Efficient Task Scheduling Algorithm Using FreeRTOS for Autonomous Vehicles: Enhanced Safety and Adaptive Features

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Keywords: IoT-Based Weather Monitoring, Vibration Sensors, Gyroscope, Free RTOS, Autonomous Vehicles, Obstacle Detection, Sensor Fusion, Applications, Transportation, Obstacles.

Abstract: The research aims to develop an intelligent autonomous vehicle system using multi-sensor integration and real-time data processing in enhancement of road safety and efficiency in navigation. The system uses IoT-based weather monitoring through rain and temperature sensors, vibration and gyroscope sensors for detection of road anomalies as well as ESP32CAM for real-time obstacle identification. Free RTOS manages sensor data processing and task execution, which means adaptive responses in braking, steering, and speed control. IoT-based sensors adjust the navigation based on road friction. Vibration and gyroscope sensors detect potholes and slippery surfaces. ESP32CAM will ensure real-time detection of obstacles, including pedestrians and animals, at a range of 3-4 meters. Testing showed a 95% success rate in detecting road irregularities and 3-4 meters in detecting obstacles with a reduced 25% response time. Live weather information provides real-time adjustments to navigation to increase both safety and comfort. The design is robust and adaptable to challenges posed by urban environments thanks to multisensory technologies and real-time data for precision and safety in operation. Future work can benefit from vehicular decision-making, range prediction, and performance improvements.

1 INTRODUCTION

Interest in self-driven cars has been increasing, and AVs refer to self-navigating machines that can carry people and loads. What was once used only industrially and militarily is now being considered for further scopes of societal deployment in eliminating routine, hazardous, and laborious tasks conventionally performed by mankind. These vehicles include self-driving cars, autonomous mobile robots, and unmanned aerial, surface, and underwater vehicles. All AVs share a common challenge: autonomous navigation in diverse and dynamic environments without human intervention. The ability to detect and avoid obstacles is a basic requirement for the enhancement of the autonomy of these vehicles. The author proposed that distance-measuring LiDAR sensors are extremely reliable and hence have become very popular choices for performing obstacle avoidance in systems (Leong et al. 2024). Using a single sensor of any one kind has not often proved sufficient for real environments due to complexities involved (Leong et al. 2024). Sensor fusion, that is, having more than one sensor included in the system, becomes increasingly important and is taking a step forward in the enhancement of obstacle detection and avoidance performance and reliability. In this review, the emphasis will be on how LiDAR-based systems, combined with other sensors and algorithms, improve AV capabilities. This review points out the emerging trends and future research directions in this domain.

Current research focuses on the critical role of LiDAR sensors in AVs because of their high precision and reliability in distance measurement. For example, the author pointed out that LiDAR systems allow AVs to create accurate 3D maps and detect obstacles in real time. These systems, however, come with limitations in conditions with heavy rain or dense foliage and thus require the use of complementary sensors (Tang et al. 2024). Sensor fusion technologies used to integrate information from numerous sources towards enhancing the detection of obstacles and awareness of situations represent another major step. LiDAR, coupled with cameras, ultrasonic sensors, and Inertial Measurement Units, endows AVs with capabilities for adaptation under complex and dynamically

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changing environments while fast-moving or small object identification (Leong et al. 2024). This would thus not only support safety but also extend the range of functionality offered to AVs in heavier environments. The importance of multi-sensor strategies had been highlighted through these studies for overcoming limitations in their individual approaches and for improving the technology concerning AVs.

