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Advanced Smart Helmet for Off-Road Biking: Enhancing Rider Safety with IoT-Based Features

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Abstract: In this paper, we have mainly focused on designing an Advanced Smart Helmet for Off-Road Biking to enhance driver's safety in difficult terrains, curved roads and highways. The helmet is equipped with RCWL sensors, vibration motors, ultrasonic sensors and GPS, which are used to detect vehicles coming from front and rear side and track real-time location of the driver respectively. The RCWL sensors are attached in front and ultrasonic sensors are attached at the back for dual confirmation for the driver. Helmet is attached with highly-efficient components which are being used to have a good detection process so that no mistake happens. Helmet is made by using an IoT-based safety system which ensures that the driver does not face any hectic situation on roads. The system mainly works on low power, has high reliability, lightweight and is made very comfortable to wear. The system promises that there will not be any delay in alerting the driver about the approaching vehicles and improving the overall protection of the driver for safe riding. To further strengthen the solidity of the helmet, it is equipped with a low-power and highly-efficient microcontroller for well-organized usage of power for longer working duration.

Keywords: Smart Helmet, Internet of Things, and Wi-Fi enabled processor, Haptic blind spot monitoring, Helmet-mounted system, Smart safety and emergency systems.

I. INTRODUCTION

The increasing concern for road safety, particularly concerning two-wheeler travelers, presents a significant societal challenge, with accidents often linked to avoidable factors such as reduced situational awareness and delayed emergency response. Recognizing this critical problem, global efforts, including stringent legislative measures like Section 129 of India's Motor Vehicles Act, have increasingly mandated the use of protective headgear, emphasizing the helmet's role as a fundamental safety device. As per World Health Organization (WHO), 40% of the deaths and 70% of severe injuries can be reduced if bike riders wear the helmet [1]. However, while normal helmets offer basic physical protection, they do not inherently address environmental hazards like blind spots, or the need for immediate post-accident intervention. The saddening reality of rising accidents from the absence of prompt medical attention and the lack of an immediate communication channel to emergency services during the "golden hour" post-collision.

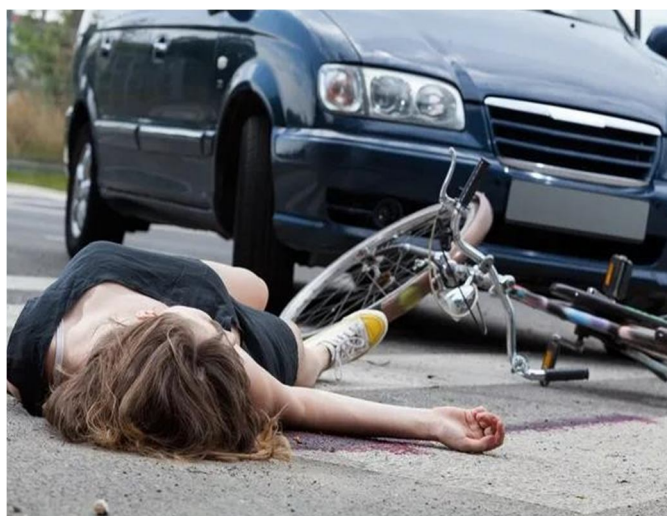


Fig. 1. Road Accident

Addressing these challenges, our project introduces an innovative smart helmet system designed to overcome the capabilities of conventional protective headgear with help of IoT. The Internet of Things (IoT) can provide an infrastructure which integrates the smart services with situational responses, and also allows mutual communication between smart things or devices and people over a network. So, we have come up with this idea of an IoT based smart helmet which ensures the safety of the rider while riding.

We have developed this helmet to enhance rider safety while aligning to governmental road safety regulations. Our smart helmet integrates advanced functionalities for proactive accident prevention and reactive emergency response with ability for corner peeking and blind spot detection. This innovative approach aims to significantly reduce the risk of collisions by providing real-time alerts and ensuring rapid, automated assistance in critical moments, thereby protecting riders from unforeseen dangers and transforming the paradigm of two-wheeler safety in high-risk zones.

