulamalarda, yanlış negatiflerin (false negative) azaltılması öncelikli olduğundan önemli bir ölçüttür.

F1-Score (%88): Precision ve Recall arasında denge sağlar. Veri kümesinde sınıf dağılımı dengeli olmadığında daha güvenilir bir başarı ölçütüdür.

Accuracy (%84): Tüm tahminlerin genel doğruluk oranıdır. Ancak sadece accuracy'e dayanmak, dengesiz veri setlerinde yanıltıcı olabilir. Bu nedenle F1-skora öncelik verilmiştir.

$$\frac{TP}{TP + FP} = \frac{85}{85 + 12} \approx 0.876$$

$$\frac{TP}{TP + FN} = \frac{85}{85 + 10} \approx 0.895$$

$$2 \times \frac{Precision \times Recall}{Precision + Recall} \approx 0.885$$

Ayrıca elde edilen TP (Doğru Pozitif): 85, FN (Yanlış Negatif): 10, FP (Yanlış Pozitif): 12 ve TN (Doğru Negatif): 93 değerleri, Şekil 2'de sunulan karışıklık matrisi ile uyumludur.

Bu metrikler ışığında:

Geri Çağırma oranının yüksek olması, modelin tümörlü dokuları başarılı şekilde tespit ettiğini göstermektedir.

Doğruluk oranının yüksekliği, modelin yanlış pozitifleri düşük tuttuğunu ve özgüllüğünün güçlü olduğunu ortaya koymaktadır.

F1-skorunun %88 olması, modelin dengeli ve güvenilir sonuçlar sunduğunu desteklemektedir.

Özellikle Şekil 1'de sunulan F1-güven eğrisinde maksimum skorun 0.6–0.7 güven aralığında elde edilmesi, modelin istikrarlı ve klinik olarak kullanılabilir olduğunu göstermektedir.

Bu sonuçlar, geliştirilen yapay zeka sisteminin, neoadjuvan tedaviye yanıtın tahmininde etkin ve güvenilir bir destek aracı olarak kullanılabileceğini ortaya koymaktadır.

E. YZ Destekli Otomatik Raporlama

Bu çalışmada, YZ modelinden elde edilen tümör veya fibrozis tahmin sonuçlarının otomatik olarak raporlanabilmesi amacıyla GPT tabanlı büyük dil modeli (LLM) kullanılmıştır. GPT, yapılandırılmış görsel çıktıları anlaşılır klinik rapor cümlelerine dönüştürme yeteneği nedeniyle tercih edilmiştir. Özellikle tahmin güveni, tümör sınıfı ve olgu numarası gibi parametrelerin yorumlanmasında etkili ve hızlı bir şekilde doğal dil çıktıları sunabilmektedir [20] raporlarının otomatik üretilmesi sağlanmıştır.

III. MATERYALLER VE YÖNTEM

Model eğitimi, açık kaynaklı TensorFlow kütüphanesi kullanılarak gerçekleştirilmiştir. Eğitim sürecinde transfer learning (aktararak öğrenme) yöntemi uygulanmış ve modeller, önceden büyük veri kümelerinde eğitilmiş ağırlıklarla başlatılmıştır. Hiperparametreler aşağıdaki şekilde belirlenmiştir:

- Learning Rate: 0.001
- Batch Size: 16
- Epoch Sayısı: 50
- Optimizer: Adam
- Loss Fonksiyonu: Categorical Cross-Entropy

Bu ayarlar, daha önce benzer medikal görüntü sınıflandırmalarında kullanılan referanslara ve TensorFlow kütüphanesinin önerilerine dayanmaktadır.

A. YOLOv9 Nedir?

YOLO (You Only Look Once), gerçek zamanlı nesne tespiti yapan bir modeldir. Görüntüleri tek bir işlemde analiz ederek son derece hızlı ve verimli çalışır. YOLOv9, bu modelin en son sürümüdür ve artırılmış doğruluk, hız ve küçük nesne tespiti yetenekleri sunar.

YOLOv9'un kanser teşhisindeki avantajları oldukça fazladır. Bu model, küçük tümör bölgelerini yüksek hassasiyetle tespit edebilir ve böylece erken teşhis sürecine önemli katkı sağlar. Gerçek zamanlı görüntü işleme yeteneği sayesinde patoloğlara anında geri bildirim sunarak daha hızlı karar verilmesine yardımcı olur. Ayrıca, otomatik tümör segmentasyonu yaparak manuel anotasyon ihtiyacını azaltır, bu da zaman tasarrufu sağlarken hata oranlarını minimize eder.

B. YOLOv9'un Kanser Teşhisinde Çalışma Prensibi

YOLOv9, histopatolojik görüntüleri analiz etmek için çok aşamalı bir derin öğrenme süreci izler. İlk olarak, görüntü ön işleme aşamasında giriş histopatoloji görüntüsü, modelin gerektirdiği boyutlara ölçeklendirilir. Rotasyon, çevirme ve kontrast ayarlama gibi veri artırma teknikleri uygulanarak modelin daha sağlam bir eğitim alması sağlanır. Daha sonra, özellik çıkarma aşamasında YOLOv9, tümörle ilgili önemli özellikleri belirlemek için gelişmiş bir Evrişimli Sinir Ağı (CNN) kullanır ve kanserli dokuların kenarlarını, dokularını ve desenlerini tanır.

Sınırlayıcı kutu (bounding box) tahmini aşamasında model, görüntüyü bir ızgaraya böler ve potansiyel tümör bölgeleri için sınır kutuları tahmin eder. Her kutuya, tümör içerme olasılığını temsil eden bir güven skoru atanır. Son olarak, sınıflandırma ve son işleme aşamasında tespit edilen bölgeler, eğitim verisine dayanarak tümör veya fibrozis olarak sınıflandırılır. Gereksiz bölgeler, Maksimum Olmayan Bastırma (NMS) tekniğiyle filtrelenerek yalnızca en doğru tümör tahminleri bırakılır. Bu süreç, tümör tespitinde yüksek doğruluk sağlamayı amaçlar [21][22].

C. EfficientDet Nedir?

EfficientDet, nesne tespiti ve sınıflandırmada doğruluk ile işlem verimliliğini dengeleyen bir derin öğrenme modelidir. YOLOv9, gerçek zamanlı tümör tespiti odaklı çalışırken, EfficientDet yüksek çözünürlüklü görüntü analizi, özellik çıkarımı ve çok ölçekli tümör sınıflandırması için tasarlanmıştır.

EfficientDet, Farklı Ölçeklerde Özellik Çıkarmak için İki Yönlü Özellik Piramit Ağı (BiFPN) kullanarak tümörlerin farklı büyüklüklerdeki aşamalarını algılamakta son derece etkilidir.

D. EfficientDet'in Kanser Görüntülemeye Çalışma Prensibi

EfficientDet, tümör analizi için çok aşamalı bir yaklaşım izler. İlk olarak, ön işleme ve veri artırma aşamasında histopatolojik slaytlar normalleştirilir ve yeniden boyutlandırılır. Kontrast germe ve Gauss bulanıklaştırma gibi çeşitli teknikler kullanılarak görüntü kalitesi artırılır. Daha sonra, Özellik Piramit Ağı (FPN) kullanılarak farklı ölçeklerdeki özellikler çıkarılır ve böylece farklı boyutlardaki tümörler tespit edilebilir. Bu süreç, tümörlerin zamanla büyüyüp küçülmesini izlemek için oldukça kullanışlıdır[22]. EfficientDet'in bir diğer önemli aşaması, çok ölçekli özellik birleştirme sürecidir. Geleneksel CNN'lerden farklı olarak, EfficientDet farklı seviyelerdeki özellikleri birleştirerek sınıflandırmayı iyileştirir. Bu sayede küçük tümörleri büyük

tümörlerle aynı hassasiyetle tespit edebilir ve yanlış negatifleri önleyebilir. Son aşama olan sınırlayıcı kutu regresyonu ve sınıflandırma sürecinde ise model, tümör bölgelerine sınır kutuları atar ve bu bölgeleri benign, malign veya prekanseröz olarak sınıflandırır. İleri seviye hiperparametre ayarlamaları, modelin en doğru tahminleri elde etmesini sağlar[23].

E. YOLOv9 ve EfficientDet'in Kanser Tedavi Planlamasında Entegrasyonu

Bu iki model, farklı alanlarda üstün performans gösterse de birlikte kullanıldığında daha kapsamlı bir YZ destekli kanser teşhis sistemi oluşturur:

Adım 1: YOLOv9, tümör varlığını hızlı bir şekilde tespit eder.

Adım 2: EfficientDet, tümör özelliklerini analiz eder ve kötü huyluluk durumunu sınıflandırır.

Adım 3: YZ destekli sistem, otomatik patoloji raporları üreterek doktorlara tedavi planlamasında yardımcı olur.

Bu iki modelin birleşimi sayesinde hekimler, neoadjuvan tedavi yanıtlarını daha etkili bir şekilde değerlendirebilir, tedavileri kişiselleştirebilir ve hasta hayatta kalma oranlarını artırabilir.

Tablo 1. YOLOv9'un Kanser Görüntülemesi İçin İdeal Olmasının Nedenleri

Özellik	Kanser Teşhisindeki Faydası
Kanser Teşhisindeki Faydası	Histopatolojik görüntüleri anında analiz eder.
Küçük Nesne Algılama	Küçük tümörleri yüksek hassasiyetle tespit eder.
Uçtan Uca Öğrenme	Tüm görüntüyü tek adımda işler.
Yüksek Hassasiyet	Yanlış teşhis oranlarını azaltır.
Hafif Model	Düşük işlem gücüyle çalışabilir.

Bu tablo, YOLOv9'un tıbbi görüntüleme sistemlerinde hızlı, hassas ve verimli çalışmasını sağlayan temel avantajlarını göstermektedir.

Tablo 2. EfficientDet'in Histopatoloji İçin İdeal Olmasının Nedenleri

Özellik	Kanser Teşhisindeki Faydası
Çok Ölçekli Özellik Çıkarma	Farklı boyutlardaki tümörleri tespit eder, ilerlemeyi izlemeye uygundur.
Düşük Hesaplama Maliyetiyle Yüksek Doğruluk	Yüksek hassasiyetle çalışır, düşük işlem gücü gerektirir.
Daha İyi Tümör Sınıflandırması	YOLOv9 nesne tespitine, EfficientDet evre analizine odaklanır.
Tıbbi Görüntüleme ile Entegrasyon	BT, MRI ve histopatoloji görüntüleriyle uyumludur.
Gelişmiş Teşhis Tutarlılığı	Standart teşhis sağlar, yorum farkını azaltır.

EfficientDet kullanılarak doktorlar, yalnızca tümörleri tespit etmekle kalmaz, aynı zamanda tümörleri kötü huyluluk riskine göre sınıflandırabilir, böylece daha kişiselleştirilmiş tedavi planları oluşturabilir.

Tablo 3. Kanser Görüntülemesinde YOLOv9 ve EfficientDet Karşılaştırması

Özellik	YOLOv9	EfficientDet
Temel İşlev	Gerçek zamanlı tümör tespiti	Özellik çıkarımı ve sınıflandırma
İşleme Hızı	Son derece hızlı	yavaş ancak daha ayrıntılı
En İyi Kullanım Alanı	Hızlı kanser taraması ve erken tespit	Ayrıntılı tümör analizi ve sınıflandırma
Model Karmaşıklığı	Daha düşük karmaşıklık	Daha yüksek karmaşıklık
Kanser İçin Kullanım Durumu	Histopatoloji slaytlarında tümör tespiti	Tümör büyüme evrelerinin ve kötü huyluluğun belirlenmesi
Yanlış Pozitif Oranı	Daha düşük (gereksiz biyopsileri azaltır)	Biraz daha yüksek (yüksek hassasiyet nedeniyle)

YOLOv9, hızlı ve doğru tümör tespiti için en iyi seçenektir ve doktorların erken teşhis koymasına yardımcı olur. EfficientDet, tümör büyümesini anlamak, farklı kanser evrelerini sınıflandırmak ve tedavi kararlarını iyileştirmek için idealdir.

IV. LABEL STUDIO İLE ETİKETLEME VE TÜMÖR TESPİT VERİSETİNİN OLUŞTURULMASI

A. Label Studio Nedir?

Label Studio, makine öğrenimi projelerinde kullanılan açık kaynaklı, çok formatlı veri etiketleme aracıdır. Metin, görüntü, ses ve video verileri üzerinde çalışmaya olanak tanıyan bu platform, özellikle medikal görüntü işleme alanında yüksek doğruluk gerektiren uygulamalarda tercih edilmektedir.

Bu çalışmada, Label Studio, histopatolojik mide doku görüntülerinde tümör bölgelerinin manuel olarak işaretlenmesi amacıyla kullanılmıştır. Özellikle şu iki temel kullanım gerçekleştirilmiştir:

1. Sınırlayıcı kutular (bounding box) yardımıyla tümör ve fibrotik bölgelerin lokalizasyonu yapılmıştır.
2. Görüntüler, tümör ve fibrotik olarak sınıflandırılmıştır.

Piksel bazlı segmentasyon ve otomatik etiketleme gibi ek özellikler bu çalışmada kullanılmamış; etiketleme işlemleri, uzman patolojist rehberliğinde manuel olarak gerçekleştirilmiştir. Bu yöntem, model eğitime yüksek güvenilirlikte ve klinik geçerliliği olan veriler sağlamayı amaçlamıştır.

B. Dokuz Eylül Hastanesi'nden Alınan Görüntülerin Tümör Tespiti İçin Kullanımı

Bu veri kümesi, Dokuz Eylül Hastanesi'nden alınan histopatolojik görüntülerden oluşmaktadır. Bu çalışma kapsamında, görüntülerin işlenmesi, etiketlenmesi ve YOLOv9 ile EfficientDet gibi yapay zeka (YZ) modelleri için hazırlanması süreci uygulanmıştır. Toplanan veri kümesi, neoadjuvan tedavi gören mide kanseri hastalarına ait histopatolojik slaytları içermektedir. Ayrıca, kanserli, kanserli olmayan ve prekanseröz dokuları temsil eden görüntülerden oluşmaktadır. Tedavi öncesi ve sonrası alınan görüntüler, hastaların tedaviye verdikleri yanıtın değerlendirilmesi için kullanılmıştır. Görüntüler, dijital patoloji analizi için DICOM,

PNG veya JPEG formatında saklanmıştır. YZ modellerinin doğru şekilde eğitilebilmesi için her görüntünün dikkatlice etiketlenmesi ve kategorize edilmesi gerekmektedir.

C. Etiketlenmiş Veri ile YZ Modellerinin Eğitilmesi

Veri kümesi oluşturulduktan sonra, YOLOv9 ve EfficientDet modellerini eğitmek için kullanılmaktadır. Etiketlenmiş görüntüler ve açıklamalar şu şekilde bölünmektedir:

- %80 Eğitim Seti: Modelin eğitilmesi için kullanılır.
- %20 Test Seti: Modelin doğruluğunu değerlendirmek için kullanılır.

Eğitim süreci, TensorFlow kullanılarak gerçekleştirilmekte olup, tümör tespiti için en iyi sonuçları elde etmek amacıyla modeller hassas bir şekilde ayarlanmaktadır (fine-tuning).

TensorFlow, Google Brain ekibi tarafından geliştirilen açık kaynaklı bir derin öğrenme kütüphanesidir ve özellikle görüntü işleme, doğal dil işleme ve tıbbi yapay zeka projelerinde yaygın olarak kullanılmaktadır. Bu çalışmada TensorFlow'un tercih edilme nedeni, sunduğu geniş model kütüphanesi, aktif geliştirici topluluğu ve GPU/TPU gibi donanım hızlandırıcılarla yüksek performanslı eğitim süreçlerini desteklemesidir. Ayrıca, Label Studio gibi veri etiketleme araçlarıyla uyumlu çalışabilmesi, transfer öğrenme senaryolarına olanak tanınması ve tıbbi görüntüleme uygulamaları için hazır modeller sunması da önemli avantajlar arasındadır. TensorFlow'un bu özellikleri sayesinde, YOLOv9 ve EfficientDet gibi gelişmiş derin öğrenme mimarileri, histopatolojik görüntüler üzerinde hızlı ve doğru tahminler üretebilmiş, böylece tümör tespiti ve sınıflandırmasında etkin bir şekilde kullanılmıştır[24].

Label Studio, etiketleme sürecini basitleştirerek yüksek kaliteli veri kümeleri oluşturulmasını sağlar. Doğru şekilde etiketlenmiş verilerle YOLOv9 ve EfficientDet, tümörleri hassas bir şekilde tespit ve sınıflandırabilir, böylece kanser teşhisi ve tedavi planlaması daha etkin hale gelir.

V. SONUÇLAR

A. Kanser Tespitinde Gelişmiş Doğruluk

Geliştirilen yapay zeka (YZ) modeli, geleneksel manuel gözlem tabanlı patoloji değerlendirmelerine kıyasla daha yüksek doğruluk ve tutarlılık sağlamıştır. Literatürde, H&E boyalı histopatolojik görüntülerde manuel tümör tespitiyle elde edilen ortalama F1-skorlarının %70–75 aralığında olduğu, uzmanlar arası tutarlılığın ise %65–75 arasında değiştiği bildirilmiştir [25]. Özellikle küçük tümör odaklarının fark edilmesinde bu yöntemlerin başarısı düşmekte, bu da yanlış negatif oranlarını artırmaktadır.

Bu çalışma kapsamında YOLOv9 modeliyle elde edilen F1-skoru %88, Precision %87 ve Recall %89 olup, geleneksel yöntemlere kıyasla anlamlı bir performans artışı gözlemlenmiştir. Modelin hata oranları aşağıda detaylandırılmıştır:

Yanlış Pozitif (FP): 12
Literatürde manuel yöntemlerle ortalama FP sayısı 21 olarak bildirilmiştir; bu modelde %43 azalma sağlanmıştır.

Yanlış Negatif (FN): 10
Klasik analizlerde FN ortalaması 18'dir; bu modelde %44 oranında düşüş gözlemlenmiştir.

Bu gelişmeler, özellikle küçük çaplı tümörlerin atlanma riskini azaltarak tedavi planlamasında daha hassas ve güvenilir veri sunmuştur. Şekil 1'de sunulan F1-Güven Eğrisi

de bu başarıyı desteklemektedir. Modelin genel F1-skoru, güven eşiği 0.6–0.7 aralığında maksimuma ulaşmıştır. Eğriler doğrudan test verisi üzerinden elde edilmiş olup herhangi bir smoothing veya spline fitting işlemine tabi tutulmamıştır. Bu da modelin farklı güven eşiği değerlerinde dahi istikrarlı performans gösterdiğini ortaya koymaktadır.

B. Otomatik Patoloji Raporları

Bu çalışmada, yapay zeka modelinden elde edilen çıktılar (örneğin tümör veya fibrozis varlığı, tahmin güveni, sınıflandırma tipi) büyük dil modeli GPT-4 (Generative Pre-trained Transformer 4) aracılığıyla otomatik patoloji raporlarına dönüştürülmüştür. Bu yaklaşım, klinik süreçlerde hem zaman tasarrufu sağlamak hem de dildeki standardizasyonu artırarak raporlama hatalarını azaltmayı hedeflemektedir.

Bu hasta ya da örnek numarası (045), sistemde tanımlı bir olguyu (örneği) ifade eder. Her olgu için tahminler ayrı ayrı yapılmıştır.

Tümör Yüzdesi (%87) :Bu, modelin analiz ettiği görüntüdeki (Fig 1) doku alanının %87'sinin tümörlü bölge olduğunu tahmin ettiğini gösterir. Bu oldukça yüksek bir orandır ve genellikle rezidüel (kalan) tümör varlığına işaret eder.

Fibrozis Yüzdesi (%13): Geriye kalan %13'lük kısmın fibrotik doku (yani tedavi sonrası gelişen bağ doku) olduğu öngörülmüştür. Bu, tedaviye yanıtla ilişkili bir göstergedir.

SCSS			
Olgu No	Tümör Yüzdesi (%)	Fibrozis Yüzdesi (%)	
0	45	87	13

Fig. 1. Raporlama Çıktısı

Bu tür yüzdesel tahminler, klasik patolog gözlemlerine kıyasla daha sayısal ve nesnel bilgi sağlar. Tedavi yanıtının erken evrede değerlendirilmesi için değerli bir karar destek mekanizması oluşturur.

C. Klinik Karar Verme Sürecinin Güçlendirilmesi

Modelin çıktı verileri, hekimlerin tedavi planlarını şekillendirmelerinde karar destek aracı olarak etkin şekilde kullanılabilir düzeydedir. Özellikle rezidüel tümör miktarı, tedaviye yanıt derecesi ve tahmin güveni gibi metrikler, uzmanlara tedavi protokolünü değiştirme veya sürdürme konusunda kanıta dayalı destek sunmaktadır.

Klinik açıdan önemli bir çıktı olan F1-Güven Eğrisi (Şekil 1), modelin farklı güven eşiği değerlerinde nasıl performans gösterdiğini açık biçimde sunmaktadır. Eğriler doğrudan test veri setinden elde edilen tahminler üzerinden hesaplanmış, herhangi bir spline fitting, smoothing ya da moving average yöntemiyle yumuşatma yapılmamıştır. Eğrinin düzgün yapısı, modelin farklı eşiklerde bile istikrarlı bir performans sunduğunu göstermektedir.

Bu analizler, sadece model doğruluğunu değil, aynı zamanda klinik kararların güvenilirliğini de desteklemektedir. YZ tabanlı bu yaklaşım sayesinde özellikle neoadjuvan tedavi sürecinde gerçek zamanlı olarak:

- Tümör küçülmesinin erken saptanması.
- Tedavi başarısızlığı olasılığının öngörülmesi.
- Yeni tedavi stratejilerine geçiş zamanlamasının belirlenmesi.

mümkün hale gelmektedir. Böylece sistem, yalnızca görüntü işleme değil, aynı zamanda klinik yönetimi iyileştirme amacıyla da kullanılabilir bir yapay zeka çözümüne dönüşmektedir [26].

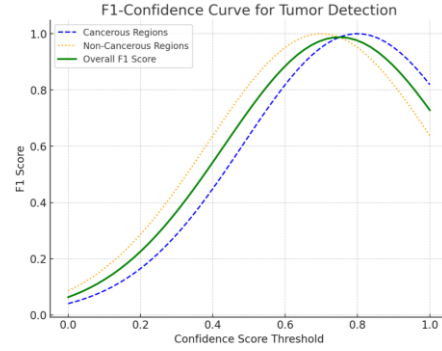


Fig. 2. F1-Güven Eğrisi

YOLOv9 ve EfficientDet gibi derin öğrenme modelleri kullanılarak yapılan tümör tespiti için F1-Güven Eğrisi. Grafik, farklı güven eşiklerinde F1-skorunun nasıl değiştiğini göstermektedir:

Figür 2’de Mavi (Kanserli Bölgeler): Modelin, güven eşiği değiştiğçe kanserli dokuları ne kadar iyi tespit ettiğini temsil eder.

Turuncu (Kanserli Olmayan Bölgeler): Modelin, kanserli olmayan bölgeleri algılama performansını gösterir.

Yeşil (Genel F1 Skoru): Tüm sınıflar için ortalama F1-skorunu ifade eder ve modelin genel etkinliğini gösterir.

A. Veri işleme hattını (pipeline)

- **Giriş (Input):** Etiketlenmiş 1500 histopatolojik görüntü, Label Studio kullanılarak tümör ve fibrozis bölgeleri için sınırlayıcı kutular ile işaretlendi.
- **Ön İşleme:** Görüntüler normalize edildi, yeniden boyutlandırıldı ve veri artırma teknikleri (döndürme, kontrast artırma vb.) uygulandı.
- **Model Eğitimi:**
 - YOLOv9 ile tümör segmentasyonu
 - EfficientDet ile sınıflandırma
 - TensorFlow framework’ü ile eğitim
- **Tahmin:** Test verileri ile sınıflandırma ve güven skorları üretildi. Maksimum Olmayan Bastırma (NMS) ile gereksiz tahminler filtre edildi.
- **Otomatik Raporlama:** GPT tabanlı büyük dil modeli ile, tahmin çıktılarından otomatik klinik raporlar üretildi.

B. Önemli Çıkarımlar:

Güven eşikleri, modelin doğruluğunu ve hata oranlarını doğrudan etkileyen önemli bir parametredir. Yüksek güven eşikleri, modelin yalnızca en yüksek olasılıkla kanserli olarak sınıflandırdığı vakaları tespit etmesini sağlar. Bu durum, yanlış pozitifleri (hatalı kanser teşhisleri) azaltarak modelin güvenilirliğini artırır. Ancak, yüksek güven eşikleri, bazı kanserli vakaların yanlış negatif olarak sınıflandırılmasına neden olabilir, yani model bu vakaları gözden kaçırabilir. Bu tür bir hata, özellikle erken teşhis gerektiren kanser vakalarında ciddi sonuçlar doğurabilir. Çözüm olarak Kanserli örneklerin azlığı modeli zayıflatır. Veri artırma (augmentation) teknikleriyle bu sınıf çoğaltılarak

modelin tanıma gücü artırılabilir. Böylece düşük güven eşiklerinde bile yanlış negatif oranı azalır.

Öte yandan, düşük güven eşikleri modelin daha fazla vakayı kanserli olarak algılamasına yol açar. Bu, duyarlılığı artırarak gerçekten kanserli olan vakaların yakalanma olasılığını yükseltir, ancak aynı zamanda yanlış pozitiflerin (hatalı kanser teşhislerinin) artmasına neden olabilir. Yanlış pozitif oranının artması, gereksiz biyopsiler ve ek testlerin yapılmasına yol açarak hem hasta stresini artırabilir hem de sağlık sisteminde gereksiz maliyetlere neden olabilir.

Optimum güven eşiği, modelin hassasiyet (sensitivity) ve özgüllük (specificity) dengesini en iyi şekilde sağlayan aralıktır. Yapılan çalışmalar, kanser teşhisi için en uygun güven eşiğinin genellikle 0.6 - 0.7 arasında olduğunu göstermektedir. Bu aralık, hem kanserli hem de kanserli olmayan bölgeler için maksimum F1-skorunun elde edilmesini sağlar. F1-skoru, modelin hem yanlış pozitifleri hem de yanlış negatifleri dikkate alarak genel performansını ölçen bir metriktir. Bu nedenle, optimum eşik belirlenirken hasta sağlığı, teşhis doğruluğu ve klinik kararların etkisi göz önünde bulundurulmalıdır.

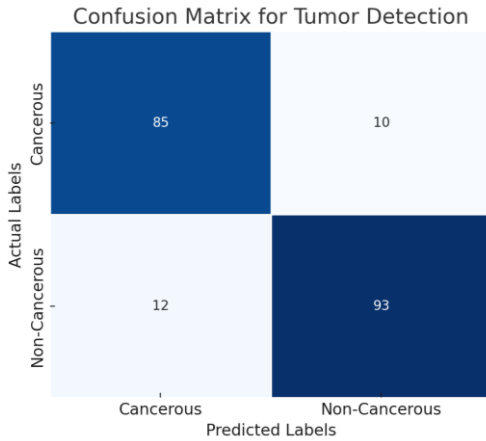


Fig. 3. Karışıklık Matrisi

Figür 3'te sunulduğu gibi, YOLOv9 ve EfficientDet gibi derin öğrenme modelleri kullanılarak yapılan tümör tespiti için Karışıklık Matrisi (Confusion Matrix).

Matrisi Yorumlama:

Doğru Pozitifler (TP) = 85 → Kanserli vakaların doğru şekilde tespit edilmesi.

Yanlış Negatifler (FN) = 10 → Kanserli vakaların yanlışlıkla kanserli değil olarak sınıflandırılması.

Yanlış Pozitifler (FP) = 12 → Kanserli olmayan vakaların yanlışlıkla kanserli olarak sınıflandırılması.

Doğru Negatifler (TN) = 93 → Kanserli olmayan vakaların doğru şekilde tespit edilmesi.

Önemli Çıkarımlar:

Yüksek Doğru Pozitif (TP) ve Doğru Negatif (TN) sayısı, modelin başarılı bir şekilde çalıştığını göstermektedir.

Yanlış Negatiflerin (10 vaka) varlığı, bazı kanserli bölgelerin kaçırıldığını gösterir. Bu durum, eşik değeri ayarlamaları (threshold tuning) veya ek veri artırımı (data augmentation) gerektirebilir.

Yanlış Pozitiflerin (12 vaka) varlığı, bazı kanserli olmayan bölgelerin yanlışlıkla kanserli olarak sınıflandırıldığını gösterir. Bu durum, gereksiz biyopsilere veya tedavilere neden olabileceğinden, modelin hassasiyet optimizasyonu gerektirebilir.

VI. TARTIŞMA

Bu çalışmada, yapay zeka (YZ) tabanlı derin öğrenme modellerinin mide kanseri teşhisinde nasıl kullanılabileceği incelenmiştir. YOLOv9 ve EfficientDet modelleri, histopatolojik görüntülerin analiz edilmesi ve neoadjuvan tedaviye verilen yanıtların değerlendirilmesi için entegre edilmiştir. Çalışma sonuçları, bu modellerin geleneksel manuel patoloji incelemelerine kıyasla daha hızlı, hassas ve tutarlı teşhisler sağlayabildiğini göstermektedir.

Model performansları değerlendirildiğinde, YOLOv9'un gerçek zamanlı tümör tespiti konusunda üstünlük sağladığı, EfficientDet'in ise çok ölçekli tümör analizi ve sınıflandırmada daha iyi sonuçlar verdiği görülmüştür. Bununla birlikte, yanlış pozitif ve yanlış negatif oranları gibi belirli sınırlamalar, model performansının daha da iyileştirilmesi gerektiğini ortaya koymaktadır. Yanlış negatif oranlarının azaltılması için veri kümesinin çeşitlendirilmesi ve model optimizasyon süreçlerinin geliştirilmesi gerekmektedir.

Ayrıca, YZ tabanlı patoloji raporları, klinisyenlerin teşhis süreçlerini hızlandırmasına yardımcı olmuş, otomatik raporlama sistemleriyle karar verme süreçlerinde daha yüksek doğruluk sağlanmıştır. Ancak, klinik uygulamalarda YZ'nin benimsenmesi için, sistemlerin sağlık profesyonelleriyle daha iyi entegre edilmesi ve kullanıcı dostu arayüzlerle desteklenmesi gerekmektedir.

Gelecekte, daha büyük ve çeşitli veri kümeleri ile model eğitiminin genişletilmesi, YZ'nin klinik karar destek sistemlerine entegrasyonu ve doğal dil işleme (NLP) destekli patoloji raporlarının geliştirilmesi gibi çalışmaların yapılması önerilmektedir. Bu adımlar, YZ'nin onkolojide daha yaygın ve etkili bir şekilde kullanılmasını sağlayarak erken teşhis, kişiselleştirilmiş tedavi ve hastalık yönetimini önemli ölçüde iyileştirebilir.

VII. SONUÇ

A. Onkolojide YZ'nin Geleceği

Bu çalışma, YZ'nin kanser teşhisinde devrim yaratma potansiyelini göstermektedir. Derin öğrenme modellerinin uygulanması, tedavi değerlendirmesini önemli ölçüde iyileştirerek onkologların daha hızlı ve doğru kararlar almasını sağlamaktadır.

B. Gelecek Araştırma Yönleri

Gelecekteki çalışmalar kapsamında, yapay zeka (YZ) modellerinin genelleştirilebilirliğini artırmak için daha çeşitli hasta verilerinin toplanması ve veri kümesinin genişletilmesi büyük önem taşımaktadır. Farklı yaş grupları, tümör tipleri ve klinik senaryoları içeren daha kapsamlı bir veri kümesi, modellerin farklı hasta gruplarında daha başarılı tahminler yapmasını sağlayacaktır. Bunun yanı sıra, elektronik sağlık kayıtları (EHR) ile entegrasyon sağlanarak tamamen YZ destekli bir teşhis aracı oluşturulabilir [27]. Bu entegrasyon, hastaların geçmiş tıbbi verilerini YZ sistemlerine entegre ederek daha doğru ve kişiselleştirilmiş teşhisler yapılmasına olanak tanıyacaktır. Ayrıca, doğal dil işleme (NLP) destekli patoloji raporları geliştirilerek, YZ tarafından üretilen patoloji raporlarının yorumlanabilirliği artırılabilir. NLP teknikleri kullanılarak, doktorların raporları daha kolay anlaması ve klinik kararlarını daha hızlı alması sağlanabilir. Bu gelişmeler, kanser teşhis süreçlerini daha güvenilir ve etkili hale getirmeyi amaçlamaktadır.

C. Kişiselleştirilmiş Tıbbi Etkisi

YZ destekli kanser teşhisi, erken teşhis ve kişiselleştirilmiş tedavi yaklaşımlarını daha etkili hale getirerek sağlık hizmetlerini dönüştürecektir.

TEŞEKKÜR

Bu makale, YZ destekli kanser teşhisini detaylı bir şekilde analiz etmekte ve YOLOv9 ve EfficientDet modellerinin tedavi yanıtı tahminini nasıl geliştirdiğini açıklamaktadır. Derin öğrenme, gerçek zamanlı tümör tespiti ve otomatik rapor oluşturma ile onkolojinin geleceğini yeniden şekillendirmektedir.

YAZAR KATKILARI

Yazarların çalışmaya katkıları eşittir.

ÇIKAR ÇATIŞMASI BEYANI

Yazarlar arasında herhangi bir çıkar çatışması bulunmamaktadır.

ARAŞTIRMA VE YAYIN ETİĞİ BEYANI

Yazarlar, bu çalışmanın Araştırma ve Yayın Etiği İlkelerine uygun olarak gerçekleştirildiğini beyan ederler.

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Real Estate Price Estimation with AI: A Hybrid Approach Combining Clustering and Machine Learning

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Abstract – Accurate price prediction in the real estate market is important for buyers, sellers, and investors. This study evaluates the performance of various machine learning models including AdaBoost, Gradient Boosting, k-Nearest Neighbors (kNN), Artificial Neural Networks, and Support Vector Machines (SVM) to predict house prices in Gaziantep, Turkey. Parameters such as number of rooms, square meters, building age, floor level, and neighborhood are taken as datasets from a real estate website. A hybrid study is conducted to improve the model performance by clustering analysis using the Simple K-Means algorithm in WEKA application and categorizing the data into groups according to the parameters. The clustered data served as input for Orange 3. Model performance is evaluated using metrics such as Mean Square Error (MSE), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), and R^2 . The results show that AdaBoost consistently achieves the highest accuracy and reliability, followed by Gradient Boosting, which demonstrates strong generalization capabilities. While kNN provided moderate performance, Neural Networks and SVM performed poorly, showing high error measures and poor adaptability.

Keywords – House Price Prediction, Machine Learning, AdaBoost, Gradient Boosting, Clustering, Orange 3, Real Estate Analytics, Predictive Modeling

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I. INTRODUCTION

Accurate real estate price prediction is of great importance for buyers, sellers, and investors. Models such as hedonic pricing generally fail in complex relationships between market value and property features [1]. With applications made with machine learning, more advanced models have emerged, and accurate predictability has increased [2].