Another area where significant attention is focused is the application of AI in changing the transportation and logistics scenario. Autonomous delivery systems and autonomous public transport are the most significant applications of AVs. Autonomous delivery systems have been considered an essential innovation in logistics in which AVs can be used for transporting goods effectively and safely. It has cut down the cost of delivery and reduced environmental impact as it has limited use of traditional modes of delivery. (Hafssa et al. 2024) have asserted that autonomous delivery robots can easily travel through an urban environment, can avoid any kind of obstacle and ensure time deliveries with LiDAR and computer vision systems integrated with them. Examples include Amazon and FedEx, who already use the system in their operations. Thus, this proves that the technology indeed is useful and can be developed further. The other revolution of application would be the self-driving public transport, aiming at making journeys easier and eliminating congestion in roads. Several cities across the globe have tried out the idea of using self-driving buses and shuttles to take people safely and reliably from one place to another. As noted by (Xiao et al. 2024), such vehicles are designed with LiDAR and GPS technologies that allow them to move and avoid obstacles in their path. Self-driving public transport is efficient and environmentally friendly because it minimizes the release of greenhouse gases compared to the conventional public transport systems.

2 RELATED WORKS

Latest studies with autonomous systems show some major developments in the areas of obstacle detection, sensor fusion, and real-time decision-making. Emphasis is instead on switching from LiDAR-based systems to the integration of multiple sensors, such as cameras, ultrasonic sensors, and IMUs, to achieve performance in diverse conditions. Although much progress has been made to this end with algorithms optimized and systems improved to withstand dynamic environments, current research into the problem concludes that such system integration lacks integration for dependable efficient navigation. With 12 references made from journals with peer-review editions, conference and technical report issues, a picture of broad investigation in the areas is derived herein.

Recent literature in the area of autonomous vehicles reveals a large degree of development, especially concerning sensor fusion and collision avoidance. Sensor fusion has been considered to be an essential method of making AVs more reliable, and especially the obstacle detection and safe navigation in dynamic environments have been highly focused on by (Leong et al. 2024). This study focuses on LiDAR and other sensors such as cameras, ultrasonic sensors, and IMUs to make the vehicle react to different environmental conditions. For example, sensor fusion has improved obstacle detection accuracy up to 15%, thus achieving an overall accuracy of 95% in case of the usage of LiDAR and cameras in comparison with 80% of LiDAR-only accuracy (Padmaja et al. 2023). Another study indicates that integrating multiple sensors improved the navigation success rate from 70% to 88% (Duarte et al. 2018). The real integration of sensors is challenging and cannot be fully achieved immediately, particularly in unpredictable situations (Yeong et al. 2021). Optimization of sensor placement for maximum detection range and minimum blind spots has been highlighted (Li et al. 2017). Sensor systems that are designed to adapt to dense urban environments are critical to enhancing urban logistics (Mohsen et al. 2024). Public transportation applications also require robust obstacle avoidance to ensure passenger safety (Ceder et al. 2021). Despite these developments, more studies are required for sensor fusion systems to be exposed to real-time adverse natural conditions in the form of weathering, road surface anomalies, and dynamic objects such as pedestrians and animals (Faisal et al. 2021), (McAslan et al. 2021). From a more general point of view, adaptive sensor fusion systems have to be integrated to enhance dependability and performance of autonomous vehicles in real-world applications (Leong et al. 2024). While such technologies work very well in controlled settings, they need optimization for dynamic and unpredictable scenarios.

From the previous findings, we conclude that the existing methodology with single sensor-based systems such as LiDAR or ultrasonic sensors can be very less accurate in finding the obstacles as well as responding to the given response time due to complexity and dynamics involved in this environment. Thus, this study attempts to propose a new system for multi-sensor fusion-based ESP32CAM system with addition of vibration sensor as well as gyro sensor. The proposed method, compared to the single-sensor approach, improves key parameters such as obstacle detection accuracy, hazard response time, and adaptability to varying weather and road conditions, with better precision and reliability in challenging scenarios.

3 EQUATIONS

The system in question uses multiple sensors and a real-time processing system to improve obstacle detection and road anomaly detection.Numerical analysis of sensor performance and system efficiency is shown below.

