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HALO-4: The Smart Helmet

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Abstract: Road accidents involving two-wheelers remain one of the leading causes of serious injuries and fatalities worldwide, particularly due to delayed emergency response and the absence of intelligent safety mechanisms. Conventional helmets offer only passive protection and fail to provide any automated assistance during or after an accident. To address this limitation, this paper presents HALO-4, a modular and intelligent smart helmet designed to enhance rider safety through real-time monitoring and automated emergency alerting. The HALO-4 system integrates sensor-based crash detection using an MPU6050 accelerometer and gyroscope module to ac- curately identify sudden impacts and abnormal motion patterns. Upon detecting a potential accident, the system automatically retrieves the rider's real-time location using a GPS module and transmits emergency alerts via a GSM module to predefined contacts such as family members, medical services, or author- ities. Bluetooth connectivity is incorporated to enable seamless interaction with a mobile application, allowing real-time status monitoring and system configuration. Additionally, the modular design supports optional features such as alcohol detection to prevent riding under unsafe conditions. The entire system is built around a microcontroller-based architecture optimized for low power consumption, reliability, and fast response time. Both hardware and software components were implemented and tested under controlled conditions to evaluate system performance. Experimental results demonstrate that the HALO-4 prototype can reliably detect crash events and transmit emergency notifications within a short time frame, significantly reducing response delays. The proposed system highlights the potential of integrating embedded systems and IoT technologies to improve road safety for two-wheeler riders. HALO-4 offers a scalable and cost- effective solution that can be further enhanced with advanced features such as cloud integration and data analytics, contributing to safer and smarter transportation systems.

Keywords: *Smart Helmet, Crash Detection, MPU6050, GSM, GPS, Arduino, Emergency Alerting, HALO-4.*

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I. INTRODUCTION

Riders of two-wheelers are a big chunk of the commuting population who depend heavily on this mode for their daily commute, especially in urban and semi-urban areas due to traffic congestion or parking space crunches or for economic reasons that keep motorcycles and scooters popular. Two- wheelers are flexible and affordable in crowded areas, yet they bring ridersup to much higher risks compared with those of four-wheeled transportations. Since riders are not enclosed, even minor impacts might cause severe injuries or death tothe rider.

While helmets and traffic rules have been made mandatory in several countries, the number of fatalitiesinvolving two wheelers continues to rise tragically. Researches show the cause of most of these deaths is not presence ofaccidents, but delay in giving immediate first aid. In various practical cases, the victimsinvolved in accidents cannot actively report themselves for help because of unconsciousness and physical injured, while others who are enabled to take pictures timely may ignore cases they see. Moreover, the lack of precise position restricts emergency response time, and leads tomore severe injuries or deaths.

Traditional helmets are effective in decreasing head injuries, however they provide only passiveprotection. They are not capable of sensing a crash, grading the rider condition, or calling for emergencyhelp. The sensationalprogress in embed- ded systems, sensor technology, and wireless communication has brought smart wearable devices to the fore as a solution for furthering road safety. More specifically,smart helmets can serve as

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intelligent intermediary mechanisms between the rider, vehicle and emergency services, offering situational awareness and automating pivotal safety interventions.

- *Overview of HALO-4*

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The system uses an accelerometer and gyroscope module (MPU6050) to identify and assess impacts by measuring abrupt changes in acceleration and angular velocity across different axes. This helps the system to reliably detect crash events while the vehicle is moving. During the event of an accident, the system uses a GPS module to find the rider's current location, then sends this information using a GSM module to emergency contacts, such as relatives, local hospitals, or ambulance services.

Alongside crash detection, HALO-4 incorporates a fatigue detection system in its helmets. Rider fatigue is a significant but often overlooked cause of road accidents. HALO-4 mon- itors drowsiness through abnormal head movements, periods of inactivity, and blink detection (in systems with this sensor). If any of these indicators are detected, the helmet issues audio and/or vibration alerts to the rider and encourages them to take corrective actions to avoid a potential crash.

Also in that which we see HALO-4 we have implemented Bluetooth which in turn works with our companion mobile app. This app we have designed for hands free navigation, voice alerts and real time system status which in turn keeps the rider in the loop without the need to pay attention to a screen. Also the we have gone with a modular design which will allow for easy addition of features and improvements to the system without large scale restructurings.