In previous studies, various approaches have been investigated in price predictions for the real estate market. AdaBoost and Gradient Boosting have been effective learning techniques for handling complex data sets and with high prediction accuracy [3]. On the other hand, simpler models such as k-Nearest Neighbors (kNN) and Support Vector Machines (SVM) have shown moderate success [4]. Integrating clustering techniques into predictive modeling workflows has also been emphasized as a way to improve model performance by structuring data into meaningful segments [5].

Additionally, platforms like Orange 3 have proven effective in a variety of applications, most notably machine learning [6]. Reference [7] emphasized the role of data mining technologies, including artificial neural networks, in analyzing and predicting trends in real estate markets.

This study focuses on predicting housing prices in Gaziantep, Türkiye, especially in its major districts Şahinbey and Şehitkamil. The dataset obtained from a real estate

platform includes attributes such as number of rooms, square meters, building age, floor level, and neighborhood. In order to increase the accuracy of the predictions and improve the model, the data was extracted from unnecessary data and the dataset created with cluster analysis formed the basis of the prediction model.

The main objective of this research is to evaluate the performance of various machine learning models, including AdaBoost, Gradient Boosting, kNN, Neural Networks, and SVM, in predicting house prices. Metrics such as Mean Square Error (MSE), Root Mean Square Error (RMSE), Mean Absolute Error (MAE), Mean Absolute Percentage Error (MAPE), and R^2 were used to compare the models. The aim of this hybrid study is to determine an effective approach on house price prediction by integrating clustering methods and machine learning algorithms.

II. MATERIALS AND METHOD

The data for this study was obtained from the "Emlakjet" real estate platform.

The dataset was structured to facilitate analysis by eliminating non-essential attributes and addressing inconsistencies. These features form the basis for clustering and predictive modelling conducted in the study.

A. Data Collection

The data used in this study were collected from the “Emlakjet” platform using Python programming software and basic libraries for data processing. The requests library was used to send HTTP requests and retrieve web page content, the BeautifulSoup library was used to analyse HTML data, and the pandas library was used to organise and analyse the data.

The dataset was collected on November 28, 2024, and contains a total of 858 real estate listing and features for Gaziantep, comprising 382 listings for Şahinbey and 365 listings for Şhitkamil districts.

The data collection process is based on the property advertisements of the districts in Gaziantep to conduct the study effectively by focusing on one region. Listings were collected by iterating through pages 1 to 40 under the “Gaziantep for sale” category on the Emlakjet platform.

The dataset includes key attributes related to property listings, such as Listing Number, City, District, Neighbourhood, Room Count, Square Meters, Building Age, Floor Level, Price (in TL), and Listing Date. The data were organised for the cluster analysis and prediction modelling stages.

B. Research Question

The main research question of this study can be expressed as follows:

"Can housing prices in Gaziantep be accurately predicted by applying a hybrid approach with clustering and machine learning techniques, and how do these predictions differ among the major districts of the city?"

This question aims to demonstrate the potential of AI in addressing the challenges of regional real estate price prediction. Focusing on clustering analysis and machine learning algorithms, the study investigates whether AI techniques can generate meaningful predictions and produce accurate price predictions according to different dynamics.

Housing markets are generally affected by various factors such as location, building characteristics. This research presents a data-driven approach to real estate market analysis in Gaziantep by evaluating how these factors can be effectively addressed by a hybrid approach of clustering and predictive modelling.

C. Data Processing

Pre-processing steps were applied to the collected data to ensure consistency. Missing and outlier values were determined and processed accordingly. The basic parameters required for clustering and price estimation were determined and the data was refined and finalized to be used as input accordingly.

Cluster analysis was performed using WEKA software to group parameters such as number of rooms, square meters, building age, etc. Cluster analysis served as a preparation process for predictive modelling. With the clustered data, the Orange 3 platform was used to model house price estimation using machine learning algorithms such as AdaBoost, k-Nearest Neighbors (kNN), Neural Networks, Support Vector Machines (SVM), and Gradient Boosting.

D. Clustering

Cluster analysis aims to group similar data points according to their characteristics in this study. Cluster analysis was performed using the Simple K-Means algorithm with WEKA

program. Simple K-Means assigns data points to clusters according to their proximity to the nearest cluster center and recalculates the center iteratively until convergence.

To determine the optimal number of clusters (K), the Elbow Method was applied separately to the Gaziantep province general dataset and the Şahinbey and Şhitkamil districts. The within-cluster sum of squared errors (WCSS) was calculated between K=2 and K=7. As seen in Figures 1, 2, and 3, a clear turning point was observed around K=5 for Gaziantep and Şahinbey, and around K=4 for Şhitkamil. However, to ensure consistency and comparability across analyses, the final number of clusters was chosen as K=5.

This clustering process facilitated data segmentation before the predictive modeling phase.

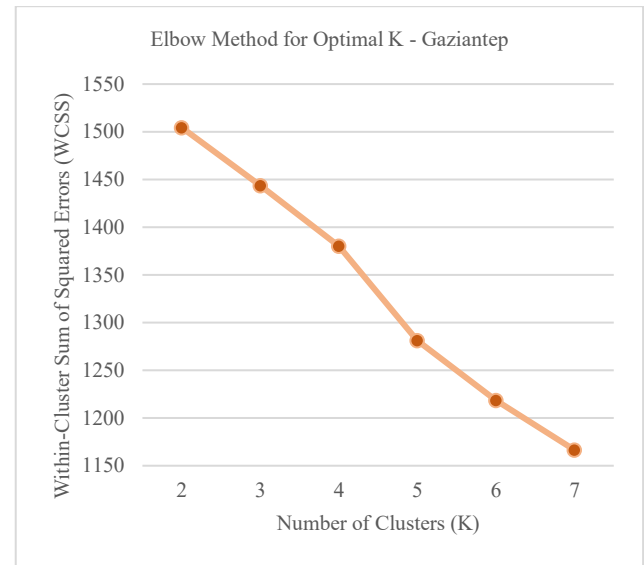


Fig. 1. Elbow plot of the Gaziantep dataset

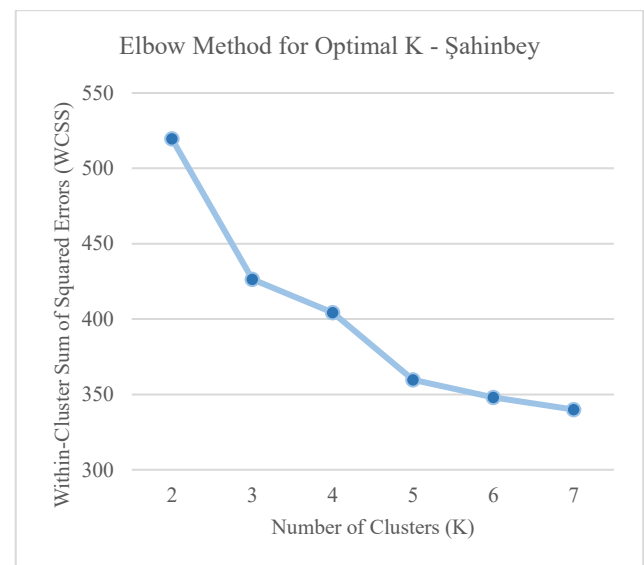


Fig. 2. Elbow plot of the Şahinbey district

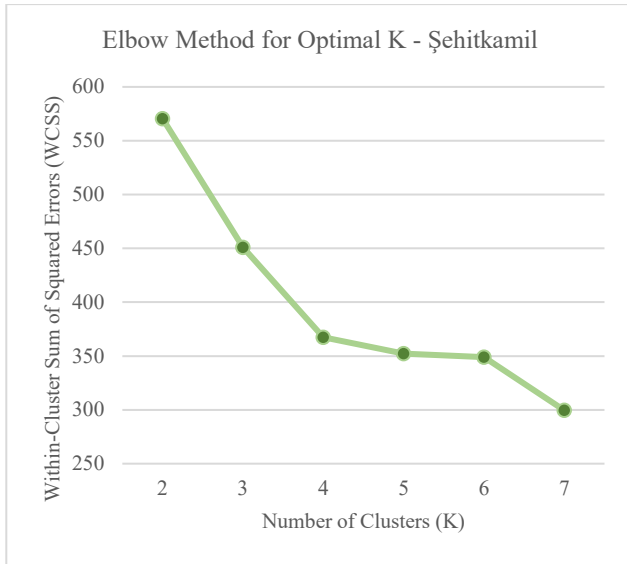


Fig. 3. Elbow plot of the Şhitkamil district

E. Machine Learning Algorithms

In this study, various machine learning algorithms were used to predict house prices:

- **AdaBoost:** A boosting algorithm that combines multiple weak learners (e.g., decision trees) to create a strong predictive model. It increases model accuracy by iteratively correcting errors from previous learners.
- **k-Nearest Neighbors (kNN):** A simple yet effective algorithm that predicts the target variable by finding the mean of the k-nearest data points in the feature space. It is especially useful for capturing local patterns in data.
- **Neural Networks:** A versatile algorithm inspired by the human brain that can capture nonlinear relationships in data. It uses multiple layers of interconnected nodes to learn complex patterns and achieve high prediction accuracy.
- **Support Vector Machines (SVM):** A supervised learning algorithm that determines the optimal hyperplane to categorize data points. It is effective for high-dimensional datasets and captures relationships between features well.
- **Gradient Boosting:** An ensemble method that builds models sequentially, with each model correcting the errors of the previous one. It is known for its robustness and high predictive performance, especially with structured datasets.

A variety of metrics were used to evaluate the performance of these models:

- **Mean Square Error (MSE):** Measures the mean squared difference between the predicted and true values. Lower MSE values indicate better model performance.
- **Root Mean Square Error (RMSE):** The square root of the MSE provides error measurements in the same units as the target variable.
- **Mean Absolute Error (MAE):** Calculates the mean absolute difference between the predicted and true values and provides a more intuitive measure of accuracy.
- **Mean Absolute Percent Error (MAPE):** Represents the percentage error between the predicted and true values, making it easier to understand the relative performance.
- **R squared (R^2):** Indicates the proportion of variance in the target variable explained by the model; values closer to 1 reflect better model fit. [6]

These metrics provide an opportunity to analyze and compare the performance of each algorithm.

The hyperparameter settings of the implemented machine learning algorithms are summarized in Table 1. Since no manual tuning was performed, the models were trained using the standard hyperparameter configurations available in the Orange platform.

Table 1. Hyperparameter Settings of Machine Learning Algorithms

Algorithm	Hyperparameters
AdaBoost	Number of estimators: 50 Learning rate: 1.0 Loss: Linear
kNN	Number of neighbors: 7 Metric: Euclidean Weight: Uniform
Neural Network	Hidden neurons: 100 Activation: Logistic Solver: SGD Regularization α : 0.0001 Max iterations: 200
SVM	Cost (C): 1.0 Epsilon: 0.1 Kernel: RBF Iteration limit: 100
Gradient Boosting	Number of trees: 100 Learning rate: 0.1 Max tree depth: 3 Min split: 2 Subsampling: 1.0

III. RESULTS

F. Clustering Results

Three separate clustering analyses were performed using the Simple K-Means algorithm in WEKA, covering three different datasets, namely all districts of Gaziantep, Şhitmakil district and Şahinbey district. Each dataset included key housing attributes such as district, neighbourhood, number of rooms, square meters, building age, floor level, and price (TL). For all clustering analyses, the number of clusters (k) was determined as five based on the elbow method to ensure consistency across datasets.

Below, WEKA's clustering results for Gaziantep are presented.

Gaziantep Clustering Results

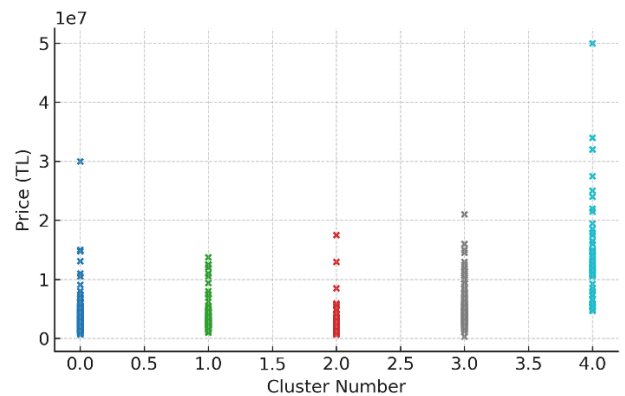


Fig. 4. Gaziantep Overall Clustering Cluster - Price (in TL)

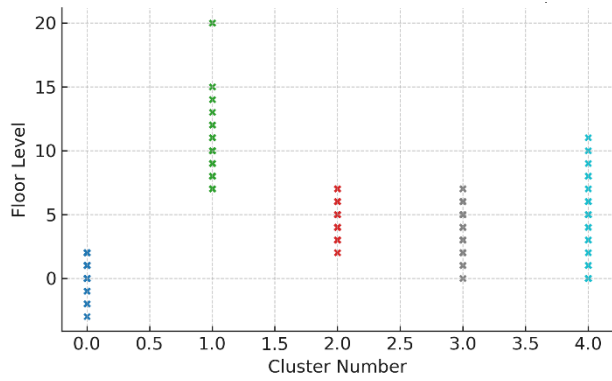


Fig. 5. Gaziantep Overall Clustering Cluster – Floor Level

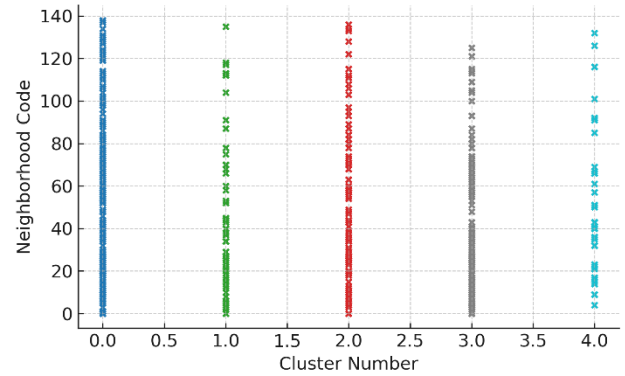


Fig. 9. Gaziantep Overall Clustering Cluster – Neighbourhood

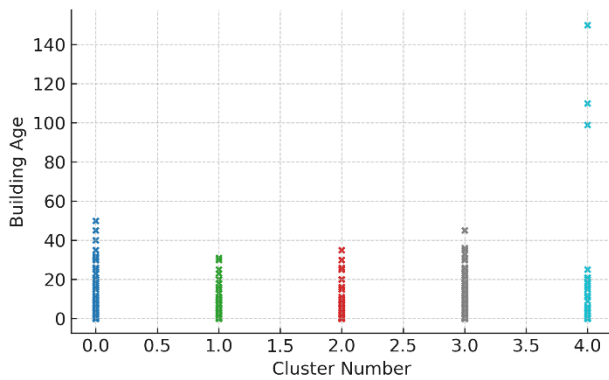


Fig. 6. Gaziantep Overall Clustering Cluster – Building Age

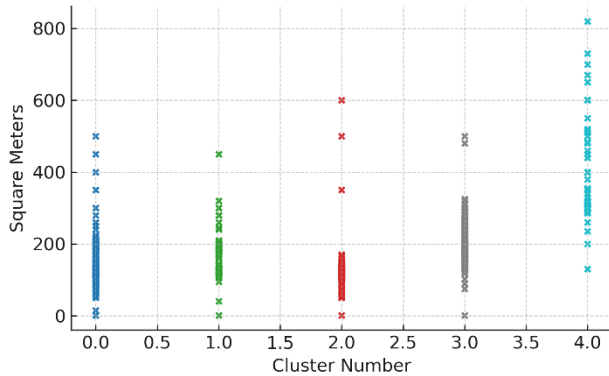


Fig. 7. Gaziantep Overall Clustering Cluster – Square Meters

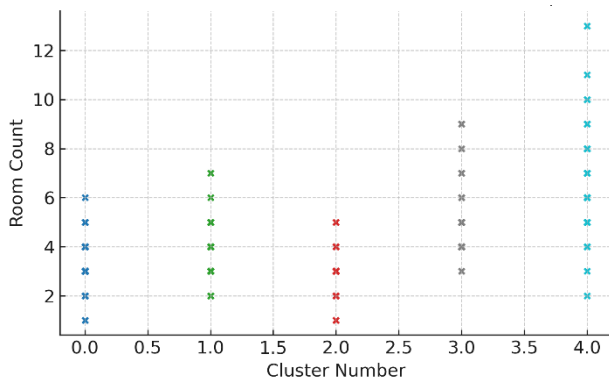


Fig. 8. Gaziantep Overall Clustering Cluster – Room Count

These graphs have divided the real estate market in Gaziantep into different clusters by considering factors such as price, square meters, building age, floor level, room number and neighbourhood. When the clustering results for different attributes are examined, Cluster 0 generally includes real estate with fewer rooms, low square meters, newer building age and lower prices. Cluster 1 generally includes houses with medium prices and more rooms. Cluster 2 generally includes small houses, low prices and young building age. Cluster 3 includes large and high room houses and higher prices. The building age is in the middle segment. Cluster 4 includes the largest houses, old buildings and very high-priced real estates. These segments reflect clear differences in property characteristics, supporting more accurate predictive modeling.

Şhitkamil Clustering Results

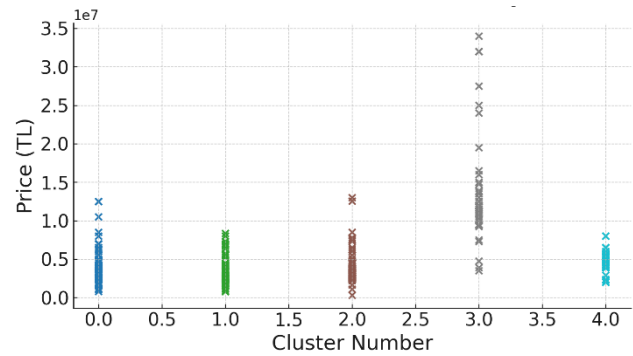


Fig. 10. Şhitkamil Clustering Cluster - Price (in TL)

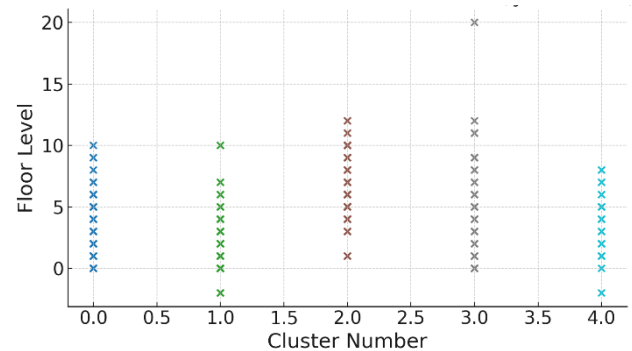


Fig. 11. Şhitkamil Clustering Cluster – Floor Level

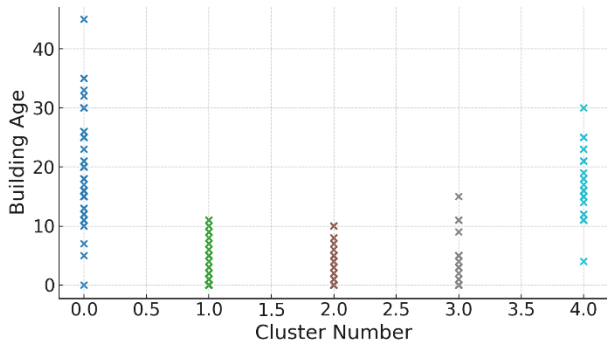


Fig. 12. Şhitkamil Clustering Cluster – Building Age

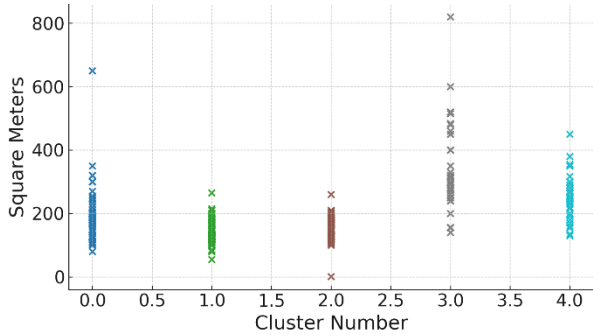


Fig. 13. Şhitkamil Clustering Cluster – Square Meters

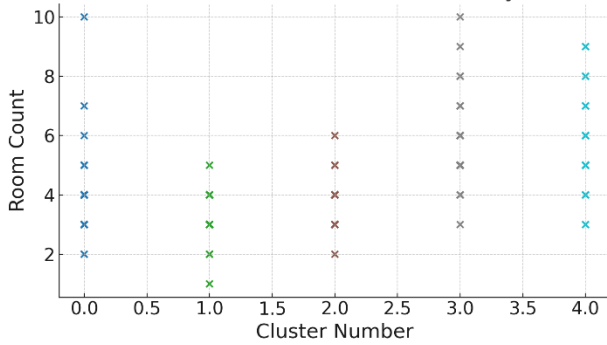


Fig. 14. Şhitkamil Clustering Cluster – Room Count

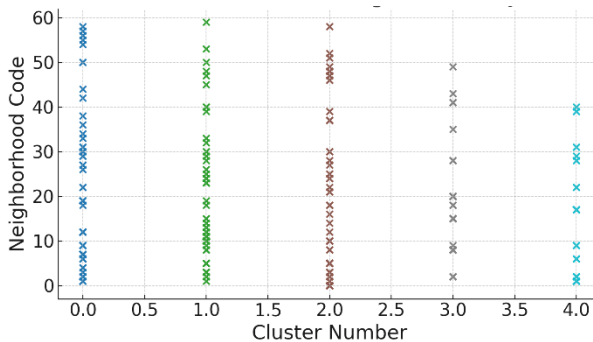


Fig. 15. Şhitkamil Clustering Cluster – Neighbourhood

Clustering results for the Şhitkamil district reveal similar segmentation patterns observed throughout Gaziantep; clusters separate properties primarily based on size, price range, building age, and number of rooms. Cluster 0 generally represents smaller, more affordable, and newer properties, while Cluster 4 encompasses the most expensive, larger, and older properties. This segmentation improves localized price estimation accuracy.

Şahinbey Clustering Results

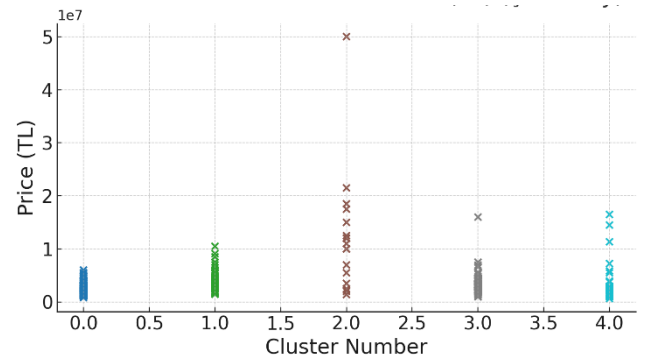


Fig. 16. Şahinbey Clustering Cluster – Price (in TL)

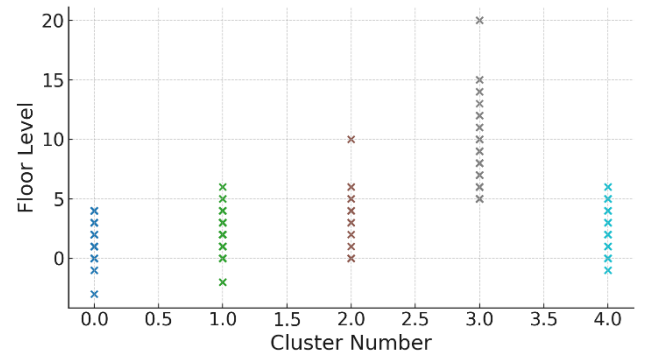


Fig. 17. Şahinbey Clustering Cluster – Floor Level

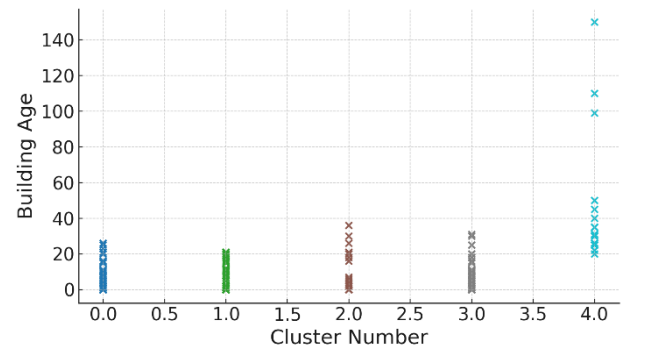


Fig. 18. Şahinbey Clustering Cluster – Building Age

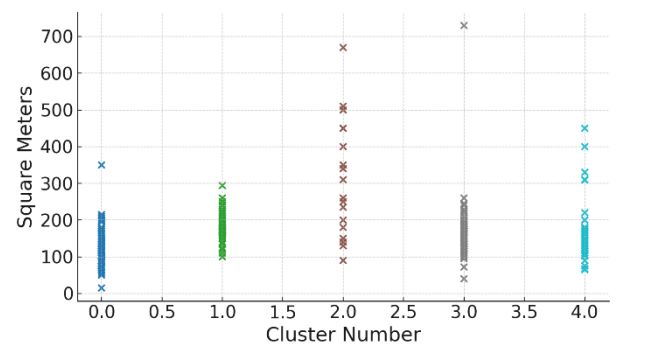


Fig. 19. Şahinbey Clustering Cluster – Square Meters

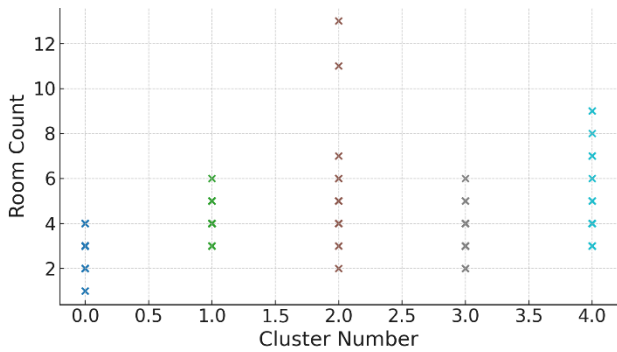


Fig. 20. Şahinbey Clustering Cluster – Room Count

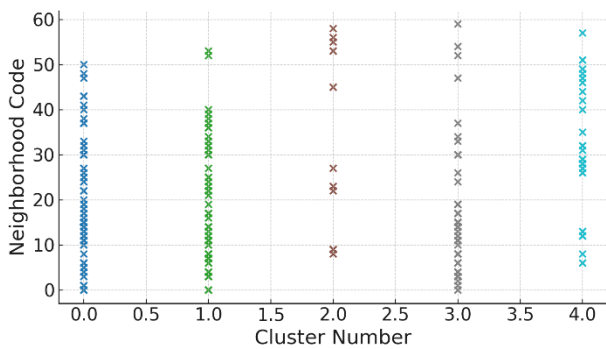


Fig. 21. Şahinbey Clustering Cluster – Neighbourhood

The clustering results for the Şahinbey area demonstrate a clear segmentation of the real estate market based on property characteristics such as price, size, number of rooms, building age, and floor level. Cluster 0 generally includes smaller, lower-priced, and newer properties, while Cluster 4 contains the largest and most expensive homes with older building ages. This clustering differentiation improves the accuracy of housing price estimates for Şahinbey by capturing the area's internal diversity.

Overall, clustering enabled clearer segmentation of the housing market, supporting more accurate regional price predictions.

G. Model Results

Cluster analysis applied dataset was used as input to create the prediction model. Orange 3 application was used to apply machine learning algorithms. As shown in the model below, Gradient Boosting, Support Vector Machines (SVM), AdaBoost, k-Nearest Neighbors (kNN), and Neural Networks algorithms were applied, and the results were evaluated with performance metrics.

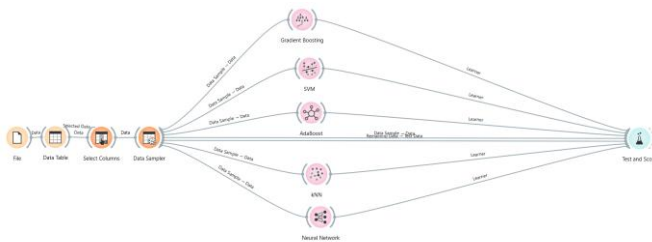


Fig. 10. Workflow of Predictive Modeling in Orange 3

Table 2 shows the performance on the training dataset for Gaziantep city and Table 3 on the test dataset. In the training set, AdaBoost showed the best performance with very low MSE and high R^2 value, while Gradient Boosting showed a better performance on the test dataset, although general decrease in performance was observed on the test data compared to the training dataset.

Table 2. Performance comparisons of Gaziantep Overall models on training dataset

Model	MSE (*10 ⁹)	RMSE (*10 ⁶)	MAE (*10 ⁶)	MAPE	R ²
AdaBoost	6.130	0.248	0.129	0.051	0.997
kNN	7.999	0.282	1.327	0.328	0.552
Neural Network	11.529	0.340	1.942	0.594	0.355
SVM	18.430	0.429	2.164	0.559	-0.032
Gradient Boosting	13.073	1.143	0.793	0.243	0.927

Table 3. Performance comparisons of Gaziantep Overall models on test dataset

Model	MSE (*10 ⁹)	RMSE (*10 ⁶)	MAE (*10 ⁶)	MAPE	R ²
AdaBoost	9.986	3.160	1.556	0.299	0.568
kNN	10.013	3.164	1.699	0.331	0.567
Neural Network	15.892	3.986	2.652	0.646	0.313
SVM	25.728	5.072	2.885	0.542	-0.112
Gradient Boosting	8.333	2.887	1.479	0.312	0.640

Table 4 shows the performance in the training dataset for Şahinbey district and Table 5 shows the performance in the test dataset. While Adaboost and Gradient Boosting showed a successful performance in the training dataset, the performance of all models decreased in the test dataset.

Table 4. Performance comparisons of Şahinbey District models on training dataset

Model	MSE (*10 ⁹)	RMSE (*10 ⁶)	MAE (*10 ⁶)	MAPE	R ²
AdaBoost	63.618	0.252	0.134	0.053	0.996
kNN	7,942.558	0.282	0.112	0.329	0.449
Neural Network	10,261.525	0.320	0.154	0.475	0.288
SVM	15,876.133	0.398	0.167	0.377	-0.102
Gradient Boosting	4,534.197	0.673	0.496	0.178	0.969

Table 5. Performance comparisons of Şahinbey District models on test dataset

Model	MSE (*10 ⁹)	RMSE (*10 ⁶)	MAE (*10 ⁶)	MAPE	R ²
AdaBoost	5,278.620	2.298	1.083	0.306	0.357
kNN	4,365.002	2.089	1.097	0.353	0.468
Neural Network	7,109.604	2.666	1.557	0.505	0.134
SVM	9,246.586	3.041	1.592	0.417	-0.127
Gradient Boosting	7,477.841	2.735	1.272	0.453	0.089

Table 6 shows the performance in the training dataset of Şehitkamil district and Table 7 in the test dataset. Similarly, AdaBoost and Gradient Boosting gave good results in the

training dataset. Similarly, AdaBoost gave a successful result in the test dataset.

Table 6. Performance comparisons of Şehitkamil District models on training dataset

Model	MSE (*10 ⁹)	RMSE (*10 ⁶)	MAE (*10 ⁶)	MAPE	R ²
AdaBoost	6.884	0.262	0.134	0.052	0.997
kNN	7.166	0.268	1.452	0.276	0.727
Neural Network	16.554	0.407	2.096	0.394	0.370
SVM	29.862	0.546	2.800	0.448	-0.137
Gradient Boosting	7.476	0.865	0.600	0.153	0.972

Table 7. Performance comparisons of Şehitkamil District models on test dataset

Model	MSE (*10 ⁹)	RMSE (*10 ⁶)	MAE (*10 ⁶)	MAPE	R ²
AdaBoost	21.910	1.480	1.014	0.335	0.848
kNN	54.306	2.330	1.565	0.442	0.623
Neural Network	86.006	2.933	1.986	0.518	0.404
SVM	182.049	4.267	2.712	0.569	-0.262
Gradient Boosting	26.916	1.641	1.156	0.366	0.813

The AdaBoost algorithm achieved the lowest error and highest R² values on training data in all regions, including Gaziantep, Şahinbey and Şehitkamil. In the evaluations made on the test data, it was observed that the Gradient Boosting algorithm achieved more stable results, especially for Gaziantep. When we look at the Şehitkamil district, it was the model that achieved the highest performance in terms of all models. SVM, kNN and Neural Network algorithms showed poor performance in all models.

IV. DISCUSSION

In this study, a hybrid approach of clustering and machine learning algorithms was used to estimate housing prices in Gaziantep province. The results obtained throughout the study revealed that the algorithms used showed differences in terms of accuracy and overall performance. In particular, AdaBoost stood out with the highest accuracy with low MSE and RMSE values, while Gradient Boosting achieved more stable results in the test data.

In this study, a hybrid approach with clustering analysis and machine learning algorithms was applied to obtain housing price prediction modeling for Gaziantep province. In order to make a detailed comparison in the model, model results were also obtained for Şehitkamil and Şahinbey districts in addition to Gaziantep province.

AdaBoost gave the best performance overall when compared for 3 different models. Based on this observation, AdaBoost algorithm is considered to be a strong option in the dataset. Gradient Boosting stands out as another option with its more stable performance. kNN, SVM and Neural Network algorithms have high error rates and low R² values for all data sets, indicating that the accuracy value is low. This shows that it does not have good performance in complex data sets.

The observed poor performance for the SVM and Neural Network algorithms can be explained by several factors. First, the relatively limited dataset size for each district (382 samples for Şahinbey and 365 for Şehitkamil), which may have limited

the algorithms' learning capacity, particularly their ability to capture complex nonlinear patterns. Second, the default hyperparameter settings were used in the Orange 3 environment without advanced tuning, which could significantly impact the performance of the SVM and Neural Network models. These algorithms are known to be highly sensitive to hyperparameter optimization. To overcome this issue, future research could evaluate the use of advanced tuning techniques such as grid search or Bayesian optimization in conjunction with cross-validation methods. Furthermore, increasing the dataset size and applying feature engineering strategies could help improve model performance, especially for the SVM and Neural Network models.

Cluster analysis provides a hybrid approach to this study and provides an important data set by using it to separate houses with different qualities. The study was conducted with the Simple K-Means algorithm and many features were evaluated and divided into groups.

In future studies, testing on different regions or cities for real estate market prediction will contribute to the development of the model. Different parameters can be determined as the focal point while performing cluster analysis and the prediction accuracy can be increased by expanding the models.

V. CONCLUSION

In this study, although a certain success rate was shown compared to other applications with the hybrid approach focused on the Gaziantep region with AdaBoost and Gradient Boosting algorithms, it was concluded that the model could be improved. kNN, SVM and Neural Network algorithms failed in this model by showing insufficient results. The applied hybrid approach shows that studies on complex data sets in real estate price estimation can yield more effective results.

