Real-Time Driver Fatigue Detection and Alert System

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Graphical/Tabular Abstract (Grafik Özet)

This study presents a Raspberry Pi–based safety system that incorporates an MPU6050 sensor, a camera, and an alert display to monitor driver behavior. Additionally, an Arduino Nano–based module, integrated into the seat belt and equipped with an RF receiver and a vibration motor, provides haptic feedback to the driver when the seat belt is fastened. / Bu çalışma, sürücü davranışlarını izlemek için MPU6050 sensörü, kamera ve uyarı ekranı içeren Raspberry Pi tabanlı bir güvenlik sistemi sunmaktadır. Ayrıca, RF alıcısı ve titreşim motoru içeren Arduino Nano tabanlı bir modül, emniyet kemerine entegre edilerek bağlandığında sürücüye dokunsal bildirim sağlar.
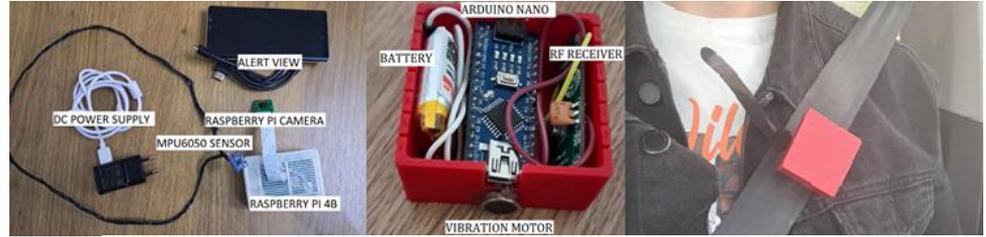

Figure A. *System Overview /* **Şekil A.** *Sistem Genel Bakışı*

Highlights (Önemli noktalar)

➤ The system detects the driver's face and eyes.
➤ The facial region is analyzed to assess the driver's level of drowsiness.
➤ If drowsiness is detected, the driver is alerted via a vibration motor integrated into the seat belt.
➤ Sürücünün yüzü ve gözleri tespit edilir.
➤ Sürücünün uyuşukluk seviyesi yüz bölgesi ile analiz edilir.
➤ Eğer sürücü uykulu ise emniyet kemerine bağlı bir titreşim motoru ile sürücüye uyarı verilir.

Aim (Amaç): *The aim of this study is to enhance traffic safety by monitoring drivers' attention and alertness. / Bu çalışmanın amacı sürücülerin dikkat ve uyanıklık durumlarını izleyerek trafik güvenliğini arttırmaktır.*

Originality (Özgünlük): *This study presents a low-cost driver-fatigue detection system that integrates visual and motion data, offering a more reliable and practical solution than existing systems in the literature. / Bu çalışma, görsel ve hareket verilerini birleştirerek düşük maliyetli bir sürücü yorgunluğu tespit sistemi sunmakta ve literatürdeki mevcut sistemlere göre daha güvenilir ve uygulanabilir bir çözüm sağlamaktadır.*

Results (Bulgular): *The system reliably detected driver fatigue by combining face and eye tracking with head-movement analysis and provided real-time alerts to the driver via a vibration motor. The use of low-cost hardware made the system accessible and practical. / Sistem, yüz ve göz takibi ile baş hareketlerinin birleştirerek sürücünün yorgunluğunu güvenli bir şekilde tespit ettikten sonra sürücüye titreşim motoru ile gerçek zamanlı uyarı sağlandı. Bu sistem düşük maliyetli donanım kullanımı ile erişilebilir hale geldi.*

Conclusion (Sonuç): *The proposed system demonstrates that integrating visual and motion data with low-cost hardware can effectively enhance driver safety through reliable fatigue detection and real-time alerts. / Önerilen sistem, görsel ve hareket verilerini düşük maliyetli donanımla birleştirmenin, güvenilir yorgunluk tespiti ve gerçek zamanlı uyarılar aracılığıyla sürücü güvenliğini etkili bir şekilde artırabileceğini göstermektedir.*

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Abstract

Driver fatigue is one of the critical factors that threaten traffic safety by impairing cognitive performance and prolonging reaction times during driving, thereby posing risks not only to the driver but also to surrounding individuals. Fatigue can negatively impact driving performance, particularly during long periods of continuous vehicle operation. This study presents the design of a real-time driver fatigue detection system based on Raspberry Pi 4 microcomputer. The system operates by monitoring facial and ocular movements using an in-vehicle camera and analyzing head movements via an MPU6050 accelerometer sensor. Facial detection and eye tracking are performed using the OpenCV library. Through image processing algorithms, the eye aspect ratio (EAR) and the percentage of eye closure (PERCLOS) are calculated to evaluate visual indicators of fatigue. Simultaneously, data obtained from the MPU6050 sensor is used to analyze head tilt, sudden head drops and deviations from the natural head position. These multimodal data streams work in conjunction to support the detection of driver fatigue, forming the basis of an assistive monitoring system.