II. LITERATURE REVIEW

- 1) "Advanced wireless techniques to avoid accidents on roads through wearing smart helmets" (2021) by Muneshwara M et al. This research put forward a "Smart Helmet" system to ensure driver safety from road accidents. The system makes sure that the vehicle starts only when the driver is wearing the helmet and has not consumed alcohol which is accomplished by the attached sensors in the helmet. GSM Module, in the situation of an accident, sends a quick SMS to his/her relatives and friends about the current geographical location of the driver[1]. This system is integrated to enhance the safety of drivers for the future in case of rules violation.
- 2) "Smart Helmet" (2021) by S. Sobhana et al. This paper put forwards a theory to ensure safe driving for people owning bikes and scooters. Equipped with alcohol detection (MQ3 sensor), helmet present verification (IR Sensor), and accident detections sensors to make sure to prevent drunk driving. Ultrasonic sensors detect upcoming vehicles, GPS/GSM transfers the current location of the driver for emergency concerns[5]. It is also equipped with NodeMCU (ESP8266) for easy and non-breakable communication. Benefits include cost-feasibility, quick messaging process, and accurate location tracking. The goal is to reduce dangers on roads and ensure safety for drivers.
- 3) "Smart helmet using internet of things" (2021) by M. Torad et al. The paper mainly focuses on guaranteeing people's safety on roads while driving and alerting emergency contacts set by them. The system uses piezoelectric sensors to calculate trauma strength with accurate measurement which is transmitted using Bluetooth to an android app[4]. For instance, if trauma crosses the preset limit, the app sends a message and the driver's real-time location to the emergency contacts. The system is equipped with ATtiny85 microcontroller, HC-05 Bluetooth module, and Firebase for real-time data happening. Helmet is feasible and works efficiently. This system targets the protection of drivers.
- 4) "Smart Helmet System for Accident Prevention" (2024) by P. V. Nandhakumar et al. Research focuses on securing safety for drivers. The system is integrated with vibration, accelerometer, pressure and IR Sensor to record real-time data. In case an accident happens, the GPS module is used to locate the driver's real-time position and send alerts using GSM And IoT services to preset emergency contacts[3]. The system is made using Node MCU, C language and Arduino IDE which is feasible in using for any project. Future scope includes additional sensors for efficient safety.
- 5) "Sentinel Safety: Enhanced Safety Helmet for Navigation and Road Safety" (2025) by Ramanath S. et al. The paper focuses on road safety of riders. The system is integrated with MQ3 alcohol sensors, accelerometers, and gyroscopes to detect accidents, speeding of vehicles and consumption of alcohol[2]. Equipped with Deepgram AI for efficient speech-to-text conversion, Gemini AI and Google TTS for methodology and navigation with the help of voice. GPS tracks the current position of the driver and IoT is used for quick alerts and sending SMS to emergency contacts in case of accident. Future scope includes its expansion in industrial works and projects.

III. PROPOSED METHODOLOGY

The proposed system focuses on enhancing the safety of motorcyclists navigating through mountainous terrains, particularly in areas where blind turns and steep curves pose a high risk of collision. The solution integrates multiple sensing and feedback mechanisms to alert the rider about approaching vehicles and rear proximity threats. The system architecture includes motion and distance sensors, a GPS module for real-time location tracking, a vibration-based feedback unit mounted on the rider's helmet, and a central processing unit based on the ESP32 microcontroller. Each component is powered using an external rechargeable battery, enabling standalone operation without reliance on the motorcycle's internal power supply.

A. System Design Overview

The system is composed of five main components: two microwave Doppler radar sensors for forward motion detection, two ultrasonic sensors to monitor rear proximity, a GPS module to track location, four vibration motors to convey alerts to the rider, and an ESP32 microcontroller to manage all processing and control tasks. The sensors are strategically positioned—radar sensors at the front and ultrasonic sensors at the rear of the motorcycle—while the vibration feedback motors are externally mounted on the helmet, targeting different head regions to indicate alert direction. The GPS module, though currently used for local tracking only, lays the foundation for future enhancements such as route logging and wireless data transmission.