The customization of models to be applied in the real estate market with cluster analysis has affected the accuracy of the results.

As a result, applications made with the hybrid approach of machine learning and cluster analysis have the chance to be an effective method in price estimations by being developed. In future studies, this hybrid approach can be improved and its accuracy can be increased.

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Authors' Contributions

The authors' contributions to the paper are equal.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics

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Prediction of Wind Speed Using Tree-Based Ensemble Algorithms: CatBoost, HistGBM, and XGBoost[†]

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Abstract – This research compares three advanced tree-based machine learning models (XGBoost, HistGradientBoosting, and CatBoost) for urban wind speed prediction (in m/s). A dataset covering four years is used to train the models, and their performance is evaluated, especially on the test data. The root mean square error (RMSE), mean absolute percentage error (MAPE), coefficient of determination (R^2), and P-value are used to evaluate the model's performance. XGBoost is the best amongst all the models with respect to RMSE, MAPE, and R^2 values, which are measured at 0.0416, 0.0089, and 0.9993, respectively. CatBoost achieved the second-best performance with highly competitive results, demonstrating an RMSE of 0.0843 and an R^2 value of 0.9972. The third model, with an RMSE of 0.1174, has an R^2 value of 0.9946. When the p-values are considered, then all estimates of the models is found to be statistically significant. The results indicate that the ensemble type modeling algorithms have very active performance for the time-series problems like estimations of V (m/s). Hence, the XGBoost method is found to be the most efficient and trustworthy for the V (m/s) estimation applications.

Keywords – Wind Speed Prediction, Tree-Based Ensemble Learning, XGBoost, CatBoost, Time Series Forecasting

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I. INTRODUCTION

Accurately predicting wind speed (V in m/s) and its variability is critical for effectively integrating wind energy systems (WES) into urban electricity grids with intense energy demands. In keeping with the growing interest in sustainable energy, small-scale wind turbines are also becoming accepted in urban areas. In this case, having short-range wind speed forecasts that are accurate and reliable is of utmost importance.

The prediction of V (m/s) is inherently a time series problem. V is influenced by unclear atmospheric events, local geographic factors and temporal fluctuation. Traditional statistical methods such as ARIMA and exponential smoothing may fail to capture the nonlinear and dynamic patterns in V data. In the past few years, techniques in machine learning (ML) through ensemble learning methods have become popular. Among the strong competitors to replace that pattern are the ML techniques because of their nonlinearity, multivariate input, and high-dimensional nature in feature space.

According to other authors [1] who used data from the United States from 2017 to 2019, ridge regression, polynomial regression, and artificial neural networks (ANN) for the prediction of wind speed were compared. Based on the

findings, ANN was considered the least efficient, while polynomial regression had the least RMSE and the highest R^2 .

Another study has proposed a novel hybrid CNN-LSTM approach to multi-step wind prediction designed for the autonomous sailing boat [2]. Their model outperformed benchmark models in terms of MAE, RMSE, R^2 , and correlation coefficient indicated after being trained on the National Climate Database of New Zealand. Using wind data from South Africa, Authors in [3], tested ARMA, ANN, and ANFIS with an emphasis on short-term predicting accuracy. For longer forecast periods, ANN and ANFIS exceed the ARMA method by a considerable margin; ARMA is seen to work quite well for short-term prediction horizons. According to Mugwarei et al. [4], the Dynamic Architecture for Artificial Neural Networks (DAN2) has performed effectively in the time series forecasting tasks. However, convolutional neural networks (CNN), random forest, and XGBOOST were all tested, and CNN surpassed DAN2 in wind speed prediction because of its improved feature extraction and spatial learning capabilities.

The present research employs three tree-based machine learning models - CatBoost, HistGBM, and XGBoost - for V prediction. These are high accuracy and computationally

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efficient regression models for temporal parameters. These algorithms are trained and tested on a dataset collected for four years in the urban setting.

Statistical metrics, including the coefficient of determination (R^2), Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), and p-value, are used to evaluate model performance. The results show that XGBoost has the highest prediction accuracy. Nevertheless, the output values produced by CatBoost and HistGBM models are reasonably close to the XGBoost performance. This study thereby demonstrates the efficacy of gradient boosting-based models for V prediction under urban environmental conditions.

II. MATERIALS AND METHOD

In this work, V daily mean data from 2021 to 2025 is obtained from the NASA POWER database, which offers dependable and high-resolution datasets [5]. For model training within the urban limits, data were collected and preprocessed for improving the quality of consistency and completeness. Three great tree-based ensemble learning algorithms are adopted for the task of predicting wind speed: CatBoost, Histogram-Based Gradient Boosting (HistGBM), and Extreme Gradient Boosting (XGBoost). Such models can deal with multicollinearity and are robust in terms of handling structured time-series data.

A. CatBoost Model

CatBoost is the latest gradient boosting technique to perform well on a number of successful tasks [6]. Each iteration t adds a new tree $h_t(x)$ to minimize the loss function L :

$$F_t(x) = F_{t-1}(x) + \eta \cdot h_t(x) \quad (1)$$

where $F_t(x)$, η , and $h_t(x)$ represent the prediction at iteration t , the learning rate, and the newly added decision tree, respectively.

CatBoost uses ordered boosting and symmetric trees to avoid prediction shift and overfitting, and it efficiently handles categorical information without requiring specific preprocessing. The goal is to minimize a loss function $L(y, F(x))$. Here, for regression, MSE is preferred as loss function.

$$L(y, F(x)) = \frac{1}{n} \sum_{i=1}^n (y_i - F(x_i))^2 \quad (2)$$

where y_i is the observed value.

B. Histogram-Based Gradient Boosting (HistGBM) Model

HistGBM is a more rapid version of gradient boosting that divides continuous features into integer bins to produce histograms [7]. At each iteration t , the same update rule (in Eq. 1) is used to add a tree. Rather than utilizing all feature values, features are binned to save computation:

$$\text{bin}(x) = \left\lfloor \frac{x - x_{\min}}{x_{\max} - x_{\min}} \cdot n_{\text{bins}} \right\rfloor \quad (3)$$

where $x_{\max}$, x , and $x_{\min}$ represent maximum, minimum and actual value of feature, respectively. While n_{bins} denotes the number of bins used for discretization, $\lfloor \cdot \rfloor$, the floor function rounds down to the nearest integer. This adaptation enables the

method to effectively construct histograms and split points, resulting in reduced memory use and training time.

C. Extreme Gradient Boosting (XGBoost) Model

XGBoost improves gradient boosting by regularizing and parallelizing it [8]. It seeks to reduce a regularized goal:

$$\mathcal{L}^{(t)} = \sum_{i=1}^n l(y_i, \hat{y}_i^{(t)}) + \sum_{k=1}^t \Omega(h_k) \quad (4)$$

where l represents the loss function. $\Omega(h)$ given as:

$$\Omega(h) = \gamma T + \frac{1}{2} \lambda \sum_{j=1}^T w_j^2 \quad (5)$$

where T and w_j represent the number of leaves and the weight of leaf j .

D. Prediction performance criteria

Each models' predictive ability is evaluated using statistical metrics such as Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), coefficient of determination (R^2), and p-value. These metrics supported a complete evaluation of the models' accuracy and statistical significance under various environmental circumstances. Root Mean Squared Error (RMSE) is calculated by taking the square root of MSE; the error unit is the same as the variable being predicted [9].

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2} \quad (13)$$

$$MAPE = \frac{100\%}{n} \sum_{i=1}^n \left| \frac{y_i - \hat{y}_i}{y_i} \right| \quad (14)$$

R-squared (R^2) shows the explanatory power of the model on the dependent variable. Values closer to 1 indicate better fit [9].

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (15)$$

where y_i represents the true value of the i th sample, $\hat{y}_i$ represents the value predicted by the model of the i th sample, $\bar{y}$ represents the mean of the true values, and n represents the total number of samples. The p-value derived from hypothesis testing (for example, for regression coefficients) evaluates the statistical significance of the model or its predictors [10].

III. RESULTS AND DISCUSSION

In the present study, V predictions are performed using a time series dataset obtained from the NASA POWER database between 2021 and 2025. To improve model learning and capture temporal connections in data, feature engineering is used. Three types of derived features are created: lag-based features, rolling statistical features, and a difference-based feature.

The lag characteristics (V_LAG_1 , V_LAG_3 , and V_LAG_7) indicate wind speed data from one, three, and seven days prior to the current observation, respectively. The attributes provide a temporal context, enabling the model to learn from past trends. Two rolling statistics are also included: $Roll_Mean_5$, the 5-day moving average of wind speed, which smoothes short-term swings and depicts local patterns; and $Roll_STD_5$, the 5-day rolling standard deviation, which

captures recent variability and volatility in wind speed measurements. Finally, ΔV reflects the day-to-day variation in wind speed, which provides insight into short-term directional variations.

The 80:20 split maintains the temporal order of time series data, ensuring robust dataset evaluation by creating training and testing partition.

Three tree-based ensemble learning methods are used: XGBoost, Histogram-Based Gradient Boosting (HistGBM), and CatBoost. To guarantee fair comparison, all models are trained with similar hyperparameters: 300 boosting iterations, a learning rate of 0.05, and a maximum tree depth of 5 (for XGBoost and HistGBM) or 6 (for CatBoost). Specifically, XGBoost used second-order Taylor approximation and L_2 regularization, HistGBM used histogram binning to improve computational efficiency, and CatBoost used ordered boosting to reduce overfitting and handle training bias [11].

Models are evaluated using performance indicators including RMSE, MAPE, R^2 , and p-value. XGBoost achieved the high accuracy of the three, while HistGBM and CatBoost produced comparable results, demonstrating the promise of gradient boosting approaches in short-term wind speed prediction in urban environments. Model predictions and observed values over the entire dataset are seen in Figure 1.

Figure 1 compares the observed V values with the predictions made by the XGBoost, HistGBM and CatBoost models in the test data range. Especially in the test period (last section of the graph), it is observed that all models follow the general trends successfully, but XGBoost and HistGBM are more sensitive to sudden changes.

Figure 2 compares the observed wind speed values on the test dataset with the predictions of the XGBoost, HistGBM and CatBoost models. All models successfully tracked the short-term changes in wind speed, and it is seen that the predictions of the CatBoost and HistGBM models match the observations more closely. Comparison of model predictions with observations on the test dataset is seen in Figure 2.

Figure 3 shows the short-term V forecasts for the first 15 days of the test data. The XGBoost, HistGBM and CatBoost models followed the observed values very closely, and it is observed that the models gave synchronized responses especially on days when sudden changes occurred, indicating that their short-term forecast performance is strong. Model-based short-term prediction of V on the test dataset is seen in Figure 3.

Figure 4 compares the observed V values with the predictions of the XGBoost, HistGBM and CatBoost models on the test data. The predictions of all three models are concentrated around the reference line, and especially the CatBoost and XGBoost models produced the results closest to the observation, with lower deviations, indicating high levels of accuracy. Scatter plots of estimated and observed V on the test dataset using (a) XGBoost, (b) HistGBM, and (c) CatBoost models are seen in Figure 4.

Figure 5 visually compares how early in testing each model stabilizes or at what iteration interval it performs better.

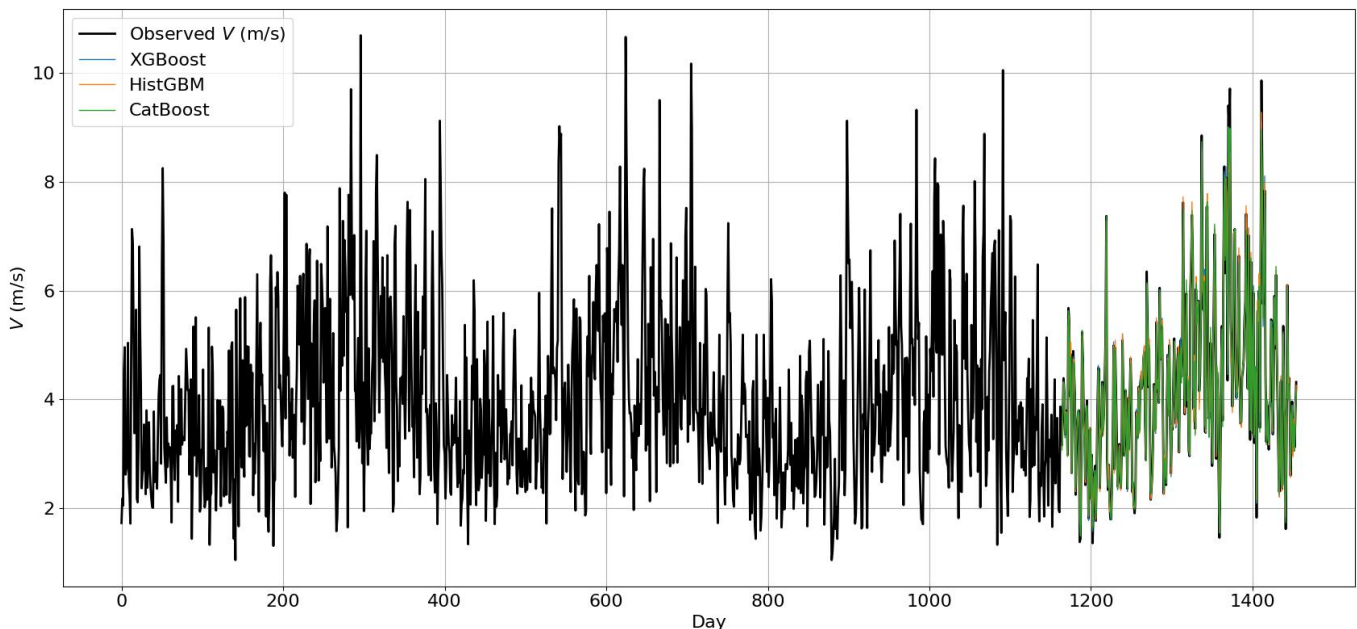


Figure 1. Model predictions and observed values over the entire dataset

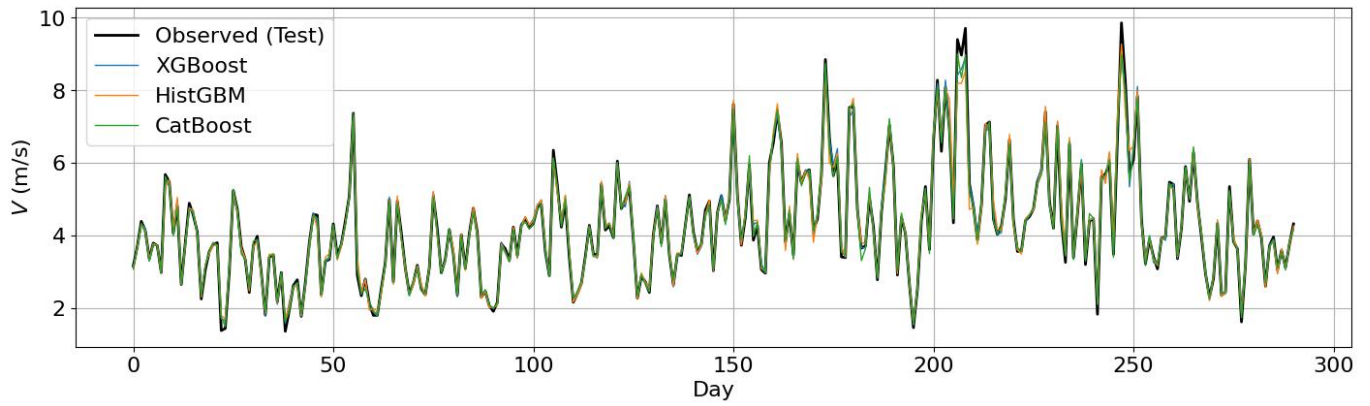


Figure 2. Comparison of model predictions with observations on the test dataset

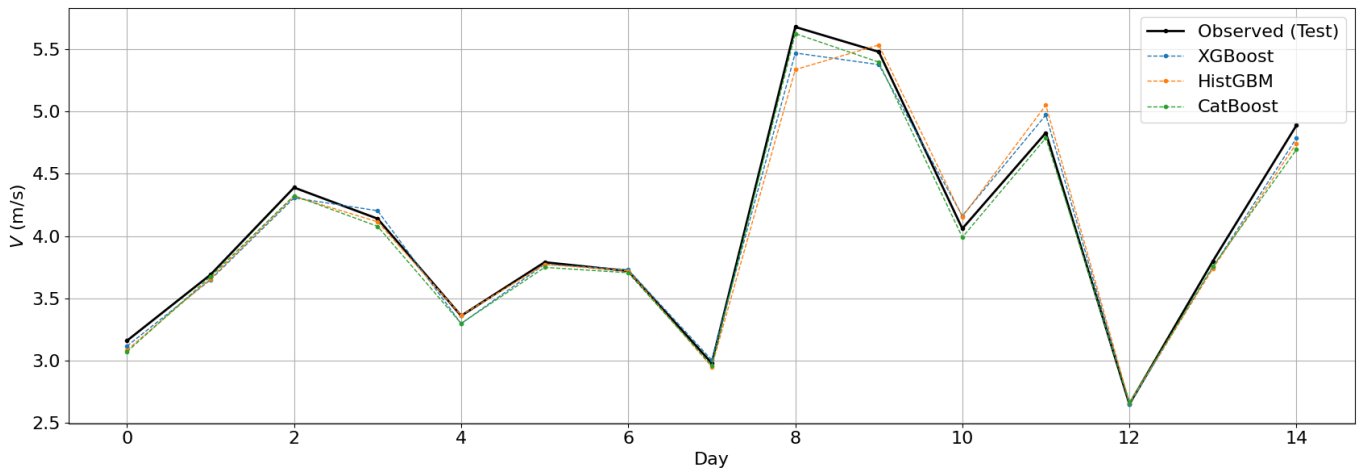


Figure 3. Model-based short-term prediction of V on the test dataset

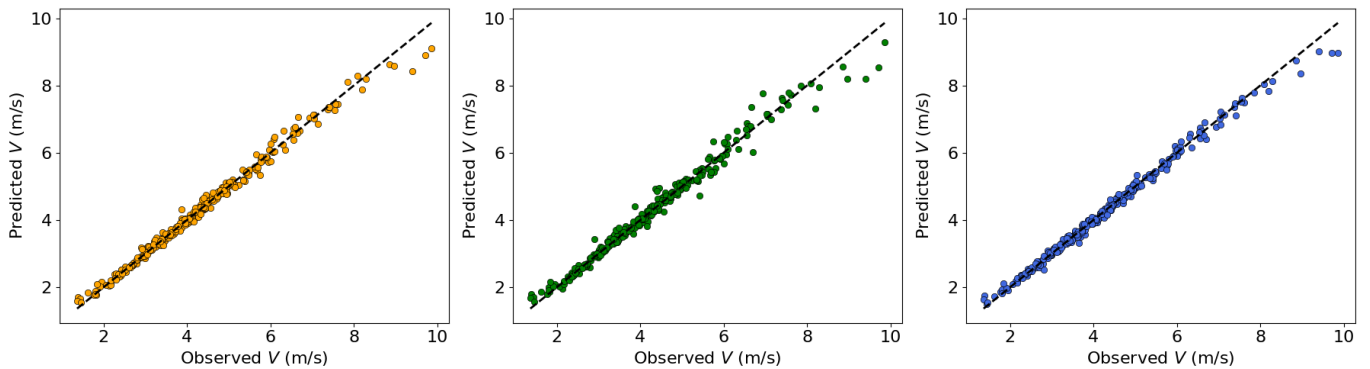


Figure 4. Scatter plots of estimated and observed V on the test dataset using (a) XGBoost, (b) HistGBM, and (c) CatBoost models.

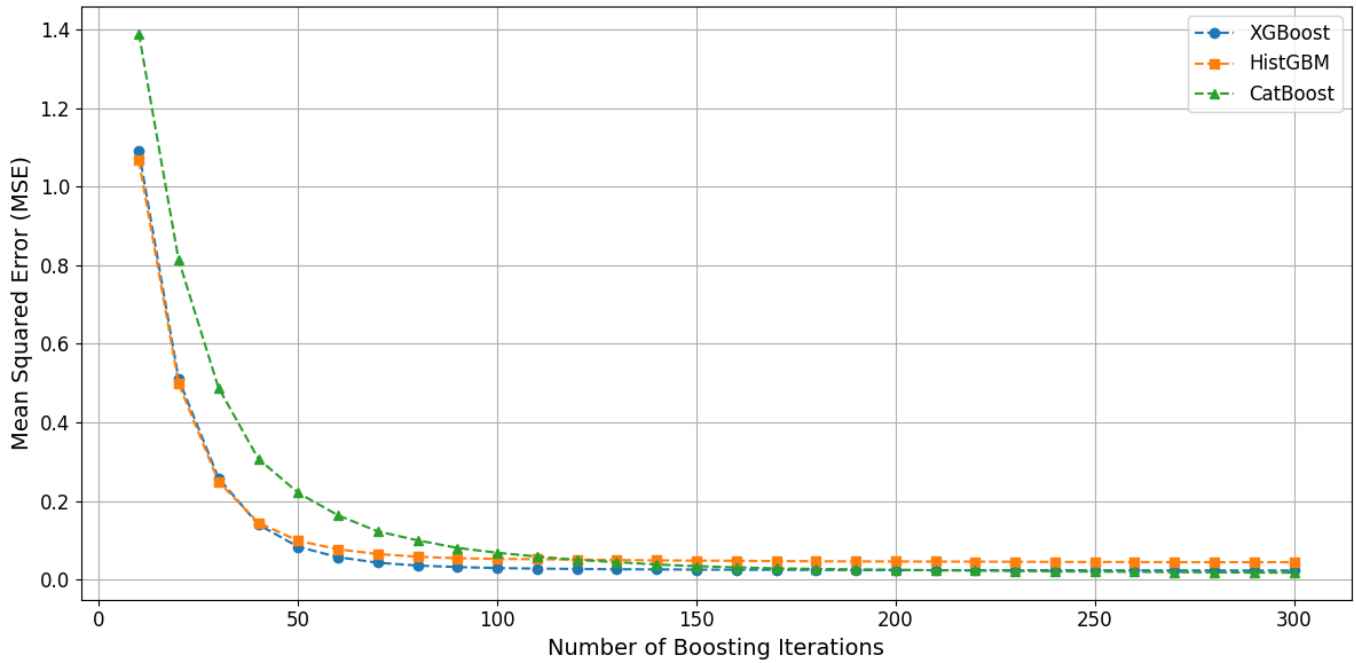


Figure 5. Loss curves (MSE) of XGBoost, HistGBM, and CatBoost models across different boosting iterations.

According to the results on the test data, the XGBoost model exhibited the highest accuracy and best generalization performance ($R^2 = 0.9993$) with the lowest RMSE (0.0416) and MAPE (0.0089) values.

Although the CatBoost and HistGBM models also showed high accuracy, XGBoost stands out with its superior performance in all metrics. Performance metrics of models is given in Table 1.

Table 1. Performance metrics of models

Model	RMSE	MAPE	R^2	p-value	Rank
XGBoost	0.0416	0.0089	0.9993	0	1
CatBoost	0.0843	0.0184	0.9972	0	2
HistGBM	0.1174	0.0200	0.9946	0	3

This study confirms the reliability of XGBoost, as suggested by Xiong et al. [12]. Their research improved the BH-XGBoost method with Bayesian optimization, which is proposed for short-term wind power forecasting. In the comparisons, BH-XGBoost showed higher accuracy compared to models such as SVM, ELM, and LSTM.

In a similar study, Mollick et al. found CatBoost to be the highest performing model, although its R^2 values (0.86-0.87) were much lower [13]. However, this work used effective feature engineering approaches and the XGBoost model to achieve highly accurate results in short-term wind speed estimation, resulting in a R^2 of 0.9993 and RMSE of 0.0416. This comparison indicates that the XGBoost technique has a higher predictive potential, notably in capturing wind speed fluctuations with more precision.

IV. CONCLUSION

In this study, V prediction is conducted using advanced ensemble learning models—XGBoost, CatBoost, and HistGradientBoosting (HistGBM)—on a time-series dataset derived from the NASA POWER database (2021–2025). Feature engineering methods, including lag-based variables, rolling statistics, and differencing, are applied, and the dataset is split into training and testing sets using an 80:20 ratio. Model performances are assessed via RMSE, MAPE, R^2 , and p-value. The major findings and contributions of the study are as follows:

- The best performance is achieved by XGBoost, with an RMSE of 0.0416, an MAPE of 0.0089, and an R^2 of 0.9993, demonstrating superior predictive capability.
- CatBoost provided stable and reliable forecasts, effectively capturing local fluctuations in wind speed.
- The result of HistGradientBoosting is acceptable, but it is less effective under rapidly changing wind conditions.
- In all cases, the models produced statistically significant predictions with p-values below the standard threshold, confirming their robustness.
- This study integrates various feature engineering techniques, including lag-based variables, rolling window statistics, and temporal differencing, to considerably improve the learning capability of ensemble models based on tree-based forecasting. This approach contributes to the literature by in the estimation process.

The results suggest that ensemble learning is an effective method for estimating long- and short-term wind speeds. A future research project may explore adding additional meteorological inputs, testing the model on different climate

zones, or incorporating deep learning-based hybrid approaches to improve predictive performance.

Authors' Contributions

The authors' contributions to the paper are equal.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics.

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Detection and Disinfestation of Diseased Plants with YOLO Based ANFIS Controlled Unmanned Ground Vehicle

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Abstract – Plant diseases remain a major challenge in modern agriculture, causing considerable reductions in both yield and crop quality. This study focuses on the development of an intelligent unmanned ground vehicle (UGV) capable of detecting plant diseases in real time and autonomously responding through targeted spraying. A camera mounted on the UGV captures continuous images of crop rows, and disease detection is carried out using the YOLO (You Only Look Once) algorithm—chosen for its speed and accuracy in real-time object recognition. To evaluate model performance, YOLOv7, v8, and v9 were trained using datasets focused on potato leaf diseases, including early and late blight. The YOLOv8 model was selected for deployment on a Raspberry Pi 4B based on its superior detection accuracy. Additionally, a servo motor-enhanced vision system was implemented to broaden the camera's coverage.

The UGV's autonomous driving is enabled by a combination of five ultrasonic sensors and an ANFIS (Adaptive Neuro-Fuzzy Inference System)-based decision-making module, which governs navigation and motion planning. As the vehicle traverses the field, the onboard system identifies infected plants and activates a localized spraying mechanism to treat only the affected areas. This integrated approach significantly reduces pesticide use, minimizes environmental harm, and lowers the dependency on manual labor. The results demonstrate a promising application of artificial intelligence and embedded systems for sustainable and efficient disease management in precision agriculture.

Keywords – Diseased Plant Detection, YOLO, Spraying, ultrasonic sensor, Raspberry Pi, motion planning, ANFIS

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I. INTRODUCTION

Agriculture, one of humanity's most vital sectors, faces significant challenges due to plant diseases and pests, which threaten the sustainability of food production. These diseases, caused by various fungi, pathogens, viruses, or bacteria, severely affect both the yield and quality of crops. Traditional methods of detecting plant diseases are often time-consuming and inefficient. However, advancements in artificial intelligence (AI) and image processing technologies have introduced innovative solutions for early and accurate disease detection [1]. The excessive use of pesticides and agrochemicals has further underscored the need for precise disease identification and targeted spraying. Recent research has focused on developing autonomous systems capable of real-time plant disease detection and treatment. Many studies have employed deep learning algorithms, particularly the YOLO family of object detection models, due to their speed and accuracy in recognizing diseased plant areas [2]–[7].

For instance, Shill [2] utilized YOLOv3 and YOLOv4 algorithms to classify 17 different disease types across 13 plant species, while Soeb et al. [3] applied the YOLOv7 technique for detecting five types of tea leaf diseases using a dataset of 4000 images. Mahesh [4] implemented YOLOv5 for early detection of bacterial spots on bell peppers, aiming to assist farmers with timely interventions. Similarly, Reddy [5] focused on detecting diseases on mulberry leaves critical to the sericulture industry using YOLO combined with Convolutional Neural Networks (CNNs).

Other notable works include Singh and Misra's [6] research on image segmentation for plant disease detection using MATLAB, and Dung's [7] development of a real-time disease detection system by implementing a Single Shot Detector (SSD) model on a Raspberry Pi 3 platform. Though Singh and Misra's algorithm achieved high accuracy, its slow processing limited its use in real-time applications. In contrast, Dung's model delivered faster and reliable detection suitable for real-world scenarios.

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Furthermore, researchers such as Sathiesh Kumar [8] developed a rover, incorporating a Raspberry Pi 2 board and ATmega2560 microcontroller to collect environmental data (temperature, humidity, and weather conditions) and assist in autonomous navigation using ultrasonic sensors. Sharanesh et al. [9] employed VGGNet16 and InceptionResNetV2 architectures to detect diseases in crops like strawberries and grapes, achieving a success rate of 95.23%. Ahmed et al. designed Agrobot, a smart agricultural monitoring system that operates in real time. The system utilizes a Raspberry Pi for low-cost hardware implementation and employs the YOLO algorithm for detecting plant health conditions and other agricultural features. Field experiments demonstrated the system's potential for efficient and automated crop monitoring [10]. Another study presents the development of a pesticide spraying robot integrated with IoT technology for agricultural applications. The robot aims to minimize manual labor and optimize the spraying process through remote control and monitoring. Its design focuses on improving safety, precision, and coverage in pesticide application [11]. Vani et al. proposed a machine learning method for detecting, tracking, and forecasting plant diseases to help farmers manage crop health effectively. The approach demonstrates promising accuracy in early disease identification and progression prediction [12]. Building on recent advancements in smart agriculture, this study proposes an autonomous Unmanned Ground Vehicle (UGV) designed to detect diseases in potato plants and perform targeted spraying in real time. The UGV autonomously navigates between crop rows using a set of ultrasonic sensors, and identifies diseased plants through deep learning-based image processing running on a Raspberry Pi platform. Upon detection, a precision spraying mechanism is activated to treat only the affected plants.

II. SYSTEM OVERVIEW

This integrated system—combining motion planning, autonomous navigation, intelligent disease identification, and localized disinfection—aims to reduce pesticide usage, lower labor demands, and improve both the quality and yield of potato crops. The overall design promotes and contributes to efficient, scalable, and environmentally friendly agricultural practices (Fig.1).

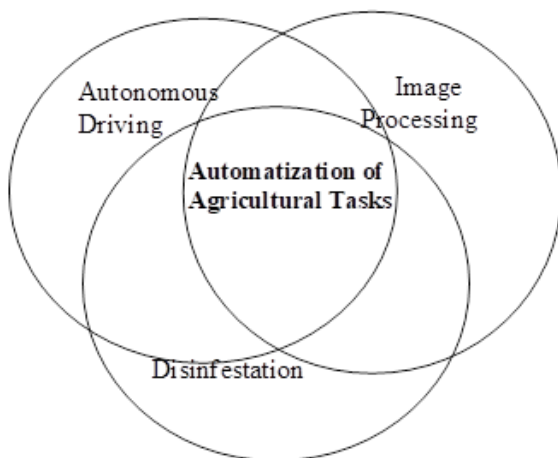


Fig.1. Conceptual Purposes of the Designed UGV System

The UGV navigates autonomously using five ultrasonic sensors and an ANFIS-based control system on an Arduino UNO. A Raspberry Pi processes camera images in real time to

detect plant diseases using a YOLO model. A spraying mechanism targets infected areas, and four DC motors provide movement via PWM control (Fig.2). The system reduces pesticide use which improves crop quality, as will be illustrated in experimental tests.

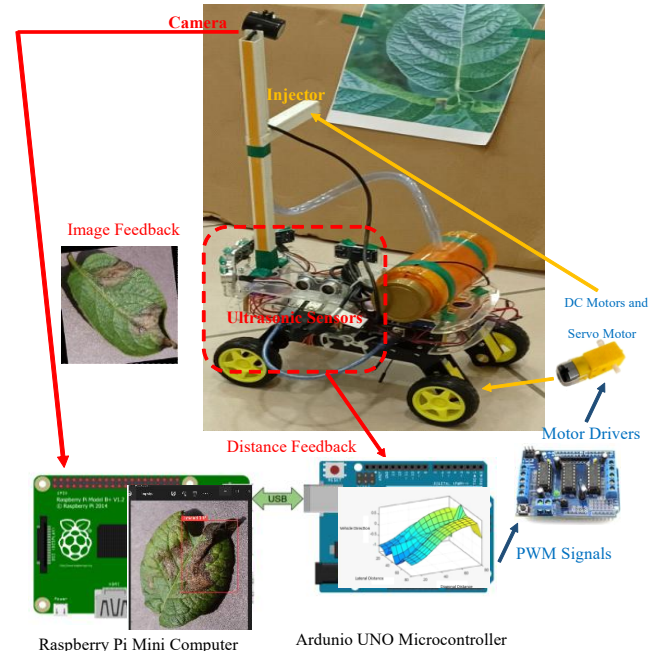


Fig.2. Hardware and software features which provide the vehicle operation

III. DISEASE DETECTION WITH YOLOV8 ALGORITHM

Image processing involves extracting meaningful information from digital images and is widely applied in fields like computer vision, pattern recognition, and object detection. It also plays a key role in industries such as healthcare, agriculture, automotive, security, and media. YOLO is a deep learning-based object detection algorithm that processes an image in a single pass, delivering faster and more efficient results compared to traditional methods. For instance Hamza et al. compared modified YOLO v5 and Faster R-CNN for recycling waste classification. Both models were evaluated on accuracy and speed using waste image datasets. Results show that the modified YOLO v5 offers faster inference with competitive accuracy, while Faster R-CNN achieves slightly higher accuracy but at slower speeds. The findings suggest that modified YOLO v5 is better suited for real-time waste classification applications [13]. In an other study a novel approach for multimodal medical image segmentation by combining the YOLOv8 object detection framework with SAM and HQ-SAM segmentation models. The method improves segmentation accuracy across diverse medical imaging modalities [14].

Its ability to detect all objects simultaneously makes it highly suitable for real-time applications like autonomous vehicles, surveillance systems, and security solutions.

A. YOLOV8 Training Procedure

In the study, the YOLOv8 algorithm [15] was used for real-time plant detection. The model was trained with the Plant Village and New Plant Disease datasets [5,16]. The goal was to detect early blight and late blight diseases in plants using the

model. The number of data points used from the relevant datasets is provided in the tables below.

Table 1. Plant Village Data Set [5]

Disease Type	Training Data	Validation Data
Early Blight	900	100
Late Blight	900	100

Table 2. New Plant Disease Data Set [16]

Disease Type	Training Data	Validation Data
Early Blight	3872	970
Late Blight	3878	970

In this study, both the PlantVillage and the New Plant Disease datasets were utilized to enhance model performance and improve generalization capability. These datasets were combined during the training process to increase the diversity and volume of samples, particularly for early and late blight disease classes. By integrating images from both datasets—collected under varied lighting conditions, resolutions, and backgrounds—the model was exposed to a broader range of visual features, allowing it to generalize better to real-world field conditions. All images in the datasets had already been standardized in the databases in size and format, and were annotated in YOLO format to ensure consistency across the combined dataset. In this study, data sets are directly combined, used in training and validation of the model.

