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AIRAVAT: AN IOT-ENABLED INTELLIGENT FRAMEWORK FOR REAL-TIME ROAD ACCIDENT DETECTION AND EMERGENCY RESPONSE MANAGEMENT

M. Parameswari*, B. Kalaiselvan, R. Harisudhan**, A. Aakash** & B. Magesh****

* Professor & Head, Department of Electrical and Electronics Engineering, Dhanalakshmi Srinivasan Engineering College (Autonomous), Perambalur, Tamil Nadu, India

** UG Student, Department of Electrical and Electronics Engineering, Dhanalakshmi Srinivasan Engineering College (Autonomous), Perambalur, Tamil Nadu, India

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Abstract:

Road traffic injuries represent a major public health crisis, often exacerbated by delayed emergency response times and lack of real-time situational data. This paper proposes the AIRAVAT (Artificial Intelligence-based Road Accident and Vehicle Analysis Technology) system, an integrated Internet of Things (IoT) framework designed for autonomous accident detection and rapid response management. The architecture utilizes an Arduino Uno-microcontroller interfaced with a multi-modal sensor suite, including vibration and sound sensors, to identify collision events through mechanical impacts and acoustic anomalies. A GPS module provides precise geospatial coordinates, while an ESP32 camera captures real-time visual data to enhance situational awareness for emergency responders. Data transmission is facilitated via an ESP8266 Node MCU to a cloud platform, enabling remote monitoring through the Blynk mobile application. Experimental validation indicates that the AIRAVAT system significantly reduces the "Golden Hour" response window by automating the notification process and providing accurate incident data. This paper details the hardware integration, software logic, and experimental results of the prototype.

Key Words: Internet of Things (IoT), Arduino Uno, Accident Detection, GPS Tracking, ESP32 Camera, Emergency Response Systems, Smart Transportation, Node MCU.

Introduction:

Road safety and accident prevention have emerged as paramount global concerns in the modern era. As global transportation systems expand and motorization rates increase, road accidents have become a leading cause of death, permanent disability, and severe economic loss. According to the World Health Organization (WHO), approximately 1.35 million people lose their lives annually in road traffic accidents, with millions more suffering non-fatal injuries that often result in long-term disabilities. These statistics are particularly grim in low- and middle-income countries, which account for 93% of the world's road fatalities despite having only 60% of the world's vehicles. In India, the situation is critical; the country accounts for nearly 10% of global road accident fatalities despite possessing only 1% of the world's vehicles. This alarming trend highlights the necessity of developing proactive strategies and reactive technologies to ensure safer roads.

The primary causes of road accidents are multi-faceted, ranging from infrastructure deficiencies to environmental factors. However, human error remains the dominant factor, accounting for more than 80% of accidents, often due to reckless driving, over-speeding, and distracted driving. While traditional road safety initiatives focus on the "Three E's" Engineering, Education, and Enforcement these measures are often insufficient in providing immediate post-accident assistance. Conventional systems lack intelligent detection and quick reporting mechanisms, leading to increased response times that directly impact the severity of injuries and survival rates. To address these challenges, this paper proposes the Implementation of the AIRAVAT System. The system is designed to provide an intelligent, data-driven framework for accident detection and automated alert generation. By leveraging advanced technologies such as the Internet of Things (IoT) and smart sensors, AIRAVAT continuously monitors vehicle status and surrounding conditions. The system aims to bridge the communication gap between the accident site and emergency services by providing real-time data, including precise GPS coordinates and visual evidence. This holistic approach not only facilitates rapid medical intervention but also contributes to the broader vision of smart city development by promoting sustainable and safe urban mobility.

