

## IMU-Based Early Warning System for Driver Drowsiness Detection via Head Movement Analysis

Desi Nurnaningsih<sup>1\*</sup>, Kuswowo Adi<sup>2</sup>, Bayu Surarso<sup>3</sup>

<sup>1</sup>Doctoral Program in Information Systems, School of Postgraduate Studies, Diponegoro University

<sup>1</sup>Department of Information Technology, Faculty of Informatics, Telkom University

<sup>2</sup>Department of Physics, Faculty of Science and Mathematics, Diponegoro University

<sup>3</sup>Department of Mathematics, Faculty of Science and Mathematics, Diponegoro University

<sup>1</sup>Jl. Raya Daan Mogot No.KM. 11, RW.4, Kedaung Kali Angke, Jakarta, Indonesia

<sup>1,2,3</sup>Jl.Prof. Soedarto No.13, Tembalang, Kota Semarang, Jawa Tengah,Indonesia

### ABSTRACT

The high incidence of road accidents caused by human error—accounting for approximately 69.7% of all motor vehicle accidents in Indonesia—demonstrates the urgent need for an effective driver monitoring system. One critical factor contributing to human error is driver drowsiness, which can be observed through behavioral indicators such as abrupt changes in head position. This study aims to develop a real-time early warning system for detecting driver drowsiness based on head movement patterns using a wearable device equipped with the MPU-6050 GY-521 accelerometer sensor. The system monitors acceleration on the X, Y, and Z axes and identifies drowsiness when simultaneous changes exceed predefined thresholds. A drowsiness event is characterized by a rapid head displacement, occurring within approximately 18–20 milliseconds. The thresholds applied for detection are 1.0g for the X axis, 3.5g for the Y axis, and 0.5g for the Z axis. In ten test scenarios simulating drowsy head movements, the system successfully identified seven instances, resulting in a detection accuracy of 70%. The novelty of this approach lies in its lightweight, non-intrusive design and its ability to function independently of lighting conditions, making it a practical solution for real-time driver safety enhancement.

**Keywords** : *wearable; drowsiness; changes in head position; accelerometer; head movement; sensor.*

#### Article:

Accepted: August 01, 2025

Revised: March 05, 2025

Issued: October 30, 2025

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#### \*Correspondence Address:

[desinurnaningsih@telkomuniversi.ac.id](mailto:desinurnaningsih@telkomuniversi.ac.id)

## 1. INTRODUCTION

The number of accidents involving motorized vehicles in Indonesia is quite high. The KNKT (National Transportation Safety Committee) released data from 2010 to 2016, showing the number of accidents demonstrates this. There have been 41 accident investigations with 443 deaths. One of the causes of accidents comes from driver error (human error). Human error was to blame for 69.7% of motor vehicle accidents, while inadequate infrastructure and facilities were to blame for the remaining 30%. Reason human error is that the driver is drowsy. Sleepiness is a transitional state between consciousness and sleep that causes a decrease in the function of all senses. Physiological analysis can be obtained by analyzing the response of heart signals or ECG (electrocardiography).

The success rate for detecting drowsiness using ECG is quite high, however, displaying heart signals requires quite complex mathematical calculations to produce precise results [1]. Apart from that, the use of ECG is also impractical because it takes a long time to set up the system, and the driver's movements also affect the sensitivity of the ECG sensor readings [2]. Detection of drowsiness through changes in the driver's facial pattern can be done using computational methods of computer vision, specifically by using a camera to take a picture of the driver's face for a computer program to process. The environment around the camera can have an impact on the process of taking pictures. For example, the intensity of ambient light changes, so this method is less effective for detecting drowsiness in drivers [3]. Driver alertness is greatly reduced, reaction times are slowed, and the chance of losing control of the vehicle is increased when drowsiness is present [4].

