

Smart Terrain-Aware Navigation: An Embedded Robotic System for Obstacle Avoidance and Surface Detection

Kadari Bhuvaneshwari

B. Tech, (ECE), Stanely College of Engineering and Technology, Hyderabad.

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Abstract: This paper presents the creation of an economical, self-sufficient mobile robot intended for real-time obstacle avoidance and detection of uneven surfaces, ensuring safe and efficient navigation in unstructured settings. Constructed on the Arduino Uno platform, the system incorporates an HC-SR04 ultrasonic sensor for proximity-based obstacle detection and an MPU6050 accelerometer/gyroscope module to identify surface inclinations and irregular terrains. Additionally, the robot features an L298N motor driver that facilitates precise movement control, while a 16×2 LCD module offers ongoing feedback regarding system status and environmental conditions. The approach includes sensor fusion, modular hardware integration, and embedded software design, enabling robust decision-making and real-time adaptability. Experimental assessments reveal the system's capability to navigate various terrains and avoid obstacles with minimal latency and high precision. The design's modularity, cost-effectiveness, and ease of deployment render it suitable for numerous applications, such as industrial automation, educational robotics, exploration, and disaster response. The findings highlight the potential of integrating obstacle avoidance with surface detection within a cohesive framework to improve autonomous robotic mobility in intricate real-world situations.

Keywords: Autonomous Navigation, Obstacle Avoidance, Uneven Surface Detection, Arduino Uno, Ultrasonic Sensor, MPU6050 Accelerometer.

I. Introduction

Incorporating autonomous mobile robots (AMRs) into industrial, exploratory, and emergency-response activities has seen remarkable growth in recent years, fueled by advancements in embedded systems, sensor technologies, and artificial intelligence. These robots are engineered to navigate through dynamically changing environments without human intervention, allowing for safer, more efficient, and scalable task execution across various sectors (Patel et al., 2020). Although significant strides have been made in obstacle avoidance technologies, primarily through ultrasonic, infrared, and LIDAR sensors, there has been relatively little focus on the complementary issue of surface detection and terrain adaptability.

Robots in real-world settings often encounter irregular, inclined, or unstable surfaces. The inability to detect and adjust to such conditions can lead to stability loss, navigation failures, or even hardware damage. The lack of integrated surface-awareness systems restricts the practical use of many obstacle-avoidance robots in high-risk or unstructured environments, such as disaster zones, industrial facilities, and outdoor terrains. Therefore, this study is prompted by a significant gap in the current literature and implementations: the absence of unified systems that can both avoid physical obstacles and detect terrain irregularities in real time.

This research seeks to fill this gap by developing a cost-effective modular robot using open-source hardware to integrate obstacle avoidance and uneven surface detection capabilities. The system is based on the Arduino Uno microcontroller. It incorporates an HC-SR04 ultrasonic sensor for detecting nearby obstacles, an MPU6050 accelerometer/gyroscope for measuring surface tilts, and an L298N motor driver to ensure smooth and responsive movement control. A 16×2 LCD module provides real-time feedback to users regarding the robot's operational and environmental status.

The uniqueness of this project is found not only in its dual-capability design but also in its focus on affordability, modularity, and practical usability. By employing accessible components and simple implementation techniques, this research makes robotics research and education more accessible. Furthermore, its results have broader implications for scalable deployment in settings where obstacle avoidance and terrain adaptability are essential for mission success.

Consequently, the study tackles a significant research and engineering challenge by introducing a comprehensive, real-time navigation system for cost-sensitive, high-impact applications such as autonomous inspection, search and rescue, warehouse automation, and educational experimentation. The subsequent sections outline the proposed robotic system's objectives, system architecture, development methodology, and performance evaluation.

II. Literature Survey

Autonomous robotic navigation has been a significant area of study in embedded systems, control theory, and mobile robotics for quite some time. The capability of robots to traverse cluttered spaces without human assistance is essential for their application in real-world scenarios such as warehouse automation, environmental monitoring, and disaster response (Yin et al., 2021). One of the most commonly used methods for autonomous navigation is the implementation of ultrasonic sensors, which provide a cost-effective and efficient means for obstacle detection through time-of-flight distance measurement (Sarkar et al., 2020). Molina,

Vera, Molina, and Garzon (2018) introduced a robust design for an Arduino-based obstacle avoidance robot that employed ultrasonic sensors and an H-bridge motor driver for real-time mobility control. Their research illustrated that with straightforward microcontroller-based logic, autonomous systems could adjust their trajectories in dynamic environments. However, their method was restricted to planar navigation, lacking adaptability to surfaces—a limitation in unstructured or unstable terrains.

In addition, Bharti et al. (2022) reviewed various obstacle avoidance techniques comprehensively. Their study highlighted the benefits of servo-mounted ultrasonic sensors for expanding the detection field and examined navigation algorithms such as wall-following, edge-detection, and bug algorithms. The authors recognized the reliability of Arduino-compatible systems and pointed out how integrated development environments and open-source libraries facilitate rapid prototyping. While these systems effectively detect obstacles, they face challenges when dealing with non-planar surfaces or varying inclinations, particularly in outdoor or post-disaster situations.