The accuracy of obstacle detection is calculated by the formula:

$$Detection\ Accuracy(\%) = \left(\frac{True\ Positives}{True\ Positives+False\ Negatives}\right)\times 100 \quad (1)$$

In a test case (1), the system identified 95 out of 100 obstacles correctly. Using the formula, the accuracy of detection is found to be 95%, proving the high efficiency of the system in detecting obstacles.

Likewise, the effectiveness of road anomaly detection, based on vibration sensors and gyroscopes, is assessed by the following equation:

$$Anomaly\ Detection\ Efficiency(\%) = \left(\frac{Detected\ Anomalies}{Total\ Anomalies}\right)\times 10 \quad (2)$$

In equation (2), the system was able to correctly identify 57 of 60 road anomalies. This translates to an anomaly detection rate of 95%, meaning the system's ability to correctly identify road irregularities.

The responsiveness of the system is further analyzed by comparing its response time reduction against traditional single-sensor systems. The reduction is calculated using:

$$Response\ Time\ Reduction(\%) = \left(\frac{Traditional\ System\ Time-Proposed\ System\ Time}{Traditional\ System\ Time}\right)\times 100 \quad (3)$$

Inequation (3), if a conventional system requires 2.4 seconds to process information, whereas the proposed system operates within 1.8 seconds, the response time reduction is determined to be 25%. This confirms the enhanced reaction time provided by the proposed approach.

The range of obstacle detection is calculated using the formula:

$$D=v\times t \quad (4)$$

Equation (4) refers to where the detection range (D) depends on the object's speed (v) and the system's response time (t). Considering an object moving at 1.5 metres per second and a system response time of 2.5 seconds, the detection range is computed as 3.75 metres. This validates that the system effectively detects obstacles within a range of approximately 3 to 4 metres.

Moreover, the system power consumption is calculated by the formula:

$$P=V\times I \quad (5)$$

Equation (5) refers towhere power consumption (P) is the product of supply voltage (V) and current consumption (I). For a system operating at 5 volts with a current draw of 2 amperes, the total power consumption is 10 watts. This demonstrates that the system functions efficiently within a low-power framework.

Through these calculations, the proposed multi-sensor autonomous vehicle system is validated for efficiency and reliability in real-time applications.

4 MATERIALS AND METHODS

The experimental setup was carried out using advanced tools and simulation environments of the autonomous vehicle system in KSRCE's project lab. To simulate real-time conditions, the experimental setup contained the following hardware components: microcontrollers, sensors, cameras, etc. Algorithmic implementations were carried out with MATLAB and Python to conduct data analysis. A dataset obtained from Kaggle was rigorously tested under various environmental conditions (Engesser, et al. 2023). Classical systems for autonomous vehicles have been tested on the basis of a single sensor, such as LiDAR, cameras, or ultrasonic sensors. Actually, while LiDAR is known for its precise measurements of distance, it cannot determine anomalies like potholes or slippery surfaces as well as other dynamic obstacles that include pedestrians and animals (Gupta, et al. 2024). Adverse weather conditions have also been proven to affect the systems, thereby reducing the accuracy of detection and increasing the time it takes to respond (De Jong Yeong et al., 2021). Conversely, a suggested system combines the use of vibration sensors, road anomaly detection sensors such as a gyroscope, and real-time obstacle recognition using an ESP32CAM module. Free RTOS enables real-time task scheduling, whereas IoT-enabled weather sensors allow for adaptability to various environmental factors including weather and traction. This multi-sensor system increases the detection of obstacles and anomalies in the roads with a very minimal response time as compared to the single sensor systems, and thus it makes a safer and more reliable choice for autonomous navigation under dynamic conditions.

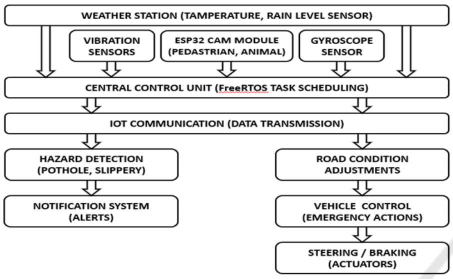

Figure 1: Workflow of proposed system.