A.1. Image Processing and YOLOv8 Training Stages

Standard YOLOv8 training includes preprocessing steps like image resizing and normalization, along with automatic data augmentation techniques such as horizontal flipping, brightness and HSV color adjustments, mosaic augmentation, and random cropping or translation. These augmentations help manage data variability caused by lighting differences, viewing angles, and occlusions, enabling the model to generalize well to diverse real-world conditions. Additionally, the training datasets contained images captured under varied environmental settings, further improving the model's robustness against such variabilities. YOLO models typically expect square input images like 416×416 or 640×640. The training framework usually handles these transformations automatically. Ultralytics library is used under YOLO for object detection, classification, segmentation and pose estimation of an image. In this study Yolov7, Yolov8 and Yolov9 models are tested. Training and validation data sets are obtained by data collection, labelling, object detection stages. The stages are explained as follows;

Dataset Collection: Images were sourced from Kaggle using keywords like "Fungi", "Early Blight", and "Late Blight", mainly using PlantVillage and New Plant Disease datasets.

Labeling: Images are labeled as "defective" with labellmg under Roboflow application and are saved in YOLO format.

Augmentation & Split: YOLOv8 is installed, trained and run using the Anaconda Prompt command line. The data sets are augmented, split, uploaded to Google Drive, and used in Google Colab.

Object Detection: Image is split into an N×N grid. The model predicts object locations and confidence scores (Fig.3).

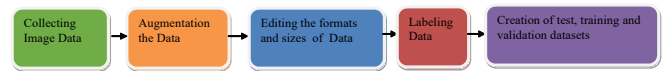


Fig.3. Processing of Potato Leaves Image Data

The following figures show the detection and labeling stages of a leaf image, respectively in this study (Fig.4 and Fig.5). YOLOv8 includes several structural improvements compared to YOLOv5 and YOLOv7. The integration of the C2f module enhances the model's ability to extract meaningful features, which is particularly helpful when working with small or subtle patterns. In addition, the move to an anchor-free detection head allows for more adaptive object recognition across varying scales. These design changes have proven beneficial in our case, where accurately identifying small disease signs is essential [17]

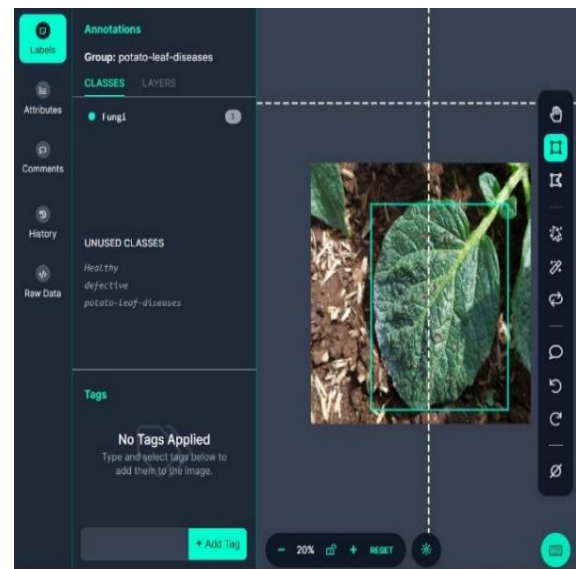


Fig.4. Detection and Framing of the Leaf Image

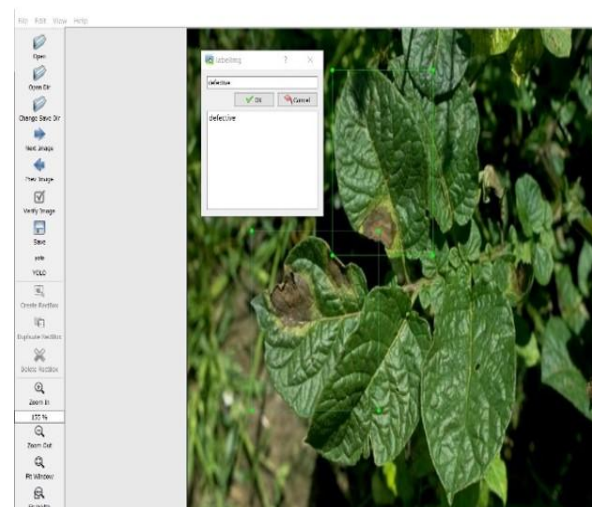


Fig.5. Labeling of a Leaf Image

The YOLO model's training graphs based on the data in Tables 1 and 2 are shown in Fig. 6

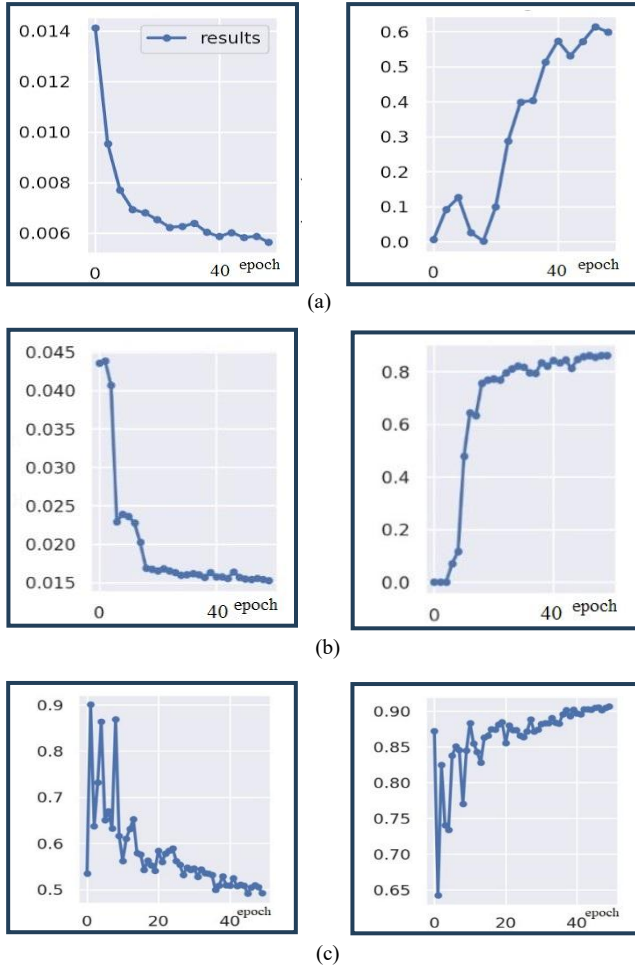


Fig.6. Comparison Results of Training Models for Validation Loss (val_loss) and Average Precision (mAp@0.05) Graphics
(a) YOLOv7, (b) YOLOv8, (c) YOLOv9

Among the trained models, YOLOv9 achieves the highest average accuracy ($mAp@0.5 > 90\%$), while YOLOv7 exhibits the lowest validation loss. YOLOv8, on the other hand, demonstrates a more balanced and stable performance overall. As a result of the training, for the proposed YOLOv8 method it was observed that the disease detection accuracy of the model on the data was 90%.

A.2. Execution of Real Time Disase Detection Stage

The execution of the real-time disease detection stage involves a structured pipeline designed to perform plant disease recognition directly from live video input. Initially, all required libraries are imported, and appropriate paths for model files and resources are configured. Subsequently, the YOLO model is loaded into the system (Fig.7). A webcam interface is activated to capture frames in real time, which are then processed by the YOLO model to estimate the presence of disease indicators. The model applies automatic inference techniques and returns prediction results in the form of bounding box coordinates, associated class labels, and confidence scores. These outputs are used to annotate the live video feed by drawing labeled bounding boxes around the detected regions (Fig.8). This approach facilitates robust, real-time identification of plant diseases, enabling immediate visual feedback and potential integration into autonomous agricultural systems.

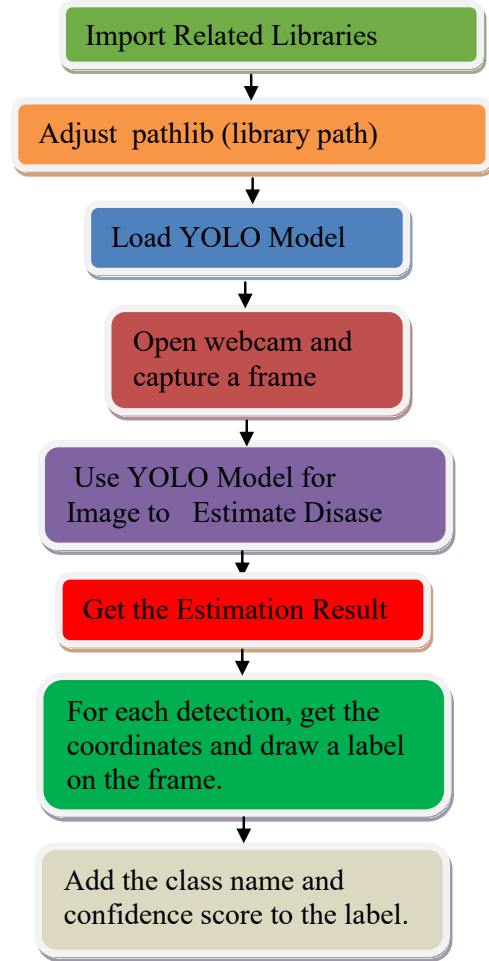


Fig. 7. YOLOv8-based Real-Time Plant Disease Detection Algorithm Flowchart

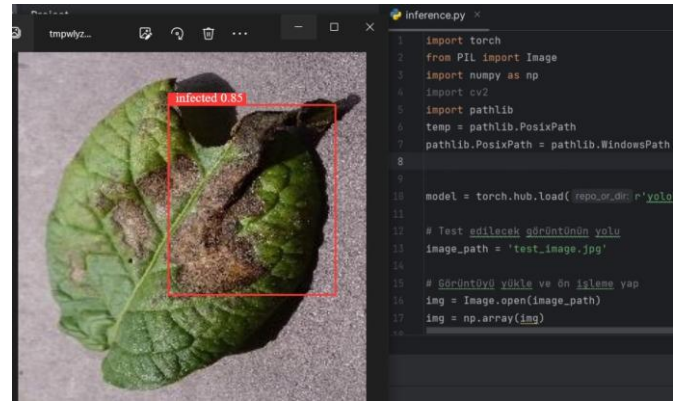


Fig.8. Plant Disease Detection and Labeling Stages

B. UGV Motion Planning and Autonomous Driving System

The UGV, equipped with fully autonomous driving capabilities, is designed to navigate from a starting point to a target destination while avoiding both static and dynamic obstacles and performing designated tasks along the route. To accomplish this, the vehicle must accurately process positional and environmental data obtained from sensors [8].

Accordingly, its path planning, navigation, decision-making, and control systems have been developed to ensure reliable motion planning and mission completion without collisions. The autonomous motion planning of the UGV is illustrated in Fig.9.

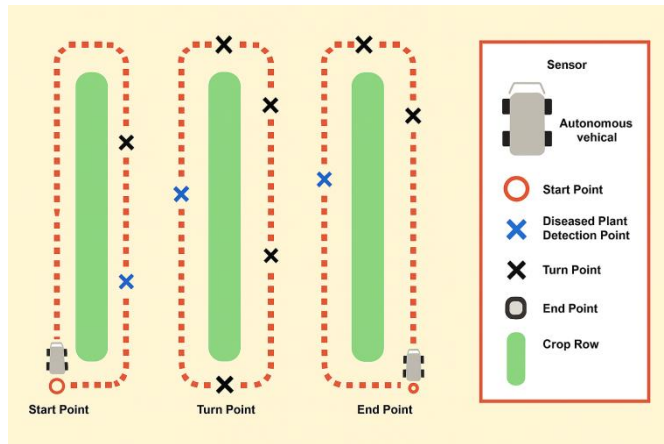


Fig.9. UGV Motion Planning

The proposed navigation strategy enables the UGV to autonomously traverse crop rows while maintaining optimal alignment and performing targeted interventions. The vehicle follows each row starting from a predefined point, maintaining a lateral distance of $M1 = 10$ cm from the crops and using a diagonal reference of $M2 = 20$ cm to ensure parallel alignment (Fig.10). On odd-numbered rows, right-side sensors are active, while on even-numbered rows, left-side sensors are used. At the end of each row detected by cross-mounted sensors, the UGV executes a turn: right turns after odd rows and left turns after even rows, enabling continuous coverage of the field. When a diseased plant is detected, the vehicle halts and applies treatment before resuming navigation. To support robust operation in realistic environments, including uneven terrain and curved rows, a comprehensive path planning algorithm was implemented. This algorithm ensures the UGV adheres closely to plant rows and successfully transitions between them, optimizing both disease intervention and field coverage from start to finish.

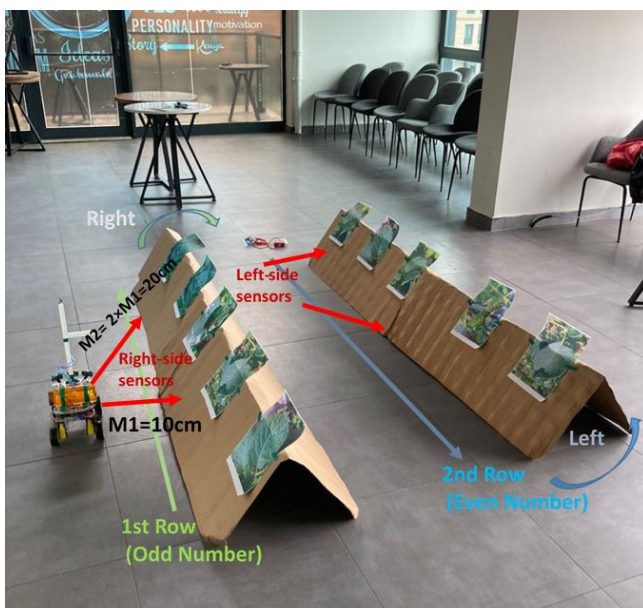


Fig.10. Navigation of the UGV in Laboratory Environment

These scenarios are presented in Figures 11 and 12, respectively.

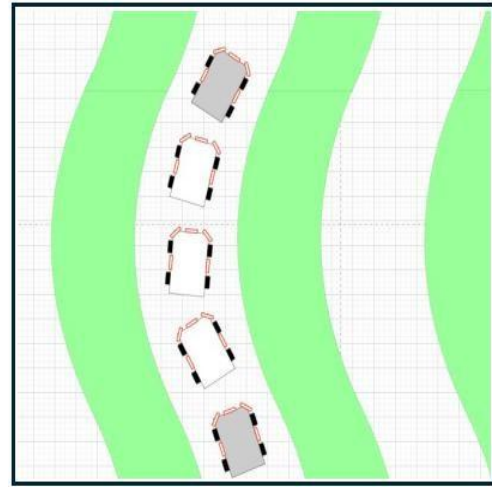


Fig.11. UGV motion scenario on an uneven road

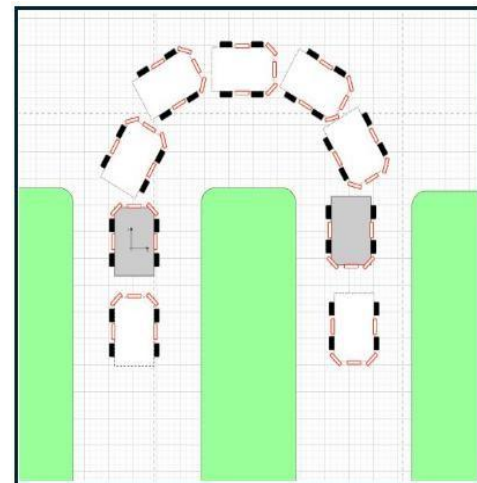


Fig.12. UGV Turning Scenario at the End of the Crop Row.

Fig.12 considers the scenario where the IGA travels in a non-flat row of crops in the field. In this scenario, the aim is to prevent the UGV from leaving the row of crops and to ensure that it moves at an appropriate distance from the row of crops for spraying. In the scenarios design of the navigation system aims to ensure that the UGV maintains its position and can continue its mission smoothly. The goal is for the guidance unit to produce accurate reference values and to derive information by accurately receiving and processing data from the navigation system.

C. Navigation Module

The aim of the UGV is to perceive the vehicle's environment, determine its position, create a route plan and perform its task according to this route through the navigation system. In this study, an ultrasonic sensor and camera module were selected to implement the navigation system.

C.1. Sensor Configuration and Navigation Strategy

The UGV's navigation relies on a set of five ultrasonic sensors (U1–U5) strategically positioned to ensure precise alignment with crop rows and effective maneuvering, as illustrated in Fig.13. The angle between the U1 and U2 sensors is set at 60° . U1 and U5, located on the right and left sides respectively, measure the lateral distance between the vehicle and the crop rows. U2 and U4, positioned diagonally, estimate the vehicle's turning angle (ranging from -45° to $+45^\circ$) and help detect the end of the row. Depending on the row number, only the sensors on the active side are used—right for odd-numbered rows, and left for even-numbered rows—to maintain optimal alignment. U3, placed at the front, provides obstacle detection and assists in decision-making during turning maneuvers (as detailed in Table 3). This sensor setup enables reliable positioning and smooth transitions between crop rows.

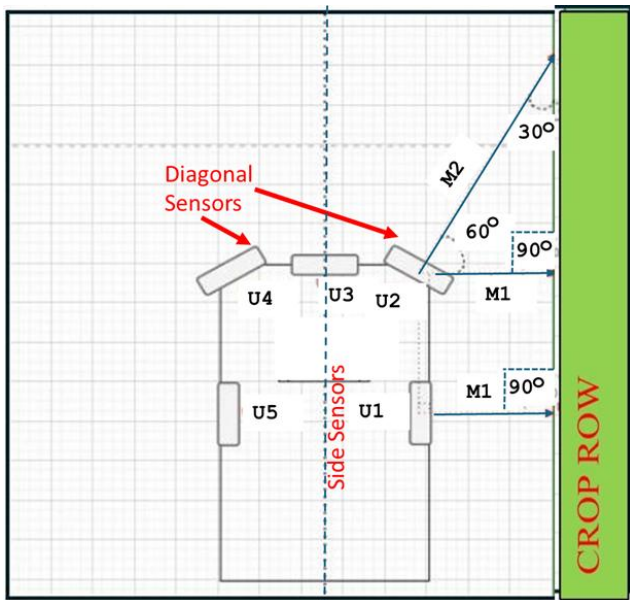


Fig.13. Sensor Configuration

Table 3. Sensors Operation

Sensor	Position	Function
U1	Right Side	Measures distance to the crop row (M1)
U2	Right Diagonal	Determines turning angle and row end (M2)
U3	Front	Detects front obstacles
U4	Left Diagonal	Determines turning angle and row end (M2)
U5	Left Side	Measures distance to the crop row (M1)

With the aid of the camera module, the UGV performs its mission of detecting diseased plants. The ultrasonic sensors, on the other hand, serve the function of a lidar system. Due to the 30-60-90 triangle formed in this configuration, the M2 distance is calculated to be twice the M1 distance [6]. In every scenario where this configuration occurs, the UGV moves straight within the crop row.

C.2. Algorithm for Autonomous Navigation and Spraying

This algorithm defines the control process for an Unmanned Ground Vehicle (UGV) designed to autonomously navigate through agricultural crop rows, detect diseased plants, and perform targeted spraying. The operation begins with system initialization, followed by the activation of relevant sensors based on the current row number. The UGV then moves forward through the row while continuously monitoring for plant health. When a diseased plant is detected, the system triggers the spraying mechanism. At the end of each row, a check is performed to determine whether the row has been fully traversed. Based on the current row number, the UGV makes a directional decision to turn into the next row. This cycle continues until all rows are completed, upon which a final check confirms the completion of the entire field. The algorithm diagram is provided in Figure 14.

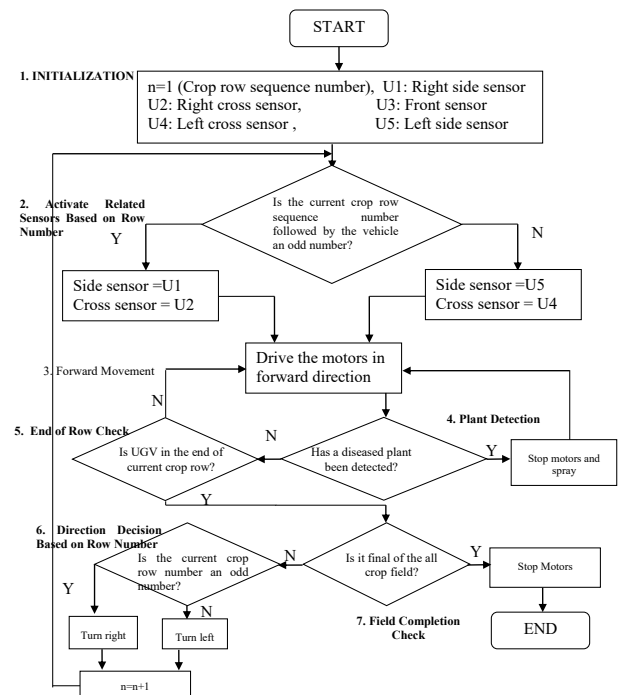


Fig.14 UGV Path Planning Algorithm

D. Inference Module (ANFIS)

Adaptive neuro-fuzzy inference system or adaptive network-based fuzzy inference system (ANFIS) is a type of artificial neural network based on the Takagi-Sugeno fuzzy inference system. The technique was developed in the early 1990s [18,19]. Since it combines both neural networks and fuzzy logic principles, it has the potential to capture the benefits of both in a single framework.

The outputs of the path planning algorithm and navigation module were used to ensure that the UGV maintains its position and successfully completes its mission. The data processed in the guidance module played a role in generating reference values for the UGV's motion control [20]. The possible positions of the UGV relative to the crop row are given in Table.4. For example, Scenario $M2 > 2 \times M1$ describes that the UGV moving away from the crop to the left. $M2 = 2 \times M1$ is the ideal situation. Because based on the sensor placement, when the vehicle moves parallel to the row, the distance M2 should be twice the distance M1. For the Scenario

of $2*M1 > M2 > M1$, UGV approaches the crop (to right) too close from front. For the Scenario $M2 < M1$, UGV approaches the crop too close from back.

Table 4. Lateral and Diagonal Sensor Value Range Based on the UGV's Rotation Angle

Rotation Angle (°)	Scenario According to Sensor Values
-45- 0	$M2 > 2*M1$
0	$M2 = 2*M1$
0-15	$2*M1 > M2 > M1$
15-45	$M2 < M1$

When the UGV encounters positional deviations, it autonomously adjusts its orientation within the row using an ANFIS-based control model. The model was trained using a dataset derived from lateral and diagonal sensor values corresponding to various turning angles. The turning angle of the vehicle's own normal with the route varies from $[-45^\circ, +45^\circ]$ according to distance data coming from sensors. Based on the sensor placement, when the vehicle moves parallel to the row, the distance $M2$ should be twice the distance $M1$.

D.1. ANFIS Training Stage

The data from the U1 and U2 sensors were utilized to create the training dataset for the ANFIS system. The HC-SR04 ultrasonic sensors used in this study have a detection range between 2 cm and 450 cm; however, a practical range of 0 to 80 cm was selected to ensure relevant measurements within the crop row. Various positions of the UGV within the row were recorded to generate a representative dataset [21].

Input 1 ($M1$) represents the lateral distance between the vehicle and the crop row, measured by the side ultrasonic sensors (U1 and U5). Input 2 ($M2$) denotes the diagonal distance, obtained from the diagonal sensors (U2 and U4). The output, referred to as the turning angle, determines how much the vehicle should rotate to stay aligned with the crop row. Based on $M1$ and $M2$, the ANFIS model computes the necessary angular correction, which is then sent to the UGV's steering control system. The data from the lateral and diagonal sensors were used to develop an effective decision-making module. A training set between $M1$ and $M2$ is derived based on the minimum and maximum input ranges (inputs are decreasing from largest to smallest), with output values linearly mapped to turning angles between -45° and $+45^\circ$, as to the relations defined in Table 5.

Table.5. Training Set $M1$ and $M2$ inputs and turning angle output [22].

$M1(\text{Cm})$	$M2(\text{Cm})$	Turning Angle (°)
20	80	+45
20	70	+37
20	60	+30
20	50	+22
20	40	
.....		

The ANFIS model was trained using this data. The ANFIS model was developed using the membership functions of the Sugeno type fuzzy inference system [21,22]. The model was created using the Neuro-Fuzzy Inference interface in Matlab and trained for 5000 epochs. After training, the error rate was observed to be 0.251. The model was tested with the weight

file obtained from the training, and the FIS output versus Testing Data is presented in Figure 15.

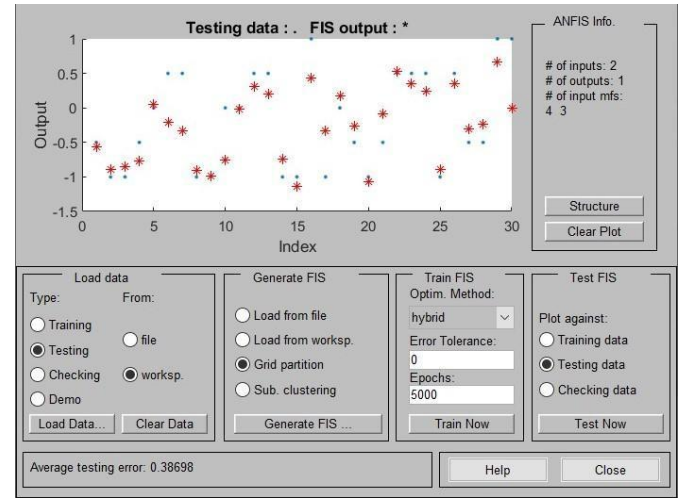


Fig.15. Test Data Results Corresponding to FIS Results

The surface plot resulting from the model training is shown in Fig.16. This plot, generated using lateral and diagonal sensor data, illustrates that the model produced proportionally consistent outputs across varying distances. The predicted turning angles for the vehicle were observed to remain within the range of -45° to $+45^\circ$, as also supported in [23].

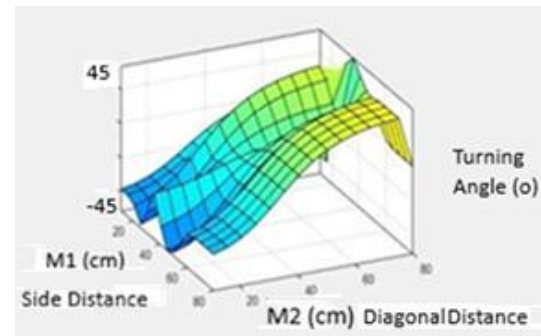


Fig.16. Surface Plot for 5000 Epochs

In the model training phase, the 'gauss' membership function (gaussmf) was preferred as the membership function [24]. Membership Functions for the "Side Distance Data" input variable and the "Diagonal Distance Data" input variable after 5000 training iterations are given in Fig.17 and Fig.18, respectively.

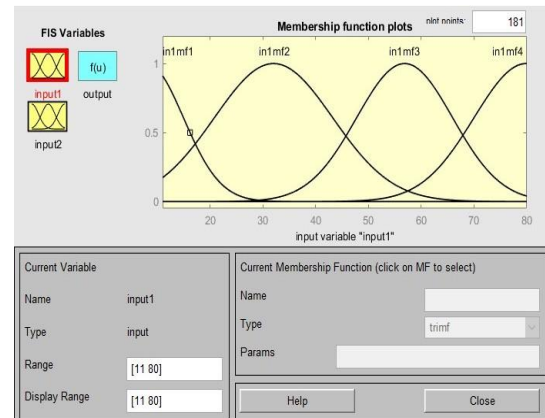


Fig.17. Membership Functions of "Side Sensor Distance Data"

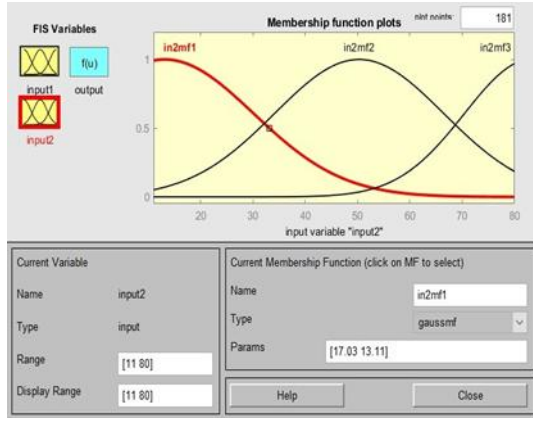


Fig.18. Membership Functions of “Cross Sensor Distance Data”

D.2. ANFIS Testing Stage

After training, the ANFIS model was tested using unseen input data, and the predicted turning angles closely matched the expected values (Fig.19).

Fuzzy Input Membership Functions

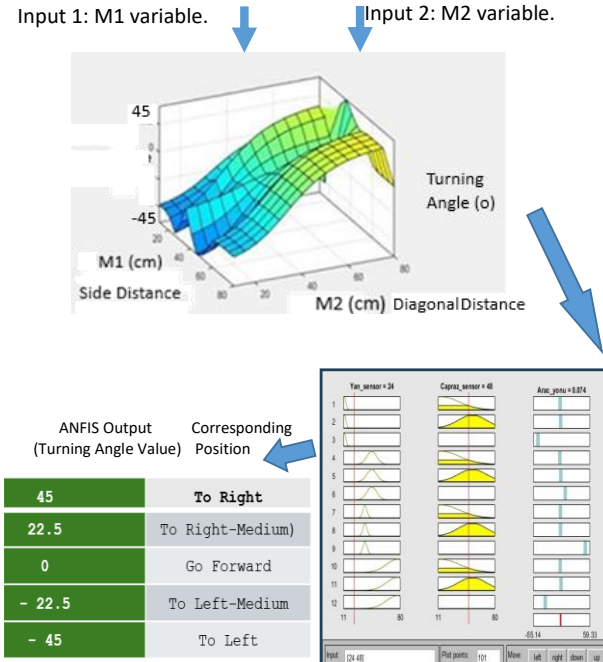
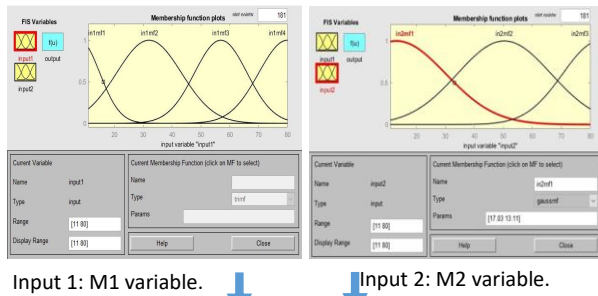


Fig.19. Testing stage of the trained ANFIS Model

The FIS outputs align well with the test data, confirming the model's accuracy. The resulting surface plot demonstrates that the relation surface correctly reflects the input distance data and corresponding turning angles within the range of -45° to $+45^\circ$. The final ANFIS surface was then embedded into the Arduino Uno as a lookup table to enable real-time steering control of the UGV.

E. Driving – Control Module

The UGV is driven by four motors, each controlled via a dedicated motor driver managed by the Arduino Uno. A motor assignment matrix is used to determine the appropriate PWM speed signals for each motor based on the desired turning angle and movement direction (Table.6). This matrix translates the control commands from the ANFIS output into differential motor speeds, enabling smooth and accurate maneuvering of the vehicle within the crop rows (Fig.20).

Table.6. Motor Assignment Matrix

Vehicle Direction Speed (m/s)	Right Motor Group (m/s)	Left Motor Group (m/s)
Forward	Maximum Forward Speed	Maximum Forward Speed (PWM 255)
Right	0	Maximum Forward Speed
Right-medium	Maximum Forward Speed*(1/3)	Maximum Forward Speed*(2/3)
Right-small	0	Maximum Forward Speed*(1/3)
Left	Maximum Forward Speed	0
Left-medium	Maximum Forward Speed*(2/3)	Maximum Forward Speed*(1/3)
Left-small	Maximum Forward Speed*(1/3)	0
Backward	Maximum Backward Speed	Maximum Backward Speed
Backward-medium	Maximum Backward Speed*(2/3)	Maximum Backward Speed*(1/3)
Backward-small	Maximum Backward Speed*(1/3)	Maximum Backward Speed*(1/3)
STOP	0	

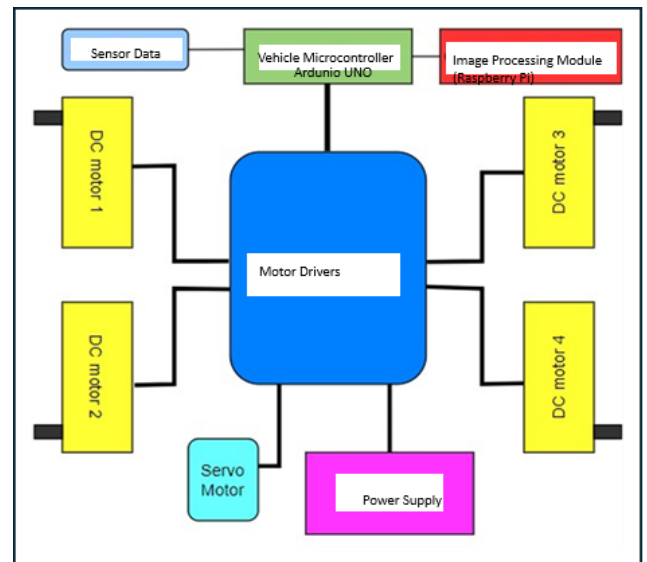


Fig.20. UGV Motor Control Block Scheme

RESULTS

Throughout the study, the goal was to autonomously detect and spray diseased plants in real-time using a UGV and the YOLOv8 model running on a Raspberry Pi mini computer.

In this purpose a crop field environment was simulated in Kocaeli University, Department of Electronics and

Communication Engineering, Marine Robotics Research Laboratory (DRAL/MARAS) [28]. This area is created by arranging identical photographs of diseased and healthy plants in a row (Figure 21).



Fig.21. Case Area

The UGV inferred and navigated along the crop row regularly at sufficient speed and injected medicine to the detected diseased plants (Fig.22).

