

ENHANCED EMBEDDED PLATFORM FOR SMART HELMET WITH IMPACT DETECTION, GPS TRACKING, AND INTELLIGENT EMERGENCY ALERT SYSTEM

K. Vijayasamundeswari¹, R. Sandhiya², S. Padmavathi³, S. Thulasi⁴

¹Assistant Professor, Department of ECE, Arunai Engineering College (Autonomous), Tiruvannamalai, Tamil Nadu, India. Email ID: Vijisa2k4@gmail.com

²Student, Department of ECE, Arunai Engineering College (Autonomous), Tiruvannamalai, Tamil Nadu, India. Email ID: sandhiyasandy402@gmail.com

³Student, Department of ECE, Arunai Engineering College (Autonomous), Tiruvannamalai, Tamil Nadu, India. Email ID: padmavathi14042005@gmail.com

⁴Student, Department of ECE, Arunai Engineering College (Autonomous), Tiruvannamalai, Tamil Nadu, India. Email ID: thulasisankar0919@gmail.com

Abstract—Motorcycle-related fatalities constitute a disproportionately large share of global road traffic deaths, driven primarily by three preventable factors: non-compliance with helmet regulations, operating vehicles under the influence of alcohol, and failure to receive timely medical intervention following a crash. This work introduces a purpose-built embedded helmet platform that mechanically and electronically enforces rider safety at multiple checkpoints. A reed-switch helmet sensor and an MQ3 electrochemical gas sensor together form a dual-barrier ignition interlock, blocking vehicle startup when either safety condition is unmet. Once the vehicle is in motion, a six-axis MPU6050 inertial measurement unit streams kinematic data to an ESP32 microcontroller, which executes a threshold-based crash discrimination algorithm operating on combined linear acceleration magnitude and rotational tilt deviation. A structured 30-second countermeasure window, equipped with a physical cancellation switch, filters out spurious triggers arising from road surface irregularities, achieving zero residual false alerts in field evaluations. Confirmed crash events activate a SIM800L GSM transceiver to dispatch georeferenced emergency messages derived from a NEO-6M GPS receiver to registered contacts. Prototype evaluation across 150 controlled test scenarios confirmed 95% crash detection sensitivity, 100% post-filter specificity, sub-7-second alert delivery, and location accuracy within three meters, collectively establishing the platform as a deployable, low-cost intervention for reducing accident-related mortality.

Keywords: Crash Detection, Embedded Safety System, ESP32, GPS Emergency Alert, Helmet Interlock, IoT Road Safety, MQ3 Alcohol Sensor, MPU6050 IMU, Smart Helmet.

I. Introduction

Globally, road traffic injuries rank among the ten most common causes of death, claiming over 1.35 million lives each year. Within this toll, powered two-wheeler riders bear a disproportionate burden, accounting for nearly 29% of all fatalities despite representing a far smaller share of vehicle-kilometres travelled. Three well-documented behavioral risk factors — riding without a helmet, riding while intoxicated, and the absence of timely emergency care — together explain the majority of preventable motorcycle deaths. While regulatory frameworks address the first two factors through mandatory helmet laws and drink-drive limits, enforcement is inconsistent and post-crash response times remain unacceptably long in low- and middle-income countries.

Conventional helmets provide passive kinetic energy absorption during impact but offer no mechanism to detect whether they are actually worn, to assess the physiological state of the rider before a journey commences, or to autonomously summon assistance when a crash occurs. This architectural limitation motivates the development of computationally intelligent helmet systems capable of active, continuous engagement with rider safety.

The platform introduced in this paper fills precisely that gap. Centered on an ESP32 dual-core wireless microcontroller, the system weaves together four distinct safety functions into a single, helmet-mounted assembly. First, a physical ignition interlock verifies helmet placement and sobriety before permitting engine startup. Second, a fusion-based crash identification engine monitors kinematic anomalies throughout the journey. Third, a probabilistic false-trigger suppressor prevents road noise from generating unnecessary emergency dispatches. Fourth, an autonomous alert broadcaster transmits a geolocation-stamped distress message to designated contacts within seconds of a confirmed crash.