Gerçek Zamanlı Sürücü Yorgunluk Tespiti ve Uyarı Sistemi

Öz

Sürücü yorgunluğu, sürüş sırasında bilişsel performansın azalmasına ve sürücünün tepki zamanının uzamasına sebep olan trafik güvenliğini tehdit eden hem sürücüyü hem de çevresindeki insanları tehlikeye atan önemli etkenlerden biridir. Sürücü yorgunluğu, uzun süreli araç kullanımı ile sürüş anında sürücünün performansını olumsuz etkileyebilir. Bu çalışma sürücünün yorgunluğunu gerçek zamanlı olarak tespit edebilmek amacıyla, Raspberry Pi 4 mikro bilgisayar tabanlı bir sistem tasarımı sunmaktadır. Sistem araç içi kamera ile yüz ve göz hareketlerinin izlenmesi ve MPU6050 ivmeölçer sensörü ile baş hareketlerinin tespit edilip analiz edilmesine dayanmaktadır. OpenCV kütüphanesi kullanılarak sürücünün yüzünün algılanması ve göz hareketlerinin tespiti gerçekleştirilmiştir. Görüntü işleme algoritmaları ile göz en-boy oranı(EAR) ve belirli bir zaman aralığında gözlerin kapalı kaldığı süre yüzdesi (PERCLOS) hesaplanmaktadır. Aynı zamanda MPU6050 sensöründen gelen verilerle sürücünün baş eğimi, başın anlık düşme hareketi ve başın doğal konumundaki hareketleri analiz edilerek sürücünün yorgunluğunu belirlenmesinde destek sistemi olarak çalışmaktadır.

1. INTRODUCTION (GİRİŞ)

In recent years, the rising incidence of traffic accidents caused by drowsy driving has become a significant threat to the safety of both drivers and passengers. Scientific investigations have shown that road traffic accidents result from the complex interplay of multiple factors, including road infrastructure, vehicle condition, environmental conditions, and most critically the physiological and cognitive states of drivers. Among these factors, driver fatigue and drowsiness play a central role in causing accidents, and neglecting these conditions can lead to severe consequences [1]. Studies examining drivers' physiological states have found that drowsiness is closely associated with prolonged driving, sleep disorders, physical exhaustion, and reduced attention. The literature recognizes these conditions as fundamental determinants that adversely affect driving performance, emphasizing

in particular that cognitive and physiological depletion during long-distance travel increases the risk of accidents [2]. Furthermore, a substantial proportion of fatigue-related accidents occur between midnight and the early morning hours, predominantly involving solo drivers. In many of these cases, drivers fail to recognize or consciously disregard signs of fatigue, resulting in a lack of preventive measures. This further underscores the need for automated systems capable of real-time detection and intervention for driver fatigue [3]. It has been reported that approximately 20% of traffic accidents in developed countries are primarily attributable to driver fatigue [4]. Owing to advancements in technology, various methods have been developed to prevent and mitigate such incidents. Physiological indicators such as eyelid movement, yawning frequency, and eye closure duration are commonly employed to assess drowsiness. Parameters including yawning frequency, blink rate, and the duration of eyelid closure are of particular importance in determining whether a driver is drowsy [5]. Accurate detection of facial features and expressions is vital for real-time video analysis. In this context, among the various methods employed, the Haar Cascade algorithm stands out for its success in detecting facial features and movements [6]. Specifically, among the widely used algorithms in the fields of facial recognition and motion analysis, the Haar Cascade algorithm is distinguished by its high accuracy, rapid processing speed, and robust structure, rendering it a reliable and efficient method in object detection applications and a preferred choice, particularly in real-time systems.

2. LITERATURE REVIEW (LİTERATÜR TARAMASI)

Fatigue detection can be broadly categorized into two main approaches.

2.1. Fatigue Detection Using Physiological Signals (Fizyolojik Sinyaller Kullanarak Yorgunluk Tespiti)

Physiological signals are biological data generated by specific bodily movements and can be detected by devices placed at specific points on the body. Such data are typically obtained using electroencephalogram (EEG) and electrocardiogram (ECG) devices [7]. The EEG measures the electrical activity of the brain, while the ECG records the electrical activities of the heart. In [8], driver fatigue and drowsiness were detected using an ECG sensor integrated into the steering wheel. In [9], researchers used neural networks to analyze heart rate variability for driver-fatigue detection and showed that heart rate patterns reliably indicate fatigue. In [10], a hybrid method combining EEG and ECG data with a support vector machine (SVM) classifier was developed, achieving 80.9% accuracy. Although physiological data based detection yields highly accurate results, these methods have practical drawbacks. In particular, equipment-related discomfort (intrusiveness) and long detection times limit their use in real-time applications.

2.2. Detecting Fatigue Using Computer Vision (Bilgisayarlı Görü Kullanarak Yorgunluk Tespiti)

Kumar and Yadav [11] enhanced the efficiency of systems for real-time facial expression recognition in drowsiness detection by utilizing similar techniques. Praveen Kumar and et al. [12] proposed a driver assistance system developed using the Haar cascade algorithm. To address drowsiness detection, the system uses interconnected modules to improve vehicle stability and prevent accidents. Priadana and Habibi [13] employed a face detection method by extracting Haar features [14] from images. In research on fatigue detection, Savaş and Becerikli presented a method that classifies driver fatigue using head-movement and blinking features [15]. Alshaqaqi et al. presented a Raspberry Pi 3 Model B–based system in which a Pi Camera Module acquired images and specific facial landmarks were employed to continuously monitor facial expressions [16]. Yousuf Hossain and Fabian Parsia proposed a nonintrusive, real-time drowsiness-detection system using a Raspberry Pi, a camera module, and audible alerts. The Haar Cascade classifier was employed to detect facial features, including the eyes. For a typical eye, the eye aspect ratio (EAR) is approximately 0.25; when the EAR dropped below this threshold, the system detected that the driver was drowsy [17]. Previous studies have applied Haar Cascade classifiers and the Eye Aspect Ratio (EAR) method across various projects. Constantin, Leonte, et al. trained Haar Cascade classifiers on driver faces and eyes to design effective face and eye detectors and proposed integrating them into a hierarchical system [18].

