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Smart Helmet with IoT Integration: Enhancing Rider Safety with Real-Time Hazard Alerts

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***Abstract*—Bike accidents, particularly among young riders, contribute to a significant number of deaths worldwide. Key factors such as alcohol consumption, poor road conditions, and the lack of proper safety gear are major contributors to deaths. The study proposes a smart helmet system designed to identify potentially hazardous situations and enhance bike rider safety. It incorporates sensors for helmet detection, alcohol monitoring, fall detection and road condition alerts. Utilizing ESP-NOW communication, the helmet and bike unit collaborate to control the bike's ignition based on real-time safety conditions. If a rider fails to wear the helmet, consumes alcohol, or experiences a fall, the ignition is automatically turned off. Additionally, the system provides timely notifications for road humps, accident-prone areas and poor road quality by leveraging GPS and a grid-cluster technique to optimize performance. Emergency SMS alerts with GPS location are sent in the event of fall detection or alcohol consumption. Overall, this smart helmet system offers a comprehensive solution to improving rider safety by actively preventing accidents and responding swiftly to hazardous situations.**

***Index Terms*—Smart helmet, Internet of Things, Alcohol detection, Fall detection, Road condition alert, Biker's safety, IoT**

I. Introduction

Rider safety has become a major concern due to the rising number of fatal bike accidents worldwide. As accident rates increase, advanced safety technologies are becoming more necessary to prevent accidents and lower fatality rates. The primary motivation behind our work is to proactively reduce accident rates by providing timely alerts to riders, enabling them to take preventive actions and navigate safely. The latest estimate by the World Health Organization (WHO) shows that road injuries are the leading cause of death among young people aged 15 to 29 globally. Because there is limited information available about these incidents, riders often receive aid only after an accident has already occurred. According to WHO, head injury is the primary cause of death for motorcyclists, often due to not wearing high-quality helmets. A safe, high-quality helmet can reduce the chance of brain damage by up to 74% and decrease the risk of death by almost six times.

In Bangladesh, the Accident Research Institute (ARI) of the Bangladesh University of Engineering and Technology (BUET) found that in 2021, 1,168 motorcyclists died in accidents, an increase from 1,097 in 2020. The report highlights that only 10% of motorcyclists were wearing helmets that meet safety standards. According to data collected by the Bangladesh Road Transport Authority (BRTA) over the past year, a total of 7,837 vehicles were involved in road accidents in 2023, with motorcycles emerging as the most frequently involved vehicle type, contributing to 1,747 reported incidents.

The majority of research on smart helmets has focused on features such as bike start control, safety mechanisms, alcohol detection, and emergency rescue requests. However, enhancing rider safety through road condition alerts could be a valuable addition. With prior warnings, bikers could better navigate unexpected hazards, such as potholes or road humps, reducing the risk of accidents. Additionally, there are numerous four-way intersections and sharp turns where accidents are more likely if riders are not alerted in advance.

Ensuring that riders are aware of road conditions is essential. Features like road condition alerts can significantly improve rider safety by addressing poor road conditions, inadequate infrastructure, sudden lane changes, and upcoming junctions. Timely alerts can enhance rider's awareness of potential challenges, allowing them to adjust their speed and mentally prepare for the upcoming dangers.

The rest of the paper is structured as follows: Section II contains the literature review. Section III covers system design and methodology. Section IV presents the discussion and result analysis. Finally, Section V concludes the paper and offers recommendations for future enhancements.

II. Literature Survey

Smart helmet development has become an emerging area of innovation to improve rider safety and mitigate accidents. An overview of the most recent approaches to this significant issue is given in this section.

Several studies have focused on core safety features like alcohol detection, accident detection and fall detection. Nanda et al. [1] proposed a system using GPS, GSM, alcohol detection and accelerometers, while Prashant et al. [2] improved upon this with the addition of tilt sensors. Jesudoss et al. [3] further added an infrared sensor for helmet detection and an alcohol breath sensor, which was also used by Md. Atiqur et al. [4], who included Bluetooth connectivity for automatic emergency alerts. Mohammad et al. [5] and Bhavesh et al. [6] followed a similar approach but enhanced communication with nRF24L01 modules and added proximity alerts through ultrasonic sensors. Additionally, S. S. Ashwini et al. [7] incorporated solar power for energy efficiency and hands-free communication in their smart helmet design.