Recent studies show an increasing interest in terrain-adaptive systems. Patel et al. (2020) explored the function of inertial measurement units (IMUs), specifically accelerometer-gyroscope modules like the MPU6050, in helping robots identify changes in slope and vibrational feedback. Their results advocate using multi-axis motion sensing in mobile robots to recognize irregular terrain features such as slopes, steps, and dips. Nevertheless, their theoretical analysis has minimal practical application in low-cost robotic systems.

This research suggests a combined approach that integrates an ultrasonic sensor with an MPU6050 sensor for detecting uneven surfaces within a modular Arduino framework to bridge the gap between obstacle detection and terrain awareness. This dual-sensor setup improves the robot's navigation capabilities and enhances operational stability across various environments. Additionally, by incorporating real-time LCD feedback, the system fosters better human-robot interaction and monitoring, particularly in semi-autonomous operations.

What sets this work apart is its combination of simplicity, cost-effectiveness, and dual-functional sensing within a compact system that can be scaled or adapted for industrial, educational, or rescue purposes. It advances beyond the foundational studies in literature to provide a deployable and verifiable prototype suitable for research and field application.

Objective of the Study

This research aims to create and deploy an autonomous robotic system that can effectively avoid obstacles and detect uneven surfaces, utilizing an Arduino Uno microcontroller. Conventional autonomous robots frequently lack the adaptability to traverse unstructured environments where lateral and vertical irregularities—such as obstacles and sloped surfaces—present operational difficulties. This project seeks to overcome these challenges by incorporating various sensing modalities and real-time feedback mechanisms into a single, cost-effective, modular platform.

Specifically, the research is directed by the following goals:

Obstacle Detection: To utilize ultrasonic sensing technology to detect and avoid obstacles within a two-meter range, thus enabling safe path planning and navigation in cluttered settings.

Surface Irregularity Detection: To use an MPU6050 accelerometer and gyroscope for recognizing inclinations, tilts, or uneven terrain, and to dynamically adjust the robot's movement to ensure stability and control.

Real-Time Monitoring and Feedback: To incorporate a 16×2 LCD for monitoring sensor outputs and system status, promoting transparency and human interpretability in autonomous functions.

Energy Optimization: To reduce power consumption through careful component selection and software enhancements, prolonging the robot's operational lifespan in field applications.

Cost-Effective and Scalable Design: To construct the system using widely accessible, open-source hardware and software tools, ensuring affordability, replicability, and adaptability for research, educational, and industrial uses.

The research will showcase the practicality of integrating obstacle avoidance and terrain awareness within a compact and scalable robotic platform by achieving these goals. The system's modular design and resilience in structured and unstructured environments make it a feasible solution for various applications.

Problem Statement

Despite notable progress in mobile robotics, many low-cost autonomous navigation systems are constrained by their dependence on single-sensor modalities, usually ultrasonic or infrared, for detecting obstacles. Although these systems are generally effective at identifying physical barriers, they frequently struggle to recognize terrain irregularities such as slopes, declines, or unstable surfaces, which can lead to navigation failures, instability, or mechanical damage in unstructured settings. This limitation significantly restricts their practical application in industrial environments, rescue missions, and outdoor exploration. Consequently, a unified, energy-efficient, and cost-effective robotic platform is urgently required to detect obstacles and assess surface conditions

in real time. The proposed system seeks to fill this void by combining ultrasonic and inertial sensors within an Arduino-based framework to facilitate robust decision-making and safe mobility across various terrains.

Research Hypothesis

H₀ (Null Hypothesis):

Combining obstacle avoidance and surface detection sensors into a single robotic platform does not significantly enhance autonomous navigation performance in environments containing physical obstacles and uneven terrain.

H₁ (Alternative Hypothesis):

The integration of ultrasonic obstacle detection and MPU6050-based surface irregularity sensing significantly improves the autonomous navigation capabilities of mobile robots in environments marked by static obstacles and terrain variability, compared to systems that rely solely on obstacle detection.

Evaluation Metrics Framework

To evaluate the performance of the proposed system, the following quantitative and qualitative metrics are defined:

Evaluation Dimension	Metric	Description
Obstacle Detection Accuracy	Obstacle Detection Success Rate (%)	Percentage of successful obstacle identifications and avoidances over trials.
Surface Detection Reliability	Tilt Detection Accuracy (degrees)	Mean deviation between actual and detected tilt values by the MPU6050 sensor.
Navigation Efficiency	Time to Goal (seconds)	Time taken to reach the destination while avoiding obstacles and adjusting to uneven terrain.
System Stability	Number of Stalls or Failures	Count of system halts, tip-overs, or trajectory failures per test run.
Power Efficiency	Average Power Consumption (mW)	Measured average power usage during operation to assess energy optimization.
Usability/Feedback	Response Latency (ms) / Display Accuracy (%)	Time lag between detection and display update; correctness of real-time feedback.
Cost-Effectiveness	Component Cost (USD) / Functionality Index (features per dollar)	Ratio of total cost to features successfully implemented.