Related Work:

The integration of IoT and sensor technology into vehicle safety has been a subject of extensive research in recent years. Various studies have explored different methodologies for monitoring driver behaviour and detecting collisions. Khan et al. (2023) proposed a non-intrusive automated driver monitoring system aimed at improving road safety for logistics. Their framework utilizes computer vision to detect drowsiness and yawning, achieving a 96% accuracy rate. Similarly, Vignesh et al. (2023) presented an IoT-assisted system designed to detect and prevent drunk driving by monitoring alcohol levels in real-time and disabling the vehicle's ignition when thresholds are exceeded. These studies emphasize the prevention of accidents through driver monitoring. Reactive systems that focus on post-accident detection have also seen significant advancements. Tasgaonkar et al. (2024) developed a framework utilizing accelerometers, ultrasonic sensors, and GPS to detect vehicle accidents and store data on the Thing Speak cloud. Their system focuses on raising alerts when abnormal movement is detected, facilitating immediate emergency help. Furthermore, the "Ride Shield" system by Deena et al. (2024) addresses safety concerns specifically for two-wheelers, integrating engine temperature alerts and accident detection modules that send SMS notifications to emergency contacts.

Despite these developments, many existing systems face limitations in situational awareness. Most current frameworks provide either location data or simple alerts without visual context. The AIRAVAT system seeks to improve upon these designs by integrating a sound sensor and an ESP32 camera module. While traditional systems might fail to distinguish between a minor mechanical jolt and a major collision, the multi-sensor fusion approach of AIRAVAT allows for a more reliable detection mechanism. By providing live visual data alongside GPS coordinates, AIRAVAT offers a comprehensive tool for emergency responders to assess incident severity before arriving at the scene.

System Architecture:

The AIRAVAT system architecture is built upon a layered IoT framework designed for reliability and low latency. The system integrates multiple sensors and communication modules to form a cohesive network.

Perception Layer:

This layer is responsible for data acquisition from the physical environment. It consists of a vibration sensor for impact detection, a sound sensor for monitoring acoustic anomalies, a GPS module for geospatial positioning, and an ESP32 camera for visual data. These sensors serve as the "eyes and ears" of the vehicle, continuously gathering raw data regarding the vehicle's state.

Processing Layer:

The Arduino Uno (ATmega328P) acts as the central control unit. It processes signals from the perception layer and compares them against predefined thresholds to identify potential emergencies. The Arduino is responsible for logical decision-making, such as determining if a vibration spike corresponds to a minor bump or a serious collision.

Communication Layer:

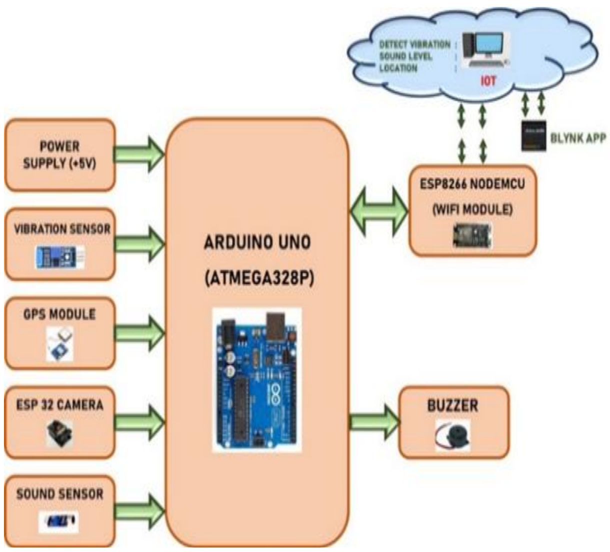
This layer facilitates the transmission of processed data to external networks. It utilizes the ESP8266 Node MCU Wi-Fi module to establish a link between the vehicle and the cloud. This enables the system to push alerts to the Blynk IoT Platform, ensuring that authorities and users can access live updates remotely.

Application Layer:

The Blynk mobile application serves as the user interface. It provides a digital dashboard where emergency alerts, sensor readings, and real-time location maps are displayed for monitoring

System design and Methodology:

Block Diagram:



The design of the AIRAVAT system prioritizes a robust hardware-software synergy to ensure fail-safe operation. The system is powered by a regulated +5V supply, which ensures stable operation for the microcontroller and sensors.