B. Forward Detection Using RCWL-0516 Radar Sensors

To identify vehicles or obstacles approaching from blind corners, the system employs two RCWL-0516 microwave radar modules. These sensors emit continuous wave signals and detect changes in frequency caused by moving objects via the Doppler effect. The output signal from each sensor is monitored by the ESP32, which interprets any detected motion as a potential threat. This method is highly reliable even under poor visibility conditions such as fog or low-light environments, where traditional optical sensors might fail. The sensors are angled to cover a broader detection field, increasing the system's ability to detect threats from either side of a curve.

C. Rear Detection with Ultrasonic Sensors

To detect vehicles that come dangerously close from behind, the system integrates two HC-SR04 ultrasonic modules mounted on the rear section of the motorcycle. These sensors operate by emitting ultrasonic pulses and calculating the time interval between transmission and echo reception to estimate distance. When an object, such as another vehicle, enters a defined safety zone (typically within 1 to 1.5 meters), the corresponding data is analyzed by the microcontroller, which then activates the vibration motors on the back of the helmet. This helps the rider become aware of fast-approaching vehicles that may not be visible inside mirrors, especially on curved or narrow roads.

D. Haptic Feedback Using Helmet-Mounted Vibrators

The alert mechanism for the rider is based on haptic feedback using four coin-type vibration motors mounted externally on the helmet—two at the front and two at the rear. When the radar sensors detect motion from the front, the front-mounted motors vibrate. Conversely, detection by the rear ultrasonic sensors activates the rear motors. The vibration alert does not vary in intensity but is enough to gain the rider's immediate attention without requiring visual or auditory input. This approach ensures that the rider remains focused on the road while still receiving timely hazard alerts.

E. Real-Time Positioning via GPS Module

The NEO-6M GPS module is included in the system to provide continuous geographic tracking of the motorcycle's position. It communicates with the ESP32 through serial interface protocols and outputs latitude and longitude values in real time. Although the current implementation does not transmit or store this data, its inclusion serves as a preliminary setup for future enhancements such as data logging, emergency response systems, or mobile application integration. These functionalities can be realized using communication protocols supported by the ESP32, including Wi-Fi or Bluetooth, in later development stages.

F. Processing Unit and Power Supply

At the heart of the system lies the ESP32 microcontroller, chosen for its dual-core architecture, built-in wireless communication capabilities, and compatibility with Arduino development environments. It handles real-time data processing from the radar and ultrasonic sensors and triggers the vibration feedback accordingly. The microcontroller is powered by an external rechargeable battery, making the system independent of the motorcycle's electrical system. This setup not only enhances portability but also allows for ease of installation and testing. Future upgrades may incorporate power optimization strategies to extend battery life, such as enabling sensor sleep modes during inactivity.

IV. TECHNOLOGIES USED

Designing a system to protect motorcyclists on winding, hilly roads isn't just about wiring components together—it's about selecting the right tools for the terrain, the risks, and the speed of reaction required. This project brings together a set of carefully curated technologies, each chosen for what it uniquely brings to the table, forming a cohesive solution that's smart, reactive, and rugged.

A. Frontline Awareness: Microwave Radar in Motion

Navigating blind turns demands a sensor that doesn't blink. Optical sensors struggle in fog or shadows, but microwave radar doesn't flinch. That's why two RCWL-0516 microwave radar modules are positioned at the front. These sensors use the Doppler effect to detect motion, sensing the slightest movement in their path—even when visibility is poor. Their ability to detect through non-metallic materials makes them highly reliable in complex outdoor environments. In this system, they act as a forward shield, constantly scanning for motion around curves and alerting the microcontroller when something—anything—moves into range.