Driver behavior detection is the most widely used method because it does not require complex system design. A change in head position is one of the indicators that a drowsy driver can detect [5]. The head position will be upright if the driver is in normal body condition and will experience a sudden change in position if the driver is sleepy. From this study, changes in head position will be detected using an IMU sensor (Inertial Measurement Units). We found that 70 % of the tests are successful. Movement patterns of the head, such as drooping, tilting, or

instability, are among the many physiological and behavioral indicators of drowsiness [4], [6], [7], [8]. Have been found to be more accurate early signs of fatigue than just looking at facial expressions or ocular conditions . Recognition of these head movement patterns can help prevent accidents before they happen. Methods based on physical principles (such as electroencephalogram (EEG) and electrocardiogram (ECG) as well as methods based on computer vision have been tried to detect driver fatigue. Physiological methods offer a high level of accuracy, but they are disadvantageous, expensive, and impractical to implement in the real world .

This research focuses on developing a robust driver drowsiness detection system using IMU sensors to monitor head movements. Unlike previous methods relying on complex physiological signals or vision-based approaches sensitive to environmental changes, this study exploits wearable accelerometer sensors to detect abrupt head position changes indicative of drowsiness. The system aims to provide practical, non-invasive, and real-time monitoring of driver alertness under varying conditions.

The rest of the paper is organized as follows: Section 2 presents our proposed method in detail. Section 3 Result and discusses the experimental setup. Finally, Section 4 concludes the paper, summarizing the key findings and contributions.

### 1.1. Related Work

#### a. Determinants of drowsiness phase disorders

The body has a tendency to order sleep when it is awake for an extended period of time, disrupting the sleep-wake balancing mechanism. The circadian rhythm is the equilibrium between the body's biological clock and sleep [9]. Drowsiness is a transitional state between wakefulness and sleep, characterized by decreased sensory responsiveness and cognitive performance, which significantly affects an individual's alertness and reaction time. This condition is primarily regulated by the circadian rhythm, an endogenous biological clock located in the suprachiasmatic nucleus (SCN) of the hypothalamus. The circadian rhythm orchestrates various physiological

functions, including hormone secretion, core body temperature, and the sleep-wake cycle, to maintain homeostasis across a roughly 24-hour period [10]. Disruptions in this rhythm, caused by factors such as extended wakefulness, shift work, or lifestyle irregularities, can lead to impaired vigilance and increased sleep propensity during inappropriate times.

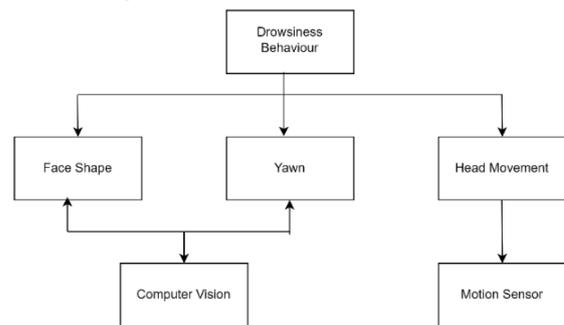
One of the key hormones influenced by the circadian system is melatonin, which is synthesized by the pineal gland in response to darkness and plays a pivotal role in promoting sleepiness by lowering body temperature and facilitating the transition to sleep [11] [12]. Melatonin production follows a distinct circadian pattern, peaking during the night and diminishing toward morning, thereby signaling the body's biological night [13]. Dysregulation of melatonin secretion has been linked to various sleep disorders and impaired alertness, contributing to drowsiness-related risks such as diminished driving performance [14] [15]. Understanding these physiological underpinnings is crucial for developing effective detection and mitigation strategies for drowsiness in safety-critical tasks.

#### b. Patterns of Driver Behavior with Drowsiness

Driver drowsiness manifests in observable behaviors, including frequent eye blinking, yawning, and sudden head movements. Computer vision techniques typically analyze eye and mouth movements through facial images captured by cameras. However, such methods can be sensitive to environmental factors like lighting changes. Drowsy drivers have an observable pattern of behavior. Some characteristics that can be observed include eyes that blink more often, a mouth that yawns more often, and the movement of the driver's head falling and returning to the starting position suddenly [16]. To recognize the characteristics of eye blinks and mouth yawns, this method is generally carried out by computer vision, namely by utilizing a camera, which is used to take images and process them using software. Meanwhile, recognition of sudden changes in head position can be done using reading-motion sensors [17]. Methods such as [18], [19] concentrate on transforming facial images from high-

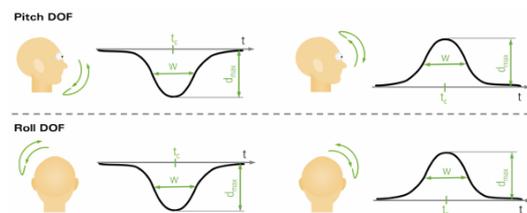
dimensional spaces to lower-dimensional smooth manifolds.

