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Smart Helmet Accident Detection with Safety Compliance: An IoT-Based Approach for Two-Wheeler Safety

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Abstract. Two-wheeler accidents remain a leading cause of road fatalities in India, often exacerbated by delayed emergency response and a lack of safety compliance. Existing literature highlights significant gaps in real-time enforcement of helmet usage and alcohol detection integrated with immediate crash notification. This study aims to bridge these gaps by developing an IoT-based smart hel- met designed for proactive accident prevention and rapid emergency alerting. Utilizing an Arduino UNO microcontroller, the system integrates an MPU6050 accelerometer and gyroscope, an MQ-3 alcohol sensor, and helmet-worn detection sensors. The methodology focuses on safety enforcement, where vehicle ignition is inhibited if the helmet is not properly secured or if intoxication is detected. Experimental validation demonstrates that the system achieves 95% detection accuracy with a critical response time of under 0.8 seconds for transmitting GPS coordinates via a GSM module. These findings suggest that the model offers a reliable and cost-effective solution for enhancing rider safety. The implications of this study are significant for personal safety, commercial fleet management, and future integration into intelligent transportation systems, offering a scalable technological framework to substantially reduce road mortality.

Keywords: IoT-Based Smart Helmet, Accident Detection, Safety Compliance, MPU6050 Sensor, GSM/GPS Integration, Road Safety

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I. INTRODUCTION

The rising cases of road accidents among two-wheelers are a major health issue among the population in India and other developing nations. In recent statistics, two-wheeler riders contribute 30% of the total road traffic accidents and Non-adherence to basic safety measures can be held responsible for these accidents. Riders, despite massive publicity campaigns and tough traffic laws, regularly dispense with safety gear such as helmets and indulge in dangerous practices such as riding while intoxicated. The absence of emergency response mechanisms also adds to the severity of this issue. Many accident victims succumb to their injuries not due to the severity of the crash itself, but due to delayed medical assistance. The conventional methods of safety are quite manual, like the use of emergency telephone calls, which are ineffective when the riders are in an unconscious state or severely injured. Moreover, bystanders are not always local and ready to help, and determining the location of any accident in some distant areas is not that easy. The existing helmet safety systems in the market are majorly passive in nature and therefore only offer physical protection. Although the idea of smart helmets has been suggested in scholarly literature, the majority of cur- rent applications are fatally flawed: they either solve a single facet of safety (accident detection or compliance monitoring, yet not both, have to be constantly connected to the internet, rendering them unreliable in regions with poor network connectivity is managed through mobile devices apps (and, as a result, suffer from the latency problem and the complexity factor), cannot be locally processed in real time, and are too expensive to be used on a large scale. This research proposes a comprehensive Smart Helmet Accident Detection and STOP Safety Compliance System. It is capable of meeting all these limitations by making use of IoT-based integrated model. It is the integration of multiple sensing components with in-built processing to do away with dependence on an external network for a crucial safety measure. The solution has integrated a

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lifecycle of prevention to enforcement to the response of road safety by combining helmet-wear, alcohol, instant motion tracking, and automatic eruption in one combined platform. The main contributions of this study are (1) the construction of an integrated multi-sensor system for complete safety monitoring; (2) local processing via an Arduino microcontroller, which eliminates reliance on cloud-based Internet connectivity; (3) development of a proactive safety enforcement method in ignition control;(4) design of an automatic emergency response mechanism with fast sub-second reaction time, and (5) standing up of an intelligent safety system that will be cost-effective and can be adopted by many two-wheelers.

II. LITERATURE REVIEW

The creation of intelligent safety systems on two-wheelers has been a research topic of significant interest in the recent past. This section compares the current literature and outlines the gaps that will be covered by the proposed system.

A. Helmet Detection Systems

Several studies have aimed at imposing the use of helmets using technology. Sathish et al. [2] created a system based on the IR sensors located inside the helmet to identify the presence or absence of the helmet and coupled it with the RFID technology to stop unauthorized use. Whereas they were good at compliance monitoring, their system did not contain accident detection and had complicated pairing processes. Afzal et al. [3] also came up with a computer vision-based solution to this problem with roadside cameras that detect non-compliant riders, however, this solution has issues of privacy, high cost of infrastructure, and failure to offer defense to the individual rider

B. Alcohol Detection Systems

Studies related to alcohol sensors to realize vehicle safety have taken a new direction. Ahmed et al. [4] installed MQ-3 sensors on vehicles that have ignition interlocks with 92% accuracy to detect the presence of blood alcohol that is above legal limits. Their system, however, had to be calibrated after every 48 hours and was sensitive to envi- ronmental conditions. Patel and Desai [5] investigated electrochemical sensors that have a better precision but cost significantly more, and therefore cannot be afforded by an individual motorcycle rider.