B. Watching Your Back: Ultrasonic Proximity Sensing

Rear-end collisions are especially dangerous on hills, where momentum and brake distances vary wildly. To catch these threats early, two HC-SR04 ultrasonic sensors are mounted at the back. Using sound waves instead of light, these sensors send out short bursts and listen for echoes, calculating distance based on the return time. They're fast, accurate, and simple—perfect for flagging when a vehicle is closing in too fast from behind. In effect, they act as a digital rearview sense, helping the system respond even before the rider notices the threat.

C. Feel the Signal: Helmet-Mounted Haptics

In high-noise environments, sound-based alerts can be missed. Visual ones demand the rider's eyes—something we can't afford to steal. So, the system speaks through touch. Four coin vibration motors are mounted externally on the helmet—two at the front, two at the back. These tiny but powerful motors activate when a threat is detected. The idea is simple: if the front motors buzz, something's ahead; if the back ones vibrate, danger's coming from behind. No confusion, no distraction—just instant awareness.

D. Knowing Where You Are: GPS Integration

While not yet transmitting data, the system is already tracking where the rider goes. A NEO-6M GPS module is embedded into the setup, quietly gathering latitude and longitude. This data can be stored, processed, or sent elsewhere in future versions—think of live tracking, route mapping, or even crash detection systems that send location data to emergency contacts. It's a small module, but it opens the door to big possibilities.

E. At the Core: ESP32 as the Brain

Every detection, every signal, every vibration—it all flows through one central unit: the ESP32 microcontroller. It's the brain of the system, interpreting sensor input and deciding when to alert the rider. It's powerful enough to handle real-time decisions, yet efficient enough to run on a portable battery. And thanks to built-in Wi-Fi and Bluetooth, it's ready for future upgrades—like syncing with a mobile app or uploading ride logs to the cloud. For now, it runs lean and fast, programmed via the Arduino IDE, and doing the hard work of turning raw data into life-saving alerts.

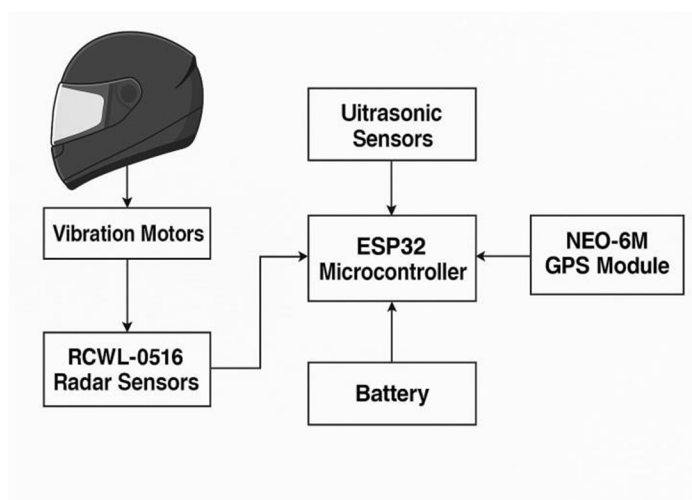


Fig. 2. Block Diagram

chemical sensor and also detects the removal of Helmet by using an IR sensor[6]. It also identifies an incident when miners are struck by an object in contradiction to their head with a high force exceeding a value of 1000 by using the Head Injury Criteria. An accelerometer was used to calculate the acceleration of the head after hit and the HIC was calculated in software.