Alternatively, sudden head position changes, such as nodding or tilting, can be detected using motion sensors such as Inertial Measurement Units (IMUs). Compared to computer vision, sensor-based detection is less affected by environmental disturbances, offering a more robust approach in various conditions. **Figure 1** illustrates the relationship between drowsiness-related behaviors and corresponding detection methods. Combining computer vision with motion sensors can enhance detection accuracy, supporting applications in driver safety and productivity monitoring.



**Figure 1.** Classification patterns of drowsy

When the driver is really sleepy, there is an abrupt shift in head posture. There is also the issue of driver weariness, which lowers the driver's level of awareness. It takes a lot of work on the part of the driver to be vigilant in this situation and still operate the car. But the driver's head moves unexpectedly, falling and then rising to its original position due to a breakdown in the body's functioning mechanism. The head's movement has an erratic direction, and it will generate a certain pattern from that direction.



**Figure 2.** The four gestures to be classified, and their shapes of the dominating DOF when plotting head displacement against time

**Figure 2**, this image shows that head movement in the pitch and roll domains can be modeled in the form of a graph as a function of time. With the analysis of head movement patterns using motion sensors or computer vision, drowsiness behavior can be detected more accurately. This information is very useful in the development of drowsiness detection-based safety systems.

1. Nodding down: Motion along the pitch DOF,  $\theta$ , starting from the center in negative direction and back
  2. Nodding up: Motion along the pitch DOF,  $\theta$ , starting from the center in positive direction and back
  3. Bending left: Motion along the roll DOF,  $\phi$ , starting from the center in negative direction and back
  4. Bending right: Motion along the roll DOF,  $\phi$ , starting from the center in positive direction and back
- When displaying head displacement  $d$  against time  $t$ , the shape of the dominating DOF of each of these gestures can be approximated well by a Gaussian function that is given by

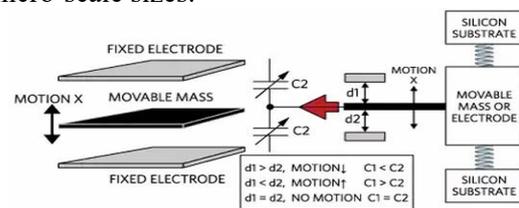
c. MPU-6050 GY-521 sensor

The MPU-6050 GY-521 sensor module consists of two sensors, namely 3-axis accelerometer and 3-axis gyroscope. The MPU-6050 GY-521 sensor module uses technology Micro Electro-Mechanical System (MEMS), namely an integrated system of mechanical and electro-mechanical structures produced using microfabrication techniques [20]. The MPU-6050 GY-521 is a compact sensor module integrating a 3-axis accelerometer and a 3-axis gyroscope, based on Micro Electro-Mechanical System (MEMS) technology. It includes a Digital Motion Processor (DMP) capable of processing combined sensor data. [21]. The sensor communicates via I2C protocol, supporting standard (100 kHz) and fast (400 kHz) data transmission modes. It is equipped with onboard voltage regulation and pull-up resistors for easier integration. Apart from that, there are supporting components in this module to make it easier to use this sensor module [22]. Data on the head movement of a drowsy driver is acquired by detecting significant variations in acceleration values on the X, Y, and Z axes of the MPU-6050 GY-521 accelerometer sensor,

which allows for the identification of a person's characteristics in a lethargic state. The accelerometer sensor MPU-6050 GY-521 is designed to detect abrupt changes in head position, namely the rate at which the head position changes from the first drop to the return to the starting position, which is less than 20 milliseconds. The sensor is linked to the STM32F429I-DISC1 microcontroller by physical connection. Inter-I2 communication C. The microprocessor receives raw data of acceleration values obtained from accelerometer readings on the X, Y, and Z axes, expressed in g-force units. In this study, the sensor measures acceleration along the X, Y, and Z axes to detect significant variations associated with drowsy head movements. Specifically, it captures rapid changes in head position occurring within less than 20 milliseconds, which serve as indicators of drowsiness.