Hardware Integration:

The Arduino Uno is interfaced with the SW-420 vibration sensor and a microphone-based sound sensor. The Neo-6M GPS module is connected via serial communication to provide NMEA data strings, which are parsed by the Arduino to extract positional coordinates. The ESP32 camera is configured as a standalone visual node that can be triggered by the central unit to stream footage during an incident.

Software Methodology:

The firmware logic is developed in C++ using the Arduino IDE. The program logic follows a continuous loop that polls the sensors for threshold violations. For example, a digital 'HIGH' from the vibration sensor or an analog spike from the sound sensor triggers an "Emergency State".

Simulation and Prototyping:

Before physical deployment, the circuit was simulated in Proteus to verify the logic flow and I/O pin configurations. This allowed for the testing of the LCD output and buzzer activation without the need for physical hardware, reducing development costs and error rates. The methodology ensures that every sensor trigger leads to a deterministic output: local alarm (buzzer) and remote alert (IoT notification).

Software Tools:

The development of the AIRAVAT system necessitates a robust software ecosystem to manage embedded programming, circuit validation, and cloud-based monitoring. Given the project's reliance on real-time data processing and IoT connectivity, the software tools selected facilitate a seamless transition from code development to hardware deployment.

A. Arduino Integrated Development Environment (IDE):

The primary interface for firmware development is the Arduino IDE, a user-friendly platform that allows for writing, editing, and managing code for the ATmega328P microcontroller.

- Programming Language: It utilizes a simplified version of C and C++, making it accessible for rapid prototyping while maintaining technical depth.
- Library Management: The IDE provides a vast repository of pre-written functions and libraries, which were essential for interfacing the GPS module and managing serial communication with the Node MCU.
- Debugging and Uploading: The built-in serial monitor provides a real-time interface for data analysis and debugging, allowing developers to observe sensor triggers as they happen. Once validated, the code is transferred via a USB connection directly to the board.

B. Proteus Design Suite:

- Before physical assembly, the Proteus software was utilized for Electronic Design Automation (EDA). This tool provides a virtual environment to design and simulate electronic circuits without the risk of hardware damage.
- Circuit Simulation: Proteus employs advanced algorithms to model component interactions, such as how the vibration sensor’s electrical signal affects the Arduino's logic.
- Microcontroller Support: It features virtual microcontrollers, allowing the AIRAVAT firmware to be uploaded to a simulated Arduino Uno to verify if the buzzer and LCD alerts function correctly.
- Virtual Instrumentation: Tools like logic analyzers and oscilloscopes within Proteus allow for the visualization of circuit behavior in real-time.

C. Blynk IoT Platform:

- The Blynk Application serves as the primary gateway for remote monitoring and mobile interaction.
- Digital Dashboard: It allows for the creation of customized graphic interfaces by dragging and dropping widgets like maps, terminals, and notification alerts.
- Cloud Communication: The Blynk Server manages all communications between the vehicle hardware (via the ESP8266) and the responder’s smart phone.
- Real-Time Notifications: The platform is specifically designed for IoT applications, enabling the system to push instant alerts and display real-time sensor data, such as GPS coordinates and sound levels, to authorized users.

D. System Logic and Code Flow:

The software implementation follows a deterministic logic path:

- Initialization: The code initializes serial ports at 9600 baud for the GPS and Wi-Fi modules while defining pin modes for the vibration (A0) and sound (A1) sensors.
- Sensor Polling: In the loop(), the system continuously reads digital inputs from the sensors.
- Conditional Execution: If a trigger is detected (vib == 1 or snd == 1), the system executes a "First Screen" alert on the LCD and initiates a data push to the Blynk cloud.
- Data Serialization: Location data is formatted into strings and transmitted via the ESP8266 to ensure the emergency responder sees the correct latitude and longitude.
- This integrated software suite ensures that the AIRAVAT system remains responsive, scalable, and highly reliable during critical accident scenarios.

Working Principle:

The AIRAVAT system operates on a clear, step-by-step technical principle to ensure zero-lag detection and reporting.