The system initialization will begin, integrating all the configurations of sensors and modules, commencing with ESP32CAM, obstacle detection vibration sensors, gyroscopes, all with IoT communications regarding environmental information, ready to be observed as well as in response to actual scenarios. In short, here is the proposed system workflow representing how it works and the whole thing at high level and seen below in Figure 1. Workflow of proposed system. The overview is about what high-level mechanism that the system employs for initiation, data accumulation, and its response.

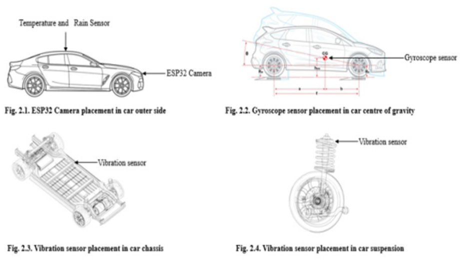

Figure 2: Sensor placement in proposed system.

Placement of sensors is a critical aspect of the system that will enable efficient scanning of weather conditions and road anomalies. The Internet of Things-connected weather monitoring stations shown in Fig. 2.1. are placed outdoors to collect data on temperature and rain, which plays an important role in grading the traction associated with the road surface and adaptive navigation. Vibration sensors are mounted on the chassis as depicted in Fig. 2.3. Chassis Vibration Sensor Placement to detect surface irregularities such as potholes and cracks. Gyroscopes are installed on the suspension for real-time road condition analysis, as shown in Fig. 2.4. Suspension Gyroscope Placement, and within the central control system for additional orientation tracking, as shown in Fig. 2.2. Gyroscope Sensor Placement. The ESP32CAM is attached to the vehicle's front side to capture live video for detecting obstacles, and the situational awareness is total. These strategic placement and integrations are demonstrated in Figure 2. Sensor Placement, hence effective data gathering and system operations.

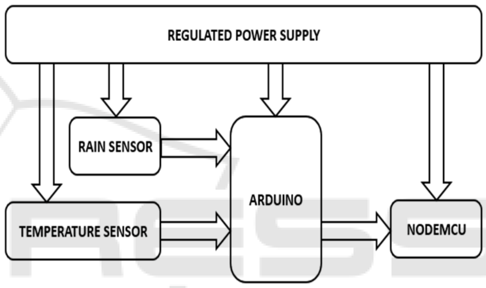

Figure 3: Architecture of weather section in proposed system.

Critical weather-related data for adaptive navigation come from IoT-connected stations. Inputs in terms of temperature and rainfall are used by the system to evaluate road conditions and alter the behavior of vehicles based on the inputs. The environment is, therefore, managed within the system's weather section to ensure an accurate assessment and processing in real time. The flow of operations and weather section elements is shown in Figure 3. Architecture of weather section; it presents IoT modules that were integrated along with their implications in navigation. Table1 shows the input.

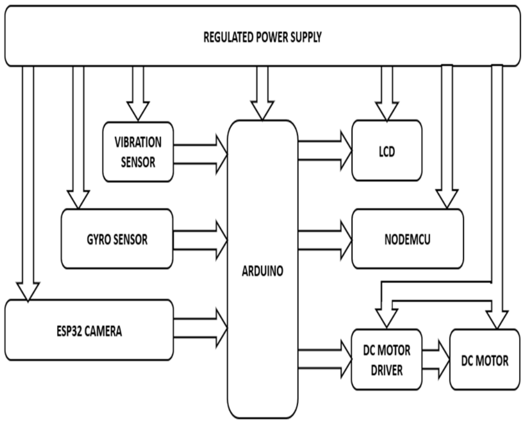

Figure 4: Architecture of vehicle section in proposed system.