This study aims to design a low-cost, integrable system capable of real-time detection of driver fatigue and improving driving safety. The system analyzes the driver's facial and eye movements using the Haar Cascade classifier method while also monitoring head movements through both an in-vehicle camera and an MPU6050 accelerometer sensor.

Table 1. A comparative analysis of the proposed approach with existing studies based on the findings of the literature review
(Önerilen Sistemin Literatür Taramasında Elde Edilen Bulgulara Dayalı Mevcut Çalışmalarla Karşılaştırma Analizi)

Work	Year	Employed Method	Results
Alshaqaqi and et al. [16]	2013	Drowsiness detection with Perclos	Real-Time
A Schmidt and A Kasiński [14]	2007	Leinhart's detector-Haar Cascade from image	94%
Md Yousuf Hossain and Fabian Parsia [17]	2018	Drowsiness detection with EAR	Real-Time
Constantin, Leonte, and et al. [18]	2018	Drowsiness detection with OpenCV-Haar Cascade	Real-Time
Priadana and Habibi [13]	2019	Drowsiness detection with OpenCV-Haar Cascade from image	71.48%
Bk Savaş and Becerikli [15]	2020	Multi-tasking Convolutional Neural Network	98.81%
Praveen Kumar and et al. [12]	2021	Drowsiness detection with OpenCV-Haar Cascade	Real-Time
Proposed method	**2025**	**Drowsiness detection OpenCV-Haar Cascade and MPU sensors**	**Real-Time**

Thus, leveraging multiple data sources overcomes the limitations of vision-only systems and improves the reliability of fatigue detection. Specifically, accelerometer-based analysis of head tilt, sudden drops, and orientation changes contributes substantially to fatigue assessment. Unlike many previous studies in the literature [11-18] that focused solely on image processing techniques, the proposed system offers a more robust analytical foundation by combining both visual and motion data. Furthermore, the system's ability to be built with low-cost hardware components (Raspberry Pi, Pi camera module, MPU6050 sensor) increases its accessibility and commercial potential. Through the integration of a vibration motor into the system, haptic feedback is delivered to the driver during operation when fatigue is detected, thereby helping to restore the driver's attention. In this regard, the proposed approach offers significant advantages over existing studies in terms of both technical capability and practical applicability. In Section 3, detailed information on fatigue detection systems is provided; Section 4 presents the experimental results.

3. MATERIAL AND METHOD (MATERYAL VE METOD)

3.1. System Components (Sistem Bileşenleri)

The system is powered by a stabilized DC power supply with a 5V output. This power source ensures the continuous and safe operation of the Raspberry Pi 4B, which serves as the central processing unit, along with other peripheral components. The consistent power delivery is critical to maintain system stability, particularly in real-time monitoring and detection applications where uninterrupted operation is essential. At the heart of the system, the Raspberry Pi 4B is tasked with multiple responsibilities, including the processing of sensor data, capturing and analyzing camera images, and communicating relevant alerts to the warning display. The computational capacity and versatility of the Raspberry Pi 4B make it an ideal choice for integrating multiple data streams and executing detection algorithms in real time. The MPU6050 sensor, which combines a 3-axis gyroscope and a 3-axis accelerometer, is connected to the Raspberry Pi 4B via the I2C (Inter-Integrated Circuit) communication protocol. This protocol allows efficient, two-way data transfer between the microcontroller and the sensor with minimal wiring complexity, thereby facilitating rapid acquisition of motion and orientation data. Whenever an anomaly such as a significant head tilt, a sudden drop, or prolonged drowsiness indicators are detected by the system, an immediate notification is transmitted to the warning screen. This alert mechanism is crucial

for promptly informing the driver and potentially preventing accidents caused by fatigue. The overall system architecture is designed to be modular and scalable, allowing future enhancements such as the addition of new sensors or the upgrade of the processing unit. Figure 1 illustrates the block diagram of the proposed system, showing the interaction between the power supply, Raspberry Pi 4B, MPU6050 sensor, camera module, RF Transmitter, RF Receiver, Arduino Nano, power supply, vibration motor, motor driver and alert view.
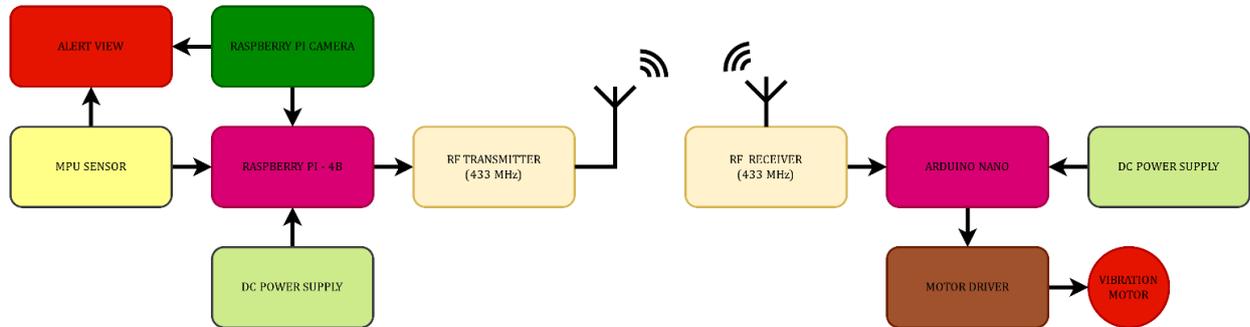