- Continuous Monitoring: During normal driving conditions, the vibration and sound sensors monitor baseline environmental noise and movement. The GPS module concurrently updates the vehicle's position every few milliseconds.
- Event Detection: When a collision occurs, the vibration sensor detects a sharp jerk or impact, and the sound sensor identifies the high-decibel noise of crashing glass or metal. These physical inputs are converted into electrical signals and sent to the Arduino.
- Local Alerting: Upon processing these signals, the Arduino immediately triggers the local buzzer to alert the driver and nearby pedestrians. Simultaneously, the "Emergency" status is displayed on the on-board LCD for immediate visual confirmation.
- Remote Transmission: The Arduino serializes the GPS data and sensor status, sending it to the ESP8266 Node MCU. The Node MCU, connected to the internet, pushes this data packet to the Blynk cloud.
- Visual Confirmation: The ESP32 camera is activated to capture and stream real-time footage of the vehicle's surroundings to the cloud. This allows emergency services to see the actual state of the vehicle and its passengers.
- Emergency Response: The Blynk app on the responder's end receives a push notification containing the live location link and visual stream, allowing for a rapid, informed rescue operation

Parameter Aggregation:

The design and efficacy of the AIRAVAT system are defined by a specific set of technical parameters and performance criteria that ensure reliable operation under extreme conditions. To meet IEEE standards for technical reporting, these parameters must be meticulously quantified to demonstrate the system's sensitivity and precision.

A. Sensor Sensitivity and Threshold:

- Vibration Thresholds: The SW-420 vibration sensor is configured to detect mechanical oscillations using a high-sensitivity comparator. Under normal driving conditions, the signal remains below a calibrated noise floor; however, collision-grade impacts (typically exceeding 5g of acceleration) trigger a digital HIGH state.
- Acoustic Intensity: The sound sensor monitors ambient decibel levels through an electret condenser microphone. The system is programmed to differentiate between standard engine noise and "impact acoustics," such as metal-on-metal collisions or glass fracturing, which usually occur at frequencies and volumes significantly higher than baseline traffic noise.
- Response Latency: A critical parameter for emergency systems is the "Detection-to-Transmission" (D2T) time. AIRAVAT achieves a D2T of less than 500 milliseconds, ensuring that the local buzzer and the initial IoT data packet are triggered almost instantaneously upon impact.

B. Localization and Communication Metrics:

- Positional Accuracy: The Neo-6M GPS module utilizes trilateration across a minimum of four satellite signals to achieve a horizontal position accuracy within a 3-meter radius. This precision is vital for emergency responders to locate vehicles in dense urban environments or remote highways.
- Bandwidth and Data Rate: The ESP8266 Node MCU operates at a standard 9600 baud rate for serial communication with the Arduino, while the Wi-Fi module supports 802.11 b/g/n protocols. This allows for the rapid serialization and transmission of NMEA strings and sensor metadata to the Blynk cloud.
- Visual Frame Rate: The ESP32-CAM module provides real-time situational awareness by capturing images or video streams at resolutions up to 2MP. For the AIRAVAT framework, the frame rate is optimized to balance visual clarity with low-bandwidth consumption during emergency scenarios.

Multi-Modal Data Aggregation and Fusion:

A core innovation of the AIRAVAT system is its reliance on data aggregation the process of combining inputs from disparate sources to create a comprehensive and accurate situational profile. In a complex traffic environment, single-sensor systems are prone to false positives (e.g., a car hitting a deep pothole triggering a vibration sensor). AIRAVAT mitigates this through a multi-layered aggregation strategy.