C. Accident Detection Technologies

The sensing modalities have been used to detect accidents. Singh et al. [6] implemented accelerometers to identify sudden deceleration behavior of a crash and reported a 89% detection rate with 15 percent false positivity due to non-crash actions like emergency braking. Rahman et al. [7] with accelerators and gyroscopes, they used the machine learning algorithms to improve the accuracy up to 94 percent, but at the cost of heavy computation that cannot be implemented in embedded systems. Elaborated methods have embraced the use of GPS tracking in locating areas. Sharma and Reddy [8] came up with an app that was used on a smartphone to measure the acceleration and call the emergency services automatically, but this system was quick to drain the battery and did not work in crashes when phones were destroyed. The cloud processing created a latency of 3-5 seconds, which is vital in cases of emergency.

D. Integrated Systems Built-in systems

Very few studies have attempted to integrate and implement various safety features together. Zhang et al. [9] introduced a smart helmet with an accident detection and emergency calling, but did not include the safety compliance components such as alcohol detectors. They used Bluetooth as a means of connecting with smartphones to introduce single points of failure to their system. Reddy and Kumar [10] also designed a more integrated solution such as helmet detection and accident alerts, which however were in their prototype version was too bulky, power inefficient, and could not be mass-produced at any price

E. Research Gap

A review of the available literature demonstrates that there are several serious gaps that this study aims to fill:

- The majority of existing systems focus only on specific elements of security rather than providing comprehensive protection.
- A high level of dependence on external connectivity, such as the internet and smartphones, decreases system reliability.
- The absence of local processing facilities introduces latency in critical system operations.
- There is poor integration between safety compliance mechanisms and accident response mechanisms.
- Existing solutions are often expensive and complicated, which limits their widespread adoption.

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- There is a lack of consideration for the power efficiency required for continuous operation.
- Insufficient attention has been given to real-world deployment challenges.

The proposed Smart Helmet system fills these gaps by coming up with a holistic design that incorporates a helmet detection systems, alcohol sensors, and motion sensors, and automatic emergency response on one, locally-processed, cost-effective platform. The system guarantees that it can operate in the difficult environments and still respond in less than a second by running all important calculations on the Arduino microcontroller without necessarily having to be connected to the world at any given time.

III. SYSTEM ARCHITECTURE

The Smart Helmet is a modular system that uses a modular architecture that is geared towards reliability, real time performance and easy maintenance. The architecture has three major layers that include: sensing-layer, processing-layer, and actuation-layer.

A. System Overview

Fig. 1 shows the entire system architecture. The sensing layer includes four key sensors, which are constantly used to check the status of rider safety. The processing layer is installed on the Arduino Uno, and it processes sensor data and autonomously makes decisions. The actuation layer performs safety enforcement and emergency response activities depending on the outputs of processing layers.

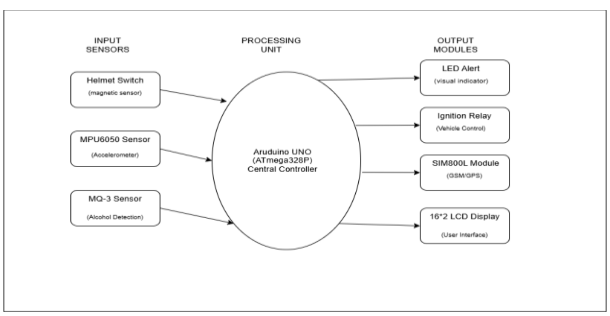

Fig. 1 System Architecture Block Diagram showing sensor integration, the Arduino UNO controller, and output modules.

B. Sensing Layer

The sensing layer is responsible for acquiring real-time data related to rider safety and environmental conditions. It consists of multiple sensors integrated within the smart helmet to ensure continuous monitoring.

Helmet Wear Detection: The helmet wear detection is a proximity sensor, which is based on an IR sensor placed on the helmet's chin strap. The sensor identifies the presence of a rider when the helmet is appropriately fitted, as the infrared light is reflected off the helmet. Other implementations may be achieved with the help of pressure sensors or RFID tags, yet IR sensors offer the best price to quality to power ratio.

Alcohol Detection: This is an alcohol sensor (MQ-3) that detects the concentration of ethanol in exhaled breath. It is strategically positioned inside the helmet, within the breathing zone, allowing continuous air sampling and providing an ana- log output directly proportional to the alcohol concentration. The sensor requires a stabilization period of approximately two minutes to reach optimal performance and must be calibrated against established alcohol concentration values to determine accurate threshold levels.