Figure 1. Block diagram of the fatigue detection system (Yorgunluk belirleme sisteminin blok diyagramı)

The information signal transmitted by the RF transmitter module connected to the Raspberry Pi 4B in the circuit shown in Figure 2 is wirelessly received by the RF receiver module. The received data is digitally processed and analyzed by the Arduino Nano microcontroller. Based on the analysis, if the system detects that the driver has entered a drowsy or sleep state, an alert mechanism is activated. In this context, the Arduino Nano triggers the connected motor driver circuit to activate a vibration motor. The vibration motor operates continuously for 5 seconds to provide physical stimulation to the driver. This process is designed to help the driver regain alertness and prevent potential accidents. The system offers a wireless, low-power, and real-time warning solution aimed at enhancing driver safety.
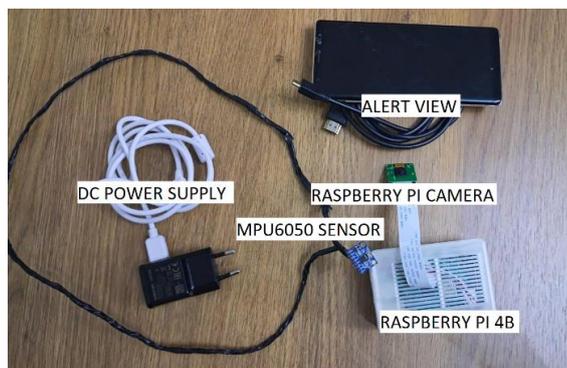
Figure 2. The circuit diagram of the drowsiness detection system (Yorgunluk belirleme devresi)
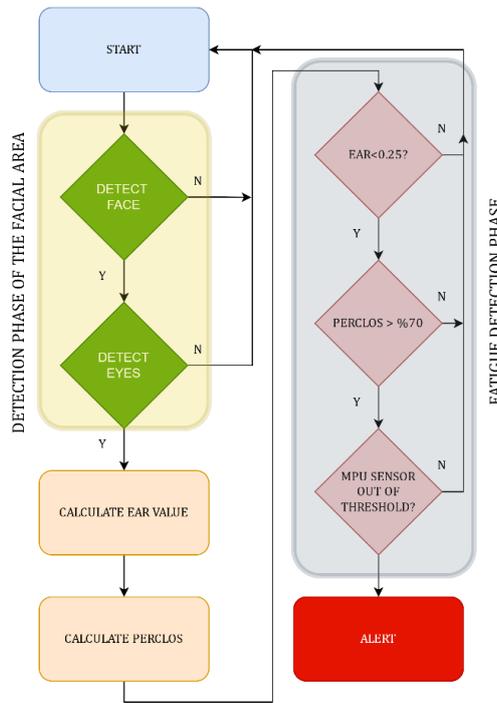
Figure 3. Fatigue detection system algorithm (Yorgunluk belirleme sistem algoritması)

In the fatigue detection system algorithm presented in Figure 3, the process begins with the complete detection of the driver's facial region. The detailed stages of facial detection are explained in Section 3.2. Once the face is successfully detected, the coordinates of the mouth and eyes are determined. This process is discussed comprehensively in Section 3.3. Subsequently, the calculation of the eye aspect ratio (EAR) and the percentage of eye closure (PERCLOS) is performed, as described in Section 3.4. When the EAR value drops below a threshold of 0.25, the system proceeds to calculate the PERCLOS value, which represents the percentage of time the eyes remain closed within a specific period. The main purpose of calculating the PERCLOS value at this stage is to avoid false alarms that could result from normal or involuntary blinking activities of the driver. If the calculated PERCLOS value exceeds 70%, indicating a high probability of drowsiness, the system then analyzes the data received from the MPU6050 sensor attached to the driver's head. If the sensor data indicates movement patterns that fall outside of predefined threshold ranges, suggesting abnormal head tilting or nodding associated with fatigue, the system triggers an alert to warn the driver. Furthermore, Section 3.5 provides detailed information about the integration of the MPU6050 sensor into the fatigue detection system and discusses its critical role in enhancing the reliability of drowsiness detection by incorporating head movement analysis along with facial monitoring.