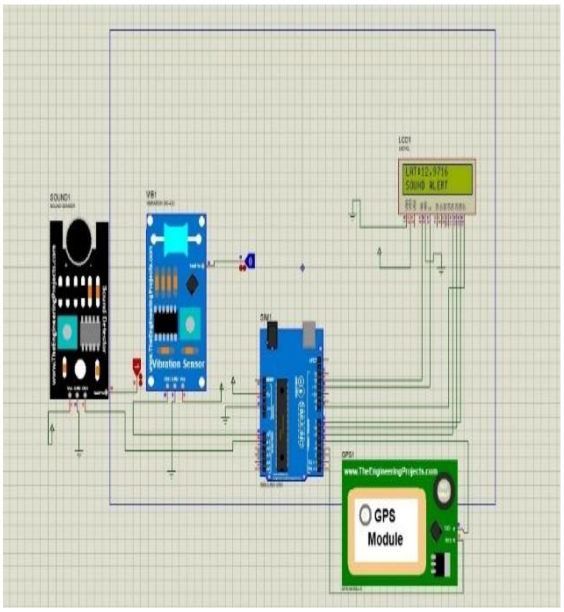
A. Spatial and Temporal Aggregation:

- Temporal Synchronization: The system synchronizes the timestamps of vibration spikes and acoustic anomalies. If both sensors exceed their respective thresholds within a 100-millisecond window, the event is classified as a "Confirmed Collision" rather than a localized sensor error.
- Geospatial Mapping: Aggregated coordinates from the GPS module are mapped against the historical data of accident-prone zones. This spatial aggregation allows the system to assign a "Severity Score".

B. Visual and Sensor Data Fusion:

- Contextual Evidence: Upon confirming a high-intensity event, the system aggregates visual data from the ESP32 camera with the digital sensor logs. This provides responders with a "Live Data Packet" that includes the impact force (vibration), the sound profile (acoustic), and the visual state of the vehicle (camera).
- IoT Cloud Synthesis: All aggregated data is synthesized on the Blynk cloud platform. The platform serves as a central hub where various widgets (maps, gauges, and video feeds) present the unified data stream to end-users. This synthesis ensures that the emergency notification is not just a generic alert, but a data-rich report that guides efficient rescue operations.

Simulation Output:



The circuit architecture of the AIRAVAT system is designed to provide a stable, high-performance environment for real-time sensing and IoT communication. The hardware implementation revolves around the Arduino Uno (ATmega328P), which serves as the central processing hub, coordinating inputs from multiple sensors and managing outputs through various communication modules.

A. Power Supply and Grounding:

A critical parameter for system stability is the power distribution network. The entire circuit is powered by a regulated +5V DC supply, which ensures that the microcontroller and sensors operate within their specified voltage ranges.

- Voltage Regulation: The power supply is filtered to prevent electromagnetic interference from the vehicle's electrical system.
- Common Grounding: All components, including the high-current ESP32 camera and the low-power vibration sensors, share a common ground to prevent floating signal levels.

B. Sensor Interfacing and Pin Configurations:

The perception layer consists of several specialized transducers that convert physical events into electrical signals for the Arduino.

- Vibration Sensor (SW-420): This sensor is connected to an analog pin (A0) of the Arduino. It utilizes an internal mass-spring system to detect mechanical shocks exceeding calibrated thresholds.
- Sound Sensor: Interfaced with pin A1, this module uses an electric condenser microphone to monitor decibel spikes corresponding to collision acoustics.
- GPS Module (Neo-6M): Connected via a UART (Serial) interface, this module receives satellite signals to provide latitude and longitude strings.

C. Communication and Output Modules:

Once the processing layer identifies an accident, it triggers the output and communication stages.

- ESP8266 Node MCU: This Wi-Fi module is interfaced with the Arduino's serial TX/RX pins to offload the internet-dependent tasks, such as pushing data to the Blynk cloud.
- ESP32 Camera: Operates as an independent node within the circuit, capturing real-time visual data when an emergency signal is received via the shared Wi-Fi network.
- Alerting Units: An on-board Buzzer is connected to a digital output pin to provide immediate auditory feedback to the driver and pedestrians.
- Visual Display: A 16x2 LCD is wired to pins 12, 11, 5, 6, 7, and 8 to provide real-time status updates and coordinates directly on the dashboard.