1. Accelerometer

Accelerometer used to measure the acceleration of a moving object, changes in position, and the acceleration of the earth's gravity. An acceleration will cause a force which will be captured by the sensor's force detection mechanism accelerometer. The amount of acceleration can be measured indirectly from the amount of force that is detected [23]. Structure of the sensor accelerometer consists of a capacitive transducer and a driving spring designed in micro-scale sizes.



**Figure 3.** Mechanism of how the accelerometer sensor works

As per the picture above, the spring is connected to the driving load and substratesilicon which is fixed. If there is movement in the direction of the spring axis, then the driving load will follow move in the same direction as the direction axis of movement and causes a change in the capacitance value. This is the big change in the capacitance of the capacitor which will be processed into a change in acceleration value by sensors accelerometer.

Censorship accelerometer will detect acceleration forces on three axes, namely the X axis, Y axis and Z axis based on the influence of the earth's acceleration. Earth's gravitational acceleration is measured in units g-force (G), where 1G is equal to 9.8 m/s<sup>2</sup>.

## 2. Gyroscope

Gyroscope is a sensor that can be used to measure the angular velocity of a moving object about the rotation axis. Gyroscope will produce a signal whose value is proportional to the angular velocity around the axis perpendicular to the rotation axis. Angular velocity units will be measured in radians per second (rad/s) or in degrees per second (0/s). The structure of the gyroscope sensor consists of an electro mechanical system in the form of a rotor disk connected to a micro-sized spring (MEMS). When the rotor rotates freely, the rotor rotation will tend to maintain its axial position. A torque will be generated on the axis output when the rotor disk rotates around the axis input. This will produce rotation around the axis output, this event is called the precision of gyroscope [24]. The time rate of change of angular momentum applied to an axis is equal to the magnitude of the torque applied to that axis [25].

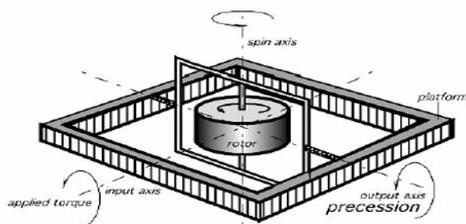


Figure 4. Electro-mechanical system of the gyroscope

### d. STM32F4 Discovery microcontroller

The sensor interfaces with the STM32F429I-DISC1 microcontroller, which features an ARM Cortex-M4 processor operating at 180 MHz, 2 MB flash memory, and 256 KB RAM. This hardware platform enables efficient data acquisition and processing. STM32F4 Discovery is a microcontroller developed by STMicroelectronics which functions as hardware for managing, processing and interactive media that is integrated with software in a system. In this final project, the microcontroller that will be used is STM32F429I – DISC1 which is a development of the previous generation, namely STM32F429I – DISC0. The block diagram of

the STM32F429I – DISC1 hardware can be seen in the following image in figure 5.

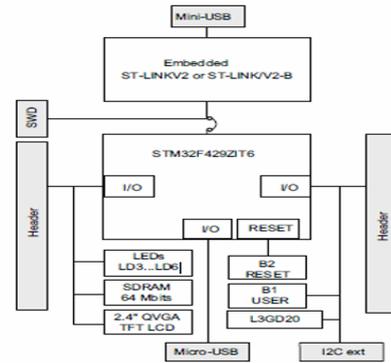


Figure 5. Block Diagram of STM32F429I – DISC1

The STM32F429I – DISC1 utilizes the STM32F429ZIT6 processor, adopting the ARM Cortex-M4 architecture and operating at a frequency of 180MHz. This architecture ensures exceptional performance throughout system processing [26]. Further characteristics include a 2MB flash memory and 256KB RAM. Furthermore, the hardware has been incorporated with STLINK/V2-B and equipped with a compact USB input for debugging purposes [27].