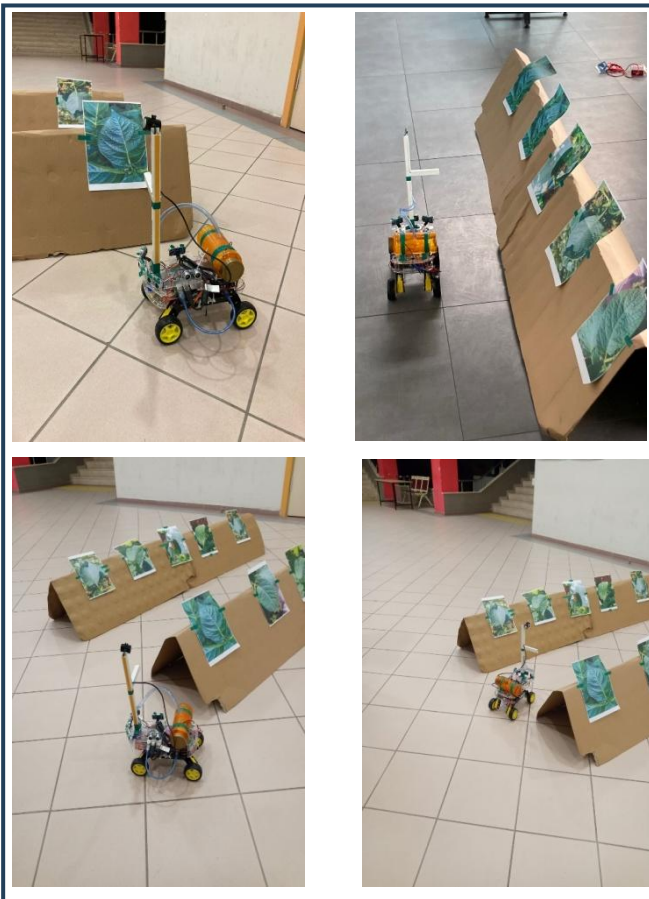


Fig.22. Navigation and Processing of UGV in the Test Area

Images of the study area and its outcomes are provided in Figures 23 and 24.



Fig.23. Detecting and Spraying Simulations by the UGV

The YoloV8 algorithm detected diseased leaves with high accuracy.



Fig. 24. YOLOv8 Detects Infected Leaves.

II. DISCUSSION

Studies on plant disease classification [25], autonomous agricultural robotic systems [26], and real-time monitoring technologies [27] contribute significantly to the advancement of agricultural automation and increases the overall yield percentage. In this study, during the test process, it was observed that UGV detected diseased potato leaves with high accuracy (average 79%). Following the detection, the spraying process was carried out using the spraying module on the vehicle. Since the 'diseased' information was delayed by 3.5-4 seconds when the disease detection process was carried out, it was actually solved with the algorithm designed on the main processor on computer.

The reported average detection accuracy of 79% was achieved in a real-time operational scenario, where the YOLOv8 model was deployed on a Raspberry Pi 4B. While this platform is energy-efficient and cost-effective, it introduces computational limitations that constrain model complexity and inference speed. The goal of this study was to implement a fully integrated, low-cost, real-time disease

detection and autonomous spraying system under field-like conditions.

When benchmarked against similar studies, the result remains competitive. For example, Shill [1] reported that YOLOv3 and YOLOv4 yielded average accuracies of 53.08% and 55.45%, respectively, for multi-class plant disease detection. Verma et al. [6] achieved over 90% accuracy using classical machine learning methods, but their approach was offline, lacked real-time performance, and did not involve autonomous operation. Dung [7] implemented SSD (Single Shot Detector) on a Raspberry Pi 3 with ~72% accuracy, but without integrated motion control or spraying. Similarly, Kumar and Dineshraj [8] developed a Raspberry Pi-based rover with environmental sensing and navigation but reported a disease detection latency of 95 seconds per image and lack of spraying function.

Unlike these works, our system performs real-time detection, navigation, and targeted spraying in a fully integrated and autonomous loop. While the 79% accuracy may seem lower than some offline benchmarks, it is acceptable and meaningful within the context of embedded, real-time agricultural robotics. A delay of approximately 4 seconds was observed between detection and spraying due to onboard inference and control processes. This latency was mitigated by limiting the UGV's speed to 0.15–0.20 m/s, minimizing the spatial offset between detection and actuation. Additionally, the UGV incorporates a basic reactive behavior: it slows down or reverses briefly when diseased leaves are detected, allowing time for proper alignment and spraying. While this approach may limit scalability in larger plots, it demonstrates the feasibility of real-time, low-cost disease management in semi-structured environments. Future improvements will focus on latency reduction and system robustness through hardware upgrades and sensor fusion. Wheel speed drift introduces small but non-negligible targeting errors in our spraying system, especially under real-time constraints. While these are currently managed by operating at low speeds and re-adjustments refer to sensorial information, future versions of the platform will incorporate wheel encoders and closed-loop control to ensure consistent drive behavior and improve targeting accuracy during spraying.

III. CONCLUSION

In this study, an autonomous unmanned ground vehicle (UGV) was developed and tested for disease detection and precision spraying in agricultural environments. The system integrates image processing via the YOLOv8 algorithm and autonomous navigation using an ANFIS-based decision model. The integration of YOLOv8 and ANFIS with embedded hardware platforms contributes to both scientific innovation and to real-world applicability. Experimental results in a controlled test area demonstrated that the UGV could reliably follow crop rows, detect diseased plants, perform targeted spraying, and execute accurate turns. Despite minor issues such as sensorial insensitivities, processing delays on the Raspberry Pi, and wheel speed variations, the overall system achieved the desired performance. We conducted our experiments in a laboratory environment with standard, fixed lighting conditions. In these experiments, the vehicle detected diseased plants with an

accuracy of 79% on images that we identified as diseased. Outside of this controlled setting, in a real field with plants and varying light conditions, both navigation and disease detection performance are expected to decrease.

The successful implementation of real-time disease detection and autonomous control highlights the system's potential for practical applications in precision agriculture. By minimizing unnecessary chemical usage and enabling efficient resource allocation, the proposed solution contributes to more sustainable and environmentally friendly farming practices.

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Authors' Contributions

The authors' contributions to the paper are equal.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics

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Multiple Object Detection and Tracking in Real-Time Aerial Imagery with Deep Learning Architectures

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Abstract – Real-time multi-object detection and tracking is one of the main challenges in analysing aerial imagery from platforms such as unmanned aerial vehicles (UAVs) and satellite systems. Traditional tracking algorithms are inadequate, especially in complex and dynamic environments, which necessitates the development of more powerful and flexible methods. This study proposes a deep learning-based solution aligned with the objectives of high extraction rate and sufficient accuracy. Within the scope of the study, the YOLOv11 model, a single-stage object detection architecture, is integrated with the ByteTrack algorithm for tracking detected objects. This approach is evaluated against the two-stage Faster R-CNN architecture (MobileNetV3-large FPN backbone), known for its high accuracy in object detection. The models were trained on a comprehensive dataset created by combining the challenging VisDrone and DOTA datasets containing objects of various sizes. The results demonstrate that YOLOv11s achieved an mAP@0.5 of 27.7% with an inference speed exceeding 15 FPS, while Faster R-CNN reached a substantially higher mAP@0.5 of approximately 47% but processed frames more slowly, at around 8 FPS. These FPS values represent the number of frames each model can process per second under the same hardware conditions, and do not correspond to the frame rate of the input video. The ByteTrack algorithm, employed in the tracking phase, improves tracking accuracy by successfully identifying detected objects. In this context, the advantages and limitations of both models are evaluated, and it is concluded that the choice of model should be based on the specific application requirements—favoring YOLOv11 for real-time use with limited computational resources, and Faster R-CNN for applications where high detection precision is paramount.

Keywords – Multi-Object Tracking, YOLOv11, Faster R-CNN, ByteTrack, Aerial Images

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I. INTRODUCTION

Today, real-time multi-object detection and tracking (MOT) has gained significant importance in a wide range of applications, including autonomous systems, unmanned aerial vehicles (UAVs), security cameras, and smart city infrastructures. Particularly in dynamic and complex environments—such as aerial and satellite imagery—the ability to accurately, rapidly, and continuously detect and track multiple objects is critical for ensuring the reliability, efficiency, and performance of these systems. However, conventional object detection and tracking algorithms often fall short in scenarios involving rapid object motion, occlusion, or temporary disappearance. Along with the high accuracy rates of deep learning-based models in the field of Classification [1-6] significant success has also been achieved in object detection.

In recent years, novel methods based on the YOLO architecture have emerged as powerful solutions for the efficient and accurate detection of small objects. For instance,

the Rotating-YOLO approach improves accuracy while reducing model complexity by addressing rotated objects [7]. PETNet introduces multi-scale feature fusion to minimize information loss in small object detection [8]. EL-YOLO distinguishes itself with a lightweight architecture, enabling fast inference on edge devices [9]. SDNet leverages attention mechanisms and advanced convolutional techniques to improve detection across varying object sizes [10]. Furthermore, enhancements in YOLOv8 have led to significant improvements in detecting small-scale targets [11]. These studies underscore the strengths of deep learning models in balancing speed and accuracy while tackling key challenges such as small object detection.

In this study, a real-time multi-object detection and tracking system has been developed specifically for use with aerial and satellite imagery. The system evaluates the single-stage, high-speed YOLOv11 architecture against the two-stage Faster R-CNN architecture—employing the MobileNetV3-large FPN

backbone—which is known for its high accuracy in complex scenarios.

The YOLOv11 model offers advantages for real-time applications due to its high inference speed, while the Faster R-CNN model enables more accurate object detection, particularly in complex scenes. The ByteTrack algorithm used for tracking ensures continuity by assigning unique identifiers to objects detected by YOLOv11, enabling reliable tracking of even temporarily invisible or fast-moving objects.

Model training was performed on a challenging and comprehensive dataset created by combining the VisDrone and DOTA datasets, which include objects of different sizes and various environmental conditions. In addition, a lighter YOLOv11 model trained only with the VisDrone dataset was also evaluated. The results of the experiments revealed the performance of each model in terms of accuracy and speed, highlighting their suitability for different application scenarios.

The primary objective of this study is to develop a YOLOv11-based object detection system on datasets containing high-resolution aerial and satellite images, integrate it with the ByteTrack algorithm, and perform multi-object tracking. Additionally, the system's performance will be evaluated by comparing it with the Faster R-CNN architecture, with the goal of comparing the training characteristics, inference speeds, and accuracy performance of different deep learning architectures. In this context, the developed system aims to create a robust infrastructure for the defence industry by enabling the effective use of AI-supported decision-making mechanisms in tasks such as navigation and target tracking for autonomous UAVs.

II. MATERIALS AND METHOD

2.1. Deep Learning Models

In this study, two popular deep learning-based object detection algorithms, YOLOv11 and Faster R-CNN, were used for multi-object detection and tracking from aerial and satellite images. Although these models are based on different artificial intelligence approaches, both provide successful results for object detection in complex scenes.

2.1.1. YOLOv11

YOLOv11 (You Only Look Once version 11) is a recent deep learning architecture introduced by Ultralytics, known for its fast and effective solutions to real-time object detection problems through a single-stage structure. Compared to previous versions, YOLOv11 features a lighter architecture, improved speed, and enhanced small object detection capability. These characteristics make it a balanced model in terms of detection accuracy and inference time, especially in complex aerial and satellite imagery containing multiple objects.

Although YOLOv11 has not yet been presented in a peer-reviewed academic publication, it has been officially released and documented by Ultralytics on their website. This release includes detailed architectural improvements and performance benchmarks, providing a solid basis for research and application in real-time scenarios.

In this study, YOLOv11 is preferred for multi-object detection due to its high performance and updated architecture.

Prior research and community applications have also begun to explore its potential. For instance, the LP-YOLO algorithm has been adapted to enhance pedestrian detection efficiency in real-time applications [12], and the SDS-YOLO architecture has shown improvement in tasks requiring positional accuracy under unstable conditions [13]. Additionally, it has been applied successfully in areas such as fire and smoke detection [14].

All these findings, supported by the latest release from Ultralytics, confirm that YOLOv11 is a fast, accurate, and reliable method for multi-object detection in aerial imagery.

2.1.2. Faster R-CNN

Faster R-CNN (Region-based Convolutional Neural Network) is a widely used, region-based two-stage deep learning architecture for object detection tasks. In the first stage of the model, the Region Proposal Network (RPN) is used to identify potential object locations in the image. The RPN generates region proposals (regions with high object probability) using a sliding window approach on convolutional feature maps.

In the second stage, these candidate regions are resized to fixed dimensions using the Region of Interest (RoI) Pooling method, followed by classification and bounding box regression operations. This two-stage structure enables Faster R-CNN to deliver superior performance in applications requiring high accuracy and detailed analysis of small objects.

Although it requires more computational resources compared to single-stage models (YOLO, SSD, etc.), it offers advantages in terms of regional accuracy and classification accuracy. For this reason, Faster R-CNN is preferred in areas such as infrastructure monitoring, agricultural analysis, and high-resolution aerial images, where complex scene structures are present.

For example, it has achieved high accuracy in infrastructure monitoring studies such as detecting bridge cracks in aerial images [15], and has been effectively used in agricultural applications such as identifying weeds [16] and counting wheat heads [17]. In these studies, Faster R-CNN's success in detecting small objects stands out.

2.2. Data Sets

2.2.1. VisDrone

VisDrone is a comprehensive dataset consisting of high-resolution aerial images captured by unmanned aerial vehicles (UAVs) in different urban environments, under various weather conditions and at different density levels. In the field of computer vision, it is considered a critical reference point for tasks such as object detection in aerial images and multi-object tracking (MOT) [18]. In this study, the VisDrone-MOT subset was used, and the dataset was divided into 25,607 images for training, 9,304 for validation, and 6,474 for testing. Fig. 1 presents a typical aerial image from the VisDrone dataset, providing a visual representation of the complex scenes and diverse object categories contained within the dataset.



Fig. 1. An example aerial image from the VisDrone dataset.

VisDrone dataset contains a total of 12 different object classes covering a wide range of objects commonly encountered in urban environments. These classes include 'ignored,' 'pedestrian,' 'people,' 'bicycle,' 'car,' 'van,' 'truck,' 'tricycle,' 'awning-tricycle,' 'bus,' 'motor,' and 'others.' This diversity enables the testing of algorithms' generalisability in real-world scenarios.

The VisDrone dataset is divided into two main sub-sets: VisDrone-DET focuses on object detection tasks on static images, while VisDrone-MOT covers multi-object tracking tasks from sequential video frames. This segmentation provides a unique resource for addressing challenging conditions such as small object detection and object tracking continuity in dynamic scenes, particularly in images captured from a UAV perspective.

The images in the dataset are commonly used to evaluate the performance of small object detection and real-time tracking algorithms (e.g., ByteTrack) due to their low altitude and complex background conditions. This makes VisDrone an important benchmark for testing the practical effectiveness of methods developed in the field of multi-object tracking (MOT).

The challenges presented by VisDrone significantly guide current research and development activities. For example, studies focusing on the domain shift problem in aerial images have provided comprehensive experimental results on the VisDrone dataset, analysing the impact of image- and instance-level shifts on detection performance [18]. Proposed innovations for the YOLOv8 architecture have also been tested on the VisDrone dataset, achieving significant improvements of 10.5% in mAP50 and 6.9% in mAP95, thereby enhancing performance in small target detection [19]. Furthermore, ablation experiments conducted on the VisDrone and AI-TOD datasets improved the metrics of YOLOv8-based anchor-free detectors by 2.2% and 1.9%, respectively, achieving a performance increase of 13.75% and 13.97% compared to the baseline [20]. These developments clearly demonstrate the critical role of VisDrone's challenging structure in enhancing the robustness and accuracy of object detection and tracking algorithms.

2.2.2. DOTA

Object detection in aerial images has gained significant importance in recent years due to strategic applications in civil and military fields [22]. The DOTA dataset plays a fundamental role in developments in this field due to its comprehensive structure consisting of high-resolution aerial

images [21]. DOTA successfully reflects complex real-world scenarios by incorporating images obtained from different platforms such as unmanned aerial vehicles (UAVs), satellites, and fixed-wing aircraft [22]. The DOTA dataset is designed to address the unique challenges of object detection in aerial imagery.

In this study, a total of 1,411 images from the DOTA dataset were used for training, 458 for validation, and 937 for testing. The dataset includes classes such as 'plane,' 'ship,' 'storage tank,' 'baseball diamond,' 'tennis court,' 'basketball court,' 'ground track field,' 'harbour,' 'bridge,' 'large vehicle,' 'small vehicle,' 'helicopter,' 'roundabout,' 'soccer ball field,' 'swimming pool,' and 'container crane.' The use of rotated bounding boxes for object labelling has made DOTA a standard reference point for rotated object detection problems. Additionally, its inclusion of small objects at different resolutions provides a critical test environment for research in small object detection [23] [24]

DOTA's contribution to the field lies in its ability to provide a benchmark for the development and evaluation of deep learning-based algorithms. Object detection models in aerial images face challenges such as complex backgrounds, limited long-range contextual information, and high pixel similarity between objects and backgrounds [23] [24]. DOTA provides a standardised platform to objectively evaluate the performance of models aimed at overcoming these challenges. For example, YOLO-based detectors such as YOLO-SM have demonstrated their effectiveness in experiments conducted on the DOTA-v1.0 and DOTA-v1.5 datasets [23]. Additionally, dynamic YOLO-based models incorporating the Luna development mechanism and innovative modules achieved significant improvements in small and flat object detection performance, reaching an average precision (mAP_{0.5}) of 90.6% on DOTA-v1.5 [24].

The DOTA dataset is considered an indispensable resource for research and development activities in the field of object detection in aerial images. Its rich and challenging data structure provides a critical foundation for testing, comparing, and designing new-generation deep learning-based algorithms. This dataset will continue to play a significant role in shaping future research directions in computer vision problems related to aerial images.

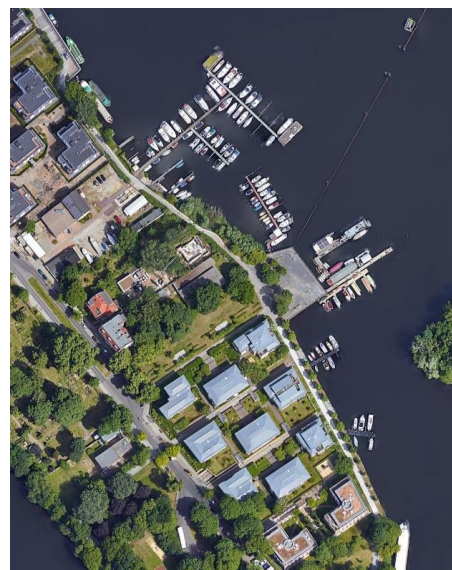


Fig. 2. Example aerial image from the DOTA dataset.

2.3. Performance Metrics

Various metrics are commonly used in computer vision to evaluate the performance of object detection models. These include precision, recall, mean mAP@0.5 (IoU), and mAP@0.5:0.95. Precision refers to the ratio of correctly detected objects to all predictions made by the model, while recall indicates how many of the objects that actually exist were correctly detected [27]. These two metrics allow for the separate evaluation of false positives (false alarms) and false negatives (misses) by the model.

The mAP@0.5 metric measures the average precision of all classes with a specified IoU (Intersection over Union) threshold value of 0.5 and quickly reflects the overall detection performance of the model [26] [28]. However, this fixed threshold value may not fully show how consistent and accurate the model performs at different IoU levels. To address this limitation, the mAP@0.5:0.95 metric is used. This metric calculates IoU values from 0.5 to 0.95 in increments of 0.05, enabling a more comprehensive and detailed analysis of model performance [25] [27] [28]. This allows for a comparison of the model's performance at both loose and strict thresholds, providing a better understanding of its robustness under real-world conditions.

The correct and detailed use of these metrics is critical, especially in challenging tasks such as object detection and tracking in aerial images, due to the density of small objects and class imbalances. Such challenges are among the key factors determining the effectiveness of object detection algorithms in real-world conditions. Metrics such as precision and recall separately highlight false detections and missed objects, enabling the identification of the model's weaknesses, while mAP values summarise the model's overall accuracy and sensitivity.

2.4. Object Tracking Algorithm

ByteTrack is a prominent algorithm in the field of multi-object tracking (MOT) that distinguishes itself by incorporating low-confidence detection results into the tracking process. While traditional MOT methods typically eliminate detections below a certain confidence threshold—leading to the exclusion of small, occluded, or low-resolution objects—ByteTrack takes a different approach. By retaining almost all detection outputs, it improves the association of objects across frames and enables more complete and continuous tracking results.

This strategy aligns with the 'tracking-by-detection' paradigm and significantly enhances the robustness of tracking in dynamic scenes. Unlike conventional approaches, which risk losing critical visual information due to strict filtering, ByteTrack increases reliability by preserving even uncertain detections. This enables the tracking of objects that would otherwise be missed due to partial occlusion or low visual quality[29].

Moreover, ByteTrack can be seamlessly integrated with high-performance object detectors such as YOLOv11 or Faster R-CNN, facilitating precise temporal tracking in real-time systems. Its compatibility with modern deep learning models and its ability to maintain object continuity under challenging conditions make it a highly effective solution for various real-world applications, including autonomous navigation, aerial

surveillance, and intelligent monitoring systems.

2.5. Experimental Setup

All training and evaluation processes were conducted using the available hardware infrastructure, which includes NVIDIA GTX 1080 Ti and RTX 3050 GPUs. The YOLOv11 models were trained using the official Ultralytics YOLO implementation, and all models were developed using the Python programming language.

Due to differences in GPU memory capacity—11 GB on the GTX 1080 Ti and 4 GB on the RTX 3050—the datasets were allocated accordingly during the training phase. The relatively smaller VisDrone-DET dataset was trained on the RTX 3050 GPU, while the training involving the combined VisDrone-MOT and DOTA datasets was carried out on the GTX 1080 Ti to meet the higher memory requirements.

III. EXPERIMENTAL STUDIES

In this study, YOLOv11 and Faster R-CNN models were employed for multi-object detection. The models were trained and evaluated on the VisDrone and DOTA datasets, and a lightweight YOLOv11 variant trained solely on the VisDrone-DET dataset was also included for comparison.

Following the detection stage, the outputs of the YOLOv11 model were processed using the ByteTrack algorithm to assign unique IDs to objects, enabling consistent tracking across frames. All tracking results were visually evaluated, and the system's real-time performance was tested.

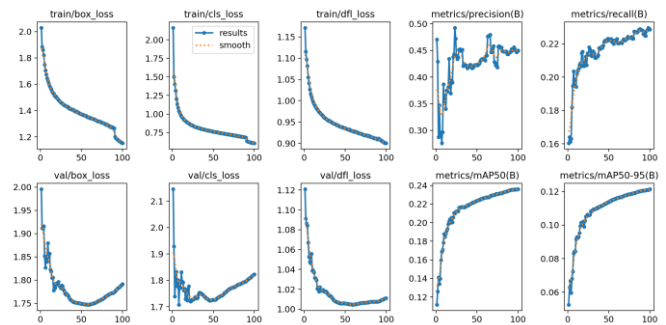


Fig. 3. YOLOv11n Training Convergence Graphs

Fig. 3. presents the performance metrics of the YOLOv11n model during training with a batch size of 4 and an image size of 640x640 pixels for 100 epochs. While the training losses show a steady decline, the validation losses (especially after the 60th epoch) exhibit a slight upward trend.

This indicates potential overfitting of the model to the training data. When examining the final performance metrics of the model, precision is acceptable at 0.44964, while recall is quite low at 0.2285. The average precision values, mAP50(B) 0.23604 and mAP50-95(B) 0.12141, indicate that the model's overall detection capability and, in particular, the accuracy of bounding box positioning need to be improved. The low sensitivity and mAP50-95 values reveal that the model misses many real objects and is insufficient in precise positioning.

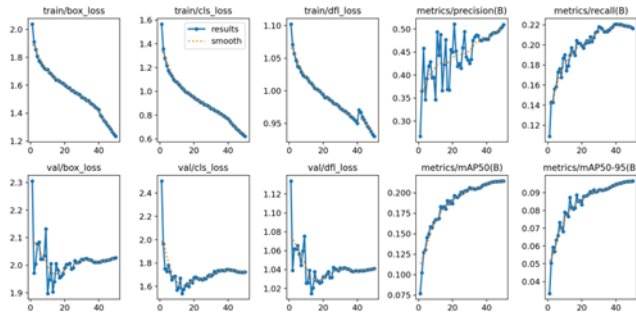


Fig. 4. YOLOv11s Training Convergence Graphs

Fig. 4. presents the performance metrics of the YOLOv11s model during training with a batch size of 4 and an image size of 640x640 pixels over 100 epochs. While training losses show a steady decline, validation losses (val/box_loss, val/cls_loss, val/dfl_loss) have stabilised relatively after the initial drop; this indicates a less pronounced overfitting tendency compared to the previous YOLOv11n model.

When examining the final performance metrics of the model at 100 epochs, precision was recorded as 0.48174. Sensitivity (recall) was 0.25666, mAP50(B) was 0.27768, and mAP50-95(B) was 0.15492, showing significant improvements in all metrics compared to the previous YOLOv11n model. In particular, the increase in recall and mAP50-95 values indicates that the model can detect more objects and achieve a significant improvement in the positional accuracy of bounding box predictions. These findings confirm that YOLOv11s offers a more effective solution in terms of object detection performance.

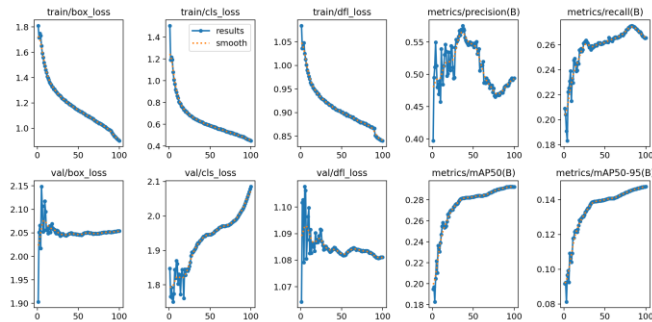


Fig. 5. YOLOv11m Training Convergence Graphs

Fig. 5. summarises the training process of the YOLOv11m model over 100 epochs, with a batch size of 1 and an image size of 640x640 pixels. While the training losses decrease, a significant increase in the validation classification loss (val/cls_loss) is observed after approximately 30 epochs, indicating overfitting.

The final metric results of the model are precision 0.4942, recall 0.26545, mAP50(B) 0.29258, and mAP50-95(B) 0.14758. These values show an improvement over the previous YOLOv11s model, particularly in terms of recall and mAP50(B), but indicate that position accuracy still needs to be improved at high IoU thresholds (mAP50-95). The single batch size (batch size 1) may have a limiting effect on the model's optimisation stability and generalisation performance. Strategies such as larger batch sizes and early stopping are recommended to reduce overfitting and improve performance.

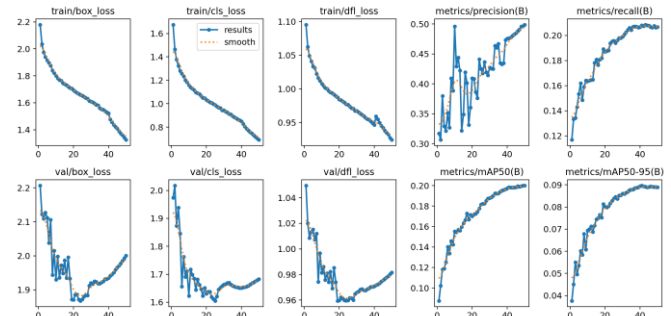


Fig. 6. YOLOv11l Training Convergence Graphs

Fig. 6. shows the training performance of the YOLOv11l model with 50 epochs, a batch size of 4, and an image size of 416x416 pixels. While training losses show a decreasing trend, the slight increase observed in validation losses (val/box_loss, val/cls_loss) after approximately 25 epochs indicates a potential overfitting issue.

The final metric results of the model are precision 0.49895, recall 0.20676, mAP50(B) 0.20003, and mAP50-95(B) 0.08892. These values indicate that the model's accuracy is moderate, but sensitivity and, in particular, positioning accuracy at high IoU thresholds (mAP50-95) need to be significantly improved. The model's overall performance is lower compared to larger YOLO models, particularly in terms of recall and mAP values. Strategies such as early stopping and hyperparameter optimisation are recommended to reduce overfitting and improve model performance.

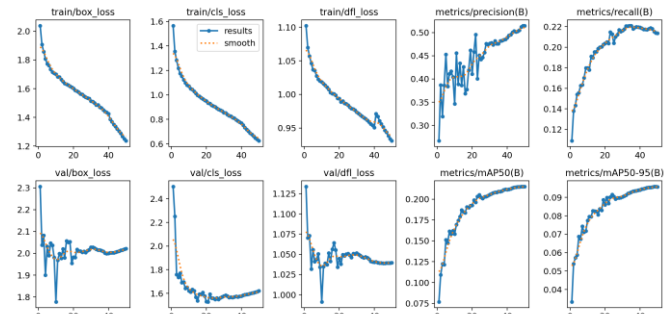


Fig. 7. YOLOv11l Training Convergence Graphs

Fig. 7. summarises the training performance of the YOLOv11l model with 50 epochs, a batch size of 8, and an image size of 480x480 pixels. While the training losses show the expected decrease, the slight increase observed in the validation classification loss (val/cls_loss) after approximately 25 epochs indicates a potential overfitting issue.

The model's final metric results are relatively good with precision at 0.51493, but recall at 0.21355 and mAP50(B) at 0.21512 are moderate, while mAP50-95(B) at 0.09579 is low. These values indicate that the model's object detection accuracy is acceptable, but it requires significant improvement in terms of sensitivity and, especially, localization accuracy at high IoU thresholds. Strategies such as early stopping and hyperparameter optimisation are recommended to reduce overfitting and improve model performance.

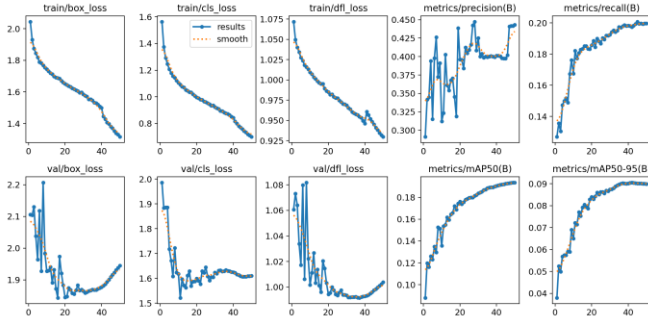


Fig. 8. YOLOv11s Training Convergence Graphs

Fig. 8. presents the training results obtained by the YOLOv11s model over 50 epochs with a 480x480 image size, a batch size of 10, and a final learning rate of 0.001. While training losses show a decreasing trend, the slight increase observed in the validation classification loss (val/cls_loss) after approximately 25 epochs indicates a potential overfitting issue. The model's final metrics (precision: 0.44296, recall: 0.19971, mAP50(B): 0.1935, mAP50-95(B): 0.08987) demonstrate lower performance compared to previous YOLOv11 configurations. In particular, the low precision and mAP values indicate that significant improvements are needed in the model's detection coverage and precise localisation ability. The combination of hyperparameters used (especially the large batch size and relatively short training time) may have contributed to this decline. Strategies such as early stopping and hyperparameter optimisation are recommended to improve performance.

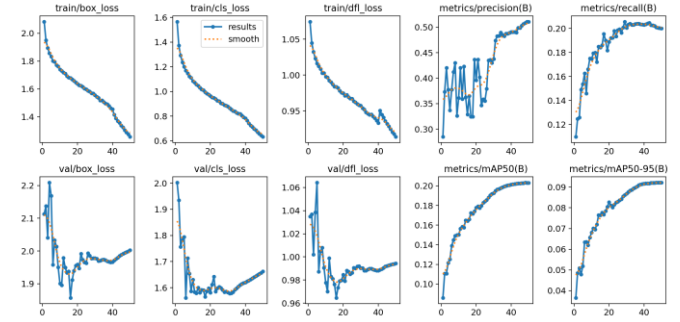


Fig. 10. YOLOv11l Training Convergence Graphs

The graphs and metric results presented in Fig. 10. summarise the training performance of the YOLOv11l model over 50 epochs with a 416x416 pixel image size, a batch size of 10, and a final learning rate of 0.001. While the training losses show the expected decrease, the slight increases observed in the validation losses (val/box_loss, val/cls_loss) after approximately 25 epochs indicate a potential overfitting issue. The model's final metrics are recorded as precision 0.51083, recall 0.20005, mAP50(B) 0.20298, and mAP50-95(B) 0.09214. These values indicate that the model's detection accuracy is relatively acceptable, but there is a need for significant improvements in sensitivity and, in particular, object localisation accuracy (mAP50-95) at high IoU thresholds. Considering the observed overfitting tendency and relatively low performance metrics, especially when using a large batch size of 10 and a relatively small image size (416x416), it is recommended to apply strategies such as early stopping and hyperparameter optimisation to enhance the model's generalisation ability.

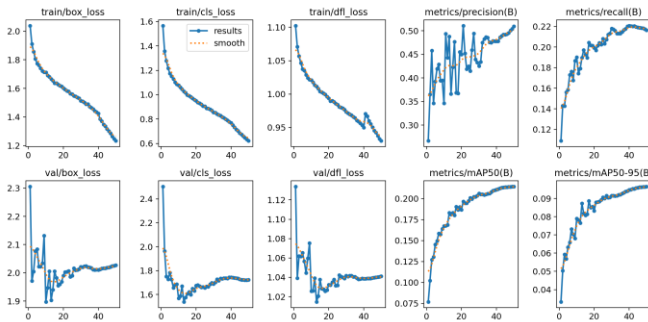


Fig. 9. YOLOv11l Training Convergence Graphs

The graphs shown in Fig. 9. and the obtained metric results reflect the training performance of the YOLOv11l model with a 480x480 pixel image size, a batch size of 8, and a final learning rate of 0.001 over 50 epochs. While the training losses show the expected decrease, the slight increase observed in the validation classification loss (val/cls_loss) after approximately 25 epochs indicates a potential overfitting issue. The model's final metrics are recorded as precision 0.50947, recall 0.21647, mAP50(B) 0.21431, and mAP50-95(B) 0.09652. These values indicate that the model's detection sensitivity is relatively acceptable, but there is a need for significant improvements in sensitivity and, in particular, object localisation accuracy (mAP50-95) at high IoU thresholds. Considering the observed overfitting tendency and relatively low performance metrics, it is recommended to apply strategies such as early stopping and more comprehensive hyperparameter optimisation to enhance the model's generalisation ability.

Model	Epoch	Batch - Size	Image - Size	lr0	lrf	mAP50(B)	mAP50-95(B)	precision(B)	recall(B)
YOLOv11n	100	4	640	0.01	0.01	0.23604	0.12141	0.44964	0.2285
YOLOv11s	100	4	640	0.01	0.01	0.27768	0.15492	0.48174	0.25666
YOLOv11m	100	1	640	0.01	0.01	0.29258	0.14758	0.4942	0.26545
YOLOv11l	50	4	416	0.01	0.01	0.20003	0.08892	0.49895	0.20676
YOLOv11l	50	8	480	0.01	0.01	0.21512	0.09579	0.51493	0.21355
YOLOv11s	50	10	480	0.01	0.001	0.1935	0.08987	0.44296	0.19971
YOLOv11l	50	8	480	0.01	0.001	0.21431	0.09652	0.50947	0.21647
YOLOv11l	50	10	416	0.01	0.001	0.20298	0.09214	0.51083	0.20005

Table 1. Training Parameters with the YOLOv11 Model

As detailed in Table 1, various YOLOv11 model variants were trained under different configurations, including varying batch sizes, image resolutions, and number of epochs. To improve the models' generalisation ability and robustness against variations in input data, a comprehensive set of data augmentation techniques was employed consistently across all training experiments.