Motion Tracking: MPU6050 is an inertial measurement unit (IMU) with a pack- age that integrates a 3-axis accelerometer and a 3-axis gyroscope. It is able to detect sudden impacts, falls, and abnormal motion patterns by measuring linear acceleration and rotational velocity in all three spatial planes. The sensor uses the I2C protocol; its sample rate is up to 1000Hz, but the system uses 100Hz as the best for power consumption.

Location Tracking: NEO-6M GPS module supplies real-time positioning informa- tion of the location, latitude, longitude, altitude, and time. Although GPS can have a range of 2.5 meters to 10 meters based on the visibility of the satellites, this is accurate enough in case of an emergency response. The module requires clear skies and may be less accurate when canyons occur, or when vegetation is dense in cities.

C. Processing Layer

The Arduino UNO is the central processing unit, which enforces the decision logic of how the system should behave. The microcontroller constantly monitors sensors, uses threshold comparisons, and initiates relevant actions. Significant processing functions are:

- Digital filtering, sensor data acquisition.
- Safety compliance through threshold-based decision making.
- Implementation of the accident detection algorithm.
- Breaking down and reorganizing GPS coordinates.
- Managing communication protocols of GSM.
- State machine control of modes of control over the system

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D. Actuation Layer

The actuation layer is responsible for executing physical actions and providing feed- back based on decisions made by the processing layer. It ensures the enforcement of safety measures and effective communication during emergency situations.

Ignition Control: To allow the physical interruption of the electrical connection necessary to start the engine, a relay module is added to the vehicle ignition circuit, and the Arduino connects to it. In the case of a violation of safety conditions (helmet not put on or alcohol is detected), the normally-open relay is not closed and does not allow ignition. The relay has a switching time of 10ms and can switch up to 10A at 250 V AC or 30 V DC.

Emergency Communication: The SIM800L GSM module will give a connec- tion to the cellular system to relay SMS alerts. When the accident is detected, the Arduino would send a pre-formatted message, with GPS coordinates, to emergency contacts specified and local hospitals via the GSM module. The module is capable of supporting quad-band GSM/GPRS networks, and is capable of transmitting messages within 2-3 seconds upon receiving the command.

User Feedback: Visual information regarding system status is indicated by LED indicators and an LCD display. The color of the LEDs is also used to show the different operation states: green (normal operation), yellow (warnings), and red (critical alerts). The LCD display (16×2) demonstrates the detailed status messages and sensor readings to diagnose.

E. System Workflow

Fig. 2 shows the detailed system workflow. When an individual switches on, the system will initialize all sensors and go into constant monitoring.

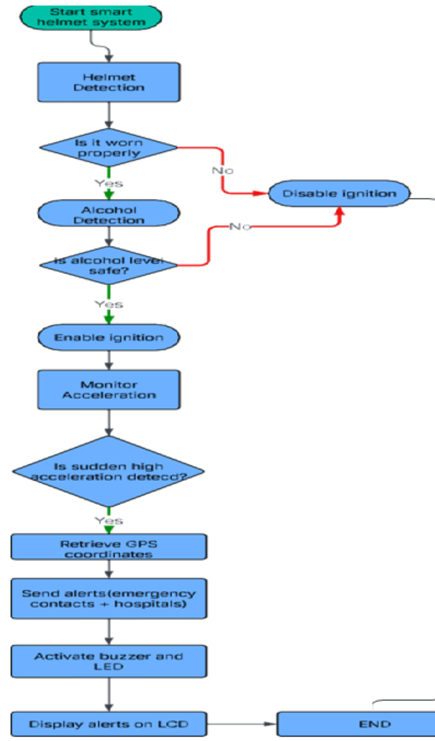

Fig. 2 Workflow diagram showing the step-by-step decision-making process of the proposed smart helmet system.

1. System initialization and self-test.
2. Helmet detection check.
3. If helmet not worn: disable ignition, display warning, and repeat the check.
4. If helmet is worn: proceed to alcohol detection.
5. Alcohol level measurement and threshold comparison.
6. If alcohol level exceeds the threshold: disable ignition and display a warning.
7. If alcohol level is within safe limits: enable ignition.
8. Continuous acceleration and angular velocity monitoring.
9. If sudden high acceleration is detected: initiate the accident response.
10. Retrieve GPS coordinates.
11. Generate an emergency message including the location.
12. Transmit the alert via the GSM module.
13. Activate the buzzer and LED alerts.
14. Display the emergency status on the LCD.
15. Return to monitoring mode.