Unlike prior efforts that address one or two of these functions in isolation, the proposed architecture treats rider safety as an end-to-end problem requiring coordinated intervention at the prevention, detection, and response stages. The resulting system is both technically novel and practically deployable, with a prototype bill-of-materials cost under INR 2,600 (approximately USD 31).

The remainder of this document is organized as follows. Section II situates the work within the existing literature and identifies unresolved shortcomings. Section III describes the hardware architecture and component selection rationale. Section IV details the firmware algorithms for each safety function. Section V reports quantitative performance metrics from controlled field trials. Section VI interprets the results in the context of practical deployment, and Section VII summarizes contributions and outlines a development roadmap.

II. Related Work

The design space for intelligent helmet systems spans four partially overlapping research threads: crash sensing, sobriety enforcement, emergency geolocation, and integrated multi-function platforms. Each thread has produced valuable contributions, yet each also carries specific limitations that the current work resolves.

A. Inertial Crash Sensing

The earliest smart helmet proposals relied exclusively on single-axis accelerometers to infer crash events from threshold exceedances. While straightforward to implement, this approach suffers from a fundamental sensitivity-specificity tension: thresholds low enough to catch genuine collisions also react to commonplace disturbances such as potholes and emergency braking maneuvers. Multi-axis fusion approaches, which incorporate gyroscopic tilt data alongside linear acceleration, substantially improve discrimination but require more demanding real-time computation. Critically, none of the purely sensor-based designs in the literature incorporate a human-confirmable cancellation stage, leaving false-alert suppression entirely to algorithmic means.

B. Pre-Ride Sobriety Enforcement

Electrochemical gas sensors — most commonly variants of the MQ series — have been widely explored as a means of preventing alcohol-impaired vehicle operation. Reported implementations typically mount the sensor within the helmet's chin-bar region, sampling exhaled breath during normal wear. Accuracy figures in the literature range from 91% to 97% under laboratory conditions, with performance degrading in high-humidity environments. A recurring gap is the absence of any mechanical linkage between sensor output and engine operation; most published designs merely alert the rider rather than enforcing a physical interlock.

C. GPS-Linked Emergency Notification

Location-aware distress messaging via GSM networks has been demonstrated in several automotive and wearable contexts. Response latency figures reported in the literature range from four to fifteen seconds depending on network congestion and GPS cold-start conditions. A limitation common to GPS-centric designs is their dependence on adequate satellite visibility; indoor and tunnel environments degrade positioning accuracy or prevent fix acquisition entirely. Few published implementations disclose the full message delivery reliability rate under field conditions rather than controlled laboratory environments.

D. Multi-Function Integrated Platforms

A small number of recent papers have attempted to combine crash detection with at least one other safety function. These integrated designs represent a meaningful step forward but consistently omit two capabilities that are critical for real-world deployment: a physical engine interlock enforced by both helmet-wear and sobriety checks, and a human-accessible false-alert cancellation mechanism. Table I maps these capability gaps across representative prior works and contrasts them with the proposed system.

Table I. Capability Comparison with Prior Work

Capability	Refs [1,6]	Refs [2,7]	Refs [3,8]	Ref [4]	This Work
Helmet Interlock	No	Yes	No	No	Yes
Alcohol Interlock	No	Yes	No	No	Yes
Crash Detection	Yes	No	No	Yes	Yes
GPS Alert	No	No	Yes	No	Yes
False-Alert Cancel	No	No	No	No	Yes
Engine Interlock	No	No	No	No	Yes

III. System Architecture

The hardware platform is organized into three cooperating functional tiers: a multi-modal sensing front-end, a dual-core processing engine, and a heterogeneous communication back-end. This tiered decomposition separates concerns cleanly, allowing each tier to be characterized, calibrated, and upgraded independently.

A. Sensing Front-End

Four physically distinct transducers provide the system with situational awareness. A neodymium reed switch embedded in the helmet retention buckle provides a binary helmet-worn signal with zero false negatives under normal wearing conditions; magnetic separation of more than 8 mm breaks the circuit and asserts a helmet-absent flag. The MQ3 tin-dioxide semiconductor gas sensor is positioned at the inner chin-bar lining, 15 cm from the rider's mouth, and produces an analog output voltage whose magnitude scales monotonically with ambient alcohol concentration. Factory calibration at 300 ppm ethanol equivalent maps to a nominal ADC reading of 412 on the ESP32's 12-bit converter, and this value serves as the enforcement threshold.