### e. Supporting Hardware and Communication Protocols

An I2C communication system necessitates just two data interfaces in figure 6. The Serial Data (SDA) and Serial Clock (SCL) are two types of signals. The line SDA is utilized for data transmission [28], [29], whereas the line SCL serves as the clock source during data transmission. Data transfer between a master and slave follows a specifically defined format. Reviewing that particular format, I2C can be distinguished into many signal circumstances [30]. The initial condition is one of START and STOP. The START condition is a signal that triggers all commands, shown by a corresponding change in SDA voltage from "1" to "0" when SCL is set to "1". The STOP condition is a signal that ends all commands, indicated by a 0 to 1 change in SDA voltage when SCL is set to 1. The transfer of data between the master and the slave is the second criterion. In general, the data delivered is 8 bits carried over SDA. The data is partitioned into two segments: 7 bits for the slave address and 1 bit for choosing the operation mode (set to "1") and the operation mode (set to "0"). Response signals provided throughout the data

transmission process between the master and slave are referred to as Acknowledge (ACK) and Non-Acknowledge (NACK) in the third condition. The ACK or NACK signals will be displayed on the 9th bit following the completion of data transfer between the master and slave ports. The ACK condition is triggered when the slave successfully receives the data transfer from the master and responds with an ACK signal [31]. This signal is transmitted when the SDA (Serial Data Attribute) is set to "0" during the 9th clock cycle. In the event that the slave ceases to receive the data transmitted by the master, it will react by emitting a NACK signal, therefore signifying that the value of SDA is changed to "1."

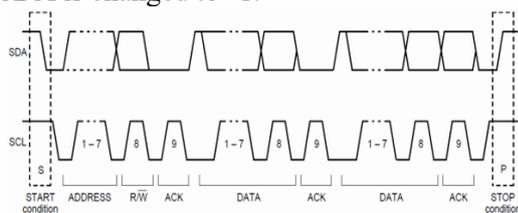


Figure 6. I2C data delivery format

Sentiment analysis is the process of understanding and classifying opinions expressed in text, particularly in the context of social media, product reviews, and customer service. This analysis is important for companies because it allows them to understand customer feelings toward their products or services, which can then be used to improve customer experience and marketing strategies (Liu, 2012).

## 2. METHODS

This section describes the methodology applied in the development of the driver drowsiness detection system using an accelerometer sensor. The explanation is detailed to enable readers to replicate the study.

### 2.1. Block Functional System

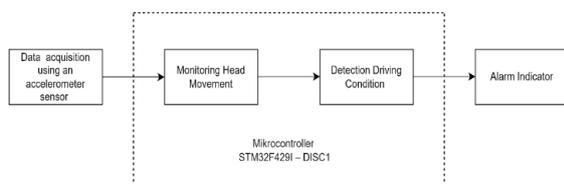


Figure 7. Block functional system

The image above shows the flowchart of the drowsiness detection system based on an

accelerometer sensor. The process begins with data acquisition using an accelerometer sensor, which functions to collect information regarding the driver's head movements. This data is then used in the head movement monitoring stage, where the system analyzes changes in angle and patterns of unusual head movements, such as the head being bowed or tilted to the side for a certain period. This analysis is very important in detecting signs of drowsiness while driving.

After monitoring head movements, the system will enter the driving condition detection phase, where the head movement patterns are compared to certain thresholds to determine whether the driver is drowsy or not. If the system detects drowsiness based on abnormal head movement patterns, it will activate an alarm indicator as a warning to the driver. This alarm can be in the form of sound, vibration, or visual alerts to wake up the driver and prevent potential accidents due to drowsiness. This system is very useful in enhancing driving safety, especially for long-distance drivers or those driving while fatigued.

### 2.2. Drowsiness Detection Algorithm

The system monitors changes in acceleration values over time to detect abrupt head movements indicative of drowsiness. Each axis has a predefined threshold value. When simultaneous fluctuations in the X, Y, and Z axes exceed these thresholds, the system flags a drowsy state.