- *Technical Challenges*

Creating smart helmet systems like HALO-4 entails com- plex difficulties that must be solved to ensure reliability, efficiency, and user acceptance. One major challenge is the differentiation between normal riding situations versus crash events. Motorcyclists and riders alike come across many road disturbances like potholes, speed bumps and sudden stops which create accelerative events that feel like crashes. Strong detection algorithms and threshold systems must be designed and developed to minimize the chance of excessive false positives while still ensuring fuel efficiency.

One more concern pertains to the reliability of wireless communication, especially where the network may be weak or absent. Given that emergency alerts depend on the GPS and GSM modules, a lack of signal or delays in transmission may diminish the system's performance. Hence, the system must be designed to cope with sustained connectivity gaps while still delivering emergency messages.

The helmet's limited battery capacity is a concern that requires attention. Sensors that are continuously monitored, Bluetooth communication, and data transfer will drain the battery quickly, if not structured. HALO-4 manages this through effective drain systems and the integration of low-power components to maximize operational life.

Finally, ergonomic integration presents a significant chal- lenge. Embedding electronic components within a helmet must not compromise rider comfort, weight balance, or safety standards. The system must be compact, lightweight, and se- curely integrated to ensure long-term usability without causing discomfort or distraction to the rider.

II. LITERATURE REVIEW

Smart helmet development has progressed considerably over recent years due to advancements in sensor technology, IoT communication modules, and artificial intelligence. Modern smart helmets now integrate features such as accident detec- tion, rider fatigue and drowsiness monitoring, and real-time communication to enhance overall rider safety. In particular, AI-based techniques are increasingly used for acceleration- based crash detection and exhaustion monitoring.

This section presents a critical review of the most relevant studies published between 2018 and 2025, with a focus on their methodological contributions, design strategies, and technological approaches. The reviewed works are analyzed in relation to key challenges in rider safety, situational awareness, and system reliability. Furthermore, their relevance to the proposed HALO-4 Smart Helmet architecture is discussed to highlight existing gaps and justify the design choices adopted in this work.

- *Accident Detection and Alcohol Monitoring*

Simi M. S. *et al.* [1] proposed a comprehensive smart helmet architecture that integrates an accelerometer, gyro- scope, and MQ-3 alcohol sensor with GPS and GSM modules. The system detects collisions by measuring sudden changes in acceleration and simultaneously monitors blood alcohol content (BAC) through breath analysis. When a crash is confirmed, the microcontroller sends the GPS coordinates and rider information to emergency contacts via SMS. The authors demonstrated that their design reduces average response time to under 10 seconds, though the threshold-based detection algorithm occasionally produced false alarms under rough driving conditions. This work established the foundation for combining physical and physiological sensing in helmet sys- tems.

Midlaj Ali P. *et al.* [8] extended this idea by integrating an alcohol sensor with a drowsiness detection module based on infrared (IR) sensing. The system continuously monitors the rider's eye status and alcohol level. If intoxication or fatigue is detected, the helmet issues an audible warning and optionally disables vehicle ignition. Their approach improved safety by addressing human factors beyond crash detection. However, the authors noted calibration sensitivity in the MQ-3 sensor, emphasizing the need for dynamic threshold tuning—an idea that the HALO-4 system later refines using adaptive filtering.

- *IoT-Based Smart Helmets*

Aswathy J. S. *et al.* [2] introduced an IoT-based helmet that employs multiple sensors—alcohol, vibration, and mo- tion—connected to a cloud-based dashboard through GSM and GPS. Their design focused on enforcing road-safety compliance, ensuring that the engine starts only when the rider wears the helmet and passes alcohol checks. The use of NodeMCU/ESP8266 for wireless connectivity improved system scalability. However, their implementation relied on centralized data storage, raising concerns about data privacy and security, which HALO-4 addresses through decentralized record management.

Dhere S. *et al.* [5] developed an IoT architecture capable of real-time accident detection and prevention. The system uses an MPU6050 module for motion sensing and an Ar- duino microcontroller for decision-making. When a crash is detected, the system triggers an alert sequence that trans- mits the vehicle's geolocation to nearby emergency contacts. Their algorithm uses a dual-threshold strategy—combining acceleration magnitude and orientation angle—to minimize false triggers. The system's simplicity makes it suitable for large-scale deployment, though its lack of machine learning integration limits adaptability.