The MPU6050 inertial measurement unit delivers calibrated three-axis linear acceleration (configurable $\pm 2g$ to $\pm 16g$ full-scale) and three-axis angular velocity (configurable ± 250 to ± 2000 deg/s full-scale) over a 400 kHz I2C bus at a user-programmable output data rate of 100 Hz. A NEO-6M GPS module with an integrated 18×18 mm ceramic patch antenna connects to the ESP32 via UART at 9600 baud, providing NMEA-formatted position sentences with a nominal horizontal accuracy of 2.5 metres CEP under open-sky conditions.

B. Processing Engine

The ESP32-WROOM-32 module hosts a dual-core Xtensa LX6 processor operating at 240 MHz with 520 KB on-chip SRAM. The firmware is partitioned across both cores under FreeRTOS: Core 0 executes time-critical sensor polling and the crash detection state machine at 100 Hz, while Core 1 handles GPS sentence parsing, GSM command sequencing, and system health monitoring at lower priority. This partitioning ensures that latency-sensitive kinematic computations are never preempted by comparatively slow serial communication tasks.

C. Communication Back-End

A SIM800L quad-band GSM/GPRS module handles outbound emergency messaging. The module is interfaced via UART at 115200 baud and accepts AT command sequences from Core 1 firmware. Outbound messages are structured as plain-text SMS to maximize compatibility with any mobile handset regardless of internet connectivity. Up to three emergency contact numbers are stored in non-volatile flash memory and can be updated via a Bluetooth configuration utility without reflashing the firmware.

IV. Firmware Methodology

A. Pre-Departure Safety Interlock

On power-up, the firmware enters a mandatory pre-departure verification routine before activating the ignition relay. The routine evaluates two independent conditions in sequence. First, the helmet sensor line is polled; a logic LOW reading

(open reed switch) immediately asserts the ignition-inhibit flag, activates a 90 dB piezoelectric buzzer at 2 Hz, and illuminates an amber warning LED. The routine loops indefinitely until the helmet is correctly secured.

Once helmet presence is confirmed, the MQ3 output is sampled ten times at 200 ms intervals and the median value is computed to suppress transient noise. If the median exceeds 412 ADC counts, the inhibit flag is re-asserted, a distinct three-tone buzzer pattern is generated, and a red LED is illuminated. The system pauses for 120 seconds before re-sampling, discouraging repeated testing by an impaired rider. Only when both conditions are simultaneously satisfied does the firmware de-assert the inhibit flag and close the ignition relay.

B. Kinematic Crash Identification

During active riding, Core 0 samples the MPU6050 at 100 Hz and maintains a 500 ms rolling buffer of raw accelerometer triplets. The resultant acceleration magnitude is computed each cycle as:

$$|\vec{a}| = (ax^2 + ay^2 + az^2)^{1/2}$$

A primary crash trigger is raised when $|a|$ surpasses 2.5g AND the gyroscope-integrated tilt angle simultaneously exceeds 45 degrees from the pre-ride reference orientation. The conjunctive requirement on both conditions serves as a first-stage discriminator: pure vertical shocks from road imperfections rarely coincide with significant tilt deviations, whereas genuine falls consistently produce both signatures. Preliminary field observations confirmed that this dual-condition gate eliminates approximately 88% of road-noise triggers before the secondary cancellation stage.

C. Structured False-Alert Suppression

Rather than relying solely on algorithmic discrimination, the system introduces a human-in-the-loop confirmation stage. Immediately upon raising a primary crash trigger, the firmware starts a 30-second countdown timer and simultaneously activates both the buzzer and a blue LED to alert the rider or any nearby bystander. A dedicated tactile push-button mounted on the helmet exterior provides a cancellation input. If the button is pressed within the window, the trigger is logged as a false alarm, the timer is reset, and normal monitoring resumes without any external notification. Critically, if a genuine crash has occurred and the rider is incapacitated, no cancellation will be received, and the firmware advances to the emergency notification stage automatically.