Fig. 3. ESP 32

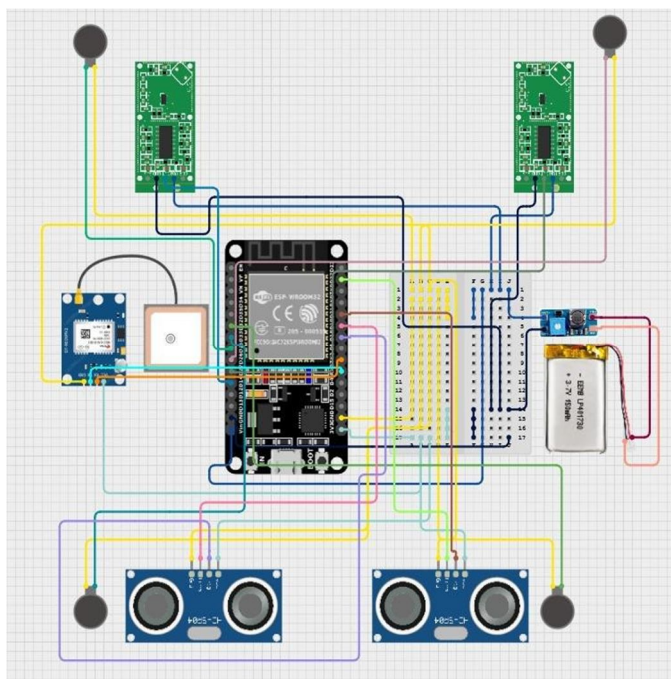


Fig. 4. Circuit Connection

V. COMPARATIVE TECHNOLOGY

In the process of literature survey, we have found a lot of smart helmets with different approaches and with different methodologies. Some Authors had proposed a smart helmet for the mining industry in order to identify hazardous event detection and air quality. This system can identify the concentration level of the harmful gases such as CO, SO₂, NO₂, and particulate matter by using an electro

VI. FUTURE SCOPE

The smart helmet system, equipped with microwave radar sensors, ultrasonic sensors, a GPS module, and an ESP32 microcontroller, offers a strong platform for improving rider safety, especially in complex terrains like curves and ghats. Its features for detecting vehicles from multiple directions and enabling emergency location sharing pave the way for significant advancements. Adding biometric sensors to monitor vital signs like heart rate or oxygen saturation [6] could provide critical health data post-accident.

- 1) **Enhanced Sensor Technologies:** The existing setup uses RCWL-0516 radar and ultrasonic sensors for vehicle detection. Future iterations could adopt cutting-edge sensors like LIDAR or high-definition cameras paired with computer vision to improve precision and detection range. LIDAR could generate detailed 3D environmental maps, identifying vehicle characteristics like size and speed, even in challenging conditions like rain or fog. Adding thermal imaging could further enhance performance in low-visibility scenarios, ensuring robust functionality across diverse settings.
- 2) **Artificial Intelligence and Predictive Analytics:** Integrating artificial intelligence (AI) and machine learning (ML) could transform the system's capabilities. AI algorithms could analyze sensor data to predict collision risks by recognizing patterns in vehicle movements. For example, ML models could distinguish between safe and hazardous approaches, reducing unnecessary alerts. Additionally, AI could enable dynamic decision-making, such as recommending speed adjustments or lane changes based on real-time traffic analysis, fostering proactive safety.
- 3) **Advanced Communication Capabilities:** The current GPS-based emergency location feature could evolve into a broader communication framework. Adding cellular or satellite connectivity would allow instant notifications to emergency services or designated contacts. Implementing vehicle-to-everything (V2X) technology could enable the helmet to exchange data with compatible vehicles, sharing information on position and speed to prevent collisions. Voice-activated interfaces could also be integrated, delivering audible alerts or navigation guidance to enhance user experience.
- 4) **Improved Crash Detection and Health Monitoring:** While the system plans to incorporate impact sensors, future versions could use advanced accelerometers and gyroscopes for precise fall or sudden-stop detection. Adding biometric sensors to monitor vital signs like heart rate or oxygen saturation [6] could provide critical health data post-accident, aiding first responders, particularly in isolated areas where immediate medical support is limited.
- 5) **Sustainable Power Solutions:** The system's 3.7V Li-ion battery with a 5V booster could be optimized for efficiency. Future designs might incorporate solar panels on the helmet's surface or kinetic energy harvesting from rider motion to extend battery life. Wireless charging could also be introduced, enhancing convenience and sustainability for extended use.
- 6) **Augmented Reality (AR) Integration:** Incorporating AR displays into the helmet's visor could revolutionize rider's awareness. AR could project real-time hazard alerts, navigation cues, or vehicle proximity data directly into the rider's view, minimizing distractions. For instance, an approaching vehicle's distance and speed could be visually highlighted, improving situational awareness.
- 7) **Scalability and Market Expansion:** The system's modular design supports scalability for other applications, such as bicycles, scooters, or pedestrian safety in urban settings. Partnerships with helmet manufacturers could enable mass production, making the technology widely accessible. Integration with smart city frameworks could facilitate real-time traffic data sharing, contributing to safer mobility ecosystems.
- 8) **Compliance and Standardization:** As the system advances, aligning with international safety standards and securing certifications will be crucial for widespread adoption. Collaborating with regulatory authorities to establish guidelines for smart helmet technologies could ensure reliability and compatibility, building user and industry confidence.