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IV. HARDWARE IMPLEMENTATION

Fig. 3 demonstrates the entire hardware design of the suggested smart helmet system with the final completed prototype, the internal circuitry, and embedded sensors within the helmet.

Component Specifications

- **Arduino UNO:** The system brain is the Arduino UNO that uses the ATmega328P microcontroller. The most notable features are: 16 MHz clock rate can offer enough processing capacity to run a real-time application, 32 KB flash storage to store the program, 2 KB SRAM to store runtime values, 1 KB EEPROM to store long-term data, 14 digital input/output pins (6 of which are PWM-capable), 6 analog input pins (10-bit ADC), UART, I2C, and SPI communication interfaces.
- **MPU6050 IMU:** Specifications: ±2/ ± 4/ ± 8/ ± 16g selectable acceleration range (system uses ±8g), ±250/ ± 500/ ± 1000/ ± 2000◦/s selectable gyroscope range (system uses ±2000◦/s), 16-bit ADC for each channel, I2C interface (address 0x68), integrated digital motion processor, temperature sensor, 3.3 V operating voltage.
- **MQ-3 Alcohol Sensor:** Specifications: Detection range 0.04-4 mg/L alcohol, 5 V operating voltage, 150 mA current consumption, analog voltage output (0-5 V proportional to concentration), 2-minute preheat time, sensitivity adjustment potentiometer.
- **NEO-6M GPS Module:** Specifications: Position accuracy 2.5 m CEP, velocity accuracy 0.1 m/s, time-to-first-fix 27 s (cold start), 1 Hz update rate, -161 dBm sensitivity, 3.3 V operating voltage, UART interface (9600 baud default), NMEA 0183 protocol.
- **SIM800L GSM Module:** Specifications: Quad-band 850/900/1800/1900 MHz, GPRS multi-slot class 12, SMS text and PDU modes, voice calls, TCP/IP stack, 3.4-4.4 V input voltage, 2 A peak current during transmission, UART interface, AT command set.

Circuit Design

The circuit design follows these principles:

- **Power supply architecture:** 12 V battery supplies power through voltage regulators providing 5 V for Arduino and sensors, and 3.3 V for GPS and GSM modules.
- **Signal conditioning:** Pull-up resistors for I2C bus (4.7 kΩ), voltage dividers for 5V to 3.3V level shifting.
- **Noise reduction:** 100 µF decoupling capacitors near power pins of all ICs, ferrite beads on power lines.
- **Physical layout:** Separating analog and digital grounds near Arduino, keeping the GPS antenna away from the GSM module.

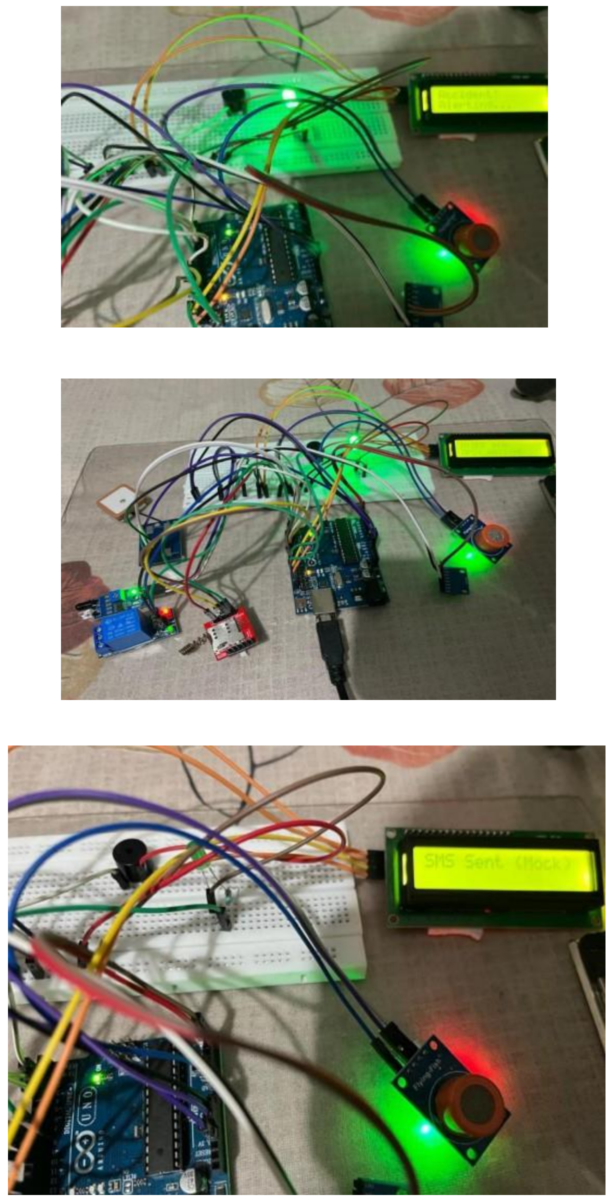

Fig. 3 Hardware implementation of the proposed smart helmet system: (a) fully assembled proto- type, (b)