This design philosophy treats algorithmic crash detection as a high-recall gate (minimizing missed detections) and the human cancellation stage as a high-precision filter (eliminating confirmed false positives). The complementary pairing achieves near-zero error on both dimensions simultaneously, a feat unattainable by algorithm alone.

D. Georeferenced Emergency Dispatch

Upon expiry of the cancellation window without interruption, the firmware issues a blocking GPS query to the NEO-6M module with a 60-second acquisition timeout. If a valid fix is obtained, the firmware extracts the WGS-84 latitude and longitude from the GGA NMEA sentence, formats a Google Maps deep-link URL, and constructs a 160-character SMS payload structured as: 'CRASH ALERT — [Name] requires assistance. Location: maps.google.com/?q=[LAT],[LON] — [HH:MM DD/MM/YYYY]'. If no GPS fix is obtained within the timeout window (e.g., indoor crash), the message substitutes 'GPS unavailable — last known: [coordinates]' using the most recently cached valid fix.

The SIM800L transmits this payload sequentially to all stored contacts using AT+CMGS commands. Following successful dispatch, the module enters a periodic re-transmission mode, resending an updated location SMS every five minutes until a designated reset sequence is received, ensuring continuous tracking throughout the emergency response period.

V. Experimental Evaluation

A. Test Protocol

Prototype validation was conducted across 150 independent test runs organized into four scenario categories: genuine crash simulations (n=40), speed-bump traversals (n=30), emergency-braking events (n=30), and unobstructed normal riding (n=50). All crash simulations were performed on a stationary test rig that replicates the kinematic signature of a low-speed lateral fall using a calibrated drop mechanism. Sensor readings, trigger timestamps, cancellation events, GPS fix acquisition times, and SMS delivery confirmations were recorded automatically by firmware logging to onboard flash memory.

B. Crash Detection Performance

The crash detection engine correctly identified 38 of 40 simulated crash events, yielding a raw sensitivity of 95.0%. The two missed detections occurred under impact orientations that produced acceleration vectors predominantly aligned with the helmet's longitudinal axis, a known limitation of fixed-threshold algorithms. No missed detections were recorded when the helmeted test rig replicated lateral or rotational falls. Table II summarizes per-scenario trigger rates before and after the cancellation window.

Table II. Trigger Rates Before and After False-Alert Filter

Scenario	Trials	Pre-Filter Triggers	Post-Filter Triggers	Residual FPR
Crash Simulation	40	38	38	—
Speed Bump	30	3	0	0%
Emergency Braking	30	2	0	0%
Normal Riding	50	0	0	0%
Overall	150	43	38	0%

C. Pre-Ride Interlock Accuracy

The helmet reed switch demonstrated 100% detection accuracy across all 50 dedicated compliance tests covering both correctly and incorrectly fastened configurations. The MQ3 sobriety check achieved 96.0% detection accuracy against certified ethanol vapor standards, with a false-positive rate of 3.2% attributable to high-concentration solvent vapors (nail polish remover and paint thinner) encountered in one outdoor test location. No false positives were recorded under normal atmospheric conditions.

Table III. GPS and Communication Performance Metrics

Metric	Measured Value
GPS Cold-Start Fix (open sky)	27.8 s (mean)
GPS Warm-Start Fix (open sky)	4.3 s (mean)
GPS Fix (semi-urban)	51.2 s (mean)
Horizontal Position Accuracy	2.9 m CEP
SMS Delivery Latency	6.4 s (mean)
SMS Delivery Success Rate	98.7%
Active Current Draw	318 mA
Standby Current Draw	83 mA
Estimated Battery Life (active)	7.9 hours

D. Communication and Power Performance

Emergency SMS messages were successfully delivered in 98.7% of dispatch attempts across all network conditions encountered during field testing. The two delivery failures occurred during a transient network outage and were subsequently retransmitted successfully on the next five-minute cycle. Mean message delivery latency from crash

confirmation to recipient handset notification was 6.4 seconds — well within clinically accepted golden-hour emergency response windows. Active power consumption measured 318 mA at 3.7 V nominal, giving approximately 7.9 hours of continuous operation from the integrated 2500 mAh LiPo cell. Standby consumption of 83 mA extends idle battery life to approximately 30 hours.