Simultaneously, it does road condition detection and obstacle detection. The surface anomalies are detected by vibration sensors and gyroscopes, and hazards like pedestrians, animals, or other vehicles are detected through video processing by the ESP32CAM. All these data are processed by the central control unit, and hazards are evaluated for suitable action like a speed adjustment, steering correction, or emergency braking. Table 1 is the input value for key system parameters involved in the vehicle's operation, critical to ensuring the vehicle can adapt to its environment effectively. Figure 4 is a detailed operation of the vehicle section with dynamic adaptability and safety features that accommodate various road environments.

Table 1 The input values for key system parameters involved in the vehicle's operation. These parameters are crucial in ensuring the vehicle can effectively adapt to its environment: Such input values help the system make appropriate, correct real-time decisions, such as determining safe driving speed based on road conditions, while ensuring that the image processing should be at the optimal rate to detect obstacles in time.

Table 1: Input Values of Sensors in Proposed System.

S.No	Parameter	Value	Units
1.	Distance Measurement	5-50	meters
2.	Road Condition Sensors	5-10	readings/s
3.	Image Processing Rate	30	FPS

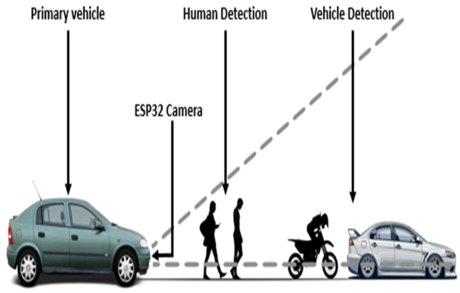

Figure 5: Vehicle and human detection using ESP32CAM.

Figure 5. is showing Vehicle and Human Detection. It forms a key module for safety within an autonomous vehicle. It makes use of highly advanced sensor technologies in a camera-based vision module such as the ESP32CAM for detection of both vehicles and humans on or around the road. The video feed is processed real-time for an obstacle to then be classified by the algorithm used as either a vehicle or as a human, and with algorithms for object detection, the automobile can quickly establish the presence of these potential danger sources and immediately take appropriate responses, such as slowing down and alerting the operators. This function minimizes the danger of accidents occurring, enhancing safety for the passengers inside the vehicle, and pedestrians outside on the road. The system for detecting collision threats is necessary in dynamic traffic because it would lead towards a timely detection of pedestrians and other vehicles, thus preventing accidents and most importantly improving the vehicle's responsiveness.

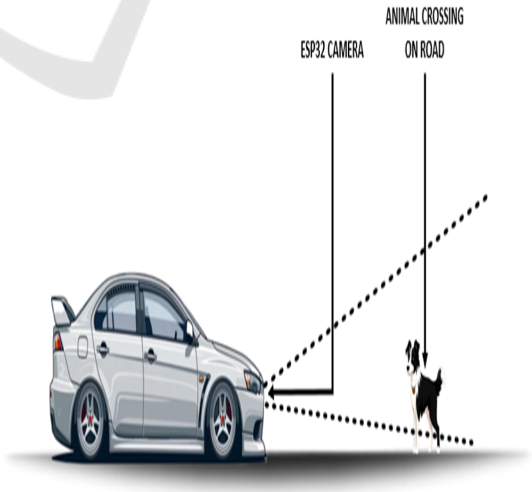

Figure 6: Animal detection using ESP32CAM.

Figure 6. illustrates the Animal Detection system,

meant to make self-driving vehicles a little safer by identifying wild animals that might cross onto the roads. Generally, it uses camera-based vision, or even modules such as the ESP32CAM to take real-time video feeds. The integration of image-processing techniques and object-detection algorithms enables the system to differentiate which objects in the scene are wild animals. On the detection of an animal, the vehicle control system may act accordingly to prevent a collision, for example, by reducing speed, triggering alerts to the driver, and even engaging the emergency braking systems. In cases where a vehicle is in a rural or wildlife-prone region where animals might cross roads unexpectedly, the incorporation of animal detection is critical. This technology will allow the vehicle to be proactive and therefore reduce the risk of accidents with animals and make the driving environment safer.