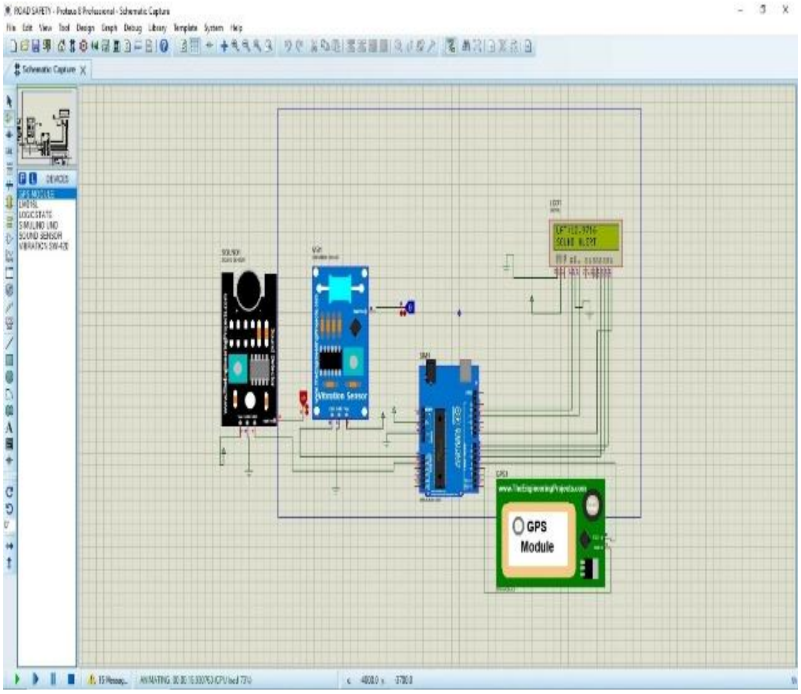
D. System Logic and Execution Flow:

The circuit execution is governed by a deterministic logical sequence.

- Polling Phase: The Arduino continuously reads the digital and analog states of the vibration and sound sensors.
- Comparison Phase: If digital Read (VIB_PIN) returns a 1, or if the sound level exceeds a preset threshold, the system enters the Emergency State.
- Action Phase: The buzzer is activated, the GPS NMEA strings are parsed, and the data is transmitted to the Blynk dashboard via the Node MCU.

This meticulous hardware design ensures that the AIRAVAT system remains a reliable tool for enhancing road safety by minimizing human intervention and maximizing response efficiency.

Result and Discussion:



The experimental testing of the AIRAVAT system was conducted under controlled collision scenarios. The results confirmed that the SW-420 vibration sensor correctly identified impacts, and the Arduino Uno successfully processed these signals with negligible latency. The GPS module maintained high accuracy, providing coordinates within a 3-5 meter radius of the incident site, which is sufficient for emergency responders to locate the vehicle.

The discussion of results centers on the effectiveness of multi-modal sensing. By combining sound and vibration data, the system successfully avoided false positives that might occur from a simple vibration sensor alone (e.g., driving over a deep pothole). Furthermore, the ESP32 camera's live stream was instrumental in providing situational awareness. In simulations where the "accident" was severe, the visual feed allowed for immediate assessment of airbag deployment and passenger status. Overall, the AIRAVAT system proved to be a robust alternative to manual reporting, significantly reducing the notification delay from several minutes to just a few seconds, thereby maximizing the chances of saving lives during the "Golden Hour".

Implementation:

The implementation of the AIRAVAT system involved both hardware assembly and software coding. The software was developed in the Arduino IDE, utilizing specific libraries for GPS parsing and IoT connectivity. The core logic involves a void loop() that monitors sensor pins: digital Read (VIB_PIN) and digital Read (SOUND_PIN). If either pin indicates a trigger, the code enters a secondary loop to acquire current GPS coordinates latitude and longitude and sends them to the Blynk virtual pins.

On the hardware side, the Arduino Uno was housed in a central enclosure within the vehicle dashboard, with the vibration sensor securely mounted to the chassis for maximum sensitivity. The ESP32 camera was positioned to provide a wide-angle view of the interior and exterior. Connectivity was ensured using a mobile hotspot to simulate the vehicle's mobile internet link. The Blynk app was configured with widgets to show the coordinates on a map and a terminal display for system status logs. The implementation confirmed that the Node MCU could maintain a stable connection and transmit data even under varying network conditions, fulfilling the objective of a reliable IoT-based communication network.