In contrast, some studies introduced entirely new features. Md. Motaharul et al. [8] employed a combination of gyroscopes and SIM808 modules for more accurate accident alerts, while P. Koteswara et al. [9] incorporated cloud-based IoT monitoring. Syed et al. [10] integrated computer vision and a heads-up display for object detection and call management. Pranav et al. [11] utilized RF communication to track helmet usage and accidents, and Sandhyar et al. [12] included pothole recognition and a light-dependent resistor for low-light conditions.Tapadar et al. [13] also contributed by introducing a Bluetooth-enabled smart helmet with sensors for alcohol monitoring and accident detection, using SVM to improve accuracy. Focusing on road conditions, Rajeshwari et al. [14] developed a low-cost method for detecting potholes and road bumps using GPS, providing real-time alerts to drivers through an Android app.

While previous studies have worked on rider safety, our approach combines accident prevention features with safety features. This helps riders change their actions in advance to stay safe and avoid dangers.

III. System Design And Methodology

A. Functionality

The smart helmet project embraces a number of safety features to safeguard and ensure the rider's safety. The table below outlines the key functionalities implemented in this project.

TABLE I
FEATURES IMPLEMENTED IN THE PROJECT

SL.	Feature	Description
1	Helmet detection	Without wearing the helmet, bike will not start.
2	Alcohol detection	If alcohol is detected, an SMS alert will be sent and bike's ignition will be turned off.
3	Fall detection	If a fall is detected, the bike's ignition will cut off and an SMS alert will be sent.
4	SMS alert with location	SMS alert will be sent to the emergency contacts with the rider's location.
5	Road condition alert	Biker will be notified about the road condition ahead.
6	Bike ignition control	Bike ignition will be controlled by bike unit. In case of any anomaly ignition will be turned off.

B. Hardware Components

The smart helmet utilizes the ESP32 WROOM microcontroller to run sensors like FSR402 for helmet detection, MPU6050 for fall detection, MQ3 for alcohol monitoring, and GSM SIM800L for SMS alerts. A relay for ignition, GPS Neo6M v2 for tracking, and a micro SD card are also included. The table below provides the model and descriptions of the components.

TABLE II
HARDWARE COMPONENTS WITH SPECIFICATIONS

Components	Model	Specifications
Micro-controller	ESP WROOM32	Processor: Dual-core Xtensa® 32-bit LX6 (240 MHz), RAM: 520KB SRAM, Flash Memory: 4MB, GPIO: 34 pins
Pressure sensor	FSR402	Sensor Type: Force-sensitive resistor, Range: 0.2N to 20N
Alcohol sensor	MQ3	Type: Semiconductor gas sensor Detection Gas: Alcohol, Benzine, CH4, Hexane, LPG and CO, Concentration Range: 0.05mg/L to 10mg/L alcohol
GSM	SIM800L	Power Supply: 3.4V to 4.4V, Supported frequencies: Quad Band (850 / 950 / 1800 /1900 MHz)
Relay module	5V Single channel	Electromechanical relay
GPS	Neo6M v2	Receiver Type: Standalone GPS receiver, Channels: 50, Frequency: GPS L1 frequency (1575.42MHz), Baud Rate: 9600 bps
Memory Adapter	Micro SD card	Memory 2GB

C. Helmet Unit

Most of the functionality of the system is developed in the helmet module. This module consists several sensors, actuators and ESP WROOM 32 microcontroller as the signal processing and decision making unit. Figure 1 represents the block diagram of helmet unit.

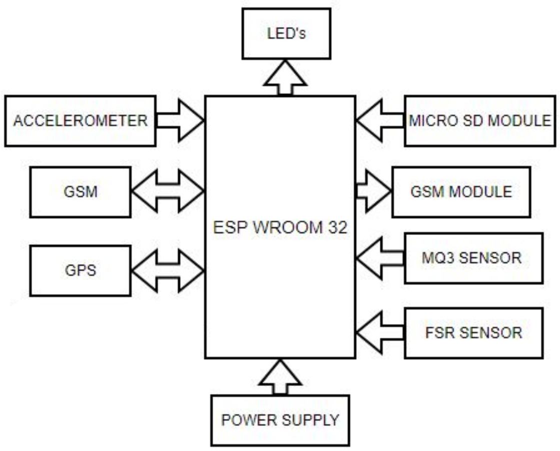

Fig. 1. Block Diagram of helmet unit.

