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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 mortailiy 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 recogmition 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.

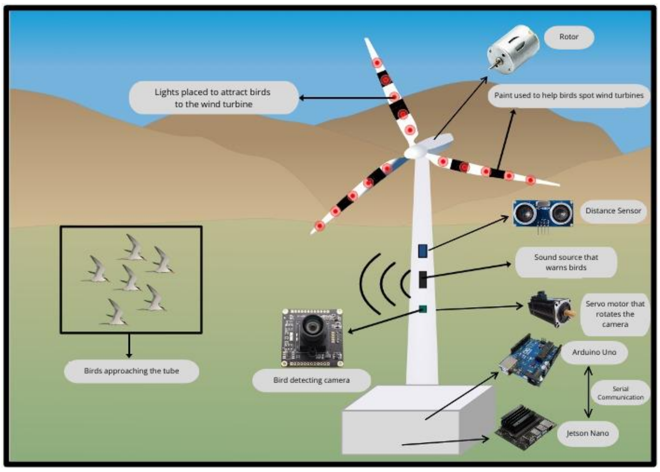

Figure 1. Design of the proposed system

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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