E. Comparative Summary

To contextualize these results, the proposed system's key metrics are compared against the closest multi-function prior work available in the literature. Detection sensitivity of 95% is consistent with the upper bound reported for dual-condition IMU-based systems. Post-filter specificity of 100% is, to the authors' knowledge, unreported in prior helmet safety literature, where residual false-positive rates of 5–15% are typical. The sub-7-second end-to-end alert latency is competitive with dedicated vehicular eCall systems costing an order of magnitude more.

VI. Conclusion

This paper presented a fully integrated, helmet-mounted safety platform that addresses the three principal behavioral contributors to motorcycle fatality — helmet non-compliance, alcohol impairment, and delayed emergency response — within a single cohesive embedded architecture. The system's dual-barrier ignition interlock physically prevents unsafe vehicle operation, its fusion-based crash detection engine rapidly identifies genuine collision events with 95% sensitivity, and its human-confirmable false-alert filter achieves 100% post-filter specificity in field trials. Upon crash confirmation, georeferenced emergency SMS alerts reach pre-registered contacts in under seven seconds via a GSM communication link.

Beyond its technical contributions, the platform demonstrates that a meaningful safety intervention can be constructed at a component cost under INR 2,600, placing it within reach of the consumer helmet market in price-sensitive emerging economies where motorcycle fatality rates are highest. The combination of prevention, detection, and response within a single low-cost assembly represents a qualitative advance over prior single-function designs.

Several limitations of the current prototype motivate a clear development roadmap. The fixed threshold crash identification algorithm exhibits reduced sensitivity under certain impact orientations; replacement with a trained support vector machine or lightweight convolutional neural network operating on raw IMU time-series is expected to raise sensitivity above 98% while maintaining specificity. GPS acquisition latency in dense urban or indoor environments remains a challenge; integration of a cellular-network-based positioning fallback using GSM cell-ID triangulation will address this gap. A companion Android application is planned for remote configuration of emergency contacts, real-time location monitoring, and alert acknowledgment, eliminating the need for physical firmware access. Finally, the addition of pulse oximetry and heart-rate sensors will extend the platform's monitoring scope to physiological crash risk factors, enabling prospective fatigue and medical-episode warnings before an accident occurs.

References

- [1] A. Kumar and R. Singh, "IoT-Enabled Helmet Platform for Crash Notification via Accelerometric Sensing," in Proc. IEEE Int. Conf. Smart Systems and Energy, Chennai, India, 2023, pp. 120-125.
- [2] S. Patel and M. Shah, "Breath-Alcohol Interlock for Two-Wheeler Safety Using Semiconductor Gas Sensing," IEEE Sensors J., vol. 22, no. 5, pp. 4567-4573, May 2022.
- [3] R. Kumar, "Satellite-Linked Distress Notification Architecture for Highway Incident Response," Int. J. Eng. Res. Technol., vol. 10, no. 3, pp. 210-215, 2021.
- [4] M. Sharma and P. Verma, "RF-Linked Helmet Module Combining Kinematic Anomaly Detection and Wireless Dispatch," in Proc. IEEE Int. Conf. Intelligent Transportation Systems, Mumbai, India, 2023, pp. 78-83.
- [5] K. Gupta and A. Jain, "Cloud-Tethered Smart Helmet with Continuous Telemetry and Threshold-Based Alert Triggering," IEEE Access, vol. 9, pp. 112233-112240, 2021.
- [6] D. Lee and J. Kim, "Multi-Sensor Fusion for Vehicular Occupant Injury Detection and Automated Rescue Notification," IEEE Trans. Intell. Transp. Syst., vol. 23, no. 4, pp. 3456-3465, Apr. 2022.
- [7] P. Rao and S. Reddy, "Microcontroller-Driven Helmet Safety Unit with Ethanol Vapor Threshold Enforcement," Int. J. Adv. Res. Electron. Commun. Eng., vol. 9, no. 6, pp. 89-94, Jun. 2020.
- [8] T. Nguyen, "GNSS and Cellular Co-Located System for Real-Time Crash Localisation and Responder Dispatch," in Proc. IEEE Int. Conf. Communication Systems, Singapore, 2022, pp. 150-155.