Gopalakrishnan M. *et al.* [9] designed an IoT-enabled hel- met specifically for two-wheelers. Their design focuses on helmet-wearing verification, alcohol detection, and accident notification. The authors integrated a relay control system that prevents the vehicle from starting unless the helmet is worn correctly. Their findings confirmed a 95% detection accuracy in field trials. However, the system's dependency on GSM coverage could result in delayed alerts in rural regions. The HALO-4 system mitigates this by incorporating message queuing and redundancy through app-based Bluetooth fallback.

- *Artificial Intelligence and Smart Detection*

Shaheel Hameed Z. *et al.* [3] proposed an AI-based framework that uses supervised machine learning algo- rithms—specifically a decision tree classifier—to identify crash events. The helmet collects multi-axis accelerometer and gyroscope data, which are then classified as either normal motion or collision. The use of feature extraction from time- domain sensor data enhances accuracy beyond threshold-based detection. The authors reported 98% precision and 96% recall on their test dataset. However, the computational complexity restricts on-device learning; HALO-4 leverages lightweight models and offloads analytics when connected to mobile devices.

Surya U. *et al.* [4] expanded on multimodal sensing by combining alcohol detection with drowsiness estimation using IR pupil tracking. Their system evaluates eye blink rate and head tilt, generating alerts for both intoxication and fatigue. The proposed fuzzy rule-based control mechanism achieved improved decision stability in variable lighting conditions. This approach is particularly relevant to HALO-4's modular design philosophy, which allows simultaneous operation of multiple sensing functions.

- *Computer Vision and Helmet Violation Detection*

Agorku G. *et al.* [6] proposed a vision-based helmet detec- tion model employing the YOLOv5 deep-learning architecture with ensemble learning to recognize helmet compliance in surveillance footage. Although focused on enforcement rather than rider safety, this study provides valuable insight into using AI for visual inference in real time. The model achieved an average precision (mAP) of 91.4% across custom datasets. The underlying principles of real-time inference and multi- class classification influenced the visualization component of HALO-4's future extensions.

Feng J. *et al.* [7] improved upon earlier YOLO architec- tures by implementing a bi-directional attention fusion (BAF) mechanism in a Vision Transformer (ViT) framework. Their study addressed occlusion and low-contrast issues common in real-world environments. The model achieved state-of-the-art helmet-wearing detection performance with 94.7% accuracy. While the system targets industrial safety, its emphasis on multi-scale attention could enhance visual analytics for adap- tive alerting in helmet-based systems.

- *Foundational Studies and Early Prototypes*

Deekshitha K. I. *et al.* [10] presented one of the earliest practical implementations of a smart helmet combining a simple accelerometer with a GSM module. Their prototype could detect abrupt acceleration spikes and automatically send text alerts. Though limited in scope, this work laid the ground- work for integrating communication modules into safety gear. The study highlighted essential design considerations such as power management, helmet ergonomics, and microcontroller optimization—all key aspects incorporated in HALO-4's sys- tem design.

- *Summary of Theoretical Insights*

The reviewed literature collectively demonstrates the evo- lution from rule-based detection systems to AI- and IoT- integrated architectures. Early works such as [10] validated feasibility, while mid-generation studies [1], [5], [8] focused on sensor reliability. Recent research [3], [7] introduced ma- chine learning and deep learning for enhanced adaptability. However, these works often neglect modular scalability, de- centralized logging, or user-friendly integration—gaps that the proposed HALO-4 system addresses through hybrid connec- tivity, adaptive algorithms, and a unified smartphone interface.

➢ *Comparative Insights*

Table 1 summarizes the reviewed studies in terms of sensors used, connectivity type, unique contribution, and limitations. From the literature, it is evident that while each approach addresses a subset of the safety problem, very few integrate all dimensions—crash detection, alcohol and fatigue monitoring, and connected alerts—into one coherent framework. HALO-4 differentiates itself through a multi-sensor modular design with hybrid GSM–Bluetooth communication and improved false- positive suppression through adaptive filtering.