3.2. Face Detection (Yüz Belirleme)

For the purpose of detecting faces from the real-time video stream captured by the webcam, a Haar feature-based cascade classifier was employed. Although several alternative methods for face detection are available, the Haar cascade classifier has been widely recognized for delivering more effective and reliable results, particularly in real-time applications [19-20]. This face detection method was originally proposed by Paul Viola and Michael Jones, who introduced it as a rapid and robust object detection framework. Their approach, based on the use of Haar-like features and an AdaBoost-based learning algorithm, significantly advanced the field by enabling real-time face detection with relatively low computational requirements. The Viola-Jones method remains a foundational technique in computer vision, particularly for applications where processing speed and resource efficiency are critical [21]. In the proposed method, various libraries were strategically utilized for both face detection and the precise localization of specific facial landmarks. A Haar feature-based cascade classifier from the OpenCV library was employed to initially detect the presence and general location of a human face within the input frame. For the subsequent, more detailed identification of key facial regions such as the eyes, mouth, and nose a highly accurate shape predictor from the dlib library was integrated into the system. This two-stage approach ensures not only a rapid initial face detection but also a refined

and precise mapping of facial features, which is essential for the reliability of fatigue assessment. Accurate localization of facial landmarks, particularly those associated with the eyes and mouth, plays a pivotal role in the performance of drowsiness detection algorithms, as these regions are directly linked to early signs of fatigue such as frequent blinking, eye closure, and yawning. The combined use of OpenCV and dlib libraries thus allows the system to achieve a balance between computational efficiency and detection precision, making it highly suitable for real-time applications where processing speed and accuracy are equally critical [22]. However, challenges encountered in facial expression recognition can vary significantly depending on several factors, such as lighting conditions, pose variability, and rotational transformations.

3.3. Detection of Mouth and Eye Coordinates
(Ağız ve Yüz Koordinatlarını Belirleme)

In this study, the 68-point facial landmark model provided by the Dlib library was utilized. This model enables the accurate detection and localization of 68 key points corresponding to essential facial regions, including the eyes, eyebrows, nose, mouth, and jawline. The Dlib 68-point landmark detector is widely adopted in various computer vision tasks such as facial analysis, alignment, and expression recognition, and has demonstrated its effectiveness in both academic and industrial contexts. As illustrated in Figure 4, facial landmarks numbered 37 to 48 were specifically employed to delineate the eye regions. Based on these points, an area value was computed and compared against a predefined threshold; if the calculated area fell below this threshold, it was interpreted as eye closure. Eye closure detection was performed in real-time to ensure timely identification of drowsiness. This methodological approach, by integrating multiple facial features, significantly enhances the overall performance and reliability of the real-time drowsiness detection system through a more comprehensive assessment of driver alertness [23].
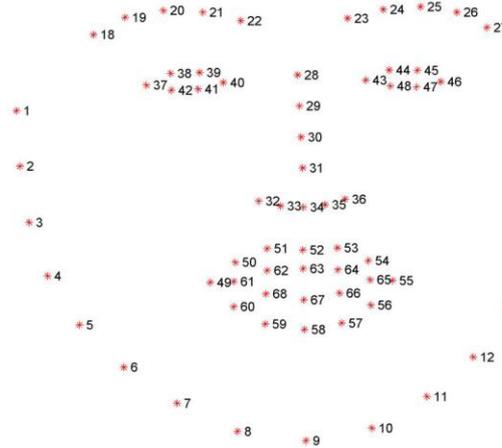
Figure 4. Face coordinates (Yüz koordinatları) [23]

3.4. Eye Aspect Ratio (EAR) (Göz Tespit Oranı)

In the field of computer vision, software systems developed for evaluating facial accuracy and consistency have achieved significant advancements through the introduction of an eye aspect ratio (EAR) computation technique. As with methods for delineating facial contours, the eye region is analyzed using specific landmark points and divided into six primary coordinate regions for detailed examination. In this context, a study conducted by Soukupová and Čech proposed a mathematical model that captures the geometric relationship between the eye landmarks and the axes defined among these points. This geometric relationship, which quantifies eye shape dynamics in a compact and computationally efficient manner, was termed the EAR. The EAR has proven particularly valuable in real-time drowsiness detection systems, as it allows for robust tracking of subtle variations in eye openness, even under varying illumination conditions and slight head movements [24]. The EAR is a metric based on the ratio between the vertical distances and the horizontal distance of the eye, providing a quantitative measure for evaluating the degree of eye openness. This ratio offers a robust and efficient means of monitoring eyelid movements, which is crucial for real-time fatigue and drowsiness detection applications. The mathematical

formulation for EAR employed in this study is presented in Equation 3.1 [24].

$$EAR = \frac{|P2-P6|+|P3-P5|}{2|P1-P4|} \qquad 3.1$$

In the EAR formula, P1–P6 are six 2D landmark points defining the eye contour: P1 and P4 are the eye corners (horizontal width), P2–P3 are on the upper eyelid, and P6–P5 are their corresponding points on the lower eyelid. |Pa−Pb| is the Euclidean distance between points (in pixels). EAR is the sum of two vertical eyelid distances divided by twice the horizontal eye width; it is dimensionless, decreases as the eye closes, and is largely scale-invariant
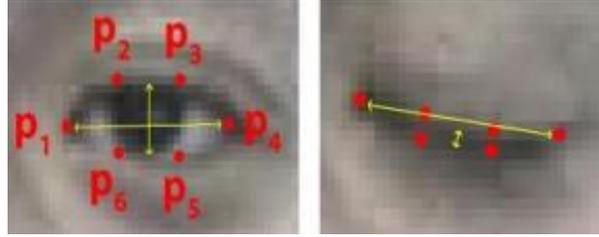

Figure 5. Eyes coordinates (Göz koordinatları) [24]