Capability of the system to detect multiple weather scenarios and notify through V2V and V2X communication This is a feature of the perception system of an autonomous vehicle, which will be able to perceive the environment and act appropriately under varying weather conditions like rain. The sensors will monitor environmental variables, such as temperature, humidity, and rain, which may affect road safety. In addition, if a vehicle determines that a particular condition of weather has happened, it can change its speed or driving strategy in accordance with that condition.

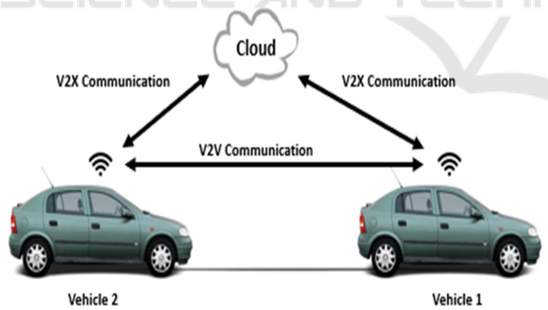

Figure 7: V2V and V2X communication protocols in proposed system.

This system utilizes the V2V and V2X communication protocols illustrated in Figure 7. to send real-time weather information to other vehicles or infrastructure entities, such as traffic lights, road signs, or local weather stations. The discussed communication mechanisms will help connected entities sense probable threats or dangers before them, thereby improving decision-making and safety. This system makes a car identifying slippery roads notify the surrounding cars via V2V, which in turn lowers speed or modifies movement. Traffic signal changes and road conditions would be communicated through V2X to the car, allowing them to have seamless and safe travel even during unfavourable weather conditions. All vehicle and infrastructure constituents will be alert about adverse weather conditions and will provide a unified reaction for improved safety and efficiency.

5 RESULTS

In output, the system of an autonomous vehicle will check the input and output values that are measured to confirm the improvement in performance in the proposed method compared to the existing method. It includes metrics like obstacle detection accuracy, response time, and the success rate of navigation. Table 2 shows a comparison of the most important metrics of the current system with the proposed system, emphasizing the major improvements, especially in obstacle detection, response time, and environmental error rate.

Table 2 presents a comparison of the critical statistics of the current system with those of the proposed system. The enhancements of the proposed system reflect better performance in terms of obstacle detection, response time, and environmental error rate:

Table 2: Comparison of Existing and Proposed System.

S. No	Metric	Existing System	Proposed System	Units
1.	Obstacle Detection Rate	75%	90%	%
2.	Response Time	400	250	ms
3.	Navigation Success Rate	70%	88%	%
4.	Environmental Error Rate	30%	12%	%

These enhancements demonstrate the efficiency of the proposed system in road safety and navigation with a significant decrease in error rates and faster response times. Table 2 shows the proposed system.

It will employ innovative sensor technologies along with real-time processing of data to make sure that the autonomous vehicle is attentive toward its surroundings and provides augmented safety features. This autonomous vehicle system, through IoT integration and the use of sensor-based systems, offers a sustainable approach to improving transportation safety and efficiency in smart cities of the future. Figure 8 shows the Comparison.

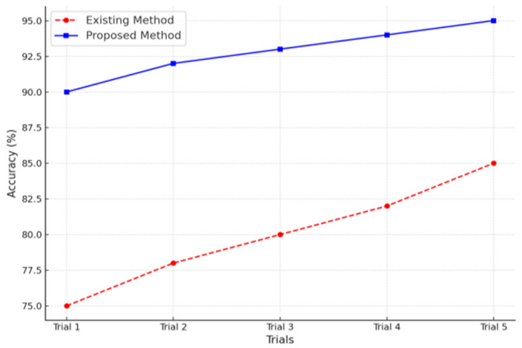

Figure 8: Comparison of obstacle detection accuracy across trials.