Table 1 Comparative Summary of Related Smart Helmet Research Works

Ref.	Authors / Year	Key Focus	Limitation
[1]	Simi M. S. et al. (2025)	Crash + alcohol detection via sensors + GSM/GPS	False alarms on vibration
[8]	Midlaj Ali P. et al. (2020)	Alcohol + drowsiness via IR sensor	Sensor calibration issues
[2]	Aswathy J. S. et al. (2025)	IoT-based safety compliance system	Centralized data, privacy risk
[5]	Dhere S. et al. (2025)	IoT accident prevention architecture	No ML adaptability
[9]	Gopalakrishnan M. et al. (2023)	Helmet verification + relay ignition control	GSM dependency
[3]	Shaheel Hameed Z. et al. (2025)	AI-based crash classification	High computational cost
[4]	Surya U. et al. (2025)	Alcohol + fatigue detection via fuzzy logic	Limited field validation
[6]	Agorku G. et al. (2023)	Vision-based helmet detection (YOLOv5)	Focused on compliance only
[7]	Feng J. et al. (2024)	Transformer-based detection (BAF-ViT)	Industrial context only
[10]	Deekshitha K. I. et al. (2018)	Early GSM-based crash alert prototype	Basic hardware, no integration

III. PROPOSED SYSTEM

A. *Overall Architecture of HALO-4*

HALO-4 follows a layered smart system architecture, in which the overall functionality is divided into well-defined layers to ensure reliability, scalability, and ease of future enhancements. The system architecture mainly consists of three layers: sensing, processing, and communication.

➢ *Sensing Layer:*

The sensing layer is responsible for collecting real-world data from both the rider and the vehi- cle using multiple sensors. The MPU6050 sensor measures acceleration and angular velocity, which are essential for detecting crashes, falls, and abnormal riding patterns. The MQ- 3 alcohol sensor detects the presence of alcohol in the rider's breath, helping to identify drunk riding conditions. The GPS module (NEO-6M) provides real-time geographical location data, which is crucial during emergency situations. A vibration sensor is used to detect sudden shocks or strong impacts, further assisting in accident detection. Optional sensors such as a microphone or blink sensor can be integrated to support rider drowsiness detection.

The primary purpose of the sensing layer is to continuously monitor the rider's condition and the vehicle's motion in real time.

➢ *Processing Layer:*

The processing layer acts as the core intelligence of the HALO-4 system. A microcontroller, such as an Arduino or an equivalent embedded controller, serves as the central processing unit. It receives raw data from all sensors and performs operations such as noise filtering, speed and tilt angle calculation, and impact force estimation. Based on predefined thresholds and logical conditions, the controller determines whether the riding condition is normal or potentially dangerous.

The objective of this layer is to convert raw sensor data into meaningful information that can be used for decision-making.

➢ *Communication Layer:*

The communication layer is responsible for transmitting information and alerts to external devices and emergency services. Bluetooth (HC-05) enables communication with a companion mobile application for real- time alerts and system status updates. The GSM module (SIM800L) is used to send SOS messages or initiate emer- gency calls. The GPS module provides accurate location data that is transmitted along with emergency alerts.

The purpose of this layer is to ensure timely communication with the rider, family members, and emergency responders.

B. *Step-by-Step Flowchart Explanation*

The system workflow of HALO-4, as illustrated in Figure 1, explains the operational sequence and decision-making process of the smart helmet.

➢ *Helmet Initialization:*

When the helmet is powered on, the system begins with helmet initialization. During this stage, the microcontroller initializes internal memory, timers, and input/output pins to ensure stable system operation.

➢ *Powering Sensors and Modules:*

After initialization, all sensors and communication modules, including the MPU6050, MQ-3 alcohol sensor, GPS module, GSM module, and Blue- tooth module, are powered on. The system verifies that each component is functioning correctly.

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➢ *Bluetooth and GPS Connectivity Check:*

The system then checks Bluetooth connectivity with the companion mobile application and verifies GPS satellite lock. This step ensures proper communication and accurate location tracking before continuous monitoring begins.

➢ *Sensor Suite Operation:*

Once connectivity is confirmed, the sensor suite operates continuously. The MPU6050 mon- itors acceleration and angular velocity to detect crashes or abnormal motion. The MQ-3 sensor measures breath alcohol concentration to detect intoxication. The GPS module con- tinuously tracks latitude and longitude, while the vibration sensor detects sudden mechanical shocks. All sensor data is forwarded to the microcontroller in real time.

➢ *Data Acquisition:*

The system collects acceleration data, gyroscope readings, alcohol sensor values, and GPS coordi- nates. This raw data is temporarily stored for further processing.