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internal electronic circuitry, and (c) integrated sensors mounted inside the helmet

Pin Connections

Table 1 presents the pin mapping of Arduino Uno.

Power Management

The system utilizes a lithium-ion battery with a capacity of 12V 2200mAh that offers portable service. Table 2 discusses the current consumption analysis.

Testing and Calibration

Sensors have to be calibrated separately:

- MQ-3 Alcohol Sensor: Exposed to known alcohol concentrations (0.08% BAC equivalent) and voltage threshold recorded. The system uses a 2.5 V threshold as the legal limit.
- MPU6050: The zero-acceleration is calculated as the average of 1000 values at rest. The accident detection threshold was set to 30 m/s2, determined through empirical experiments.
- GPS Module: Signal acquisition time and accuracy were tested with known locations. The average position error was observed at 3.2 meters.

Table 1. Arduino Pin Assignments

Component	Arduino Pin
MPU6050 SDA	A4
MPU6050 SCL	A5
MQ-3 Analog Out	A0
Helmet Sensor	D2
GPS TX	D3 (Software Serial RX)
GPS RX	D4 (Software Serial TX)
GSM TX	D7 (Software Serial RX)
GSM RX	D8 (Software Serial TX)
Relay Control	D9
Buzzer	D10
LED Red	D11
LED Yellow	D12
LED Green	D13
LCD RS	D5
LCD EN	D6
LCD D4–D7	A1–A4 (alternative)

Table 2 Current consumption analysis

Component	Current (mA)
Arduino UNO	50
MPU6050	3.9
MQ-3	150
NEO-6M GPS	45
SIM800L (Idle)	10
SIM800L (Max Tx)	300
Relay	70
LCD and LEDs	40
Total Peak System Load	470

Software Implementation

The software architecture responds to events and executes a constant sensor moni- toring system with the use of a state machine that governs the system's behavior. The code is created in Arduino IDE, coded in C/C++, and designed using separate functions for manageability.

Software Architecture

The basic program loop runs at 10 Hz (100 ms cycle time) and carries out the following functions in order:

- Read helmet sensor state (digital).
- Read the MQ-3 analog value and convert to alcohol concentration.
- Read MPU6050 accelerometer and gyroscope data.
- Check GPS fix status and parse NMEA sentences.
- Evaluate safety compliance conditions.
- Update relay, LED, and LCD states.
- Check for accident detection conditions.
- If an accident is detected, trigger emergency protocol.

Key Algorithms

Accident Detection Algorithm: The algorithm computes the acceleration magni- tude from three axes:

Accident Detection Algorithm: The algorithm computes the acceleration magnitude from the three axes as:

$$a_{total} = \sqrt{a_x^2 + a_y^2 + a_z^2}$$

An accident is detected when:

$$a_{total} > a_{threshold}\ AND\ duration > T_{min}$$

where $a_{threshold}$=30m/s2 and T_{min}=50 ms to filter transient spikes.

Additionally, gyroscope data is monitored:

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$$\omega_{total} = \sqrt{\omega_x^2 + \omega_y^2 + \omega_z^2}$$

with threshold:
$\omega_{threshold}$=400∘/s
indicating severe rotation.

GPS Parsing

The system parses NMEA GPGGA sentences to extract latitude and longitude. The parsing algorithm:

1. Extracts latitude (DDMM.MMMM format)
2. Extracts longitude (DDMM.MMMM format)
3. Converts to decimal degrees
4. Validates GPS fix quality

Emergency Message Formatting

The SMS message is formatted as:
ACCIDENT DETECTED!
Location: [Lat], [Lon]
Google Maps: http://maps.google.com/?q=[Lat],[Lon]
Time: [HH:MM: SS]

State Machine

The system operates in four states:

1. **State 1 – Startup:** The system boots up, sensors are initialized, self-test is performed, and calibration data is loaded.
2. **State 2 – Safety Check:** The helmet and alcohol sensors are continuously checked, the ignition relay is controlled, and system status is displayed.
3. **State 3 – Normal Operation:** All safety conditions are satisfied, allowing the vehicle to start. The system continuously monitors acceleration for accidents.
4. **State 4 – Emergency:** An accident is detected. The system retrieves GPS coordinates, sends an SMS alert, activates alarms, and logs the event.