3.5. Validation of the Fatigue Detection System Using Motion Processing Unit (MPU) Sensor Data (Hareket İşleme Birimi (MPU) Sensör Verilerini Kullanarak Yorgunluk Algılama Sisteminin Doğrulanması)

The Motion Processing Unit (MPU) sensor is a six-axis motion tracking sensor that integrates a three-axis gyroscope and a three-axis accelerometer, and it has proven to be highly effective in monitoring driver behavior. In this study, the MPU6050 sensor was strategically positioned at the top of the driver's head to accurately capture head movements during driving. By measuring movements along three orthogonal axes, the sensor can detect head tilts to the left, right, forward, and backward directions. Experimental calibration determined the threshold values, allowing detection of head orientations up to 80 degrees. Real-time sensor data are continuously analyzed to detect abnormal head movements such as sudden or excessive tilts that may indicate fatigue or drowsiness. However, before interpreting these movements as indicators of fatigue, the system first verifies whether the drowsiness detection module is actively monitoring the driver. Only if the system is active and the defined threshold values are exceeded, the MPU6050 sensor readings are further evaluated.

3.6. Driver Alert Notification System (Sürücü Uyarı Bildirim Sistemi)

The signal received by the RF receiver is processed by the Arduino Nano microcontroller. When signs of driver fatigue are detected through integrated data from the onboard camera and the MPU sensor, the system activates the alert notification mechanism. As part of this mechanism, the vibration motor is triggered and operates continuously for 5 seconds, delivering haptic feedback to the driver during vehicle operation. This feedback aims to restore driver alertness and enhance road safety. The hardware components of the proposed system are illustrated in Figure 6.
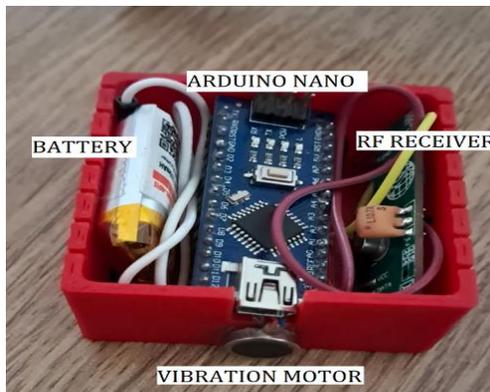

Figure 6. Receiver system hardware (Alıcı sistem donanımı)

## 4. FINDINGS AND DISCUSSION (BULGULAR VE TARTIŞMA)

Figure 7. Sample haar image for detection of face region (Yüz bölgesini belirlemek için örnek haar görüntüsü)

The first step of the algorithm involves the training of the classifier. This technique requires two distinct sets of image collections: positive images and negative images. As illustrated in Figure 7, positive images contain the targeted facial features of interest, such as eyes, mouth, or the whole face region. In contrast, negative images consist of scenes or subjects that do not include these features. Differentiating between positive and negative samples is crucial for enabling the classifier to learn and generalize effectively. During the training process, a large number of Haar-like features are computed for each image. For every feature, the difference between the sum of the pixel values within the white rectangular regions and the sum of the pixel values within the black rectangular areas is calculated. This difference serves as the basis for distinguishing the presence or absence of specific facial attributes within an image. The mathematical formulation of this computation is presented in Equation 4.1 [21].

$$Pixel = \left(\frac{Sum\ of\ whites}{Number\ of\ whites}\right) - \left(\frac{Sum\ of\ blacks}{Number\ of\ blacks}\right) \quad 4.1$$

In the calculation of Haar features, the sum of pixel intensity values within grayscale rectangular regions is utilized. Each Haar feature is systematically applied across all training images to assess its discriminative power. This process aims to determine the most effective threshold value for classifying images as positive or negative. By identifying the optimal threshold for each feature, the algorithm can accurately distinguish between the presence and absence of the targeted facial attributes, thereby enhancing the overall performance and reliability of the classifier [19]. Instead of fixing individual features across the entire image, groups of connected features are used, and the Haar classifier is applied sequentially to these groups. If an error occurs during image detection, the algorithm discards the first feature set and ignores the remaining features. OpenCV provides a training technique based on the Haar Cascade model, which can be used for detecting eyes in an image. First, the OpenCV library is imported, and then the relevant XML files are loaded [19]. These XML files contain a collection of features that will be applied to the image. Then, the detection of eyes is performed by using the detectMultiScale function, and rectangular coordinates for the detected eye regions are obtained. An example image is provided in Figure 8.
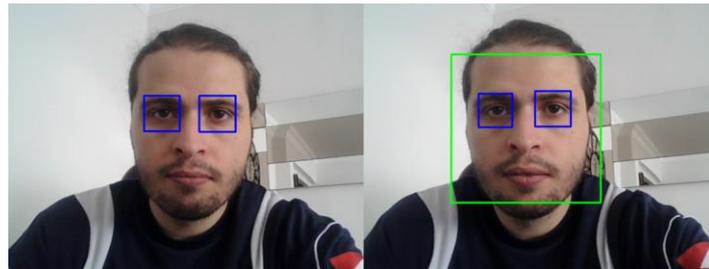
Figure 8. Detection of face and eye area (Yüz ve göz bölgesinin belirlenmesi)