➢ *Data Preprocessing and Analysis:*

The preprocessing stage removes noise and filters out false signals. The system computes parameters such as speed, tilt angle, and impact severity. Crash patterns and alcohol thresholds are evaluated, and drowsiness indicators such as abnormal head movement or prolonged inactivity are analyzed. This stage converts raw data into actionable information.

➢ *Decision Making:*

At this stage, the system evaluates whether a crash or alcohol consumption has been detected. If no abnormal condition is identified, the system continues normal monitoring and may optionally upload telemetry data to the cloud. If an abnormal condition is detected, the system proceeds to event confirmation.

➢ *Event Confirmation:*

To reduce false alerts, the system performs time-based confirmation, GPS stability verification, and multi-sensor validation. Only confirmed events trigger emergency actions.

➢ *Alert Generation:*

Once an event is confirmed, the system generates an alert record containing the time of occurrence, location, and type of incident, such as a crash or alcohol detection.

➢ *Emergency Actions:*

The system sends an SOS alert via the GSM module, including the rider's GPS location. Emergency calls may also be initiated. Simultaneously, notifications are sent to the connected mobile application through Bluetooth, and the incident data is logged to cloud storage or IPFS for future analysis.

➢ *Safety Protocol Activation:*

Safety protocols are triggered based on the detected event. For example, ignition locking can be activated if alcohol consumption is detected, or continuous alerts can be issued if the rider is suspected to be unconscious.

➢ *AI Assistant and Navigation Support:*

During normal operation, the system supports an AI-assisted module that provides voice commands, navigation guidance, hazard alerts, and blind-spot warnings to improve rider awareness without causing distraction.

➢ *Indicator and Lighting Control:*

The system also man- ages indicator signals, headlight control, and other visual safety indicators to enhance road visibility and rider safety.

C. Sensor Processing and Crash Detection Algorithm

Crash detection consists of low-pass filtering of raw ac-celerometer data, computing resultant acceleration magnitude $a = \sqrt{a_x^2 + a_y^2 + a_z^2}$, detecting spikes where $a > a_{thresh}$, checking gyroscope rotation for fall patterns, and applying debounce logic and GPS speed checks to avoid false positives.

D. Software Stack and Decision Logic

➢ *Software Stack:*

The HALO-4 system is implemented using Embedded C through the Arduino IDE. Dedicated sensor drivers are used for interfacing with the MPU6050, MQ- 3, and GPS modules. Communication with Bluetooth and GSM modules is handled using AT commands. The system employs threshold-based logic enhanced with basic AI-assisted techniques. A mobile application provides user interaction, and an optional cloud backend supports data storage and analytics.

➢ *Decision Logic:*

The decision logic relies on predefined threshold values for crash detection and alcohol level iden- tification. Multi-sensor validation is used to confirm critical events and minimize false positives. Timers and state-machine- based logic ensure stable transitions between normal monitor- ing and emergency states. In future implementations, machine learning models can be integrated to improve prediction accu- racy and adaptive decision-making.

This section details the HALO-4 hardware architecture, software stack, and decision logic.

IV. HARDWARE IMPLEMENTATION

➢ *Wiring and Mounting Notes*

Place the MPU6050 near the helmet center of mass to reduce rotational artifacts. Use small LiPo batteries with proper regulation and safety protection. Ensure antennas for GPS/GSM are positioned for best reception.

➢ *Mobile Application Interface*

The HALO-4 mobile application provides voice destination commands, Google Maps route guidance, and an emergency "HALO Assist" trigger. Figure 2 shows sample screenshots.