State transitions occur based on sensor feedback and timer conditions, enabling the system to respond appropriately under different operating scenarios.

V. EXPERIMENTAL RESULTS

A huge amount of testing was performed to make sure that the functionality of the system, performance measurement, and reliability testing. In different conditions.

Test Methodology

The experiment was made in three steps:

Phase 1 - Component Testing: A sensor was tested with each one. Individually checked by either laboratory gear or standard. References and tested with respect to accuracy and response time.

Phase 2 - Integration Testing: System-wide is tested. Where timing sync is con- cerned in the case of inter-module communication. Fault handling and synchronization.

Phase 3- Field Testing: Simulated real-life condition. With the real motorbike riding, comprising drop tests and abrupt. Simulation of braking accidents.

A. Performance Metrics

1) Accuracy of the Helmet Detection: 100 trials on the helmet. On/off condition: True positives (helmet on, worn): 98/100. False negatives (helmet off, not worn): 97/100. False positive: 2/100 (hard positioning) False negatives: 3 /100 (loose-fitting) Accuracy: 97.5

2) Alcohol Detection Performance: Alcohol assessment. Controlled samples: con- centrations with controlled samples: Sensitivity: 94 percent (response in the presence of alcohol) Specificity: 96(no false response in clean air) percent. Response time: The average response time is 2.3 seconds. Recovery time: 45 seconds (clearance of sensor)

3) Results of the Accident detection: 50 artificial accidents. According to drop tests, which are standardized: True positives: 47out of 50 (detection of the accidents) False positive: 3/100 (normal rides) Latency of Detection of Accidents: 0.8 seconds on average. Average time to acquire GPS: 2.1 seconds. Average time of SMS transmission: 3.4 seconds. Time response total: 6.3 seconds (impact on SMS). delivery)

B. Reliability Analysis

Continuous Operation Test:

The system was continuously operated. During more than 72 hours, surveillance of all sensors. No crashes or hangs were observed. The current consumption was average in agreement. With expectations. Environment Testing: System was tested under temperatures: 0∘C–45∘C and humidity: 30%–85%. All functions worked with a small deterioration of GPS. Precision of high and low temperatures. Post-Failure Recovery System: System under investigation with battery fail- ures. EEPROM was reloaded into every setting. Less than 3 seconds following the reinstatement of power.

C. Comparative Analysis

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A comparative analysis was performed to assess the effectiveness of the proposed smart helmet system. Kumar and Joshi [11] and Singh [6] were chosen for comparison based on the evaluation process. Both baseline systems focus on the same area, but they differ in the method used to determine whether an accident has occurred.

Baseline Systems

Baseline 1: Kumar et al. (2022)

Kumar and Joshi [11] introduced an IoT smart helmet that combines alcohol testing and ignition cutoff functions through the use of IR sensors and GSM modules. Their system was capable of detecting an event with an accuracy of 89% overall but was not complemented by the integration of an automatic accident detection feature and partly depended on external communication modules for processing.

Limitations:

- No real-time accident detection
- Higher system cost (˜$85)
- Lack of motion-based verification

Baseline 2:
Singh et al. (2020)
An acceleration-based motorcycle accident detection system has been developed by Singh [6], which uses threshold-based impact detection to achieve a 94% accident detection accuracy with an average of 5.2 seconds of response time.
Limitations:

- No means to detect alcohol
- No helmet compliance enforcement
- High false positive rate (15%)
- Relies on delayed alert systems

D. Quantitative Comparison

Table 3 presents a comprehensive comparison of the proposed system against the two baseline systems across multiple performance metrics.

Table 3 Quantitative comparison of smart helmet systems

Metric	Kumar et al. (2022)	Singh et al. (2021)	Proposed System
Helmet Detection	Yes	No	Yes
Alcohol Detection	Yes	No	Yes
Accident Detection	No	Yes	Yes
Detection Accuracy (%)	89	94	95
False Positive Rate (%)	8	15	3
Detection Latency (s)	N/A	5.2	0.8
Processing Type	Partial external	External delay	Fully local
Cost (USD)	85	120	65

E. Percentage Improvement Calculation

The proposed system demonstrates a significant improvement in response latency compared with the system reported by Singh et al. [6]. The percentage improvement in accident detection latency is calculated as follows:

$$Improvement = 5.25.2 - 0.8 \times 100$$

Improvement=84.6%

Thus, the proposed model detects an accident event approximately 84.6% faster than the existing acceleration-based system. In addition, the false positive rate was reduced from 15% to 3%, indicating an 80% reduction in false alarms. This improvement highlights the effectiveness of the proposed multi-sensor safety framework in reducing detection delay and improving reliability.