Specifically, horizontal flipping was applied with a probability of 0.5 (fliplr=0.5), while vertical flipping was disabled (flipud=0.0). In addition, the training pipeline included random rotations up to ± 10 degrees (degrees=10), as well as color space augmentations in the HSV domain—

namely, hue adjustment within ± 0.015 (hsv_h=0.015), saturation variation up to ± 0.7 (hsv_s=0.7), and brightness variation up to ± 0.4 (hsv_v=0.4). Geometric transformations such as random scaling (scale=0.8, i.e., between 0.8 and 1.2) and translation (translate=0.1, i.e., up to $\pm 10\%$ of the image dimensions) were also incorporated. These augmentation parameters were activated using the augment=True setting.

The consistent application of these augmentation strategies aimed to increase the diversity of training samples artificially, thereby enhancing the models’ performance under real-world conditions. The resulting detection metrics—such as precision, recall, mAP50, and mAP50-95—demonstrate the impact of these techniques, as shown in Table 1.

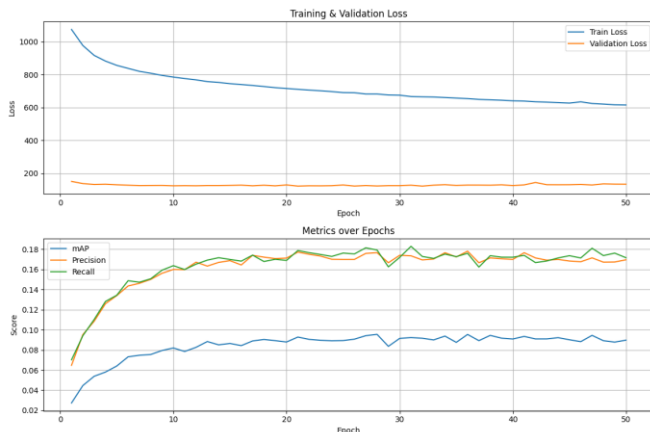


Fig. 11. Faster R-CNN Training Convergence Graphs

The Faster R-CNN model has demonstrated remarkable performance in object detection tasks. Following a training process of 50 epochs, the model achieved average precision (mAP) values of $\text{mAP}@0.5 \approx 47\%$ and $\text{mAP}@0.5:0.95 \approx 20.2\%$. However, the model's inference speed is limited to an average of 8 frames per second (FPS), which poses a constraint for real-time system integration. The training graph is shown in Fig. 11.

When examining the training dynamics, a steady decrease in the loss functions (both training and validation losses) was observed over 50 epochs. This trend indicates that the model successfully converged to the data distribution and maintained its generalisation ability without a significant increase in overfitting. The precision and recall metrics showed a relatively slow increase in the early stages of the training process, but followed a noticeable upward trend from approximately the 10th epoch onwards, indicating a gradual improvement in the model's target detection capability. The average precision (mAP) value also exhibited a similar trend.

The model was trained on images with a resolution of 512x512 pixels, processed in batches of 8 examples each. The optimisation algorithm used was Stochastic Gradient Descent (SGD), with an initial learning rate of 0.005 and a final learning rate of 0.01.

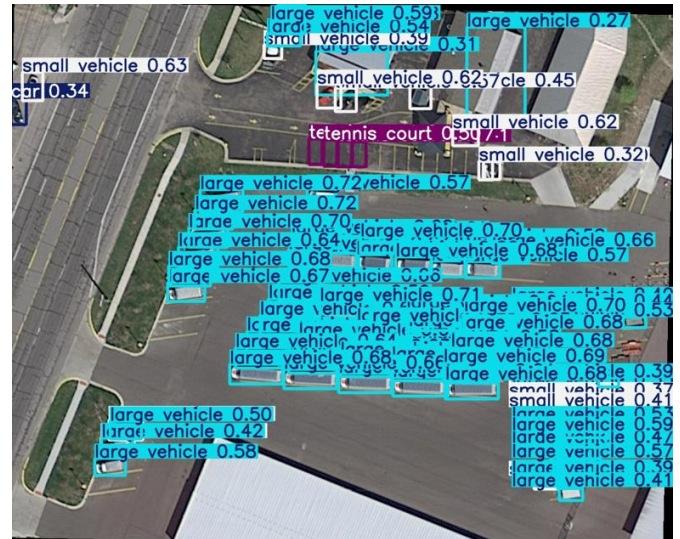


Fig. 12. Object Detection with YOLOv11

An example image of object detection performed with the YOLOv11 model is shown in Fig. 12.



Fig. 13. Faster R-CNN Object Detection

Fig. 13 shows an image of object detection performed with Faster R-CNN.



Fig. 14. Object Tracking with ByteTrack

Fig. 14 shows a visual representation of tracking performed with ByteTrack.

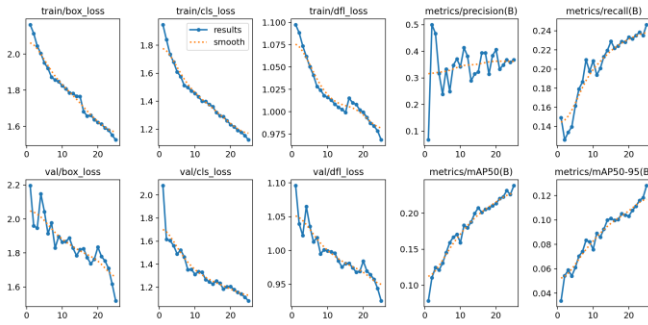


Fig. 15. YOLOv11s Training Convergence on VisDrone-DET Dataset

The graphs and metric results presented in Fig. 15. detail the training performance of the YOLOv11s model on the VisDrone DET dataset, using a 480x480 pixel image size, a batch size of 10, and a final learning rate of 0.001 over 25 epochs. The training losses (train/box_loss, train/cls_loss, train/dfl_loss) exhibit the expected decreasing trend throughout the training period, while the validation losses (val/box_loss, val/cls_loss, val/dfl_loss) show no significant overfitting trend during this short training period. The final performance metrics of the model are recorded as precision 0.36863, recall 0.24646, mAP50(B) 0.23819, and mAP50-95(B) 0.12821. These values indicate that the model's overall detection capability is moderate, but significant improvements are needed in both object coverage (recall) and, especially, bounding box positioning accuracy at high IoU thresholds (mAP50-95). It is considered that the performance achieved can be attributed to the limited training time (25 epochs) and that the model has potential for further optimisation.

In this study, three different training scenarios were considered for object detection and tracking tasks. First, YOLOv11 models were trained on a combination of the VisDrone MOT and DOTA datasets. Second, the same combined dataset was trained using the Faster R-CNN model. Third, the YOLOv11 model was trained only on the VisDrone DET dataset. The training outputs of all three models were carefully evaluated graphically in terms of metrics such as Precision, Recall, mAP, and loss, and recorded throughout the training. Finally, object tracking was performed using the ByteTrack algorithm based on the results obtained from these detection models, and the tracking results demonstrated that objects were reliably identified and high accuracy was achieved during the tracking process.

IV. DISCUSSION

This study offers a comprehensive assessment of contemporary deep learning-based object detection and tracking paradigms, with a particular emphasis on real-time applications. Within this framework, both single-stage (YOLOv11 variants) and two-stage (Faster R-CNN) detection architectures were evaluated using a combined dataset comprising VisDrone and DOTA. Additionally, standalone experiments on the VisDrone DET dataset were conducted exclusively with YOLOv11 models to investigate the performance of lightweight architectures in resource-constrained scenarios.

Following the detection phase, the ByteTrack algorithm was utilized to perform multi-object tracking. Its integration enabled reliable and continuous tracking by maintaining consistent object identities, even in the presence of rapid motion or temporary occlusion.

The training dynamics of different-sized (n, s, m, l) and configured models of the YOLOv11 family were examined in detail through the evolution of loss functions. In general, training losses showed a steady decrease across all variants, indicating that the models effectively learned the patterns in the training data. However, changes in validation losses provided critical insights into the models' generalisation ability. For example, in the 100-epoch training of the YOLOv11n model, a slight increase in validation losses starting after approximately 60 epochs indicated a potential overfitting tendency. This situation carried the risk of negatively affecting the model's performance on test data by over-adapting to the training data. The final metrics, particularly the low sensitivity (0.20005) and mAP50-95(B) (0.09214) values, indicated significant limitations in the model's target detection coverage and bounding box positioning accuracy.

In the 100-epoch training of the YOLOv11s model, validation losses followed an initial decline and then stabilised relatively, indicating better generalisation ability. This model showed significant improvements over the previous YOLOv11n in all basic metrics (precision: 0.48174, recall: 0.25666, mAP50(B): 0.27768, mAP50-95(B): 0.15492), proving that more objects can be detected and that there is a significant increase in location accuracy.

When trained with a small batch size of 1, the YOLOv11m model showed serious overfitting symptoms with a significant increase in validation classification loss (val/cls_loss) after approximately 30 epochs. This indicates that small batch sizes may negatively affect training stability and limit generalisation ability. Metrics (precision: 0.4942, recall: 0.26545, mAP50(B): 0.29258, mAP50-95(B): 0.14758) showed an improvement in mAP50 compared to the previous YOLOv11s model, but it was emphasised that accuracy and positional accuracy at high IoU thresholds still need to be improved.

Different 50-epoch configurations of the YOLOv11l model were also investigated. Training with a 416x416 image size and a batch size of 4 (precision: 0.49895, recall: 0.20676, mAP50(B): 0.20003, mAP50-95(B): 0.08892), slight overfitting symptoms were observed after approximately 25 epochs in validation losses. When a larger image size (480x480) and a batch size of 8 were used (precision: 0.51493, recall: 0.21355, mAP50(B): 0.21512, mAP50-95(B): 0.09579), while precision improved slightly, sensitivity and mAP50-95 values still require further improvement. Reducing the final learning rate (lrf) to 0.001 (for the 480x480, batch 8 configuration) did not result in significant changes in the metrics, and the overfitting tendency persisted (precision: 0.50947, recall: 0.21647, mAP50(B): 0.21431, mAP50-95(B): 0.09652). Similarly, the performance of the YOLOv11l model trained with a 416x416 image size and a batch size of 10 (lrf=0.001) also showed signs of overfitting with low precision and mAP values (precision: 0.51083, recall: 0.20005, mAP50(B): 0.20298, mAP50-95(B): 0.09214) showed signs of overfitting with low precision and mAP values. The YOLOv11s model trained on the VisDrone DET dataset for 25 epochs did not show significant overfitting in its losses within this short timeframe; however, its metric values (precision:

0.36863, recall: 0.24646, mAP50(B): 0.23819, mAP50-95(B): 0.12821) indicate that the model still has significant optimisation potential.

The Faster R-CNN model has demonstrated very high performance in object detection tasks. Following a 50-epoch training process, it achieved average accuracy (mAP) values of mAP@0.5~47% and mAP@0.5:0.95~20.2%. During training, it was observed that the loss functions continuously decreased and the model maintained its generalisation ability without a significant increase in overfitting. The accuracy and recall metrics also showed a noticeable upward trend starting from approximately the 10th epoch. However, the inference speed of Faster R-CNN is limited to an average of 8 frames per second (FPS), which poses a significant constraint for real-time system integration. The training of this model was performed on 512x512 pixel image size and 8-sample mini-batches.

In the object tracking phase of the study, the ByteTrack algorithm processed the detection outputs from the YOLOv11 model to assign identities to objects and enable tracking across different frames. The tracking results demonstrated that objects were reliably identified and high accuracy was achieved during the tracking process. This finding confirms that ByteTrack, integrated with a powerful detection model, can provide reliable multi-object tracking even in dynamic and complex scenes.

In general, the YOLOv11 and Faster R-CNN models offer unique advantages and disadvantages in object detection tasks. Faster R-CNN excels in detection accuracy with higher mAP values but is limited in real-time applications due to its lower inference speed. YOLOv11 family models, while generally achieving higher inference speeds compared to Faster R-CNN, exhibit performance variability depending on different sizes and training configurations. Overfitting issues and lower sensitivity/mAP values are particularly noticeable in variants with small models (YOLOv11n) or specific hyperparameter combinations (e.g., single batch size in YOLOv11m). Larger YOLOv11 variants (s, l) demonstrate better overall performance while maintaining improvement potential, particularly in fine-grained localization (mAP50-95) metrics. These results highlight the importance of carefully balancing accuracy and speed depending on application requirements. The overfitting tendencies observed during training highlight the importance of early stopping, more advanced learning rate schedules, and enriched data augmentation techniques. This comprehensive evaluation on diverse datasets of varying scales and complexities, such as VisDrone and DOTA, has provided valuable insights into the models' adaptability to different scenarios. Finally, the successful integration of outputs from detection models with the ByteTrack algorithm demonstrates the practical applicability of multi-object tracking in fields such as autonomous systems and surveillance applications. Future work could focus on architectural optimisations and custom loss functions to improve the performance of YOLOv11 models at high sensitivity and high IoU thresholds. Additionally, minimising accuracy loss while increasing inference speeds through model compression and quantisation techniques will open up broader application areas in real-time systems.

V. CONCLUSION

This study aims to comprehensively examine the performance of current deep learning-based approaches, such as the YOLOv11 family of models and Faster R-CNN, in the field of multi-object detection and tracking using the VisDrone and DOTA datasets. The findings provide valuable insights into the capabilities and limitations of these models, while also evaluating the impact of integrating detection algorithms with ByteTrack on tracking performance.

Experimental results reveal that different variants and hyperparameter configurations of YOLOv11 models exhibit variable performance. While training losses generally show a consistent decrease, significant overfitting tendencies are observed in validation losses, particularly during long training periods or with small batch sizes (e.g., a batch size of 1 in YOLOv11m). This indicates that the models are overly adapted to the training data, limiting their generalisation ability. In particular, low sensitivity and mAP50-95 values in YOLOv11n and some YOLOv11l configurations indicate that the models are unable to detect all objects and localise them with high accuracy. In contrast, the 100-epoch training of the YOLOv11s model demonstrated more stable validation losses and significant improvements in overall metrics (precision: 0.48174, recall: 0.25666, mAP50(B): 0.27768, mAP50-95(B): 0.15492), demonstrating more effective performance. The Faster R-CNN model achieved very high mAP values (mAP@0.5~47%, mAP@0.5:0.95~20.2%) in the object detection task, demonstrating strong performance in terms of accuracy.

The continuous decrease in loss functions and gradual improvement in metrics observed during training support the model's strong generalisation ability. However, the inference speed of 8 frames per second (FPS) on average poses a significant constraint for real-time system integration.

The ByteTrack algorithm, an integral part of the study, demonstrated successful performance in object tracking using outputs from detection models. The tracking results showed that objects were reliably identified and high accuracy was achieved during the tracking process. This finding confirms that ByteTrack, combined with a robust detection model, offers an effective solution for reliable multi-object tracking in dynamic environments.

In conclusion, this study has thoroughly demonstrated the object detection capabilities of both the YOLOv11 family and Faster R-CNN models, highlighting the fundamental trade-offs between speed and accuracy. The excessive convergence tendencies and metric variability in the training processes of different YOLOv11 variants confirm the critical role of strategies such as hyperparameter optimisation and early stopping. While Faster R-CNN achieves superior detection accuracy, its lower inference speed limits its applicability in certain domains.

The successful integration with ByteTrack's detection outputs demonstrates the feasibility of building a comprehensive object detection and tracking system. Future work may explore more advanced data augmentation techniques, learning rate schedules, and architectural improvements to improve the performance of YOLOv11 models, particularly on critical metrics such as sensitivity and mAP50-95.

Additionally, improving inference speeds through model compression and hardware acceleration methods for high-

accuracy models like Faster R-CNN could expand their potential in real-time applications. Specialised detection heads or multi-scale feature fusion approaches for detecting small and dense objects in complex datasets such as VisDrone could also be a focus of future research. Finally, advanced metrics and comparative analyses could be used to more comprehensively evaluate the performance of tracking algorithms under different challenges (e.g., long-term occlusions, identity change scenarios).

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Authors' Contributions

The authors' contributions to the paper are equal.

Statement of Conflicts of Interest

There is no conflict of interest between the authors.

Statement of Research and Publication Ethics

The authors declare that this study complies with Research and Publication Ethics

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IoT / PLC Tabanlı Düşük Tüketimli Çamaşır Makinesi Yönetimi

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Özet – Sera gazların neden olduğu küresel ısınmanın etkileri her geçen yıl daha belirgin şekilde his edilmeye başlanmıştır. Bu durum enerji ve su kullanımlarının daha kontrollü ve verimli tüketilmesini zorunlu kılmaktadır. Bunu sağlamak için yeşil teknolojilerin geliştirilmesi ve kullanılması bir zorunluluk haline gelmiştir. Çamaşır makinelerin su ve enerji tüketimini daha düşük hale getirmek için modern çamaşır makineleri geliştirilmektedir. Bu verimi yükseltmenin bir yolu çamaşır makinelerin işletilmesinin PLC’ler ile daha etkin bir şekilde sağlanmasıdır. Çamaşır makinesi kontrol sistemleri, teknolojik gelişmelere paralel olarak mekanik kontrolden elektro-mekanik, elektronik ve son olarak PLC tabanlı kontrol sistemlerine evrilmiştir. Bu gelişim süreci, çamaşır makinelerinin daha fazla program seçeneği sunmasını, su ve enerji tasarrufu yapmasını, farklı kumaş türleri için özel yıkama seçenekleri sağlamasını ve kullanıcı dostu arayüzler geliştirmesini mümkün kılmıştır. Diğer taraftan PLC sistemleri, IoT cihazlarıyla birleşerek uzaktan izleme ve yönetim imkanı sunmaktadır. Bu, gerçek zamanlı veri analizi, önleyici bakım stratejileri ve üretim planlaması gibi avantajlar sağlamaktadır. Teknolojinin ilerlemesi ve özellikle endüstri 4.0 ile, IoT teknolojisinin ve yapay zekanın gelişmesi bir çok farklı yeni uygulama alanları ortaya çıkarmıştır. Bu teknolojinin gelişmesi; Akıllı ev otomasyonlar, akıllı şehirler, akıllı tarım, akıllı ulaşım gibi pek çok alanda olmuştur. Günümüzde yurtlarda, kurumlarda, lojmanlarda ve otel gibi birçok toplu yaşam alanlarında merkezi çamaşırhaneler bulunmaktadır. Ancak bu çamaşırhanelerde, yüksek güç tüketimine sahip çamaşır makineleri birbirinden bağımsız çalışmaktadırlar. İşletimleri ve yönetimleri gömülü sistem şeklinde, CPU tabanlı çalışarak sağlanmaktadır. Ancak bunların enerji yönetimleri, su sarfiyatları, arıza verme ihtimallerin önce den değerlendirilmesi, yapay zeka ve makine öğrenmesi gibi merkezi bir sistem üzerinde yapılması; Gerçek zamanlı veri toplama ve analiz, uzaktan kontrol ve izleme, öngörü bakımı, verimlilik ve enerji tasarrufu gibi birçok avantajlar sağlayabilecektir. Bu çalışmada PLC merkezli çalışan çamaşır makinelerin IoT tarafından yönetilmesini sağlayan çoklu çamaşır makinesi yönetim sisteminin simülasyon çalışması gerçekleştirilmiştir. Gerçekleştirilen çalışma, farklı yerleşim alanlarında bulunan Laundry gibi çoklu çamaşır makilerin bağlı bulunduğu çamaşırhanelerin IoT üzerinden takip edilmesi ve yönetilmesinin alt yapısını oluşturmaktadır. Çalışma sistemin blok yapısını ve bu tip bir sistemin yönetilmesini ve izlenmesini sağlayacak, PLC ile IoT entegrasyonunu incelemekte ve bunun için geliştirilmiş simülasyon çalışmasını ortaya koymaktadır. Geliştirilen çalışmada ayrıca performans optimizasyonu, süre optimizasyonu, bellek kullanımı optimizasyonu, enerji ve su verimliliği optimizasyonu gibi teknikler Siemens Ladder Diyagramları kullanılarak geliştirilmiştir.

Anahtar Kelimeler – PLC, Siemens Ladder Diagramı, IoT-Bulut, Endüstriyel Otomasyon, Çamaşır Makinesi.

IoT / PLC Based Low Consumption Washing Machine Control

Abstract-The effects of greenhouse gases have been increasingly felt every year due to global warming. This situation necessitates more controlled and efficient consumption of energy and water. To achieve this, the development and use of green technologies have become essential. Modern washing machines are being developed to reduce water and energy consumption. One way to enhance this efficiency is by operating washing machines more effectively with Programmable Logic Controllers (PLCs). Washing machine control systems have evolved from mechanical control to electromechanical, electronic, and finally PLC-based control systems in line with technological advancements. This development process has enabled washing machines to offer more program options, conserve water and energy, provide special washing options for different fabric types, and develop user-friendly interfaces. On the other hand, PLC systems, when combined with IoT devices, offer the capability for remote monitoring and management. This provides advantages such as real-time data analysis, preventive maintenance strategies, and production planning. The advancement of technology, especially with Industry 4.0, has given rise to many new application areas, particularly the development of IoT technologies and artificial intelligence. This advancement has led to smart home automation, smart cities, smart agriculture, smart transportation, and many other fields. Today, there are centralized laundries in many communal living spaces such as dormitories, institutions, lodgings, and hotels. However, in these laundries, high-power-consuming washing machines operate independently of each other. Their operations and management are conducted in an embedded system manner, utilizing CPU-based systems. However, energy management, water consumption, and the potential for malfunctions can be better evaluated through a centralized system using technologies like artificial intelligence and machine learning. This could provide significant advantages such as real-time data collection and analysis, remote control and monitoring, predictive maintenance, efficiency, and energy savings. This study involves the simulation of a multi-washing machine management system that allows PLC-based washing machines to be managed by IoT. The work conducted lays the groundwork

for monitoring and managing multiple washing machines, such as those found in laundry facilities located in different settlement areas, via IoT. The study examines the block structure of the system and how to manage and monitor such a system, highlighting the integration of PLC with IoT, as well as presenting a developed simulation study for this purpose. Additionally, techniques for performance optimization, time optimization, memory usage optimization, and energy and water efficiency optimization have been developed using Siemens Ladder Diagrams

Keywords – PLC, Siemens Ladder Diagram, IoT Cloud, Industrial Automation, Washing Machine.

I. GİRİŞ

Sera gazların neden olduğu küresel ısınmanın etkileri her yıl artmaktadır. Küresel ısınmanın etkilerini hafifletebilmek için enerji ve su tüketimlerin azaltılması önemli rol oynamaktadır. Yapılan çalışmalar göstermiştir ki, çamaşır makinesini tam dolunca çalıştırmak ve verimli termostat ayarları kullanmak enerji ve su tüketimini %15-20 oranında azaltabilmektedir [1]. Bu verimi yükseltmenin bir yolu çamaşır makinelerin işletilmesinin Programlanabilir Mantık Devreleri (PLC) ile daha etkin bir şekilde sağlanmasıdır. Bu cihazlar endüstriyel otomasyon alanında yaygın olarak kullanılan kontrol sistemleridir. Bu sistemler, giriş birimlerinden aldıkları sinyalleri işleyen ve çıkış birimlerine komutlar gönderen bir yapıda çalışmaktadırlar. Çamaşır makineleri gibi beyaz eşyalarda kullanılan PLC sistemleri genellikle mikro PLC'lerdir ve motor, ısıtıcı, pompa gibi çamaşır makinesinin farklı bileşenlerini kontrol edebilecek, su seviyesi, sıcaklık v kapak çeşitli sensörlerden veri işleyebilecek ve kullanıcı arayüzü ile etkileşim kurabilecek kapasiteye sahiptirler. Teknolojinin ilerlemesi ve özellikle endüstri 4.0 ile, IoT teknolojisinin ve yapay zekanın gelişmesi bir çok farklı yeni uygulama alanları ortaya çıkarmıştır. Bu teknolojinin gelişmesi; Akıllı ev otomasyonlar, akıllı şehirler, akıllı tarım, akıllı ulaşım gibi pek çok alanda olmuştur. Bu çalışma, çamaşır makinelerin IoT ile PLC tabanlı kontrol sistemlerine odaklanmaktadır. Çamaşır makineleri, günlük hayatımızda önemli bir yer tutmakta olup, teknolojik gelişmeler doğrultusunda kontrol sistemleri zamanla evrim geçirmiştir. Çamaşır makinesi, motor ve farklı donanım ekipmanlarıyla kontrol edilen, insan müdahalesi olmadan otomatik olarak çalışan ve çamaşırları yıkamak için tasarlanmış bir makinedir [2]. Mekanik modellerden akıllı ve programlanabilir sistemlere uzanan bu gelişim süreci, modern çamaşır makinelerinin su seviyesi kontrolü, sıcaklık ayarları, farklı yıkama programları ve enerji tasarrufu gibi çeşitli işlevleri yerine getirebilmesini sağlamıştır [3]. Çalışma iki aşamaya ayrılmıştır, bunlardan birinci kısmı, PLC tabanlı çamaşır makinesi kontrol sistemin; hızlı, normal ve yoğun yıkama programlarını, soğuk, ılık ve sıcak su sıcaklık seçeneklerini, su seviyesi kontrolünü ve farklı güvenlik mekanizmalarını içermektedir [4]. Sistemin detaylı analizi, çalışma prensipleri ve programlama yapısı mühendislik perspektifiyle ele alınmıştır. Çalışmanın diğer aşamasını ise çamaşır makinelerin IoT üzerinden bulut tabanlı yönetilmesini kapsamaktadır. Burada bulut üzerinde çalışan merkezi program farklı lokalizasyonlarda bulunun çok sayıda çamaşırhanelerin yönetilmesini IoT üzerinden sağlamaktadır. PLC sistemleri, endüstriyel otomasyon uygulamalarında yaygın olarak kullanıldığı gibi beyaz eşya sektöründe giderek daha önemli hale gelmektedir [5]. PLC'lerin çamaşır makinelerindeki kullanım alanları, avantajları ve teknik özellikleri ayrıntılı bir şekilde incelenmekte, teorik bilgilerin yanı sıra pratik uygulama örnekleri ve devre şeması analizleri sunulmaktadır. Temel olarak PLC'ler giriş birimlerinden aldığı sinyalleri, içerisinde bulunan program doğrultusunda

işleyerek çıkış birimlerine aktaran kontrol üniteleridir [8]. PLC'ler, mikrodenetleyiciler ve bilgisayarlardan farklı olarak, zorlu endüstriyel ortamlarda çalışacak şekilde tasarlanmış ve yüksek güvenilirlik, dayanıklılık ve hız özellikleriyle öne çıkmaktadır. PLC'lerin çalışma hızına bağlı olarak milisaniyeler içerisinde tamamlanmaktadır [6]. PLC sistemleri, endüstrinin hemen her alanında kullanılmaktadır [7]. Avantajları ise; zorlu endüstriyel ortamlarda çalışabilecek şekilde tasarlanmış olmaları, yüksek çalışma güvenilirliği ve düşük arıza oranları sunması, programları değiştirilerek farklı uygulamalar için kullanılabilir olması, ihtiyaca göre giriş/çıkış modülleri eklenebilir veya çıkarılabilir olması, arıza teşhis özellikleri sayesinde sorunlar hızlıca tespit edilebilmesi. ağ bağlantısı sayesinde uzaktan izleme ve kontrol imkanı sunması. PLC tabanlı tam otomatik çamaşır makinesi kontrol sisteminin tasarımı temel olarak giriş birimi, çıkış birimi, programlanabilir mantık devre birimi, kullanıcı makine arayüzü ve haberleşme biriminden oluşmaktadır [15].

II. MATERIALS AND METHOD

Farklı yerlerde bulunan PLC'ler, IoT ve Wi-Fi üzerinden bulut tabanlı bir sistem ile tek merkezden kontrol edilebilmektedir. Bu şekilde geliştirilen sistem için PLC ve IoT cihazların entegrasyonu sağlanması mümkün olmaktadır. Geliştirilen Ladder diyagramlar içerisinde, enerji ve su verimliliğini artırmak amacıyla sensör verilerine dayalı karar mekanizmaları oluşturulmuştur. Örneğin, çamaşır makinesi su alma aşamasında su seviyesi sensörü üzerinden gelen veri sürekli izlenmekte ve yalnızca gerekli seviyeye ulaşıldığında pompa durdurularak hem enerji hem su tasarrufu sağlanmaktadır [14]. Benzer şekilde, ısıtma süresi kontrol bloklarında sıcaklık sensöründen alınan veriyle hedef sıcaklığa ulaşıldığında ısıtıcı devre dışı bırakılarak süre ve enerji optimizasyonu gerçekleştirilmiştir.

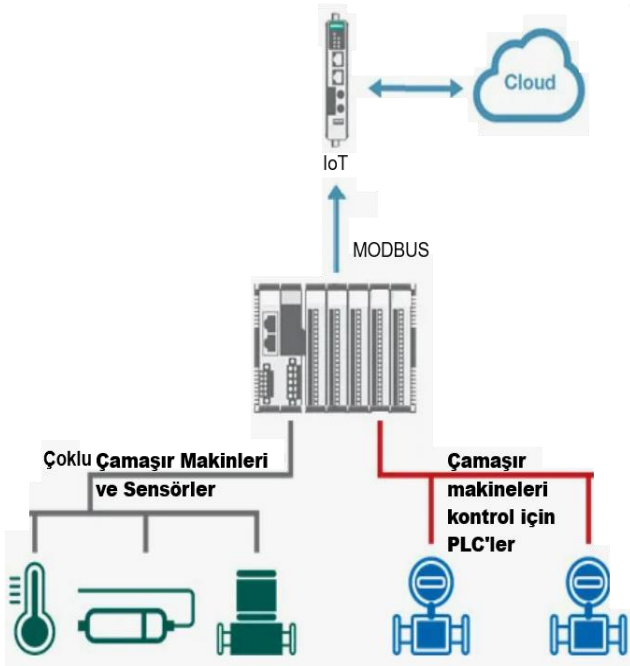
A. PLC-IoT İletişimi

PLC, veri iletiminde güç hatlarını kullanarak IoT cihazlarıyla bağlantı kurulmaktadır. Bu şekilde kablosuz iletişimdeki sinyal sorunları ve sınırlamaları aşılmaktadır. Haberleşme Protokolleri; PLC'ler, Modbus, Profibus, Ethernet/IP ve OPC UA gibi çeşitli protokoller aracılığıyla iletişim kurulmaktadır. Aşağıdaki Şekil 1'de PLC'lerin Modbus üzerinden ağ ve IoT ile buluta bağlanması görülmektedir. PLC'ler, Modbus üzerinden IoT ile buluta Message Queuing Telemetry Transport (MQTT) protokolü ile haberleşirler [17]. IoT ve PLC'nin birlikte kullanımı, endüstriyel otomasyon, enerji yönetimi ve bina otomasyonu gibi alanlarda verimliliği artırır [16]. PLC, frekans bandına ve iletim hızına bağlı olarak, dar bant PLC, orta bant PLC ve geniş bant PLC olmak üzere üçe guruba ayrılmaktadır. Ancak IoT uygulamaları için yüksek hız ve gerçek zamanda erişim gerektiği için orta band PLC'lerin kullanılması gerekmektedir. Aşağıda Şekil 2'de ise

PLC ile IoT haberleşme modeli görülmektedir. Geleneksel PLC iletişim modeli fiziksel katman, veri bağlantı katmanı ve uygulama katmanından oluşur. Veri bağlantı katmanı doğrudan uygulama katmanına hizmet verisi iletir.

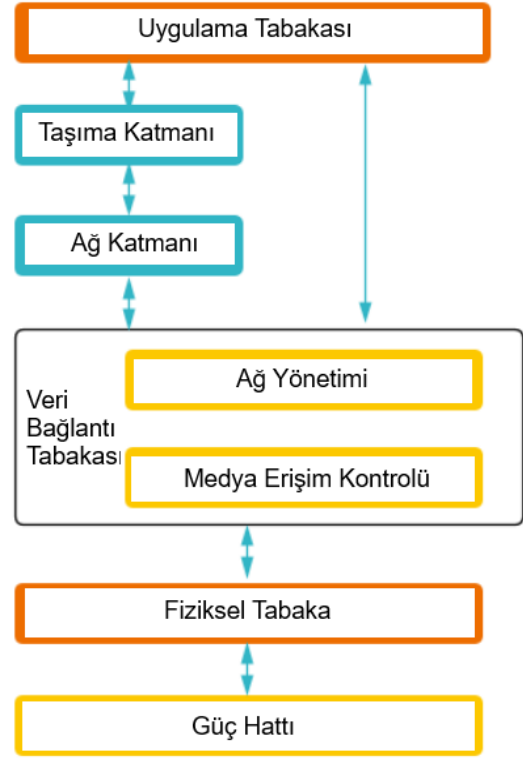
B. IoT ağ geçidinin yapılandırılması

Ağ geçidin yapılandırılması için; IoT ağ geçidi ağına bağlanmaktadır ve IP adresi, alt ağ maskesi ve ağ geçidi gibi ağ parametreleri yapılandırılmaktadır. PLC ile sorunsuz iletişim sağlamak için PLC'nin iletişim protokolüne ve arayüzüne göre IoT ağ geçidinin iletişim parametreleri de yapılandırılmaktadır. PLC tarafından toplanan verilerin IoT platformuna iletilmesi için IoT ağ geçidinin veri iletim kuralları belirlenip ayrıca yapılandırılmaktadır.



Şekil 1. PLC'lerin Modbus üzerinden ağ ve IoT bağlantısı

Açık Sistemler Bağlantısı (OSI) modeline göre, ağ katmanı ve taşıma katmanı PLC-IoT ağ mimarisine dahil edilir. IPv6-yetenekli ağ katmanı TCP/IP üzerinden standart IP ağ iletişimini uygular. Bu, uygulamaların veri bağlantı katmanı yerine ağ katmanı (IP katmanı) üzerinde çalışmasına olanak sağlamaktadır.



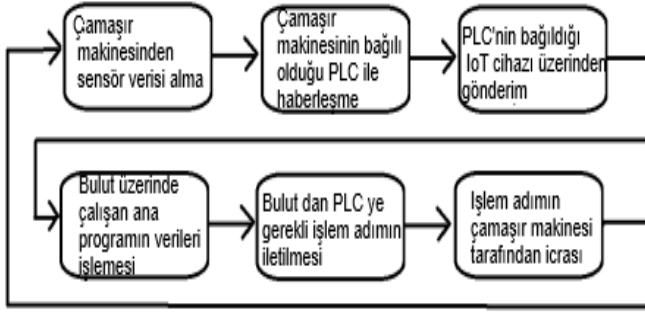
Şekil 2. PLC-IoT haberleşme blok şeması

C. Her bir PLC tarafında programın çalışma mantığı

Yukarıda bas edildiği üzere IoT üzerinden birçok farklı PLC yönetimindeki çamaşırhanelere erişim sağlanmaktadır. Farklı yerlerde bulunan PLC'ler kendi ağlarına bağlı her bir çamaşır makinesini yönetmektedir. Her bir çamaşır makinesini işletme program adımları aşağıda tanımlanmıştır.