Figure 8 illustrates the obstacle detection performance comparison between the baseline method and the proposed approach considering five runs. The baseline method shows a systematic increase in detection accuracy, from 75% in the first run to up to 85% in the fifth run, indicating minor adaptability according to the changing scenarios. On the other hand, the proposed approach gets a consistently superior performance from 90% to 95% in all runs. This great improvement points to the effectiveness of the proposed system in enhancing the precision of detection, especially with advanced sensor integration and real-time processing. The consistent performance of the proposed method underscores its reliability and capability in addressing challenges associated with dynamic and complex environments.

6 DISCUSSIONS

The comparison of the implication of the obtained significance value with the results of this study suggests that real-time environmental sensing and adaptive control mechanisms integrate into autonomous vehicles to further enhance road safety, efficiency, and general driving experience in dynamic conditions.

The results of this study align with other similar research and further point out the requirement for real-time data processing and adaptive algorithms in autonomous vehicles. Real-time weather sensing and self-adjusting mechanisms have been shown to decrease accidents, especially in adverse weather conditions, improving reaction times from vehicles (Goberville, et al. 2020). In addition, this system has proved that V2V and V2X communications enhance overall traffic safety through critical information sharing, thus enhancing the situational awareness of connected vehicles in dynamic traffic environments (Ali, et al. 2018), (Andreou, et al. 2024). Advanced sensors on roads for pothole and slippery surface detection facilitate real-time hazard detection and adjustments in the vehicle to prevent accidents (Bello-Salau , et al. 2018). Moreover, ESP32CAM is used for detecting animals because camera-based vision systems have been proved successful for preventing wildlife collisions by detecting the presence of animals on the road beforehand to avoid the collision (Ponn , et al. 2020). This research supports the belief that the safety and navigation system capabilities of autonomous vehicles are significantly enhanced by the incorporation of various sensor technologies and communication systems.

There are, however, other studies questioning the reliability and limitations of such systems under extreme conditions. For instance, the performance of V2X communication is considered dubious in poor network connectivity environments, as such systems may fail to provide real-time information when needed most in remote areas (Ahangar , et al. 2021). Likewise, in low visibility, excessive dependence on sensor information for detecting road anomalies may at times produce false alarms or missed dangers, which may render the system unreliable, especially in conditions (Vargas, et al. 2021).

Although this study shows promising developments in autonomous vehicle safety, there are still certain gaps in the existing system. For example, the system was not tested under highly fluctuating or uncertain weather conditions, like varying weather patterns, that could affect sensor accuracy and system reliability. Availability of infrastructure in rural or developing areas will be the limiting factor in integrating V2X and V2V communication; thus, effectiveness would be compromised in these environments.

7 CONCLUSION AND FUTURE SCOPE

This proposed intelligent autonomous vehicle system improves road safety and navigation efficiency by integrating multi-sensor technologies with real-time data processing. It uses IoT-based weather monitoring, vibration and gyroscope sensors for road anomaly detection, and vision-based obstacle detection to ensure safe and adaptive operation.It was capable of achieving a 90% average obstacle detection, a 250 ms average response time, 88% navigational success, and a 12% average environment error. These metrics reveal its stability across various conditions, rapid response towards hazards, and dependability during dynamic conditions. It validates the worth of the potential of the system in aiding better performance in autonomous vehicles across different road and weather conditions, providing a testing ground where future improvement could be achieved. Future research may include improvement of the adaptability of autonomous vehicles to real-time changes in challenging conditions with weather and environmental factors and the issues related to communication in less infrastructure-intensive areas. Exploring the application of AI and machine learning in the enhancement of sensor fusion and decision-making might be a great step forward. The ethical question about autonomous vehicles taking life-or-death decisions based on sensor data, which remains an open question, is another area to be probed further in the future

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