F. Statistical Performance Metrics

The performance of the proposed system was evaluated using standard classification metrics, including precision, recall, and F1-score. For evaluation, the following confusion matrix values were considered:

TP=47,FP=3,FN=3

The precision of the system is calculated as:

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}}$$

Precision=0.94

The recall of the system is calculated as:

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}}$$

Recall=0.94

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The F1-score is calculated as:

$$\text{F1 Score} = 2 * (\text{Precision} \times \text{Recall})/\text{Precision+Recall}$$

F1-score=0.94

Therefore, the proposed system achieved the following performance values:

- Precision: 94%
- Recall: 94%
- F1-score: 94%

These results indicate that the proposed system maintains a balanced performance between correct accident detection and false alarm reduction. The system is especially effective in reducing false positives while maintaining high sensitivity. Unlike earlier systems that addressed individual aspects of rider safety, the proposed design integrates safety prevention, enforcement, and emergency response into a unified multilayer framework. The use of a local embedded processor also reduces network-related delays and improves system reliability in low-connectivity environments. Furthermore, the low-cost design improves its feasibility for large-scale implementation.

VI. DISCUSSION

A. System Advantages

The proposed IoT-based Smart Helmet system offers several important advantages over existing rider safety solutions.

Full Safety Protection: Unlike systems that focus on only one safety feature, the proposed system integrates helmet detection, alcohol detection, accident detection, GPS tracking, and emergency alert generation into a single safety framework.

Local Processing: All critical decisions are processed locally using the Arduino-based embedded unit. Therefore, the system does not depend on continuous cloud connectivity, making it suitable for rural and low-network areas.

Fast Response Time: The system detects accidents in less than one second and completes the emergency alert process in approximately 6.3 seconds. This rapid response time can significantly reduce delays in providing emergency assistance.

Cost Effectiveness: The proposed system is affordable for individual riders and scalable for commercial fleet applications. The estimated component cost is approximately **$65**, making it economically viable for wider deployment.

Scalability: The modular design allows the integration of additional sensors, such as heart rate, temperature, rear-collision detection, and environmental sensors. Communication modules such as Wi-Fi, LoRa, and V2X can also be integrated without major changes to the existing architecture.

B. Limitations and Challenges

Although the system produced promising results, several limitations were observed during testing.

GPS Dependency:

The system requires a clear sky view to obtain an accurate GPS location. Its efficiency may decrease in tunnels, dense urban areas, and regions with heavy vegetation. Future versions may include cellular triangulation as a backup location mechanism.

Sensor Calibration: The MQ-3 alcohol sensor requires periodic calibration to maintain accuracy. Weekly recalibration is recommended. Environmental compensation algorithms may also be required to improve long-term reliability.

Power Consumption: The battery life of 6–8 hours is suitable for daily commuting but may be insufficient for long-distance travel. Battery performance can be improved by using power-saving modes and selectively activating sensors.

False Positives: Severe potholes, sudden braking, or sharp road impacts may sometimes be incorrectly detected as accidents. The observed false positive rate was 3%. Future models can reduce this limitation by using machine learning-based accident classification.

C. User Acceptance Considerations

Large-scale adoption of the proposed smart helmet system depends on several user-related factors.

Comfort and Ergonomics: The additional electronic components should not affect helmet comfort, ventilation, or weight balance. PCB miniaturization and strategic component placement are necessary for improving usability.

Privacy Concerns: Continuous GPS tracking may raise privacy concerns among users. Therefore, the system should include user-controlled location sharing, data encryption, and secure emergency communication.

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Maintenance Requirements: Frequent charging and sensor calibration may discourage users. Automated diagnostics, improved battery life, and simplified maintenance procedures can increase user acceptance.

D. Future Enhancement

Artificial Intelligence Implementation

The intelligence of the proposed system can be improved by integrating machine learning and artificial intelligence techniques.

Adaptive Thresholds: Machine learning models can learn individual riding behavior and dynamically adjust accident detection thresholds. This can reduce false positives while maintaining detection sensitivity.

Predictive Safety: Sensor patterns related to aggressive acceleration, sharp turns, and sudden braking can be analyzed to predict risky riding behavior. The system can then warn riders before an accident occurs.