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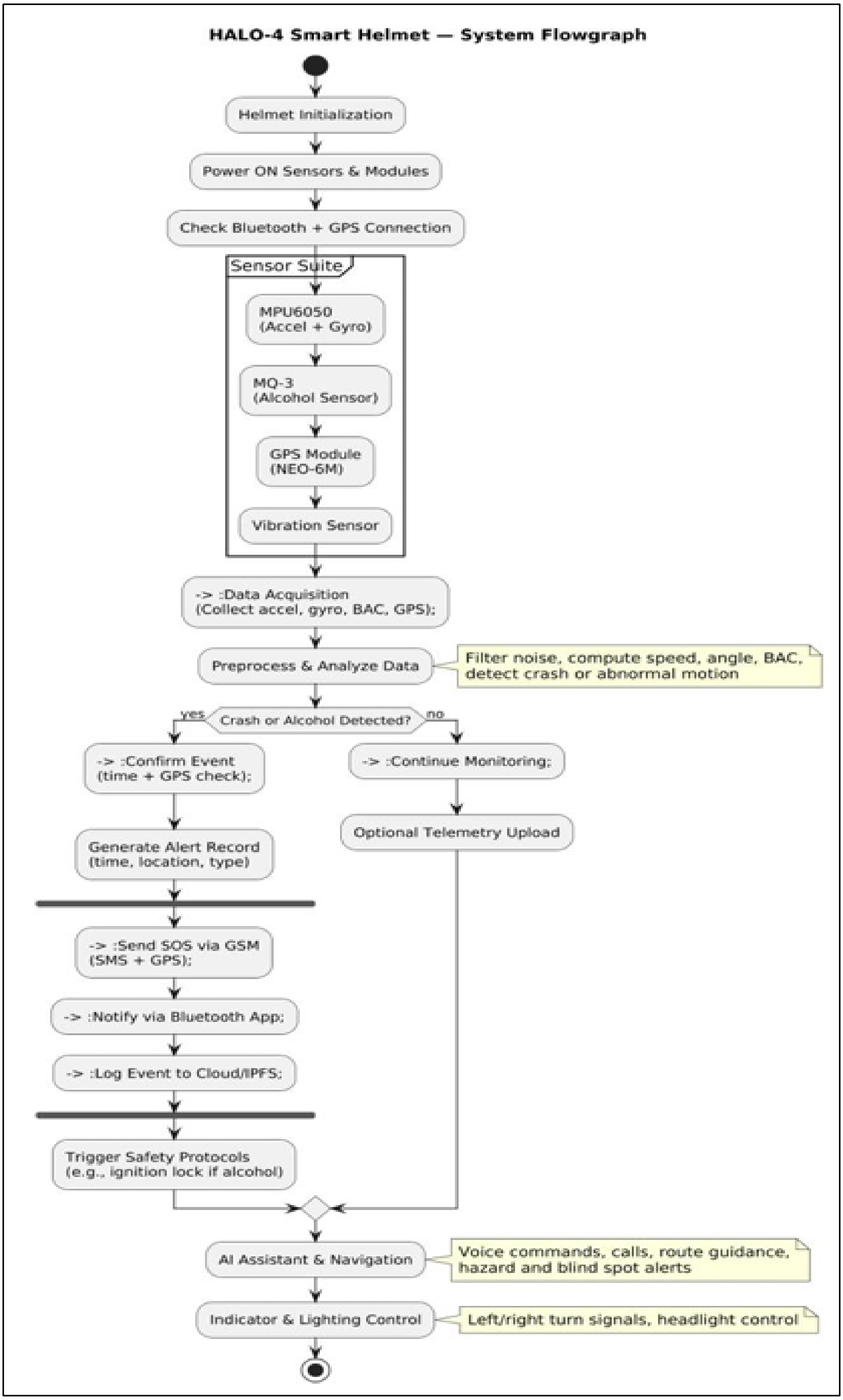

Fig 1 System Workflow of HALO-4 Smart Helmet

Table 2 Hardware Components Used in Smart Helmet

Component	**Model / Type**	**Purpose**
Microcontroller	Arduino Uno	Central controller for sensor data processing and communication
Accelerometer/Gyro	MPU6050	Detects crash using 3- axis acceleration and ro- tation
GPS Module	NEO-6M	Provides real-time loca- tion coordinates
GSM Module	SIM800L	Sends SMS or call alerts during emergencies
Bluetooth Module	HC-05	Connects helmet to mo- bile application
Relay Module	5V Relay	Controls ignition based on safety conditions
Power Supply	Li-Po Battery	Provides portable power to the system
LED/Buzzer	Indicators	Gives visual and audio alerts