1) Helmet Detection: The primary feature of the smart system is to ensure the rider is wearing a helmet. For reliable detection, a Force Sensing Registor (FSR) is utilized. Threshold value of 700 is chosen for the FSR sensor since it is the least amount of pressure experienced after wearing a helmet. When pressure is more than 700, the system will detect as helmet worn.

2) Alcohol Detection: To detect whether rider has consumed alcohol or not, an MQ3 alcohol sensor is used. When the alcohol level is higher than the threshold a SMS will be sent to the emergency contacts and a negative signal will be sent to the bike module that will turn off the ignition. Following formula calculates alcohol level by converting the MQ-3 sensor's raw reading to a 0-5V voltage:

$$\text{Alcohol Value} = \text{analogRead}(MQ3) \times \frac{5.0}{4096.0} \tag{1}$$

where,

- $\text{analogRead}(MQ3)$ is value read from the sensor pin.
- 5.0 is the reference voltage.
- 4096.0 is the resolution of the 12-bit ADC.

Using a 12-bit ADC, this formula scales the raw MQ3 sensor's reading to a 0–5V range in order to represent the alcohol concentration. To determine the minimal voltage required for alcohol detection, a threshold of 2V is set.
Figure 2 shows a detailed representation of the workflow of helmet unit, highlighting the features.

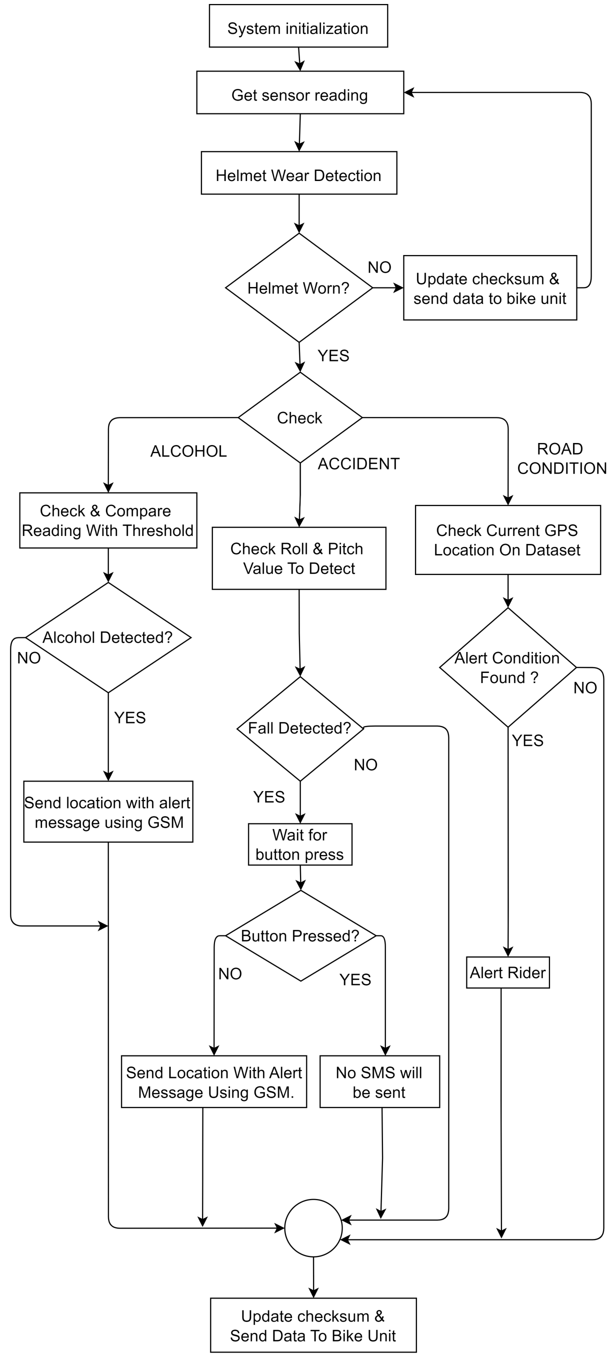

Fig. 2. Work flow of helmet unit.