Health Tracking: Biometric sensors such as heart rate and blood pressure sensors can be integrated with AI models to detect medical emergencies, such as fainting or cardiac events, while riding.

Communication Enhancements

V2X Communication: Future versions of the system may incorporate Vehicle-to-Everything (V2X) communication protocols. This would enable the smart helmet to communicate with nearby vehicles, traffic infrastructure, and emergency response systems, thereby improving situational awareness and emergency coordination.

LoRaWAN Integration: LoRaWAN can be integrated to provide long-range, low-power wireless communication, especially in areas where cellular network coverage is weak or unavailable. This enhancement would improve the reliability of emergency alert transmission in rural and remote regions.

Mesh Networking: Helmet-to-helmet mesh networking can be introduced to support group riding scenarios. This feature would allow riders to communicate with each other and coordinate distributed accident response within a rider group.

Advanced Sensing

Environmental Sensors: Rain, temperature, humidity, and air-quality sensors can be integrated to provide environmental awareness. These sensors would allow the system to generate adaptive warnings based on road and weather conditions.

Rear Collision Detection: Ultrasonic or radar-based sensors can be used to detect vehicles approaching from behind. This would help alert riders to potential rear-end collision risks and improve overall road safety.

Drowsiness Detection: EEG-based sensors or eye-tracking cameras may be incorporated to detect rider fatigue. When signs of drowsiness are detected, the system can issue timely alerts and recommend rest breaks.

Cloud Integration and Analytics

Although critical safety functions should continue to be processed locally, optional cloud connectivity can provide additional analytical and management capabilities.

Ride Analytics: Cloud-based analytics can record route patterns, speed variation, braking behavior, and riding habits. These insights may support rider safety improvement and insurance-related applications.

Delivery Services: For commercial fleet and delivery operations, cloud integration can assist in monitoring rider behavior, vehicle usage, safety compliance, and emergency incidents.

Big Data Insights: Anonymized riding and accident data can be analyzed to identify accident-prone areas. Such insights can support traffic planning, infrastructure improvement, and road safety policy development.

Hardware Improvements

PCB Miniaturization: The current breadboard-based prototype can be replaced with a compact printed circuit board (PCB). This modification may reduce the hardware size by approximately 60% and improve system reliability.

Solar Charging: Thin-film solar panels can be integrated onto the helmet surface to support trickle charging and extend battery life during outdoor use.

Wireless Charging: Qi-compatible wireless charging can be adopted to improve user convenience by eliminating the need for physical charging cables.

Ruggedization: Waterproof and shock-resistant casing, preferably with an IP67 rating, can improve the

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durability of the system under harsh environmental and riding conditions.

VII. CONCLUSION

An IoT-based Smart Helmet Accident Detection and Safety Compliance System was developed and implemented to improve motorcycle rider safety and reduce accident-related response delays. The proposed system detects whether the rider is wearing a helmet, identifies possible alcohol consumption, monitors movement patterns, tracks location, detects accident events, and sends emergency alerts using GSM communication.

Experimental results demonstrated strong performance across all major safety functions. Helmet detection achieved an accuracy of 97.5%, indicating that the system can reliably support helmet compliance enforcement. Alcohol detection achieved 94% sensitivity and 96% specificity, demonstrating effective discrimination between intoxicated and non-intoxicated riders. Accident detection achieved an overall detection rate of 95%, with a false positive rate of 3%.

The system also achieved rapid emergency response performance. The average accident detection time was 0.8 seconds, GPS location acquisition required 2.1 seconds, and GSM-based SMS transmission took 3.4 seconds. Therefore, the total time from accident detection to emergency alert delivery was approximately 6.3 seconds.

The results confirm that the proposed architecture provides both proactive and reactive safety capabilities. Proactive safety is achieved through ignition control based on helmet and alcohol detection, while reactive safety is achieved through automatic accident detection and emergency alert transmission. Since the system is implemented using an Arduino UNO, critical processing is performed locally, reducing dependence on internet connectivity and improving reliability in low-network areas. In addition, the estimated implementation cost of approximately $65 makes the system affordable for individual riders and scalable for broader deployment.

However, the system has some limitations, including dependence on GPS availability, the need for periodic MQ-3 sensor calibration, and limited battery life. Future work may focus on adaptive machine learning algorithms, improved power management, PCB miniaturization, cloud analytics, advanced sensing, and enhanced communication technologies. Overall, the study demonstrates that low-cost, locally processed IoT-based smart helmet systems can significantly improve two-wheeler rider protection by enforcing safety compliance, detecting accidents rapidly, and enabling timely emergency communication.

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