Upon detecting drowsiness, the system triggers an alarm (e.g., buzzer sound) to alert the driver. This is Pseudocode of the Detection Algorithm.

```

Initialize MPU-6050 sensor and STM32F429I
microcontroller
Set thresholds: Threshold_X, Threshold_Y,
Threshold_Z

Loop:
  Read raw data from MPU-6050 registers:
  Data_X, Data_Y, Data_Z
  Convert raw data to acceleration (ax, ay,
  az) using eqns (1)-(3)
  Store acceleration data in buffer

  If |ax - ax_prev| > Threshold_X AND
  |ay - ay_prev| > Threshold_Y AND
  |az - az_prev| > Threshold_Z Then
    Trigger alarm signal
  End If

  Update ax_prev, ay_prev, az_prev with
  current values
End Loop
    
```

### 2.3. Architecture System

In section the project's mechanical design encompasses the development and implementation of the headpiece specifically designed for the placement of the MPU-6050 GY-521 sensor and alarm. The headgear is specifically engineered to be worn on the driver's head in order to detect any alterations in the driver's head posture particularly when they are feeling sleepy. The headgear is 22cm x 15cm and is fitted with a rear knob for customising to suit the driver's head size dimensions. The headgear is made from polypropylene (PP), a durable and lightweight material that enhances wear comfort.

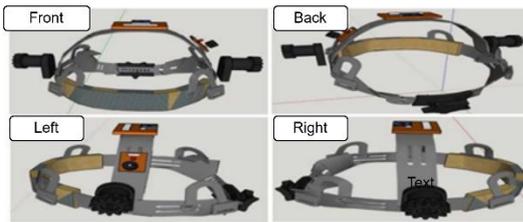


Figure 8. Design headgear viewed from various points of view

During the retrieval of acceleration data from the accelerometer sensor, the master STM32F429I – DISC1 transmits 8-bit slave addresses to the MPU-6050 GY-521. In order to activate the sensor, it is necessary to access the 6B registry and transmit data '0x00' consisting of 8 bits. The accelerometer sensor's complete resolution range is established at  $\pm 2g$  by transmitting 8-bit data '0x00' to the 1C registry. Following this, the sensor will collect 16-bit data from each axis of the sensor accelerometers (x, y, and z) transmitted by the 3B up to 40 Mpu-6050GY-521 register. The data is transformed into acceleration values in g-force (g) units via the method described by the following equation.

$$\alpha_x = \text{Data X (16 bit)} \times \frac{1}{16834} \quad (1)$$

$$\alpha_y = \text{Data Y (16 bit)} \times \frac{1}{16834} \quad (2)$$

$$\alpha_z = \text{Data Z (16 bit)} \times \frac{1}{16834} \quad (3)$$

Where  $\alpha_x$  is the acceleration value for the X axis in units of 'g',  $\alpha_y$  is the acceleration value for the Y axis in units of 'g' and  $\alpha_z$  is the acceleration value for the Z axis in units of 'g'. The acceleration data is sent to a data processing computer using serial

communication. Data processing software using MATLAB 2024. The baud rate for transmitting the acceleration values from the accelerometer sensor is set to 115200. After that, a buffer is provided to store data from the three axes of the accelerometer sensor. The values stored in the buffer will be analyzed to determine if there are any drastic changes occurring in the three axes of the accelerometer sensor when a person is drowsy, characterized by sudden changes in head position.

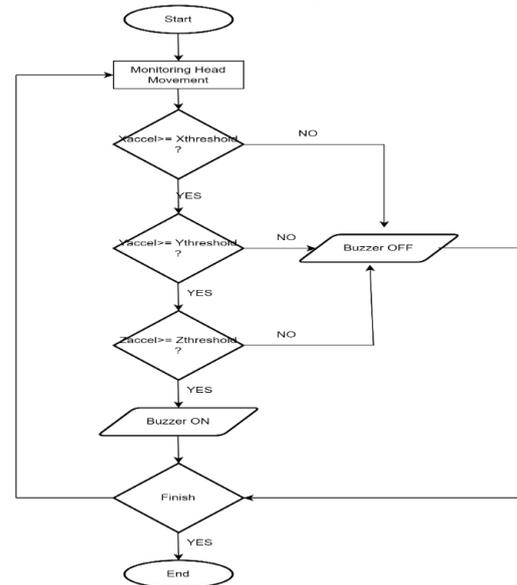


Figure 9. Data flow diagram and ekstraksi accelerometer

The threshold value is allocated to each axis and is utilized to identify drowsiness by analyzing the concurrent fluctuations in values across the X, Y, and Z axes. Upon meeting the specified threshold value, the driver's head movement pattern is identified as indicative of a drowsy state. Upon detecting the driver as drowsy, the buzzer indicator is triggered as a cautionary signal to the driver.