3) Fall Detection: In case of any accident when rider falls off the bike, the system will detect fall and initiate emergency communication via SMS and stops ignition of the bike. A 3-axis accelerometer, measures an object's roll and pitch angles. The following formula is used to compute the roll and pitch angles:

$$\text{Roll} = \arctan 2\left(\frac{a_y}{a_z}\right) \times \frac{180}{\pi} \tag{2}$$

$$\text{pitch} = \arctan 2 \left(\frac{-a_x}{\sqrt{a_y^2 + a_z^2}} \right) \times \frac{180}{\pi} \tag{3}$$

Where, Roll measures object's tilt with respect to the X-axis, it indicates whether the rider has fallen to the left, right or slipped. Pitch refers to the tilt of the object around the Y-axis, indicating whether the rider has experienced a front or back fall.

Figure 3 highlights the roll and pitch dynamics by showing the bike's axes in both upright and leaned positions.

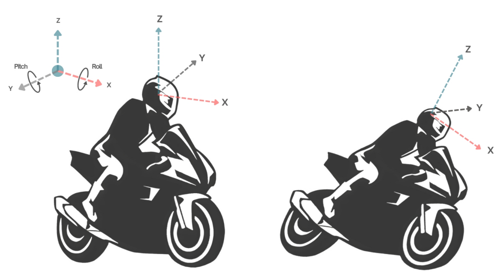

Fig. 3. Roll and Pitch Dynamics in Helmet Orientation

If roll or pitch value is greater than 45 degree, a fall will be deemed probable, necessitating a 30-second wait to confirm. The rider can cancel this presumption during this time, or otherwise a fall will be considered.

4) Road Condition Alert: The road condition alert is to reduce or prevent the accident rate of bikers, which sends alert of the upcoming road condition (road hump, accident prone areas and the bad road qualities) to riders when the rider is near to a alert zone. For the purpose of the experiment a dataset was developed containing only 50 entities. The dataset has five columns: latitude, longitude, road humps, accident prone, road quality. The data was gathered through direct observation while traversing on the roads, enabling precise and accurate recording of the situations present. Fraction of the dataset is presented in figure 4.

Latitude	Longitude	Road Hump	Accident prone	Road Quality
23.761964	90.349786	0	1	0
23.760896	90.347351	1	0	1
23.760313	90.346469	0	1	0
23.759301	90.343855	0	1	0
23.759279	90.343698	1	0	1
23.759085	90.342433	0	1	0
23.758431	90.338595	0	1	0
23.758306	90.337811	0	0	1
23.758118	90.337132	0	0	1
23.757897	90.337175	0	0	1
23.757016	90.336989	0	0	1
23.756178	90.339032	0	1	0

Fig. 4. A snippet of project dataset.

The road condition alert system continuously tracks the bike's location and heading using GPS data. To optimize the alert process, the system first identifies the grid corresponding to the current location and divides the dataset into grid clusters. The Grid-based clustering approach is used to divide the map into smaller sections (or grids) based on latitude and longitude. By checking points within the same grid as the bike, the system reduces unnecessary calculations and improves efficiency. Grid clusters latitude and longitude is calculated by dividing the GPS latitude and longitude by the grid size. Here, grid size is 0.05 degree.

A grid size of 0.05 degree means that each grid cell measures 0.05 degree in both latitude and longitude. Since one degree of latitude and longitude at the equator is equivalent to approximately 111 kilometers, this means a 0.05-degree grid cell covers about 5.55 kilometers. For points within the same grid, the system uses the Haversine formula [15] to calculate the distance between the bike's current location and these points. This formula finds the shortest path between two geographical coordinates (latitude and longitude) on the Earth's curved surface.

Haversine formula:

$$a = \sin^2 \left(\frac{\Delta\phi}{2} \right) + \cos(\phi_1) \cos(\phi_2) \sin^2 \left(\frac{\Delta\lambda}{2} \right) \tag{4}$$

$$c = 2 \cdot \text{atan2} \left(\sqrt{a}, \sqrt{1-a} \right) \tag{5}$$

$$d = R \cdot c \tag{6}$$

where,

- ϕ_1, ϕ_2 are the latitudes of the two points.
- λ_1, λ_2 are the longitudes of the two points.
- $\Delta\phi = \phi_2 - \phi_1$ is the difference in latitude.
- $\Delta\lambda = \lambda_2 - \lambda_1$ is the difference in longitude.
- R is the Earth's radius (mean radius = 6,371 km).
- d is the distance between the two points.

The Haversine formula is essential for geofencing, as it helps determine whether a user's location is within a specified distance while also identifying the closest point. By calculating the distance between geographical coordinates, the formula helps the system to accurately identify the locations of points within the geofenced area. After calculating the distances, the system checks if any of these points are within the defined geofence area. Geofence area is a virtual boundary surrounding a specific real-world location. In this case, the geofence is a 1 kilometer radius surrounding the rider.