By using Equation 3.1, the EAR value decreases when a person's eyes are closed because the distance between the two vertical axes reduces as the eyes close. Since blinking and eye closure are distinct concepts, the duration for which the eyes remain closed is calculated based on the PERCLOS index. The variable N_a, refers to the number of video frames within a one-minute interval during which the subject's eyes are detected as open, whereas N_m represents the total number of frames captured during that same time period. This ratio is often used to assess the driver's eye openness level as an indicator of alertness or drowsiness. The PERCLOS index is calculated as shown in Equation 4.2 [25]. When the index exceeds 70%, the driver is considered to be drowsy. Figure 9 illustrates the detection phase during the facial fatigue stage.

$$PERCLOS = \frac{N_m - N_a}{N_m} \times 100 \qquad 4.2$$

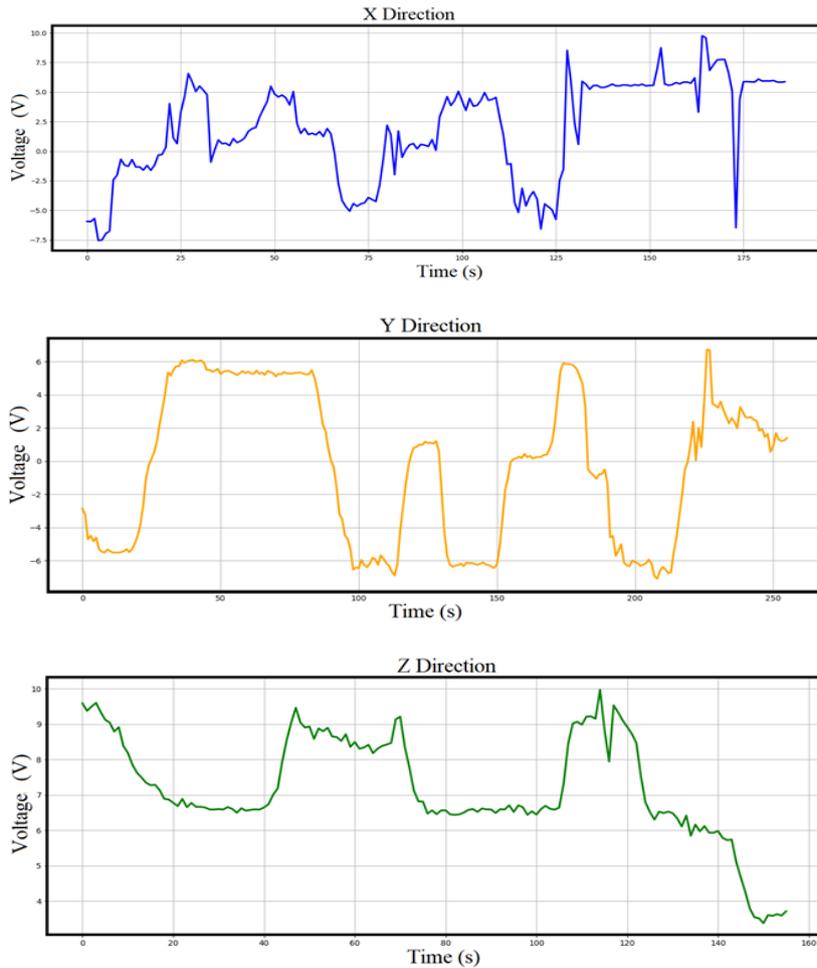**Figure 9.** Detection of sleepiness (Uyuşukluk belirleme)

Figure 10. MPU 6050 sensor instantaneous measurement values (MPU 6050 sensörünün anlık ölçüm değerleri)

The graph shown in Figure 10 presents data from the three axes of the MPU6050 sensor. The head's lateral tilt is detected by the movement along the X-axis of the MPU6050 sensor, while the forward or backward tilt of the head is detected by movement along the Y-axis. Additionally, both lateral and forward or backward tilts of the head are detected through movement along the Z-axis. It has been observed that the values range from -8 to +10. In the developed system, no alert is generated when the head movements are within the following ranges: X-axis (-5, +5), Y-axis (-4, +4), and Z-axis (-8, +10). This threshold value has been set to prevent false alerts caused by regular head movements during driving. However, sudden head movements or unstable orientations that exceed these limits are interpreted as signs of attention loss or drowsiness in the driver.

A sample visual output obtained after integrating the MPU6050 sensor into the system is presented in Figure 11. In this visual, it is clearly observed that the visual monitoring system and the motion tracking module are operating in an integrated and synchronized manner. When the driver's eyes close and the head simultaneously tilts to the side, the fatigue detection system is activated, and an instant notification is displayed on the screen to alert the driver. This situation demonstrates that the system operates in a fully integrated manner, combining both the visual analysis and motion tracking components effectively.
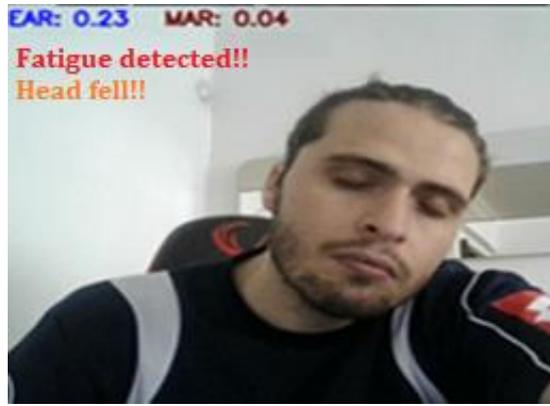
Figure 11. Instantaneous measurement value (Anlık ölçüm değerleri)

As part of the system, the receiver circuit is integrated into the driver's seatbelt and positioned on the chest area during driving. This placement allows the system to provide feedback from a location close to the driver's physiological responses, thereby enhancing its effectiveness**.** The receiver unit, illustrated in Figure 12**,** is designed with an ergonomic structure and compact dimensions to ensure user comfort is not compromised. The circuit is composed of low-cost electronic components commonly used in the field of driving safety (RF receiver module, vibration motor, Arduino Nano, etc.), making it both budget-friendly and suitable for large-scale implementations.