VII. LIMITATIONS

While the smart helmet system offers various innovative features to enhance rider safety, it also presents certain constraints that need to be acknowledged during development and future refinement.

To begin with, the RCWL-0516 radar sensors used for detecting vehicles from the front may sometimes provide unreliable signals. These sensors are designed to sense motion through microwave reflection but lack the capability to differentiate between objects. Consequently, they may give false alerts for non-threatening movements, such as nearby people, animals, or fluttering leaves. If such alerts occur frequently, riders may begin to disregard them, weakening the overall effectiveness of the system.

Secondly, the rear ultrasonic sensors have detection and environmental limitations. These sensors are generally only effective within a short range and may become unreliable under specific weather conditions such as rain, fog, or dust. In addition, environmental interference and reflective surfaces may impact the accuracy of the readings, making it harder to judge the proximity of vehicles approaching from behind.

Another limitation is the absence of real-time emergency alert transmission. Even though the GPS module keeps track of the rider's location, the current setup does not include a feature to automatically send alerts to emergency contacts in the event of an accident. This becomes a serious drawback, particularly in isolated areas where quick response is crucial. Incorporating GSM, LoRa, or other communication modules could help overcome this gap in future updates.

The entire system relies on battery power, which is another point of concern. It uses a rechargeable lithium-ion cell paired with a voltage booster to supply power to all components. If the battery is drained and not recharged in time, the safety functions stop working. Hence, maintaining adequate power becomes the user's responsibility, and any lapse could lead to system failure during important moments.

From a design perspective, integrating various modules like sensors, motors, wiring, and the power source could increase the overall weight and bulk of the helmet. This may impact comfort, especially during long-duration rides, and could discourage users who prefer lightweight and minimalist gear. The added bulk might also affect helmet balance and fit.

Resistance to environmental elements is also an issue. The current version of the system might not be fully waterproof or dustproof. Exposure to rain or dirt, especially in rugged or off-road use, could result in malfunctions or permanent damage to internal electronics. Therefore, weather-sealed casings or enclosures would be necessary for improved durability.

The vibration-based alert mechanism, while practical, may not always be noticeable. At higher speeds or in noisy environments, the rider might miss these subtle cues. To address this, combining vibrations with visual or audible alerts could enhance the clarity and urgency of warnings. Lastly, the prototype lacks a crash detection mechanism, such as an accelerometer or impact sensor. Without such a feature, it cannot automatically detect falls or collisions and notify help. This limits the helmet's ability to assist in emergencies when the rider is unable to seek help manually.

Overcoming these challenges through future enhancements will greatly improve the system's dependability, comfort, and overall effectiveness in ensuring rider safety.

VIII. OBJECTIVES

To develop intellectual helmet system using the ESP32 microcontroller

- This project aims to use ESP32 boards to control all advanced features of helmets

To activate real-time obstacle detection while riding – Utilizing ultrasonic sensors and RCWL-0516, the helmet will spot obstacles like rocks, other bikes on the road.

To awake rider instantly using haptic response

- When an obstacle is detected, the helmet will vibrate without disturbing the rider perceptually.

To automatically send emergency notification after detecting accident

- If the system senses a prolonged period of immobility, it will send an SOS message through the GPS module.