### 3. RESULTS AND DISCUSSION

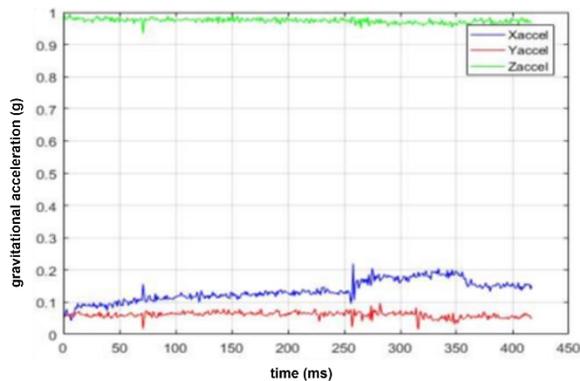
In this section, it is explained the results of research and at the same time is given the comprehensive discussion. Data collection of acceleration from the accelerometer sensor is conducted while the head is in a stationary position. The purpose of this test is to determine the acceleration values along the X, Y, and Z axes when the driver is in a normal condition, meaning there are no sudden changes in head position, which is interpreted as a state of drowsiness. The acceleration data is sent to a

computer using USB TTL serial communication to be stored in MATLAB 2024 as data processing software. The accelerometer sensor testing reveals that under normal conditions, during which there is no sudden movement in head position, the acceleration values are approximately 0.05g for the X-axis, 0.05g for the Y-axis, and around 0.98g for the Z-axis.

**Table 1.** Acceleration value without change in head position

Time (ms)	ax (g)	ay (g)	az (g)	Note
1	0.056152	0.052734	0.993408	Head Note Move
2	0.06543	0.05957	0.976563	Head Note Move
3	0.078125	0.059326	0.97583	Head Note Move
4	0.060547	0.057373	0.984619	Head Note Move

The following is a graphical representation of the acceleration data from the three axes while the head is stationary, which is stored in the buffer.



**Figure 10.** Acceleration data graph when the driver's head is still

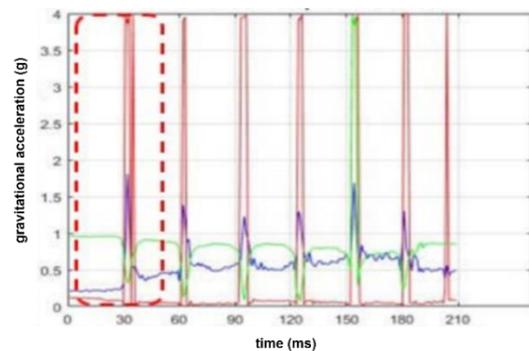
The objective of this test is to detect the parameters of persons in a condition of sleepiness by monitoring significant variations in acceleration values along the X, Y, and Z axes. The testing is carried out on participants by providing them with headgear that has been equipped with accelerometer sensors. The participants will thereafter imitate alterations in head posture as if they were experiencing sleepiness. Analysis of the test findings revealed that the acceleration values on the X axis, Y axis, and Z axis varied between 0.8g and

1.8g, 3.8g and 3.9g, and 0.35g and 0.45g, respectively, with changes in head position.