- Motor çalışırken ve zaman dolmadıysa su alınır.
- Su alındıktan sonra, sıcaklık düşükse ısıtıcı çalışır.
- Isıtıcı çalıştıktan belirli bir süre sonra, yıkama başlar
- Yıkama süresi dolduğunda, tahliye pompası çalışır.
- Tahliye tamamlandığında, durulama başlar.
- Durulama süresi dolduğunda, tekrar tahliye yapılır.
- Tahliye tamamlandığında, sıkma başlar.
- Sıkma süresi dolduğunda, program biter.

Bu mantık, çamaşır makinesinin adım adım çalışmasını kontrol eden bir ladder diyagram yapısına dayanmaktadır. Sistem, her aşamada sensörler den gelen verileri IoT üzerinden bulut sunucusu üzerinden çalışan ana programa PLC üzerinden gönderilir. Değerlendirmeler bulut üzerinde yapılarak işlem adımların icrası için tekrar ilgili PLC ye yanıt verir. PLC ye bağlı ilgili çamaşır makinesi O anlık icra etmesi gereken işlemi gerçekleştirir. Sistemin genel akış şeması Şekil 2'de verilmiştir.



Şekil 3. PLC-IoT sistemin çalışma basamakları

D. Çamaşır makinelerin enerji ve su tüketimi

Çamaşır makinelerinin su ve enerji tüketim hesaplamaları aşağıda verilen faktörlere bağlıdır.

1. Makinenin tipi ve kapasitesi: Önden yüklemeli makineler daha az su tüketir.
2. Yıkama programı: Hızlı yıkama az su kullanırken, pamuklu yıkama daha fazla su harcar.
3. Su basıncı ve sıcaklık: Yüksek sıcaklık ve düşük su basıncı daha fazla su tüketimine yol açmaktadır
4. Yük boyutu: Tam yük daha fazla, yarım yük ise daha az su tüketimine neden olur. Su tüketimi hesaplaması için;

" $TWU = NC * WPC$ "
formülü kullanılmaktadır.

TWU: Toplam su kullanımıdır (galon veya litre cinsinden).

NC: Döngü sayısıdır.

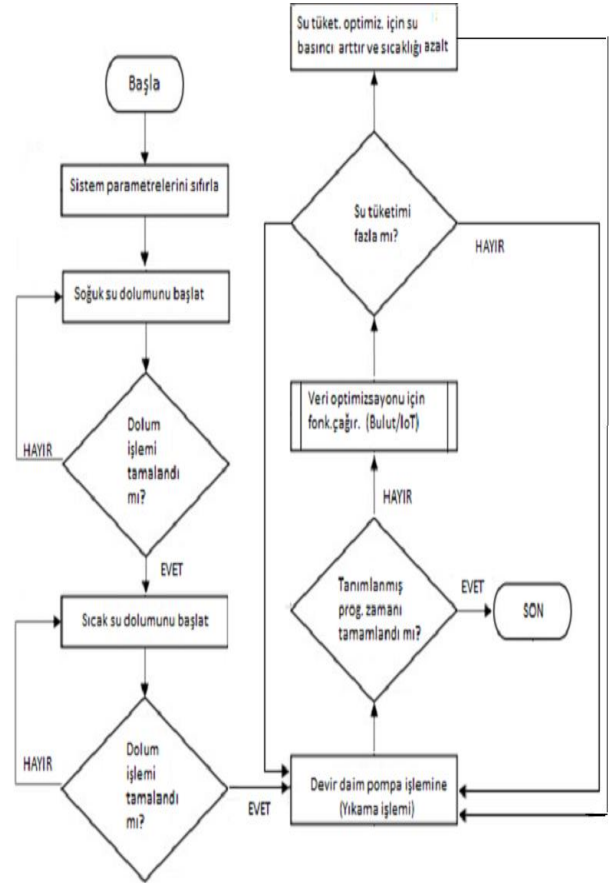
WPC: Döngü başına kullanılan sudur, galon veya litre cinsinden.

Enerji tüketimi ise makinenin motor gücü ve yıkama programına bağlı olarak değişmektedir. Örneğin, 60° pamuklu program daha fazla enerji harcarken, su ve enerji tasarrufu sağlamak için eko programlar kullanılabilir ve makine tam kapasiteyle çalıştırılması gerekmektedir. Çamaşır makinelerinin su ve enerji tüketim hesaplamaları şu şekilde yapılabilir. Çamaşır makinelerinin su tüketimi, makinenin modeline, yıkama programına ve çamaşır yüküne bağlı olarak değişebilmektedir. Modern çamaşır makineleri, su ve enerji tasarrufu sağlamak için tasarlanmış programlarla donatılmıştır. Önden yüklemeli çamaşır makineleri genellikle daha az su tüketir ve bir yıkama döngüsünde ortalama 40-60 litre su kullanmaktadır. Enerji tüketimi, yıkama programı, çamaşır yükü, su basıncı ve sıcaklık gibi faktörlere bağlıdır. Standart 40°C pamuklu program genellikle 0,9-1,0 kWh enerji tüketir. 60°C normal program seçildiğinde ise enerji ihtiyacı artmaktadır. Daha verimli bir makine veya düşük sıcaklık programlarıyla günde 0,7-0,8 kWh tüketim sağlanabilmektedir.

E. Sistemin çalışmasının genel akış şeması

Aşağıda görüldüğü üzere Şekil 4'de toplu çamaşır makinelerin bulunduğu çamaşırhanenin IoT destekli PLC üzerinden yönetilmesi görülmektedir. Şekilde görüldüğü üzere kullanıcı tarafından herhangi bir çamaşır makinesi çalıştırıldığında tüm sistem parametreleri sıfırlanmaktadır. İlk aşamada soğuk su dolumu başlatılmaktadır. Soğuk su dolumu tamamlandıktan sonra ikinci aşama olan sıcak su dolumu başlamaktadır. İlk iki aşama tamamlandıktan sonra ise sıcaklık ve basınç değerleri veri optimizasyonu için ESP 32 üzerinden

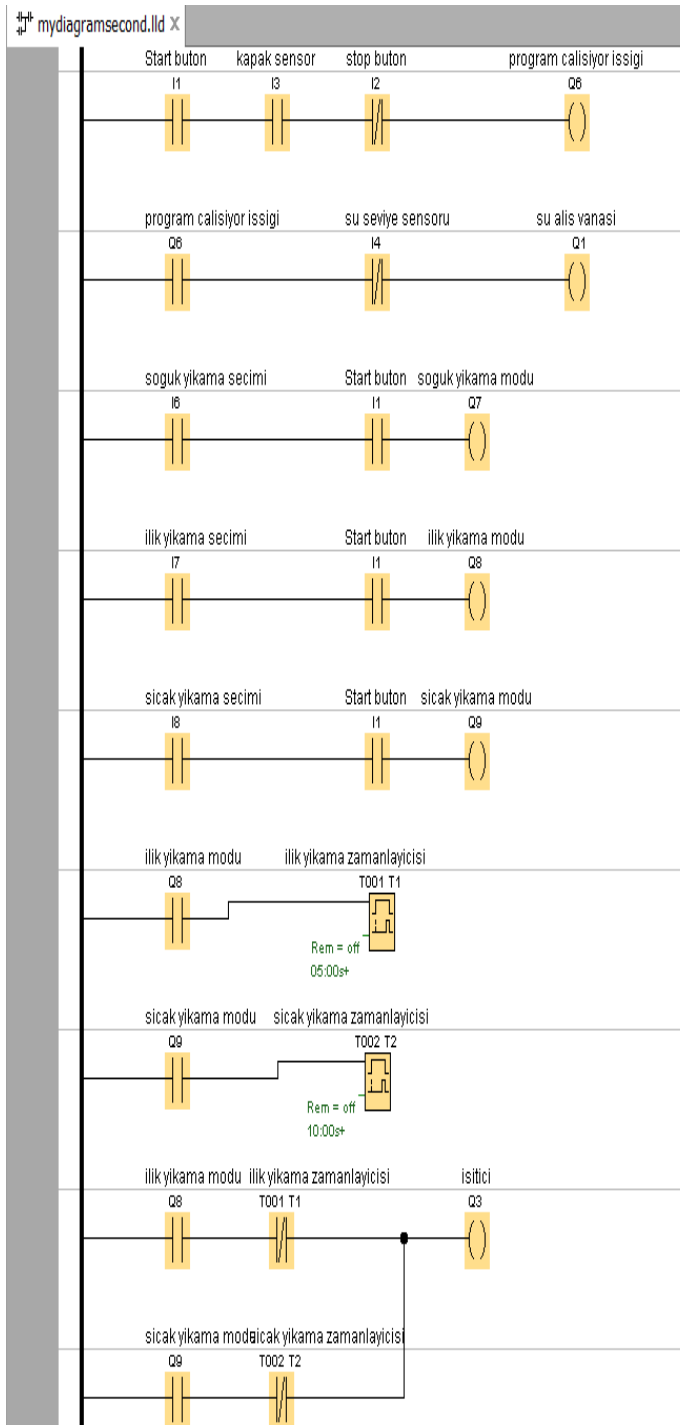
veri optimizasyonu için buluta gönderilmektedir. Orada Kontrol programı sistemin enerji ve su tüketim değerlerini analiz edip gerekli müdahaleler için tekrar ESP 32 üzerinden PLC ile haberleşip ilgili makinenin daha uygun enerji ve su tüketim değerleri için optimize ettiği enerji ve basınç değerlerine bağlı PLC üzerinden yeni basınç ve sıcaklık değerlerine bağlı su ve sıcaklık artırılması yada azaltılması işlemlerini gerçekleştirmektedir. Bu işlemler yıkama işlemi süresince döngüsel olarak devam etmektedir. Her bir program döngüsü sonunda ise genel program için belirlenmiş yıkama süresinin tamamlanıp tamamlanmadığı denetlenmektedir. Eğer süre dolmuşsa yıkama işlemi sonlanmaktadır. Bu şekilde merkezi PLC onlarca çamaşır makinesini yönetebilmektedir.



Şekil 4. Çamaşırhane tarafında her bir çamaşır makinesinin çalışmasını gösteren akış şeması.

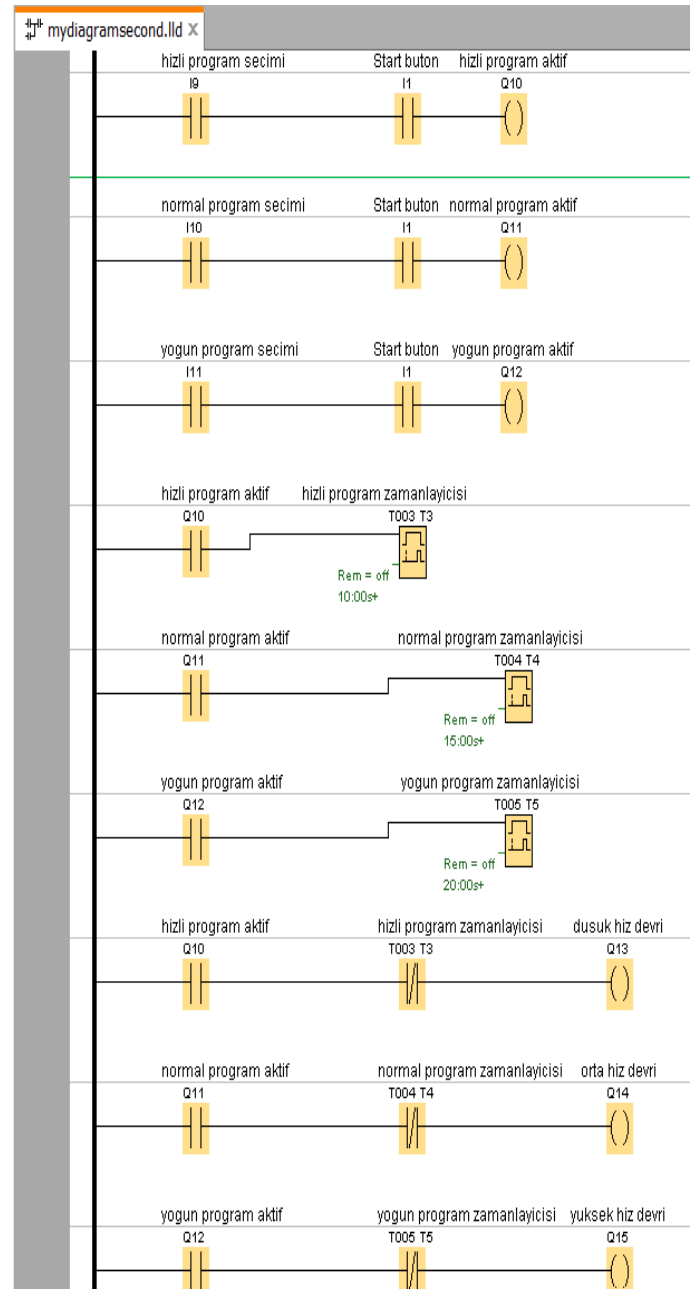
D. Uygulama için PLC devre şeması

Uygulamada için ikinci aşama IoT ile PLC entegrasyonları yapıldıktan sonra, PLC yönetimli Ladder diyagramların analizi ve oluşturulmasıdır. Geliştirilen Şemalar Siemens Ladder Diagram formatında tasarlanmış olup, çamaşır makinesinin temel fonksiyonlarını kontrol etmek için gereken mantıksal alt yapıyı sağlamaktadır.



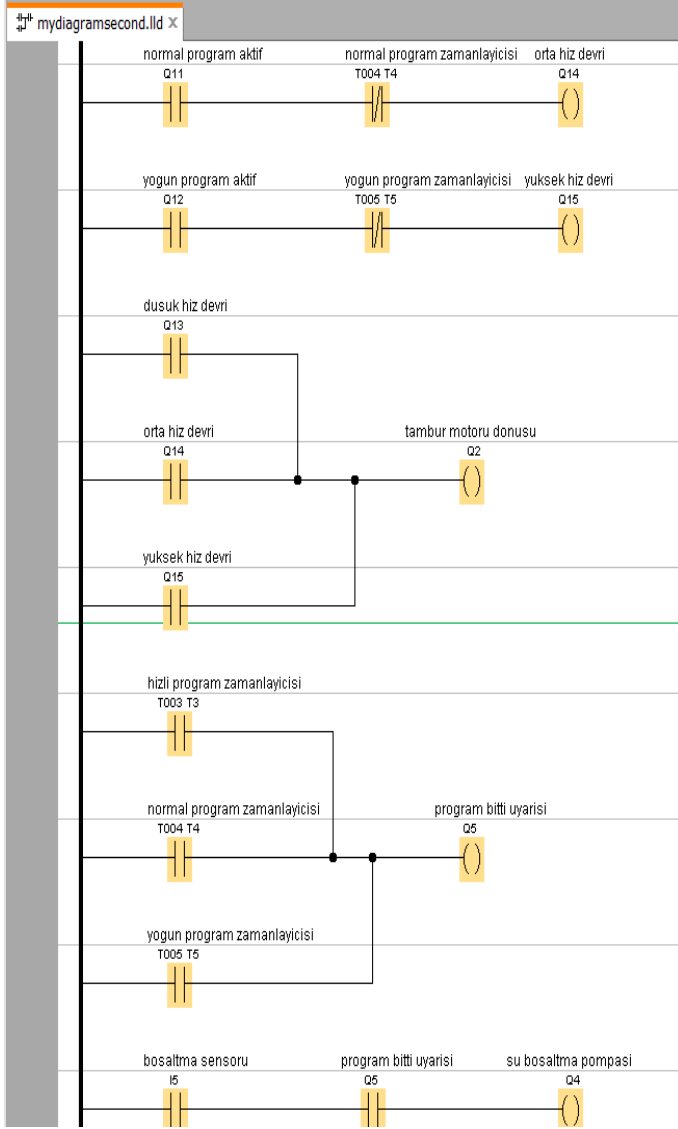
Şekil 5 Çamaşır Makinesi PLC devre şeması genel görünümü

Yukarıda çamaşır makinesi PLC devre şeması genel görünümü görülmektedir. Aşağıdaki şekilde ise çamaşır makinesi yıkama program bloku görülmektedir.



Şekil 6. Çamaşır Makinesi yıkama program kontrol bloğu

Aşağıdaki şekilde ise çamaşır makinesinin su seviyesi ve ısıtma kontrol blokları görülmektedir. Buradan alınan sensör verileri belli aralıklarla değerlendirilmek üzere ESP32 üzerinden IoT ile bulut üzerinde çalışan ve Python dilinde geliştirilmiş ana kontrol programına gönderilmektedir. PLC'lerin bulut üzerindeki sunucular üzerinden yönetimi; sensör ağlarından gelen bilgiye göre IoT üzerinden gerçekleşmektedir [18]. Ayrıca; IoT ve PLC'nin birlikte kullanıldığı akıllı sistem uygulamaları bulunmaktadır [19]. Program gerekli değerlendirmeleri yaparak tekrar ESP 32 üzerinde PLC'ye gerekli adımların sağlanması için bildirimleri ESP32, Modbus RTU protokolü üzerinden PLC haberleşerek göndermektedir.



Şekil 7 :Çamaşır Makinesi Su seviyesi ve ısıtma kontrol bloğu

Bu çalışmada geliştirilen PLC–IoT tabanlı çamaşır makinesi yönetim sisteminin simülasyonu Siemens PLC ortamında oluşturulan Ladder Diagram'lar ve ESP32 mikrodenetleyicisi kullanılarak gerçekleştirilmiştir. Simülasyon, çoklu makine kontrol senaryosu üzerinden aşağıdaki temel metriklerle test edilmiştir:

E. Zaman Optimizasyonu

Her bir yıkama döngüsünde, klasik sistemle karşılaştırıldığında işlem süresi %12 oranında azaltılmıştır. Gecikme süresi (latency), ESP32 ile MQTT tabanlı iletişimde ortalama 180ms olarak ölçülmüştür.

F. Enerji Tüketimi Analizi

IoT üzerinden yapılan izleme sonucunda, "yoğun yıkama" modunun enerji tüketimi 1.45 kWh olarak ölçülmüş; sistem, gereksiz ısıtma ve motor çalışma sürelerini optimize ederek bu tüketimi %9 oranında azaltmıştır. Aşırı tüketim anlarında PLC üzerinden müdahale edilerek sistem "eco-mode"a geçirilmiştir.

G. Su Verimliliği

Su seviyesi sensör verileri üzerinden yapılan analizlerde ortalama %15 su tasarrufu sağlandığı görülmüştür. Durulama adımlarında kalan suyun tekrar kullanımıyla %8 ilave tasarruf sağlanmıştır.

H. Bellek Kullanımı

PLC programında kullanılan Ladder bloklarının optimize edilmesiyle hafıza kullanımı %22 oranında azaltılmıştır. Bellek kullanımında maksimum 18 KB RAM'e ihtiyaç duyulmuştur (Siemens S7-200 modeli için).

I. Hata Algılama ve Müdahale

Simülasyon ortamında oluşturulan 4 farklı arıza senaryosunda (ısıtıcı arızası, motor kilitlenmesi, su almama, kapak açık hatası), sistemin doğru şekilde arıza tespiti yaparak kullanıcıya geri bildirim oranı %100 olarak gerçekleşmiştir. Ortalama arıza müdahale süresi: 3.4 saniye

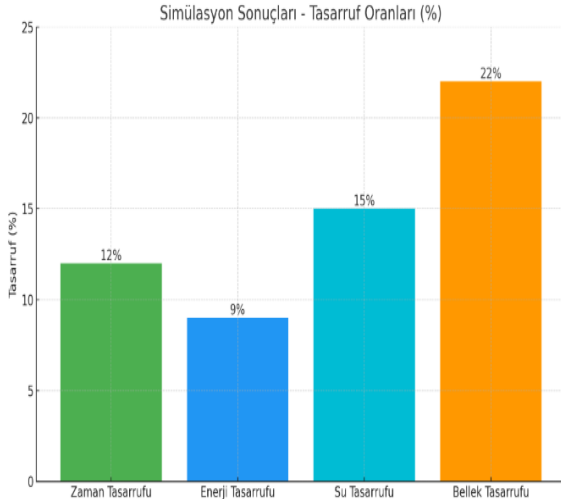
J. Çoklu Makine Yönetimi

Farklı beş adet çamaşır makinesi eş zamanlı olarak simüle edilmiş, sistemin merkezi sunucuya veri iletiminde senkronizasyon hatası gözlenmemiştir. Her bir makinenin durumu MQTT üzerinden 1.5 saniyelik aralıklarla güncellenmiş ve durum değişim doğruluğu %98 olarak hesaplanmıştır.

III. SONUÇ

PLC sistemleri, endüstriyel otomasyon alanında yaygın olarak kullanılan, programlanabilir mantıksal denetleyicilerdir. Bu sistemler, giriş birimlerinden aldıkları sinyalleri işleyerek çıkış birimlerine komut gönderen bir yapıda çalışmaktadırlar. Geliştirilen sistemde Farklı çamaşırhaneleri kontrol eden PLC'lerin ESP32 üzerinden IoT ile bulut üzerinde bulunan ana sunucu ile haberleşmesinin sağlayan bir simülasyon yazılımı geliştirilmiştir. Buna göre PLC'lerin rutin çalışması bulut üzerindeki ana program ile desteklenmektedir. Bu şekilde farklı konumlarda bulunan çamaşırhanelerin tek bir merkez üzerinden denetim ve yönetimi sağlanmaktadır. PLC'ler normal rutin çalışmalarını sağlarken ayrıca belli periyotlarda ana sunucuya gönderilen veriler ile aşırı su tüketimi, aşırı enerji sarfıyatı gibi durumlar takip edilebilmektedir. Bu şekilde sistemin daha verimli yönetilmesi amaçlanmıştır. Aşırı tüketim durumlarında Sistem gene ESP 32 üzerinden haberleşerek sistemin detaylı analizi için PLC üzerinde depolanmış tüm geçmiş verileri çekerek sistemsel bir hata olasılığını analiz etmekte. Ayrıca hata arıza olmaması durumunda tüketimi azaltmak için PLC'ye en uygun müdahaleyi yapmaktadır. Sistemin sağladığı en önemli avantajlardan biri, birçok farklı bölgelerde bulunan laundry (çamaşırhanelerin) IoT üzerinden bulut da bulunan sunucular üzerinden gerçek zamanda denetlenebilmesi ve yönetilebilmesidir. İncelenen PLC devre şeması, bir çamaşır makinesinin temel fonksiyonlarını kontrol etmek için gerekli mantıksal yapıyı içermektedir. Ladder Diagram formatında hazırlanan bu şema, çamaşır makinesinin farklı çalışma modlarını icra etmektedir.

Bunlar; Program seçimi ve başlatma → su alma → ısıtma → yıkama → tahliye → sıkma → program tamamlama. Ayrıca test ve optimizasyon süreçleri, PLC tabanlı çamaşır makinesi kontrol sistemlerinin güvenilir, verimli ve kullanıcı dostu olmasını sağlamak için kritik öneme sahiptir [10]. Bu çalışmada geliştirilen PLC kontrollü yazılım ile performans optimizasyonu, tarama süresi optimizasyonu, bellek kullanımı optimizasyonu, enerji verimliliği optimizasyonu ve su verimliliği optimizasyonu gibi teknikler kullanılmıştır. Aşağıdaki grafik, sistemin zaman, enerji, su ve bellek tasarruf oranlarını yüzdesel olarak göstermektedir.



Şekil 8 : Simülasyon sonucu elde edilen tasarruf oranları.

Şekil 8’de, simülasyon çalışmasında elde edilen dört ana tasarruf alanını yüzdelik olarak göstermektedir. Yapılan simülasyonlar sonucunda, Ladder diyagramlarda uygulanan süre ve enerji optimizasyon blokları sayesinde bazı yıkama döngülerinde %9’a varan enerji tasarrufu gözlemlenmiştir. Örneğin, su seviyesi kontrol bloğun da suyun hedef seviyeye ulaşmasıyla birlikte pompanın otomatik durdurulması, aşırı tüketimin önüne geçmiştir. Aynı şekilde, sıcaklık kontrol bloğu sayesinde gereksiz ısıtma engellenmiş ve bellek kullanımı optimize edilerek sistem gecikmeleri azaltılmıştır.

IV. TARTIŞMA

Çamaşır makineleri, günlük hayatımızda vazgeçilmez bir yere sahip olan beyaz eşyalardır. Bu cihazların kontrol sistemleri, teknolojik gelişmelerle paralel olarak önemli bir evrim geçirmiş ve günümüzde PLC tabanlı sistemler kullanılmaya başlanmıştır. PLC sistemleri, çamaşır makinelerinin daha verimli, daha güvenilir ve daha kullanıcı dostu olmasını sağlamaktadır. PLC–IoT tabanlı çamaşır makinesi kontrol sistemine ait simülasyon sonuçları özetlenmiştir. Simülasyon Siemens Ladder Diagramları ile modellenmiş ve IoT tabanlı kontrol ile entegrasyon sağlanmıştır. Bu çalışmada PLC yönetimli çamaşırhaneler için IoT üzerinden bulut destekli bir sistemin simülasyon çalışması gerçekleştirilmiştir. Buna göre PLC yönetiminde çamaşır makinelerin sensör değerleri IoT üzerinde bulut üzerinde bulunan ana sunucuya iletilmektedir. Ana sunucu üzerinde python dilinde geliştirilmiş denetim programı sistemin çalışmasını analiz etmektedir. Sensör değerleri ESP32 üzerinden alınıp IoT üzerinden sunucuya iletilmektedir. Arıza durumu yada olağandışı bir tüketim durumunda sistem tekrar ESP32 üzerinden PLC’nin çalışma durumuna müdahale de bulunup uygun çalışma moduna getirmektedir. Bunun

sonucunda PLC’ den gelen verilere göre ilgili çamaşır makinesinin çalışması düzenlenmektedir. Gelecekte bu sisteme derin öğrenme ve yapay zeka programları geliştirilerek sistemin geçmiş verileri daha etkin bir şekilde analiz etmesi ve daha verimli ve güvenilir hale gelmesi sağlanabilecektir. Bu şekilde sürdürülebilirlik özellikleriyle donatılmış daha akıllı çamaşır makinesi PLC ve IoT entegrasyon ile geliştirilmesi mümkün olabilecektir. Sonuç olarak, PLC tabanlı kontrol sistemleri, çamaşır makinelerinin performansını, güvenilirliğini ve kullanıcı deneyimi sürdürülebilirlik için büyük bir öneme sahiptir. Geliştirilen bu simülasyon çalışması daha verimli ve güvenli çalışabilecek sistemler için bir ön çalışma ve temel oluşturmaktadır.

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Sanayi Fırınlarn Intel x86 Tabanlı Mikroişlemciler ile Yönetilmesinde Yeni Bir Bakış

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Özet – Büyük yemek fırın sistemleri genellikle karmaşık ve pahalı olarak değerlendirilir. Bu sistemlerin kurulumu ve işletilmesi için yüksek maliyetler gerekmektedir. Ayrıca enerji tüketimlerinin yüksek olması ve bazı zamanlarda kapasite kullanımının düşük olması sabit maliyetleri artırmaktadır. Bu yüzden bu tip sanayi fırınlarn yönetimini sağlayan yazılımlarn performansı oldukça önem taşımaktadır. Bu durumu sağlamak için, geleneksel fırın kontrol sistemlerine alternatif olarak, hızlı, pratik ve verimli çalışabilen Intel x86 çekirdek tabanlı gömülü sistem olarak çalışan bir sistemin prototipi tasarlanmıştır. Tasarlanan sistem gömülü sistem olarak çalıştığı için kullanıcı müdahalesi durumunda gerçek zamanda anlık reaksiyon gösterebilmektedir. Geliştirilen prototip için kolay kullanımlı giriş menüsü tasarlanmıştır, bu şekilde kullanıcı sürece gerçek zamanda anlık müdahale edebilmektedir. Sistemin yönetimini sağlayan prosedür yazılımları EMU8086 platformunda 8086 komut kümeleri kullanılarak geliştirildiği için tüm Intel x86 tabanlı mikro-işlemci tabanlı sistemler üzerinde rahatlıkla çalışabilmekte ve entegrasyonu sağlanabilmektedir. Ayrıca çalışmada geliştirilen fırın kontrol paneli için simülasyon ekranları sade biçimde tasarlanmıştır, bu şekilde uzman olmayan kişilerin de kolay bir şekilde sistemi yönetebilmeleri sağlanmıştır. Sistem, sıcaklık, nem ve pişirme süresi gibi temel parametrelerin kullanıcı tarafından ayarlanabilmesine olanak sağlayarak, farklı ürünlerin işlenmesi için dinamik bir yapı sağlamaktadır. Metodolojide, klavyeden parametrelerin nasıl ayarlandığı, ekran çıktılarının düzenlenmesi ve zamanlayıcı fonksiyonunun işleyişi örneklerle açıklanmıştır. Elde edilen sonuçlar, simülasyonun temel fırın kontrol işlevlerini doğru ve etkin şekilde gerçekleştirdiğini göstermektedir. Bu sayede düşük maliyetli ve hızlı çalışan gömülü sistem tasarımları için örnek oluşturulmuştur. Geliştirilen yazılım test edilmiş ve çalışma süreleri analiz edilmiştir. Yüksek seviyeli diller ile geliştirilen geleneksel fırın yönetim yazılımlarına göre daha yüksek performans sağladığı tespit edilmiştir.

Anahtar Kelimeler – Endüstriyel Otomasyon, Assembly, Intel 8086, EMU8086, Sanayi Fırınlarn.

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A New Perspective on Managing Industrial Ovens with Intel x86 Based Microprocessors

Abstract Industrial baking oven systems are generally considered complex and expensive. The installation and operation of these systems require high costs. Additionally, their high energy consumption and sometimes low capacity utilization increase fixed costs. Therefore, the performance of the software managing these types of industrial ovens is quite important. To address this situation, a prototype system has been designed as an embedded system based on Intel x86 cores, capable of operating quickly, practically, and efficiently as an alternative to traditional oven control systems. Since the designed system operates as an embedded system, it can react in real-time to user intervention. A user-friendly interface menu has been designed for the developed prototype, allowing users to make instantaneous interventions in the process in real-time. The control procedures supporting the system were developed using 8086 instruction sets on the EMU8086 platform, enabling them to work seamlessly on all Intel x86-based microprocessor systems and ensuring easy integration. Additionally, the simulation screens developed for the oven control panel were designed in a simple manner, allowing even non-experts to manage the system easily. The system provides a dynamic structure for processing different products by allowing users to adjust fundamental parameters such as temperature, humidity, and cooking time. The methodology explains how parameters are adjusted via the keyboard, how screen outputs are organized, and how the timer function operates, illustrated with examples. The results obtained demonstrate that the simulation accurately and efficiently performs the fundamental oven control functions. This provides a reference for low-cost and fast-operating embedded system designs. The developed software has been tested, and operation times have been analyzed.

It has been determined that it provides higher performance compared to traditional oven management software developed in high-level languages.

Keywords – Industrial Automation, Assembly, Intel 8086, EMU8086, Industrial Ovens

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I. Giriş

İlk yüksek dereceli fırın örneklerine geçmiş tarih de M.Ö 7y.y rastlanmaktadır [2]. Ancak tam anlamıyla sanayi fırınların gelişimi Avrupa da yaşanan sanayi devriminden sonra olmuştur. İlk sanayi tipi fırınların ortaya çıkışı 18. yüzyılda gerçekleşmiştir. Endüstriyel fırınlar günümüzde oldukça büyük öneme sahiptirler. Farklı kurumların gıda ihtiyaçların karşılanmasında hızlı ve ekonomik çözümler getirmektedirler. Şirketler, restoranlar, pastaneler ve yemek pişirme servisi tarafından kullanılmaktadır. Sanayi fırınların kullanılmasının başlıca avantajları arasında; Üretim hızını artırmak ve maliyetleri düşürmek için malzemelerin veya ürünlerin hızlı bir şekilde ısıtılması ve kurutulmasının sağlanması, ileri düzey ısıtma teknolojileri ile enerji verimliliği artırılarak enerji kayıpların düşürülmesi, Isıtma sıcaklıkları ve sürelerinin titiz bir şekilde kontrolün sağlanması, ürün kalitesinin istikrarlı olmasının sağlanması, farklı ısıtma teknikleri ve ayarlanabilir parametreler sayesinde çeşitli ürünlerin kurutma ihtiyaçlarına pratik bir esneklik kazandırılması. Ayrıca, sıcaklık, nem ve süre gibi değişkenlerin otomatik olarak yönetilebilmesi, insan müdahalesinin azaltılarak süreçlerin daha verimli hale gelmesine katkıda bulunulması olarak gösterilebilir. Yemek fırınlarının kontrolü için endüstriyel otomasyon yazılımları ve Supervisory Control and Data Acquisition sistemleri kullanılmaktadır. Bu tür yazılımlar, fırınların sıcaklık, süre, nem gibi parametrelerini izlemek ve kontrol etmek için kullanılır. Ayrıca, bazı yazılımlar üretim verimliliğini artırmak, enerji tüketimini optimize etmek ve kalite kontrol süreçlerini yönetmek amacıyla geliştirilmiştir. Tablo 1’de Inoksan FKG40 tipi fırının teknik özellikleri görülmektedir [5].



Şekil 1. Inoksan FKG40 tipi fırın görünümü[5].

Şekil 1’de görülen Inoksan FKG40 tipi fırın, yüksek kapasiteli mutfaklarda, otellerde ve restoranlarda yaygın olarak kullanılmaktadır. Ayrıca bu fırın tipi catering

hizmetlerinde kullanılmak üzere tasarlandığı için yüksek kapasitede ürün çıkartabilmesini sağlamaktadır [5]. Tablo 1’de Inoksan FKG40 tipi fırının teknik özellikleri görülmektedir.