To merge data from multiple sensors for better accuracy

- Data from all sensors will get processed together to assure more consistent detection.

To carry out energy efficient power management

- This helmet is designed to use power cleverly so it can work for a long time without repeated charging.

To store ride-related data

- The helmet will record useful information like paths where one travels, which can be seen later for safety purposes.

To execute field testing in real off-road circumstances

- The helmet will get tested in a variety of conditions like hills, forests, etc. to ensure its performance.

To integrate all components without exposing comfort – All the electronic parts are placed in a way that keeps the helmet lightweight & protected for the rider.

To assure the helmet works in rough & intense outdoor conditions

- The helmet will be assembled to resist water, dust, and verify reliable operation in rocky terrain.

IX. DISCUSSION

The smart helmet system takes off-road biking safety to the next level by linking radar, ultrasonic sensors, GPS, and haptic feedback. The radar optimally spots objects, obstacles like rocks, trees while ultrasonic sensors measure the distance to obstacles with precision and if obstacles are in range then haptic motors will vibrate. Haptic motors play a key role in notifying the rider through subtle vibrations, ensuring they can respond quickly without relying on sight or sound.

In the unfortunate event of an accident, the GPS module kicks into action—using GPS to pinpoint the rider's location and send an emergency alert to a pre-saved contact. This feature proved reliable in areas with strong GPS connectivity and stable mobile signals. However, like any innovation, the system has its challenges. High power consumption, decreased GPS precision in dense environments, and Dependence on mobile networks for alerts are areas that need improvement. Despite these difficulties, the helmet demonstrated solid performance and promising potential to boost rider safety.

X. CONCLUSION

Ensuring the safety of two-wheeler commuters, particularly in hilly regions and busy city streets, is a significant issue because of reduced visibility, unexpected turns, and erratic vehicle behaviour. Prompt notifications can aid in avoiding accidents that are often caused by these conditions. Our innovative helmet project aimed to tackle these challenges by offering real-time alerts for vehicles and providing clear feedback to the rider.