**Table 2.** Acceleration Value With Change in Head Position

Time (ms)	ax (g)	ay (g)	az (g)	Note
29	0.252686	0.068359	0.911865	Head Note Move
30	0.308105	0.049072	0.750244	Head Note Move
31	0.884033	3.963623	0.450195	Head Movement
32	1.810547	3.855225	0.318604	Head Movement
33	1.152832	3.961914	0.357666	Head Movement
34	0.549561	0.006104	0.620361	Head Note Move

The graph below displays a sample of 100 data points on acceleration from the three axes during the change in head position retrieved from the buffer



**Figure 11.** Head movement monitoring graph

Assigning threshold values to each axis will enable the detection of drowsiness by detecting abrupt changes in the driver's head position. The experimentation was carried out using a simulation of head motion that represents the state of a fatigued automobile driver. Movement of the head is sporadic; nonetheless, when an individual is seated in an upright position, the center of gravity will be inclined forward. Thus, an individual who is fatigued in such posture will abruptly see their head quickly inclined forward. Measured using a stopwatch, the rate at which the head's position changes from the beginning falling process to its return to the starting position is less than 20 ms.

**Table 3.** Detection drowsiness test

No	Move ment	Velocity (ms)	Category	Note
1	1	20	Drowsiness	success
2	2	18	Drowsiness	success
3	3	19	Drowsiness	Fail
4	4	18	Drowsiness	success
5	5	20	Drowsiness	success
6	6	20	Drowsiness	success
7	7	18	Drowsiness	Fail
8	8	19	Drowsiness	success
9	9	20	Drowsiness	success
10	10	19	Drowsiness	Fail

The drowsiness detection test performed within the vehicle comprises 10 head movements, with reference thresholds of 1 for the X-axis, 3.5 for the Y-axis, and 0.5 for the Z-axis. Among the 10 head motions identified, 7 were accurately recognized while 3 were not. The exam achieved a success rate of 70%.

To evaluate detection performance, a confusion matrix was constructed based on the 10 test movements:

**Table 4.** Evaluate detection performance

	Predicted Drowsy	Predicted Not Drowsy
Drowsy	7 (True Positive)	3 (False Negative)
Not Drowsy	0 (False Positive)	0 (True Negative)

To quantitatively assess the performance of the drowsiness detection system, a confusion matrix was constructed using the results from the 10 simulated head movements. Out of these, the system correctly identified 7 instances of drowsiness (true positives) and failed to detect 3 instances (false negatives). No false alarms (false positives) or correct rejections (true negatives) were recorded in this test scenario.

$$\text{Precision} = \text{TP} / (\text{TP} + \text{FP}) = 7 / 7 = 100\%$$

$$\text{Recall} = \text{TP} / (\text{TP} + \text{FN}) = 7 / (7 + 3) = 70\%$$

$$\text{F1-Score} = 2 * (\text{Precision} * \text{Recall}) / (\text{Precision} + \text{Recall}) \approx 82.4\%$$

Based on the results of testing 10 simulated head movements representing drowsy conditions, the system successfully detected 7 movements accurately (true positives) and failed to detect 3 others (false negatives). No incorrect detections (false positives) were observed,

resulting in a precision score of 100%, indicating that every alarm triggered by the system corresponded to an actual drowsiness event. However, since three drowsiness events were missed, the system's recall was 70%, reflecting the current limitation in capturing all instances of drowsiness. Consequently, the F1-score, which represents the harmonic mean of precision and recall, was calculated at 82.4%, suggesting that the system demonstrates reasonably balanced detection performance, though improvements are still needed in its sensitivity to more subtle head movement variations.

## CONCLUSION

This study explores indicators of driver drowsiness by analyzing simultaneous fluctuations in acceleration values along the X, Y, and Z axes. Under drowsy conditions, the acceleration values recorded range from 0.8g to 1.8g on the X axis, 3.8g to 3.9g on the Y axis, and 0.35g to 0.45g on the Z axis. The velocity of head displacement from initial tilt to return was consistently measured at below 20 milliseconds using stopwatch calibration. Based on testing with 10 simulated head movements, the system achieved a detection accuracy of 70%.

While these results demonstrate the feasibility of using IMU-based head movement analysis for detecting drowsiness, further improvements are necessary. Refining the threshold values and detection logic may enhance accuracy and reduce false negatives. Additionally, future research should consider integrating multi-modal sensor data—such as eye-tracking or heart rate monitoring—and applying machine learning algorithms to enable adaptive, real-time drowsiness detection systems that are more robust and generalizable across diverse driver profiles and conditions.

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