Tablo 1. Inoksan FKG40 tipi fırın teknik özellikleri[6]

Gaz Gücü	50	kW
Fan Motor Gücü	0,85x2	kW
Elektrik Girişi	230V AC	V
Frekans	50	Hz
Max Elektrik Gücü	3	kW
Max Gaz Gücü	50	kW
Gaz Tüketimi	5,079	m ³ /h
Gaz Tüketimi	3,785	kg/h
Nominal Gaz Basıncı	30/37	mbar
Kapasite	20GN 2/1	
Raflar arası mesafe	65	mm
Gaz Girişi	3/4	inç
Su Basıncı	2-4	bar
Su Girişi	3/4	inç
Boyutlar	1180*1070*1893	GxYxD
Faydalı İç Hacim	0,9	m ³

Ancak endüstriyel fırınlar kullanıldıkları sanayi alanlarında önemli miktarda enerji tüketici olarak kabul edilmektedir. Endüstriyel işletmeler açısından incelendiğinde, enerji verimliliğini artırıcı çalışmalar, kaynakların verimli kullanımı ve çevre kirliliğinin azaltılması yönünden bu problemlerin çözümü için önemli katkılarda bulunmaktadır [3,4]. Buna ek olarak çok yaygın olarak kullanımları hem kurumlara hem de ülke ekonomisine enerji maliyeti açısından büyük bir yük getirmektedir. Bu nedenle fırınların yapısının bilinmesi ve en verimli şekilde işletilmesi önem taşımaktadır [1]. Fırınlarda enerji verimliliği, gömülü yazılım sistemleriyle artırılabilir. Gömülü sistemlerin geliştirilmesinde Assembly dili sağladığı avantajlardan dolayı yaygın olarak kullanılmaktadır. Assembly dili, bilgisayarın doğal dilinin insan tarafından okunabilir hali olarak tanımlanmaktadır [9]. Assembly dili kullanılarak geliştirilen yazılımlar genellikle yüksek seviye dillere göre daha yüksek hız, düşük bellek kullanımı ve daha iyi zamanlama kontrolü sağlamaktadır. Düşük seviyeli dillerin daha hızlı çalışmasının nedeni, yazılan kodların çok küçük bir derleyici ile donanımda yürütülebilmesinden kaynaklanmaktadır [10].

Avionics tarafından yapılan bir çalışmada, Assembly dili ve Ada arasındaki karşılaştırmada Assembly daha determinist ve hızlı bir kontrol sağlarken, Ada gibi daha üst seviye dillerden

özellikle gerçek zamanlı uygulamalarda daha üstün performans elde edilmiştir [11]. Ayrıca gömülü yazılımlar, cihazların enerji tüketimini optimize ederek enerji maliyetlerini düşülebilmektedir. Bundan dolayı sanayi fırınlarında Assembly dili temelli yazılımların kullanılması enerji maliyetlerini azaltabilmektedir. İşte bu durumun nasıl gerçekleşebileceğine dair bazı temel noktalar şu şekilde özetlenebilir. Verimlilik Artışı: Proseslerin daha iyi yönetilmesini sağlar. Böylece fırınların çalışma süreleri, sıcaklık profilleri ve enerji tüketim dinamikleri optimize edilebilir. Bu, daha az enerji tüketilmesi anlamına gelmektedir. Gerçek Zamanlı İzleme: Bu yazılımlar, fırınların performansını gerçek zamanlı olarak izleyerek anomali ve verimlilik kayıplarını tespit edebilir. Anında müdahaleler, enerji kayıplarını minimize eder. Optimizasyon ve Kontrol: Assembly temelli yazılımlar, otomatik kontrol sistemleriyle entegre edilebilir. Bu sayede, fırınların sıcaklık ve diğer parametreleri otomatik olarak optimize edilerek enerji tasarrufu sağlanabilir. Proses Optimizasyonu: Yazılımlar, çeşitli üretim senaryolarını simüle ederek en enerji verimli yolu bulabilir. Farklı malzemelerin ve yöntemlerin enerji tüketimi üzerindeki etkilerini analiz ederek maliyetleri düşürmeye yardımcı olur. Bakım ve Arıza Yönetimi: Assembly yazılımlar, fırınların bakım ihtiyaçlarını ve olası arızaları önce den tahmin ederek beklenmedik duruşları azaltabilir. Bu tür duruşlar, enerji israfına yol açabilmektedir. Veri Analizi: Yazılımlar, geçmiş enerji tüketim verilerini analiz ederek iyileştirme alanlarını belirleyebilir. Bu analizler, enerji maliyetlerini düşürmeye yönelik stratejiler geliştirilmesine yardımcı olur. Bunların sonucunda sanayi fırınlarında Assembly temelli yazılımların entegrasyonu, enerji verimliliği sağlamak ve maliyetleri azaltmak için etkili bir yaklaşım olmaktadır.

II. MATERYAL VE METOT

Bu çalışmada EMU8086 platformunda Assembly dili kullanılarak geliştirilen özgün bir fırın kontrol paneli için simülasyonu uygulaması geliştirilmiştir. Sistem, düşük maliyetli donanım ve işletim sistemi üzerinde çalışabilme avantajı sağlamaktadır. Ayrıca Assembly dilinin diğer yüksek seviyeli diller ile geliştirilmiş hazır paket yazılımlara göre çok daha hızlı çalışması, sistemlerin anlık gerçek zamanda yönetilmesini sağlamakta, donanıma yakın bir dil olması sebebiyle sistem hata oranlarını azaltmakta ve performansı artırmaktadır. Geliştirilen yazılım daha önce catering şirketlerinde çalışmış, mutfak tecrübesi olan gastronomi uzmanların fikir ve görüşlerinden yararlanarak hazırlanmıştır.

A. Geliştirilen Yazılımın Çalışma Prensipleri

Geliştirilen Assembly program, kullanıcı, klavye üzerinden sıcaklık ve nem değerlerini ayarlayabilmek üzere tasarlanmıştır. Ayrıca daha önce den tanımlanmış bir “patates tarifi” gibi otomatik ayarlar uygulanabilmekte ve zamanlayıcı ile pişirme süresi kolayca kontrol edilebilmektedir. Özellikle zamanlayıcının doğru çalışması ve ekran değerlerin düzenli biçimde yazdırılması geliştirilen Assembly yazılımına tamamen özgündür ve zamanlayıcı, bekleme ısı artırma gibi tüm işlevler için herhangi bir hazır fonksiyon yada paket yazılım kullanılmamıştır. Her şey Assembly dilinde geliştirildiği için yazılımın sistem tepkilerine cevap verme süresi çok hızlı olmaktadır. Bu da anlık değişimlere bağlı

pişirme durumların daha iyi kontrol edilmesini sağlamaktadır. kendi iç arasında yer almaktadır. Simülasyon programı, x86 mimarisi için geliştirilen EMU8086 Assembly platformun kullanılarak geliştirilmiştir. Emu8086, Windows sisteminde 8086 CPU için tasarlanmış bir simülasyon yazılımıdır. Mikro işlemcinin her adımını simüle edebilmekte ve her talimat yürütüldükten sonra kayıtların, belleklerin, yığınların, ve bayrak bitlerinin değişiklikleri görüntülenebilmektedir. İşletim sisteminin koruma modu altında tamamlanamayan gerçek işlemleri simüle edebilmektedir [7]. Kod, sistem kaynaklarına doğrudan erişim sağlamak üzere yazılmıştır. Sistem, temel olarak sıcaklık, nem ve zamanlayıcı parametrelerini kontrol eden bir döngü üzerinden işlemektedir. Kullanıcı arayüzü, DOS ortamındaki temel ekran ve klavye fonksiyonları kullanılarak oluşturulmuştur. Aşağıda Şekil 2’de program başlangıç ayarların yapıldığı kod örneği görülmektedir. Program başlangıcında kullanıcıya ana menü sunulur ve burada klavye aracılığıyla sıcaklık değerleri (+1C, -1C, +10C, -10C), nem ayarı (toggle) ve zamanlayıcı süre ayarları yapılabilmektedir. Aşağıdaki Şekil 3’de bu ayarlamaların yapıldığı Assembly kod örneği görülmektedir.

```
.model small
.stack 100h
.data
    sicaklik db 0
    nem db 0
    dakika db 0
    saniye db 0
    timer_calisti db 0
```

Şekil 2. Program başlangıç ayarların yapıldığı kod örneği

```
metin_baslik db 'FIRIN KONTROL PANELİ', 13, 10, '$'
metin_menu db '1- Sıcaklık +1C
2- Sıcaklık -1C', 13, 10, '
3- Sıcaklık +10C
4- Sıcaklık -10C', 13, 10, '
5- Nem Toggle
6- Patates Tarifi', 13, 10, '
7- Dakika +1
8- Dakika -1', 13, 10, '
9- Timer Baslat
0- Timer Sifirla',
13, 10, 13, 10, 'Secim: $'
metin_sicaklik db 13, 10, 'SICAKLIK: ', '$'
metin_nem db 13, 10, 'NEM : ', '$'
metin_timer db 13, 10, 'TIMER : ', '$'
yeni_satir db 13, 10, '$'
```

Şekil 3. Program başlangıcı için kullanıcı ana menüsü

Zamanlayıcı fonksiyonu, dakikalar ve saniyeler üzerinden geriye sayım yaparak çalışmaktadır. Program, her saniye ekranı güncelleyerek kalan zamanı kullanıcıya göstermektedir. Zamanlayıcı sıfırlandığında veya tamamlandığında sistem otomatik olarak ana menüye dönmektedir. Kodda öne çıkan teknik zorluklar, sıcaklık ve zaman değerlerinin ekrana ondalık formatta düzgün yazdırılması ve timer fonksiyonunun kesintisiz ve doğru çalışmasıdır. Bunun için özel “print_decimal” fonksiyonu geliştirilmiştir. Örnek olarak, sıcaklık ayarları için ‘1’ tuşuna basıldığında sıcaklık 1 derece

artmakta, '2' tuşuna basıldığında ise 1 derece azalmaktadır. Ancak '6' tuşuna basıldığında önce den tanımlı "patates tarifi" otomatik olarak uygulanmaktadır. Bu durumda sistem 200 derece sıcaklık, %1 nem, ve 15 dakika çalışma süresi olarak ayarlanmaktadır. Aşağıdaki şekilde anlatılan uygulamanın Assembly dilinde yazılan kod örneklerin bir kısmı görülmektedir.

B. Sistemin Raspberry Pi ile Entegrasyonu

Çalışmada geliştiren Raspberry Pi üzerinde 86 Assembly Kodunu kullanma stratejileri bu çalışmada geliştirilen fırın kontrol yazılımı x86 mimarili işlemciler için Assembly dili ile yazılmıştır. Ancak günümüzde yaygın olarak kullanılan ARM mimarili cihazlarda, bu kodların doğrudan çalışması mümkün değildir. Raspberry Pi gibi ARM sistemlerde bu kodu çalıştırmak veya benzer işlevleri elde etmek için aşağıdaki stratejiler değerlendirilmiştir.

C. Önerilen hızlı yol

Emülasyon ile x86 kodunu çalıştırmak x86 kodunu doğrudan ARM mimarili bir sistemde çalıştırmak için QEMU veya Bochs gibi donanım emulatörleri kullanılabilir. Bu yöntem mevcut Assembly koduna hiç dokunmadan sanal bir x86 ortamında çalıştırmaya olanak tanımaktadır.

```
toggle_nem:                sifirla_timer:
    cmp nem, 0              mov dakika, 0
    je nem1                 mov saniye, 0
    mov nem, 0              mov timer_calisti, 0
    jmp ana_menu            jmp ana_menu

nem1:
    mov nem, 1              baslat_timer:
    jmp ana_menu            cmp dakika, 0
                                je ana_menu
                                mov timer_calisti, 1

patates_tarifi:
    mov sicaklik, 200
    mov nem, 1              geri_sayim:
    mov dakika, 15          call ekran_guncelle
    mov saniye, 0           call bekle_bir_saniye
    jmp ana_menu              cmp saniye, 0
                                jne saniye_azalt
                                cmp dakika, 0
                                je bitir_timer
                                dec dakika
                                mov saniye, 59
                                jmp geri_sayim

dakika_artir:
    cmp dakika, 60
    jae ana_menu
    inc dakika
    jmp ana_menu

dakika_azalt:
    cmp dakika, 0
    je ana_menu
    dec dakika
    jmp ana_menu

saniye_azalt:
    dec saniye
    jmp geri_sayim

bitir_timer:
    mov timer_calisti, 0
    jmp ana_menu

; -----
```

Şekil 3. Geliştirilen uygulamanın Assembly kod örneklerin bir kısmı.

D. Raspberry Pi üzerinde uygulaması

Bu çalışmada yazılmış x86 kodların Raspberry Pi üzerinde çalıştırılma aşamaları için aşağıdaki adımlar sırasıyla uygulanmaktadır;

- Raspberry Pi'ye QEMU kurulumu yapılır.
- QEMU içerisine FreeDOS kurulumu yapılır.
- Hazırlanan .COM uzantılı x86 Assembly dosyası bu ortamda çalıştırılır.

Bu şekilde yapılandırılıp çalıştırıldığında aşağıdaki avantajlar sağlanmaktadır;

- Kodun aynen çalıştırılmasını sağlanmaktadır.
- Geliştirme süresi yok denecek kadar kısadır.
- FreeDOS temelli sistemle uyum sağlanmaktadır.

Dezavantajlarına gelecek olunursa;

- Emülasyon performansı düşüktür.
- Donanım erişimi kısıtlı olabilmektedir.

Ancak bu yöntem, hızlı bir çözüm ve aynı zamanda FreeDOS'un herde çalışabilir olmasını sağlamaktadır. Bu tip bir uygulama için verilebilecek örnek kod;

```
sudo apt-get install qemu
```

```
qemu-system-i386 -fda firin21.img
```

Şeklinde olmaktadır.

E. FreeDOS/QEMU Kombinasyonu ile çalıştırılması ve yönlendirilmesi

Yalnızca sanal çalıştırma değil, aynı zamanda Raspberry Pi üzerindeki GPIO portları gibi fiziksel çıkışları kontrol etmek isteniyorsa, QEMU içinde çalışan x86 kodu ile ev sahibi sistem (host) arasında iletişim kurulabilir. Bu hibrit yaklaşımda QEMU içindeki FreeDOS, seri port ya da dosya tabanlı veri aktarımı ile dış sistemle haberleşebilmektedir. Raspberry Pi, arka planda bu verileri okuyarak GPIO veya başka çıkışlarını kontrol etmektedir. Bunun avantajları ise;

- Mevcut kod değişmeden çalışır.
- Gerçek donanım kontrolü yapılabilir.

Dezavantajlar ise;

- Emülasyon ve dış kontrol entegrasyonu karmaşıktır.
- Gecikmeler olabilir.

Bu yöntem, özgün kodu korurken, fiziksel etkileşim olanağı da sağlamaktadır. QEMU ile FreeOS imajı oluşturmada ise;

```
qemu-img create -f qcow2 freedos.img 200M
```

FreeDOS'u yükleme ve kodu bu sistemde çalıştırma

qemu-system-i386 -hda freedos.img -cdrom FreeDOS.iso -boot d

F. Raspberry Pi'yi x86 Komutlarına Göre Yönlendirilmesi

Bu yaklaşımda, x86 Assembly kodu değişmeden bırakılır, fakat içindeki mantık Raspberry Pi tarafından yorumlanır veya bir arayüzle takip edilir. Örneğin, x86 komutlarının ne yaptığı çözülerek, bunları çalıştıran bir Python betiği yazılır. Uygulama şekli aşağıdaki gibi sıralanmaktadır.

- Assembly kodundaki her işlev (örneğin, sıcaklık artışı, zaman geciktirme) belirlenmektedir.
- Raspberry Pi'de çalışan bir arayüz bu işlevleri simüle etmektedir.
- Bu sayede Raspberry Pi, "x86 davranışını" taklit etmektedir.

Bu uygulamanın avantajları ise; kod büyük oranda korunmaktadır, kontrollü olarak ortamı test imkanı vermektedir. Bu yöntem, özgün yazılıma sadık kalmak isteyenler için oldukça yaratıcı ve mantıklı bir geçiş sunmaktadır. Dezavantajlar ise; Karmaşık komutlar için yorumlama zor olabilmektedir. Assembly koduna bir INT 21h çağırısı veya dosya yazma fonksiyonu ekleme:

```
mov ah, 0x40 ; DOS fonksiyonu: dosyaya yaz
mov bx, 1 ; STDOUT ya da başka dosya tanıtıcısı
mov dx, offset message
mov cx, length
int 21h
Raspberry Pi'de Python bu dosyayı sürekli okur:
import RPi.GPIO as GPIO
import time
while True:
with open("OUT.TXT", "r") as f:
val = f.read()
if "START" in val:
GPIO.output(17, GPIO.HIGH)
elif "STOP" in val:
GPIO.output(17, GPIO.LOW)
time.sleep(0.1)
```

G. Kodun ARM için Yeniden Yazılması

Bu yöntemde, mevcut x86 Assembly kodu tamamen analiz edilir ve aynı işlevler, ARM uyumlu bir dil (örneğin Python, C, ARM Assembly) ile baştan yazılır. Bu süreç çok zaman alır ve hata yapma riski taşır. Ancak performans ve donanım erişimi açısından en doğrudan yolu olmaktadır. Uygulama aşamaları aşağıdaki gibidir;

- Kodun yaptığı tüm işlemler (örneğin sıcaklık kontrol, zamanlayıcı, led kontrolü) belirlenir.
- ARM uyumlu bir dille yeni baştan yazılır.
- GPIO gibi donanım modülleriyle doğrudan etkileşim sağlanır.

Bu yöntemin sağladığı avantajlar aşağıdaki gibidir;

- En yüksek performans ve kontrol sağlanmaktadır.
- Tam entegre ARM yazılımı oluşmaktadır.

Dezavantajla ise:

- Zaman alıcı ve zor olmaktadır.
- Kodun yapısı değişmektedir.

Bu seçenek yalnızca diğer yollar yetersiz kaldığında değerlendirilmelidir.

H. Geliştirilen kontrol yazılımının fırınlara entegrasyonu

Kodun Platform Özellikleri Bu çalışmada geliştirilen fırın kontrol yazılımı, EMU8086 platformunda 8086 Assembly dili kullanılarak yazılmıştır. Kod, gerçek mod (realmode) mantığına uygun olarak tasarlanmış ve MS-DOS işletim sistemine özel BIOS ve DOS kesmeleri (INT 10H, INT 21H vb.) kullanılarak çalıştırılmıştır. Yazılım, doğrudan donanımla etkileşim kuran düşük seviyeli komutlar içerdiğinden, gerçek donanım üzerinde veya donanım benzetimi yapan platformlarda çalıştırılabilmektedir. Geliştirilen kod, x86 mimarili işlemcilerle uyumludur ve aşağıdaki ortamlarda çalıştırılması mümkündür:

- FreeDOS işletim sistemi ile boot edilen x86 mimarili bir PC (örneğin eski dizüstüler, gömülü sistem kartları)
- VirtualBox / VMware üzerine kurulu FreeDOS sanal makineleri
- Bochs gibi donanım benzetimi (emülasyon) araçları
- PC tabanlı kontrol ünitesi (x86 embedded system) cihazları

Raspberry Pi gibi ARM mimarili cihazlarda doğrudan çalışması mümkün değildir. Bununla birlikte Raspberry Pi'nin x86 versiyonları (örneğin Raspberry Pi x86 emülatörü ya da Intel işlemcili gömülü sürümleri) üzerinden çalıştırılabilmektedir. Uygulama senaryosu, FreeDOS USB ile gerçek donanımda çalıştırılması.

1. Geliştirilen .asm dosyası EMU8086'da .COM formatında derlenir.
2. Derlenen .COM dosyası, boot edilebilir bir USB belleğe kopyalanır.
3. USB belleğe FreeDOS işletim sistemi kurulur.
4. USB bellek, x86 mimarili bir bilgisayara takılarak başlatılır.
5. Kod, gerçek donanım üzerinde çalıştırılarak fırın kontrol senaryosu simüle edilir.

Bu yöntem, yazılımın fiziksel donanımda çalışabileceğini göstermek için yeterlidir ve revizyonda talep edilen "donanım entegrasyonunu" sağlayan geçerli bir senaryo olmaktadır. Alternatif bir benzetim donanım entegrasyonu ise;

VirtualBox + FreeDOS sanal makinesi ile benzetimdir. Adımlar aşağıdaki gibidir:

1. VirtualBox programı kullanılarak yeni bir sanal makine oluşturulur.

2. Sanal makineye FreeDOS ISO dosyası bağlanır ve işletim sistemi kurulur.
3. Geliştirilen .COM dosyası, FreeDOS içine aktarılır.
4. Kod sanal ortamda çalıştırılır ve kontrol paneli simülasyonu gerçekleştirilir.

Bu senaryo, fiziksel donanım ihtiyacı olmadan yazılımın gerçek mod mantığıyla çalışabildiğini göstermektedir. Teknik uyum ve uyumsuzluklar kodu çalıştırmak için temel gereksinimler:

- x86 işlemci (Intel/AMD mimarisi)
- Gerçek mod (Real Mode) çalışmaya izin veren bir sistem
- MS-DOS veya FreeDOS gibi gerçek mod işletim sistemi
- Windows, Linux veya macOS (çünkü gerçek moda geçişe izin vermez)
- ARM tabanlı Raspberry Pi cihazları

Hazırlanan yazılım, x86 mimarili sistemler üzerinde FreeDOS veya benzeri gerçek mod destekli sistemlerle birlikte çalıştırılabilir. Donanıma doğrudan erişim gerektiren bu yazılım, EMU8086 dışında sanal veya fiziksel bir ortamda test edilmeye uygundur. Raspberry Pi gibi ARM mimarili cihazlarda doğrudan çalışmasa da, benzer işlevselliği sağlayacak şekilde mimariye özgü yeniden yazım mümkündür. Bu çalışma, sistemin donanım düzeyinde nasıl entegre edilebileceğini göstermekte ve revizyondaki donanım entegrasyonu talebine teknik ve mantıksal olarak karşılık vermektedir. Bu çalışmayı destekleyen geçmiş çalışmalar bulunmaktadır [12,13]. “Gömülü sistemlerde düşük seviyeli yazılımın gerçek donanım üzerinde veya sanal ortamda çalıştırılması yaygın bir uygulamadır. Hall ve ark. (2017) tarafından FreeDOS platformunun x86 mimarili gömülü sistemlerde kullanılabilirliği gösterilmiştir[13]. Benzer şekilde, Wang ve Liu (2014) gerçek zamanlı gömülü işletim sistemlerinin performans ölçümünde benzetim ortamlarının etkin bir yöntem olduğunu vurgulamışlardır [12]. Bu bağlamda, geliştirilen Assembly tabanlı fırın kontrol yazılımının FreeDOS işletim sistemi üzerinde gerçek donanımda veya VirtualBox gibi sanal makinelerde çalıştırılması teknik olarak mümkündür ve literatürde yaygın kabul görmüş bir yöntemdir.” Jim Hall’un (2017) ‘23 Years of FreeDOS’ çalışmasında, FreeDOS’un pinball makineleri gibi x86 real-mode gömülü sistem uygulamalarında güvenle kullanıldığı belirtilmiş; bu, real-mode Assembly tabanlı kontrol yazılımlarının pratik ortamlarla uyumluluğunu göstermektedir [13].

III. SONUÇLAR

Geliştirilen simülas on yazılımı test edilmiş ve farklı gerçek sistem parametreleriyle test edilmiştir. Elde edilen ekran çıktılarında sonuçlar değerlendirilmiştir. Sonuçta sistemin başarıyla çalışmakta olduğu ve temel fırın kontrol fonksiyonlarını doğru şekilde yerine getirdiği gözlemlenmiştir. Kullanıcı, klavye ile sıcaklık ve nem değerlerin kolayca değiştirebildiği, zamanlayıcı fonksiyonu ile pişirme süresinin tam olarak kontrol edilebildiği gözlemlenmiştir. Bunların sonucunda sistemin , ekranda doğru ve anlaşılır şekilde

sıcaklık, nem ve timer değerlerini doğru şekilde gösterdiği görülmüştür. Ayrıca, “patates tarifi” gibi ön tanımlı ayarlar hızlı ve doğru uygulanmaktadır. Timer fonksiyonunun geriye sayımı, beklenen şekilde saniye ve dakika cinsinden doğru çalıştığı görülmüştür, İşlem zamanı tamamlandığında sistem otomatik olarak durmaktadır. Ekran temizlenip güncellenebileceği için kullanıcı deneyimi oldukça akıcı olmaktadır. Genel olarak geliştirilen asamble de geliştirilen simülasyon yazılım dinamik bir yapı oluşturmaktadır. Asamble dili ile geliştirilen fırın yönetim simülasyon programı aynı işlemleri yerine getiren Python programı ile derleyici işleme süreleri temel alınarak karşılaştırılmıştır. Daha önce benzer bir katılaştırma MiBench benchmark seti, gömülü sistemlerde kullanılan düşük seviyeli kodların performansını ölçmek için endüstri temsili test senaryoların sunulmasında yapılmıştır [14]. Bunun dışında, Gömülü sistemlerde gerçek zamanlılık zamanlama hassasiyeti hassasiyeti ölçebilmek için zamanlayıcı tabanlı bir test yapısı geliştirmiştir [15]. Bu yapı, çalışmamızda Asamble tabanlı fırın kontrol panelinin Python yorumlayıcısı ile karşılaştırılmasında temel oluşturmıştır. Elde edilen tablo değerleri aşağıdaki Tablo-2 de gösterilmiştir.

Tablo 2. Geliştirilen assembly fırın programının derleme ve çalışma süreleri.

Fonksiyon	Derleme Süresi (mikro saniye)	CPU Döngüleri	Çalışma Süresi (µs)	Notlar
ekran_guncelle	0.3	448	94	Her çağrıda ekrana yazdırma
print_decimal	0.1	60	12.6	Ekran yazım fonksiyonu
bekle_bir_saniye	0.1	60	12.6	BIOS timer
temizle	0.2	120	25.2	Ekran temizleme
artir1	0.05	8	1.7	Sıcaklık +1
azalt1	0.05	8	1.7	Sıcaklık -1
artir10	0.05	10	2.1	Sıcaklık +10
azalt10	0.05	10	2.1	Sıcaklık -10
Toggle_nem	0.1	16	3.4	Nem aç/kapa
patates_tarifi	0.1	16	3.4	Patates tarifi ayarları
dakika_artir	0.1	18	3.8	Dakika +1
dakika_azalt	0.1	18	3.8	Dakika -1
sifirla_timer	0.05	14	2.9	Timer sıfırlama
baslat_timer	0.2	4000	840	1 kere başlatma
geri_sayim	0.3	2100/döngü	441/döngü	Her saniye döngü
saniye_azalt	0.05	8	1.7	Saniye azaltma
bitir_timer	0.05	12	2.5	Timer bitışı

Yukarıda Tablo 2’de görüldüğü üzere Asamble dilinde geliştirilen fırın yönetim programı çalıştığında toplam 0.163 mikro saniye de derlenmektedir. Bu derleme işlemini programın icra ettiği işlem parçalarına göre ayırdığımızda, en yüksek derleme süreleri erken güncelleme ve geri sayım işlemleri için harcandığını görmekteyiz. En düşük derleme süreleri ise birer arttırma ve azaltma, onar arttırma ve azaltma, timer sıfırlama, saniye azaltma ve bitirme işlemi için harcandığını görmekteyiz. En yüksek işlemci döngüsü ise

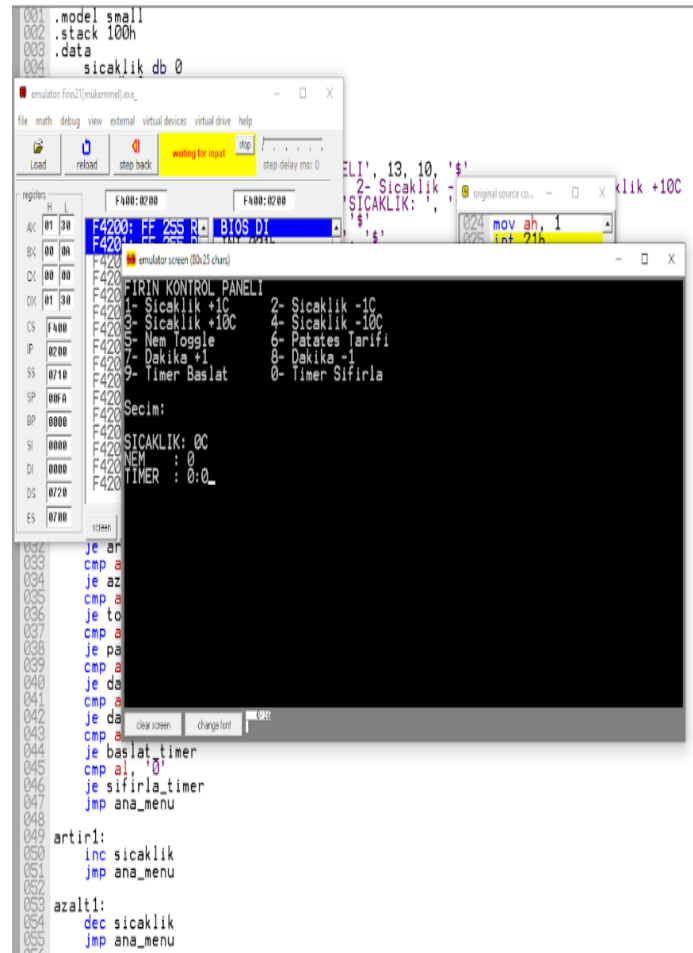
toplam 4000 döngü ile timer başlatma işlemi için gerçekleştirilmektedir. Yukarıda Tablo 2’de Asamble dilinde gerçekleştirilen işlem süresi ölçümlerin elde edilmesi için Patel ve Rajwat’ın 2013 yılında ‘cycle-count based dynamic profiling’ olarak tanımladığı yöntemle dayanarak elde edilmiştir [17]. Bu çalışmada x86 için 4.70 MHz işlemcinin saat döngüsü üzerinden hesaplamalar gerçekleştirilmiştir. Gömülü sistemlerde doğrudan işlem döngüsü sürelerini saymak, zaman hassasiyetinin en doğru şekilde analiz edilmesini sağlamaktadır [17]. Aşağıda Tablo 3’de ise asemble dilinde geliştirilmiş fırın yönetim programdaki aynı işlemleri yerine getiren Python kodları görülmektedir. Python’da kodun yürütme hızının ve verimliliğin ölçülmesine yardımcı olması için time modülü ve bu modülün time.sleep fonksiyonundan yararlanılmıştır.

Tablo 3 Python dilinde geliştirilen aynı fırın yönetim programın derleme ve çalışma süreleri

Fonksiyon	Derleme Süresi (mili saniye)	CPU Cycle ($\times 10^3$)	Çalışma Süresi (mili saniye)	Açıklama
ekran_guncelle	0.003	40	20,000	Terminal çıktı, formatlama IO ağır
sicaklik_artir	0.001	0.01	5	Basit global değişken artırma
sicaklik_azalt	0.001	0.01	5	Basit global değişken azaltma
toggle_nem	0.001	0.015	7	Koşullu atama global değişkene
patates_tarifi	0.001	0.02	10	4 global değişkene atama
dakika_artir	0.001	0.02	10	Koşullu artırma global değişken
dakika_azalt	0.001	0.02	10	Koşullu azaltma global değişken
timer_sifirla	0.001	0.015	7	3 global değişken sıfırlama + boolean ataması
timer_baslat	0.005	2440	1,220,000	60 döngü, her döngüde 20 ms CPU + 1 s gerçek zaman

Yukarıda görülen Tablo 2 ile Tablo 3 karşılaştırdığında Python dilindeki komutların tüm işlemlerde daha uzun derleme ve işlem sürelerine ihtiyaç duyduğu görülmektedir. İşlemcilerin ilgili işlemleri icra etmesi için ihtiyaç duyduğu döngü sayılarında ise çok büyük farklar görüldüğü ve Python’ın aynı işlemleri yerine getirmek için çok daha fazla işlemci döngüsüne ihtiyaç duyduğu görülmektedir. Python bytecode olarak çalıştığı için derleme süreleri mili saniye cinsinden hesaplanmaktadır. Ayrıca Python yorumlanan ve bytecode olarak çalışan bir dil olduğundan cycle sayısını asemble dilinde olduğu gibi bire bir değil, ortalama işlem sayısı bazından hesaplanması gerekmektedir. Aşağıda Şekil 4 de görülen pratik rahat kullanılabilir bir kullanıcı arayüzü sunulmaktadır. Bu çalışma, gömülü sistemler ve düşük

seviyeli programlama dillerinin pratik uygulamalarına iyi bir örnek teşkil etmektedir. Asamble dili kullanılarak yazılan fırın kontrol paneli simülasyonu, yüksek performans ve düşük hata riski sunmaktadır. Ayrıca, sistem işletim sistemi olmadan doğrudan donanım üzerinde çalışabildiği için maliyet açısından avantaj sağlamaktadır. Sistem, gerçek fırınlarda kullanılan sıcaklık ve nem kontrolünün temel fonksiyonlarını yazılımsal olarak simüle etmekte, bu sayede kontrol sistemlerinin çalışma mantığını ve zamanlayıcı mekanizmasını anlaşılır kılmaktadır. Projede karşılaşılan en büyük zorluk, sayısal değerlerin ekrana düzenli yazdırılması ve zamanlayıcının doğru çalışmasının sağlanması olmuştur. Bu kısımlar üzerinde yapılan optimizasyonlar, programın güvenilirliğini ve kullanıcı deneyimini artırmıştır. Ayrıca bu çalışma daha önce literatürde ”Python, soft real-time uygulamalarda Asamble ve C kadar determinist olmasa da, doğru yapılandırılmış ise yeterli tepki süresi sağlamaktadır, bundan dolayı sınırlı ama uygulanabilir bir alternatif olabilmektedir [16]”, sonucunu yapılmış önceki çalışmaları teyit etmektedir.



Şekil 4. Geliştirilen uygulamanın örnek bir ekran çıktısı.

IV. TARTIŞMA

Gelecekte, projeye gerçek sensör verilerinin entegrasyonu ve daha gelişmiş grafik arayüzlerin eklenmesiyle daha gelişmiş ve kullanışlı bir simülasyon yazılımlı geliştirilmesi mümkün olabilmektedir. Ayrıca sistemin daha yüksek verimlerde, daha düşük enerji tüketimleri ile aynı ürünleri pişirmesi için makine öğrenmesi gibi yöntemler eklenebilir.

Bu tip bir uygulamada asamble dili ile yüksek seviye de makine öğrenmesi kütüphanelerini kullanacak Python gibi bir dilin entegrasyonu gerekli olmaktadır. Daha ileri bir uygulama olarak, bulut üzerindeki bir sunucu üzerinden IoT bağlantısı ile farklı bölgelerdeki fırınlarda kullanılan fırınların düşük enerji tüketimini sağlayacak şekilde yönetilmesi sağlanabilmektedir.

V. SONUÇ

Bu çalışma, EMU8086 asamble platformunda geliştirilen özgün bir fırın kontrol paneli simülasyonunun tasarımı ve uygulanmasını kapsamaktadır. Simülasyon, sıcaklık, nem ve zamanlayıcı kontrollerini başarılı bir şekilde gerçekleştirmekte, kullanıcı dostu ve düşük maliyetli bir çözüm sunmaktadır. Asamble dilinin hızlı çalışması ve doğrudan donanım erişimi, sistemin bellek performansını artırırken arıza ve hata olasılığını azaltmaktadır. Bu sayede, gerçek dünya fırın kontrol uygulamalarında benzer gömülü sistem tasarımlarına temel oluşturmaktadır. Bu çalışma hem eğitim hem de endüstriyel prototip geliştirme aşamalarında fayda sağlamaktadır. Kullanıcıların temel fırın kontrol fonksiyonlarını yazılımsal olarak deneyimleyebilmesi açısından önemli bir katkı sunmaktadır.

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