If a point is within the geofence distance, the system calculates its bearing. Bearing is the angle between the bike's current direction (heading) and the direction to the point, measured clockwise from true north. If the bearing angle is less than 30 degrees from the bike's heading (obtained from GPS), the system considers the point to be in the rider's path. When a point enters the alert zone (which is a 500-meter radius around the rider's current location), the system alerts the rider for the closest point that is in the bike's direction. This ensures that alerts are only triggered for points that may pose hazards, helping riders stay focused on what's ahead on their route.

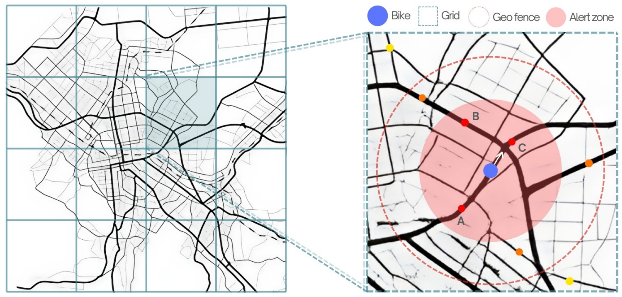

Fig. 5. Road Condition Alert System.

Figure 5 illustrates the road condition alert system. It shows how the grid functions, followed by a zoomed-in view of the bike's current grid location. Where the bike is the blue dot. The yellow points represent locations within the same grid as the bike, for which the system calculates distances using the Haversine formula. The orange points fall within the geofence, where the system checks if their bearing aligns with the bike's heading. The red points are inside the alert zone, which triggers an alert for the closest point in the bike's direction. Here, Point C will activate an alert.

5) SMS Alert with Location: The SMS alert system is designed to send real-time notifications to specified contacts in the event of a bike fall or alcohol detection. The SMS contains vital information such as the rider's status, their current GPS coordinates (sourced from the GPS module) and a link to their location on Google Maps. The GSM module, is responsible for sending the SMS, which involves specifying the recipient's phone number and transmitting the composed message. The system ensures that each SMS is sent only once per detection event by marking the SMS as sent upon transmission, thus preventing redundant alerts.

D. Bike Unit

The bike unit controls the ignition system of the bike based on the signal from the helmet unit.

Two ESP's have been used in this project. Here, ESP-NOW is used as the communication system between both units. ESP-NOW is a low-power, peer-to-peer wireless communication protocol used by ESP devices. Our system is using one-way communication from bike unit to helmet unit. The block diagram of bike unit is shown in figure 6.

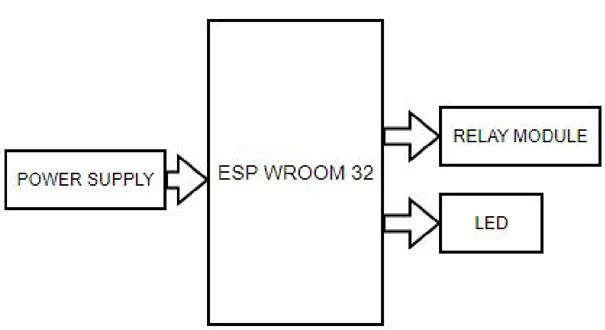

Fig. 6. Block Diagram of bike unit.

Figure 7 illustrates the workflow of the bike unit, detailing the various processes and interactions involved in its operation.

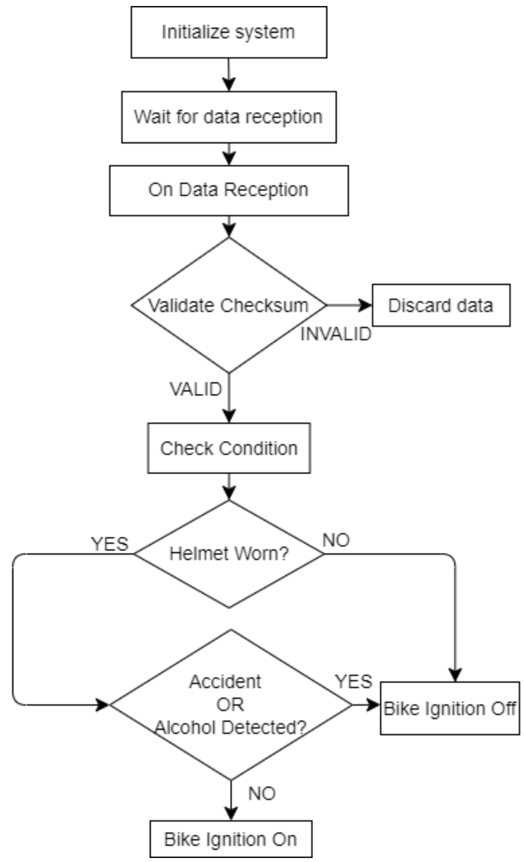

Fig. 7. Work flow of bike unit.