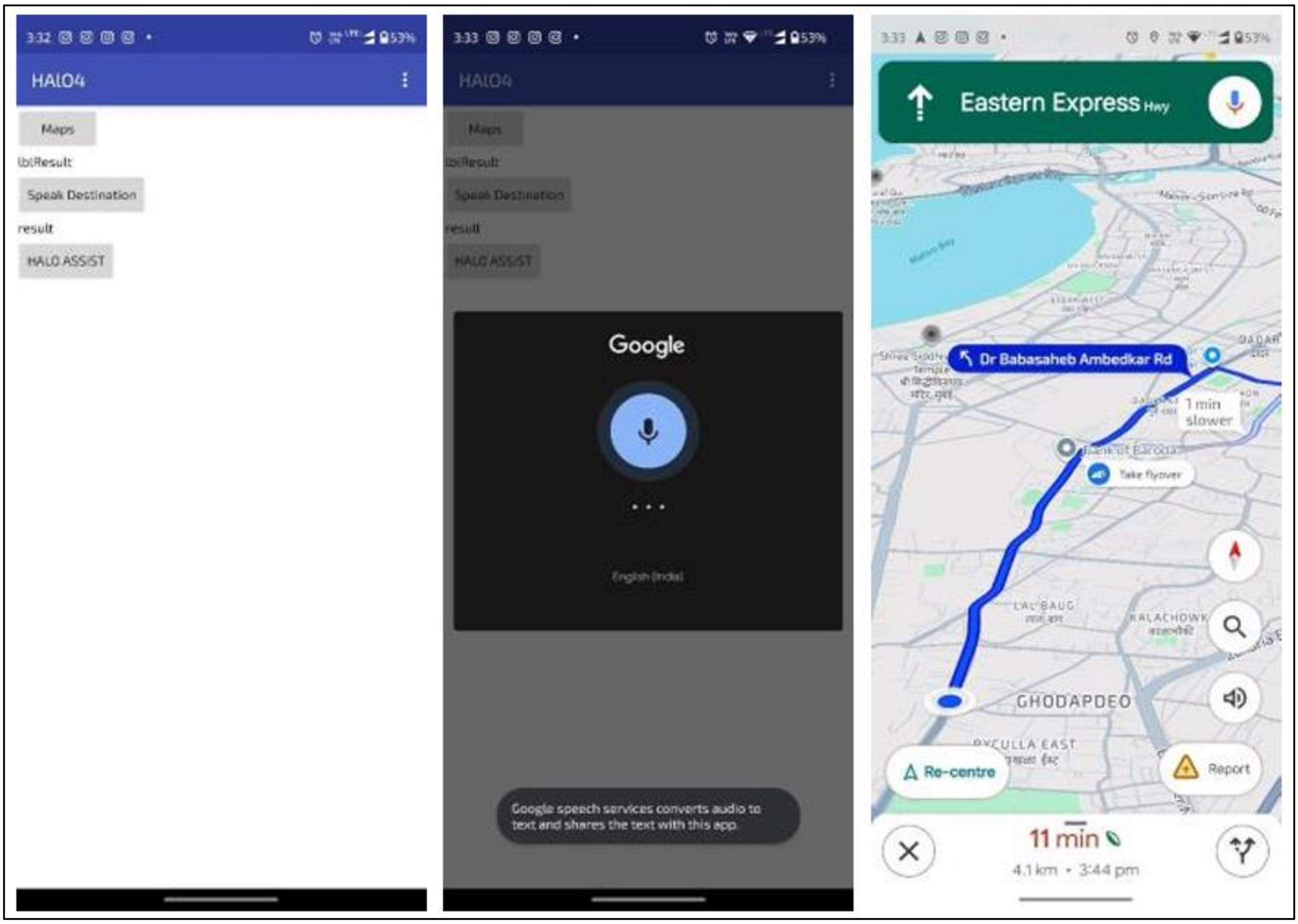

Fig 2 HALO-4 App Interface: (a) Main Menu, (b) Voice Command Interface, (c) Navigation Integration.

➤ *Discussion and Limitations*

Prototype limitations include the bulk of the Arduino Uno (replaceable with ESP32 or custom PCB), GSM timing variance with signal conditions, MQ-3 sensor calibration needs, and scope for ML-based false-positive reduction.

V. CONCLUSION AND FUTURE WORK

HALO-4 demonstrates feasible integration of crash detection, geolocation, and emergency alerting in a helmet-mounted system with high detection accuracy and acceptable alert latency. Future improvements include migrating to a compact controller (ESP32), edge ML for adaptive thresholds, cloud logging and dashboards, LTE-M / NB-IoT connectivity, and ergonomic user studies.

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