Figure 12. Driver alert system (Sürücü uyarı sistemi)

5. RESULTS AND RECOMMENDATIONS FOR FUTURE WORK (SONUÇLAR VE GELECEĞE YÖNELİK ÖNERİLER)

The study proposes a low-cost, integrable, and accessible system capable of real-time driver-fatigue detection. The system, powered by a Raspberry Pi 4, analyzes facial and eye movements using an in-vehicle camera with OpenCV and Haar cascade classifiers, while an MPU6050 accelerometer monitors head motion, supplying multi-source data for fatigue detection. By employing image processing algorithms, the eye aspect ratio (EAR) and the percentage of eye closure (PERCLOS) were calculated, while head tilt, sudden head drops, and orientation data were also evaluated to enhance the system's accuracy. The proposed system surpasses the limitations of methods based solely on visual data by combining visual and motion data to provide a more robust and reliable analysis framework. Considering that most studies in the existing literature focus only on image processing-based methods, the use of multiple data sources presented in this study constitutes a significant innovation. Moreover, the selection of low-cost hardware components, such as the Raspberry Pi, the Pi camera module, and the MPU6050 sensor, increases the system's economic accessibility and commercial potential.

In conclusion, the developed system offers an effective solution for enhancing driving safety through its technical proficiency, practical applicability, and low-cost structure. It has the potential to contribute significantly to the prevention of traffic accidents caused by driver fatigue. The findings of this study demonstrate that the use of multiple data sources is effective in detecting driver fatigue. However, to further improve the system's accuracy and adaptability to different driving conditions, several enhancements are recommended for future work. Firstly, it is suggested to integrate more advanced image processing techniques and deep learning-based methods such as convolutional neural networks (CNNs), long short-term memory networks (LSTMs) to enhance system performance under low-light, variable lighting, and adverse weather conditions. This would enable higher accuracy in face and eye detection, particularly in nighttime driving or other challenging environments. Additionally, incorporating biometric data such as heart rate, skin conductivity, and facial temperature analysis could transform the system into a comprehensive multi-modal fatigue detection mechanism. This approach would enable a system that responds not only to physical movements but also to physiological changes, providing a more holistic assessment of the driver's state. Assessing performance on drivers with diverse ages, genders, and body types would enhance the model's ability to generalize. Furthermore, conducting long-term field tests in real-world driving environments would enable the evaluation of the system's stability and long-term reliability.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

Murat AVŞAR: He designed and implemented the system architecture, developed the software framework for real-time data acquisition, and integrated the camera and MPU6050 sensor modules with the Raspberry Pi for fatigue detection. He developed the algorithms for facial and eye detection using OpenCV and Dlib libraries, implemented the EAR and PERCLOS calculations, and optimized the decision logic for fatigue classification. He conducted experimental tests to validate the system performance and analyzed the obtained sensor and visual data. He also contributed to the writing and revision of the manuscript.

Sistem mimarisini tasarlayıp uyguladı, gerçek zamanlı veri toplama için yazılım çerçevesini geliştirdi ve yorgunluk tespiti için kamera ve MPU6050 sensör modüllerini Raspberry Pi ile entegre etti. OpenCV ve Dlib kütüphanelerini kullanarak yüz ve göz tespiti algoritmaları geliştirdi, EAR ve PERCLOS hesaplamalarını uyguladı ve yorgunluk sınıflandırması için karar mantığını optimize etti. Sistem performansını doğrulamak için deneysel testler gerçekleştirdi ve elde edilen sensör ve görsel verileri analiz etti. Ayrıca, makalenin yazımına ve revizyonuna da katkıda bulundu.

Mithat ÖNDER: He contributed to the development and optimization of the fatigue detection algorithms, particularly in integrating visual and motion data for improved accuracy. He designed the wireless communication interface using RF modules and assisted in the implementation of the Arduino-based alert mechanism. He supervised the overall system integration, data analysis, and documentation process, and contributed to the writing and technical review of the manuscript.

Yorgunluk tespit algoritmalarının geliştirilmesine ve optimizasyonuna, özellikle de doğruluğu artırmak için görsel ve hareket verilerinin entegrasyonuna katkıda bulundu. RF modülleri kullanarak kablosuz iletişim arayüzünü tasarladı ve Arduino tabanlı uyarı mekanizmasının uygulanmasına yardımcı oldu. Genel sistem entegrasyonunu, veri analizini ve dokümantasyon sürecini denetledi ve makalenin yazımına ve teknik incelemesine katkıda bulundu.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.

Bu çalışmada herhangi bir çıkar çatışması yoktur.

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