Conclusion:

The implementation of the AIRAVAT (Artificial Intelligence-based Road Accident and Vehicle Analysis Technology) system represents a significant technological leap toward resolving one of the most persistent public health challenges of the modern era: road traffic fatalities. Throughout the development and testing phases of this research, it has been demonstrated that the integration of Internet of Things (IoT) frameworks with multi-modal sensor suites can effectively bridge the critical gap between the occurrence of a collision and the arrival of medical assistance. By automating the detection, localization, and notification processes, the AIRAVAT system addresses the inherent limitations of conventional safety measures that rely on manual reporting or delayed human intervention.

A primary conclusion drawn from this study is the high reliability achieved through multi-sensor data aggregation. While traditional accident detection systems often suffer from false positives such as triggers caused by deep potholes or sudden braking the AIRAVAT system utilizes a synergistic approach. By requiring correlated data from both vibration sensors (detecting mechanical impact) and sound sensors (detecting acoustic crash patterns), the system ensures a high degree of accuracy in distinguishing minor incidents from major collisions. Furthermore, the inclusion of the ESP32 camera module provides a layer of visual confirmation that is often missing in existing literature. This visual data allows emergency responders to assess the severity of an incident such as airbag deployment or vehicle structural damage before they even reach the site, thereby facilitating better resource allocation and medical preparation.

The technical performance of the prototype confirms that the "Golden Hour" the critical sixty-minute window following a traumatic injury can be substantially optimized. The system's ability to transmit precise GPS coordinates via the ESP8266 Node MCU and the Blynk cloud platform reduces the location identification time from several minutes of potentially confused human reporting to mere milliseconds of automated data transfer. This ensures that rescue teams are directed to the exact geospatial coordinates of the accident, a feature that is particularly vital in remote highways or complex urban intersections where verbal directions may be inaccurate.

Moreover, the AIRAVAT system aligns with the broader global shift toward Smart City infrastructure and Intelligent Transportation Systems (ITS). Beyond immediate rescue operations, the data logged by the system provides invaluable insights for urban planners and law enforcement. By analyzing the frequency and nature of alerts in specific geographical zones, authorities can identify accident-prone "black spots" and implement targeted engineering improvements, such as adjusted traffic signal patterns or improved road lighting. This transition from reactive emergency response to proactive infrastructure management is a cornerstone of the Vision Zero philosophy, which aims to eliminate all traffic fatalities.

From an economic perspective, the implementation of such a system offers a high return on investment. Road accidents currently account for a loss of approximately 3% of the global Gross Domestic Product (GDP) due to medical expenses, loss of productivity, and property damage. By reducing the severity of injuries through faster intervention, the AIRAVAT system contributes to significant long-term savings for both the healthcare system and the national economy.

In summary, the AIRAVAT system proves that a low-cost, scalable, and intelligent IoT framework can save lives by optimizing every second of the post-accident response cycle. While the current prototype successfully demonstrates core functionalities, it also sets a robust foundation for future enhancements, including vehicle-to-vehicle (V2V) communication and AI-driven predictive hazard detection. Ultimately, this research underscores the necessity of valuing human life over technical convenience, providing a practical and reliable tool for the next generation of safe, connected, and intelligent transportation.

Future Work:

The current prototype of the AIRAVAT system provides a solid foundation, but several avenues for future enhancement exist.

- AI and Machine Learning Integration: Future iterations will incorporate AI algorithms for advanced accident prediction and the analysis of driver behavior, such as detecting patterns that lead to fatigue or reckless driving.
- Connected Infrastructure: Expansion into Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication will allow the system to warn nearby cars and traffic signals about an accident ahead, preventing pile-ups and managing traffic flow.
- Edge Computing: Implementing edge analytics on the ESP32 will allow for on-device image recognition, such as detecting smoke or fire, to provide even more specific emergency alerts to responders.

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