1) Bike Ignition Control: The bike's ignition control system obtains real-time data from the helmet unit. Encapsulated in a structured message with a checksum for integrity verification, this data covers helmet usage, alcohol and fall detection. The bike unit validates the checksum upon receiving the data. Once the data is validated, the system checks the conditions for bike ignition. Matching the conditions allow the bike to start. However, if any condition doesn't match, the ignition will be turned off.

IV. Discussion and Result Analysis

The smart helmet enhances bike rider safety by implementing the necessary precautions to reduce the risk of accidents.

The smart helmet has been developed and tested under various conditions to evaluate its effectiveness. Throughout testing, the helmet demonstrated 100% accuracy in detecting whether it was worn correctly. The alcohol detection and fall detection systems in our prototype achieve 100% accuracy, ensuring no missed SMS notifications. However, during testing, there were some delays, mainly because the GPS module takes time to respond due to adverse conditions.
Figure 8 shows the received message by the emergency contact for both alcohol and fall detection.

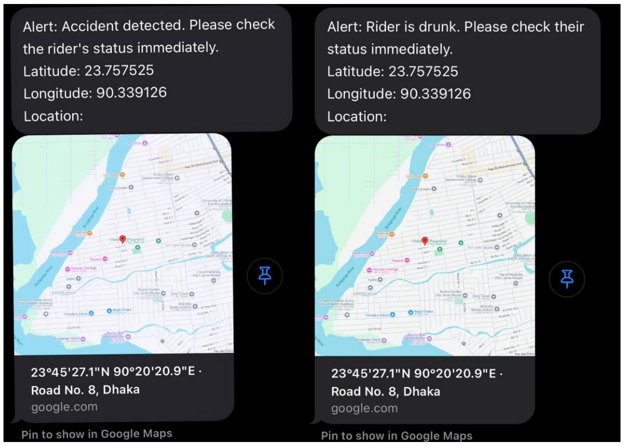

Fig. 8. Message received by Emergency contact

Our system provides road condition alerts with an accuracy rate of approximately 70-80%. During outdoor testing, we found that the system does not generate any false alerts. However, it sometimes sends late alerts, notifying the rider about alert point only when they are very close or even after passing it. Though missing a point is very rare. This delay or missed alerts are mainly due to the limitations of the GPS module. Which may struggle to connect to satellites, especially in cloudy weather.

TABLE III
EXPERIMENTAL RESULTS OF SYSTEM FEATURES

Feature tested	No. of trials	Successful trials	Observation
Helmet detection	40	40	Successfully detects, no false positives or negatives observed.
Alcohol detection	40	40	Accurately every time. No false detection.
Fall detection	40	40	Detects falls accurately. No missed detection.
SMS alert with location	35	33	SMS sent promptly, Occasional latency or connection issues with the GPS.
Road condition alert	20	15	No false alert, occasional late alerts due to GPS.
Bike ignition control	30	30	Eliminating invalid data by validating helmet signal.

The SMS includes a link to a Google map, which consistently displays an accurate location with no errors. Response times for GPS modules might vary.

Overall, the system proved effective in detecting helmet usage, alcohol consumption, and falls with faultless accuracy. While road condition alerts performed well, they were occasionally impacted by unusual factors like GPS delays. Despite this, the system provides a reliable and comprehensive safety solution.

V. CONCLUSION AND FUTURE ENHANCEMENT

The smart helmet system presented in this paper enhances bike rider safety through real-time monitoring and hazard detection by integrating various safety features to support proactive accident avoidance. The system ensures timely emergency alerts and notifications. This scalable and cost-effective solution can be further improved by incorporating machine learning and dynamic data updates to enhance rider safety and predictive capabilities, providing a strong foundation for safe biking experiences and advancements in road safety technology.

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