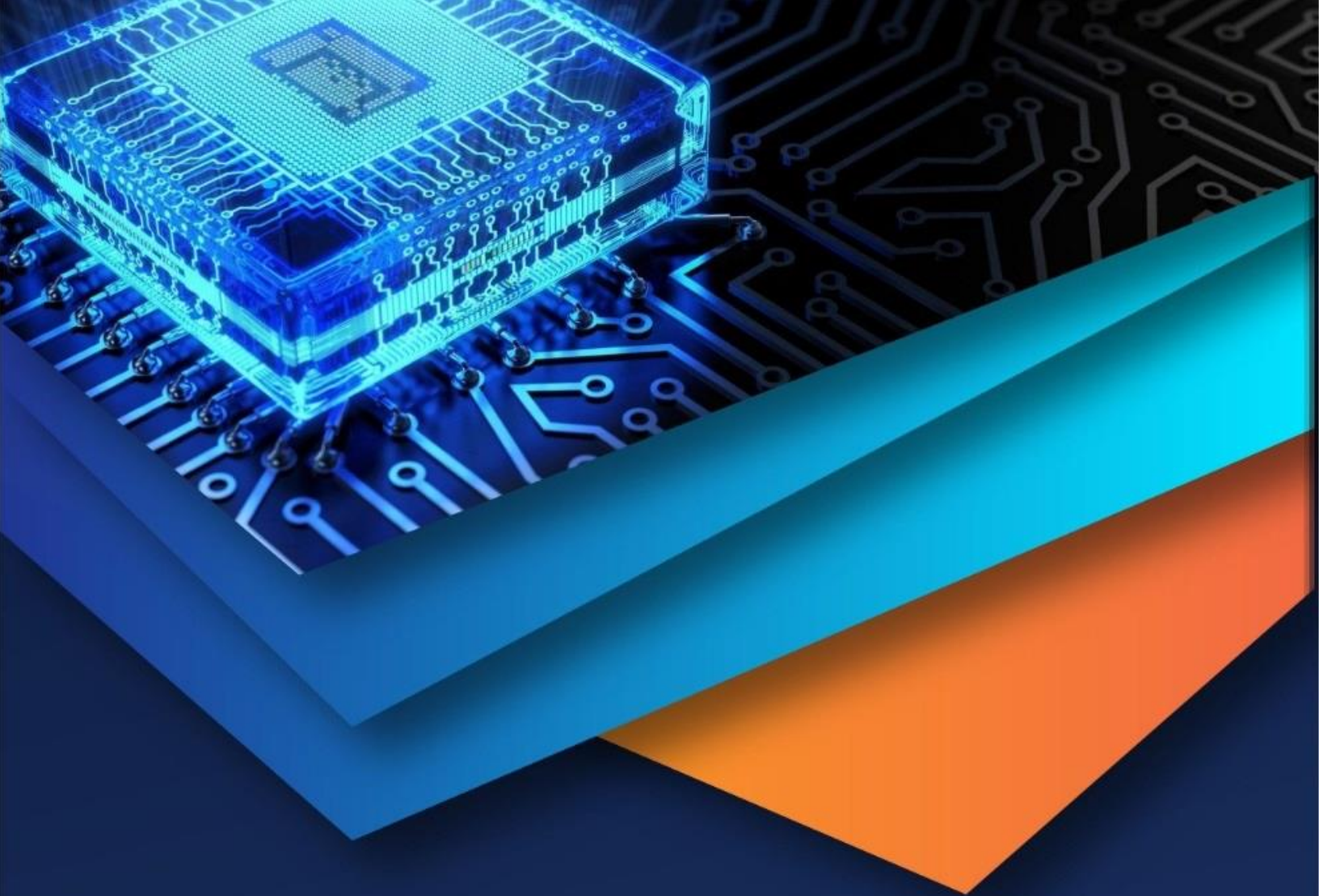
The system includes two rcwl-0516 microwave radar sensors mounted at the front of the helmet, which can detect vehicles approaching from blind turns or curved roads, like those encountered in ghat sections. When the sensors detect movement, they trigger the vibration motors located within the helmet. This tactile feedback immediately notifies the rider of an approaching vehicle, enabling them to react accordingly without taking their eyes off the road. The helmet incorporates two ultrasonic sensors placed at the rear to keep an eye on the surroundings. These devices measure the distance between the rider and vehicles approaching from behind. If a vehicle comes within a 200 cm distance, the rear vibration motor is activated, giving the rider an immediate warning. The feature is advantageous in areas with heavy traffic and a higher chance of unexpected overtaking or rear-end collisions.

The ESP32 is responsible for controlling the helmet because of its exceptional performance, numerous connections, and energy efficiency. It receives input from all sensors and controls the functioning of vibration motors. Additionally, a modern GPS module is integrated into the device to consistently monitor the rider's whereabouts. Although the current implementation primarily focuses on detecting and alerting vehicles, this gps data can also be utilized for future enhancements such as automatic accident reporting and sharing location information with emergency services. The helmet is powered by a 3.7v lithium-ion battery, which is connected to a 5v boost converter. This setup ensures a stable voltage for all the components of the helmet, without adding much weight to it. This ensures usability without compromising on portability and convenience. Through rigorous testing in various real-world scenarios, such as curved roads and controlled traffic environments, it was proven that the system consistently delivers precise and prompt alerts.

The vibration motors generated distinct, perceptible feedback without causing any discomfort or distraction to the user. Additionally, the design of the system is modular, enabling easy expansion by incorporating wireless communication modules or accelerometers for impact detection. In conclusion, the smart helmet offers a practical and scalable solution to enhance rider safety by utilizing real-time sensory input and providing immediate physical feedback. Because it's small, affordable, and works well, it helps lower accidents for motorcyclists by making riders more aware of nearby vehicles, particularly in visually restricted environments. This project demonstrates the impactful use of embedded systems and sensor technology in developing personal safety equipment.

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