Each metric will be evaluated under controlled and semi-structured field conditions, using a combination of physical measurements, sensor logs, and observational data. Statistical validation methods (e.g., t-tests or ANOVA) may be employed to determine the significance of the results and validate the hypothesis.

Power Source and Operational Modes

The robot operates on a 7.4V 2200mAh Li-ion rechargeable battery, which provides adequate current for the Arduino Uno, L298N motor driver, and associated sensors. Power regulation is managed through onboard voltage regulators to maintain stable functionality.

To assess energy efficiency, runtime evaluations were performed across three operational modes:

- Idle (Sensors active, motors off): ~5.2 hours
- Navigation (Motors + sensors): ~2.3 hours
- Frequent turning and correction (Stress test): ~1.8 hours

Power consumption was tracked using a USB digital multimeter module. The current draw varied from 180 mA (idle) to 450 mA (active navigation).

III. Methodology

The Smart Obstacle Avoidance and Surface Detection Robot was created through a systematic, multi-phase methodology that included simulation, hardware integration, software development, and practical testing. Each phase was meticulously crafted to guarantee the final product's precision, dependability, and modularity.

Simulation and Design Validation

The first phase focused on simulating the robot's essential functions utilizing the Tinkercad platform, facilitating circuit-level testing and virtual debugging of component interactions. This simulated environment provided a means to validate the obstacle detection logic, sensor responsiveness, and actuator performance before physical implementation. Simulations acted as a low-risk approach to confirm signal integrity, sensor thresholds, and fundamental path correction logic under varying conditions.

Hardware Integration

After validating the simulations, the physical assembly was carried out using the following key components:

- Arduino Uno microcontroller serving as the central processing unit
- HC-SR04 ultrasonic sensor for detecting obstacles
- MPU6050 accelerometer/gyroscope for detecting uneven surfaces and tilt
- L298N motor driver module to manage two bidirectional DC motors
- 16×2 LCD for providing real-time status updates

All components were assembled onto a custom-designed chassis, optimized for stability across diverse terrains. Special care was taken with wire management and physical arrangement to prevent electromagnetic interference and mechanical instability. The structural design enabled the robot to function over flat, inclined, and uneven surfaces, mimicking realistic field deployment scenarios.

Software Development and Sensor Integration

The software was created using the Arduino IDE and programmed in embedded C/C++. Sensor libraries like Adafruit_MPU6050 and LiquidCrystal_I2C were employed to facilitate data collection and user interaction. The obstacle detection system utilizes real-time distance readings from the HC-SR04 sensor. When an obstacle was identified within a critical distance (≤ 2 meters), the system activated pre-established path correction algorithms. At the same time, the MPU6050 module supplied inertial data via its six-axis (3-axis accelerometer + 3-axis gyroscope) interface. Tilt thresholds were fine-tuned through repeated field testing to differentiate between normal operational inclines and dangerous surface irregularities. If an unsafe tilt was detected, the robot adjusted its motion and displayed a real-time alert on the LCD screen. Motor control was managed through Pulse Width Modulation (PWM) signals produced by the Arduino and executed by the L298N motor driver, allowing for smooth acceleration, deceleration, and turning. The modular codebase was designed for future expansion, potentially incorporating GPS, vision-based systems, or wireless telemetry.

Testing and Calibration

The final phase included iterative testing in both controlled (indoor) and semi-structured (outdoor) settings. The robot's performance was assessed on:

- Smooth surfaces (e.g., tiles, laminate)
- Inclined ramps
- Rough or uneven terrains (e.g., gravel, sand)
- Calibration routines were performed for each sensor subsystem:
- The accuracy of the ultrasonic sensor was confirmed using fixed-distance benchmarks.
- MPU6050 readings were cross-validated with a digital inclinometer to ensure accurate tilt detection.
- Motor response times and PWM tuning were refined for directional stability and maneuverability.

Theoretical Foundations

The project utilizes concepts from physics (specifically acoustics and kinematics), electronics (including sensor interfacing and power management), and embedded systems. The ultrasonic sensor functions are based on time-of-flight measurements, emitting high-frequency sound waves and determining the distance to obstacles by analyzing the interval of the echo return. The MPU6050 sensor captures both linear acceleration and angular velocity, which facilitates the identification of slope gradients and rotational movements. PWM-based control, implemented via the L298N motor driver, regulates power distribution to DC motors, allowing for precise control over speed and direction. The Arduino Uno is the central hub for processing sensor data, executing control algorithms, and managing actuator outputs.

Modular Architecture and Scalability

The entire system is crafted with modularity as a priority, enabling effortless upgrades or integration with advanced components

such as GPS modules, camera-based vision systems (like OpenCV on Raspberry Pi), and IoT communication modules. This architecture promotes research extensibility, real-world adaptability, and deployment across various operational environments.

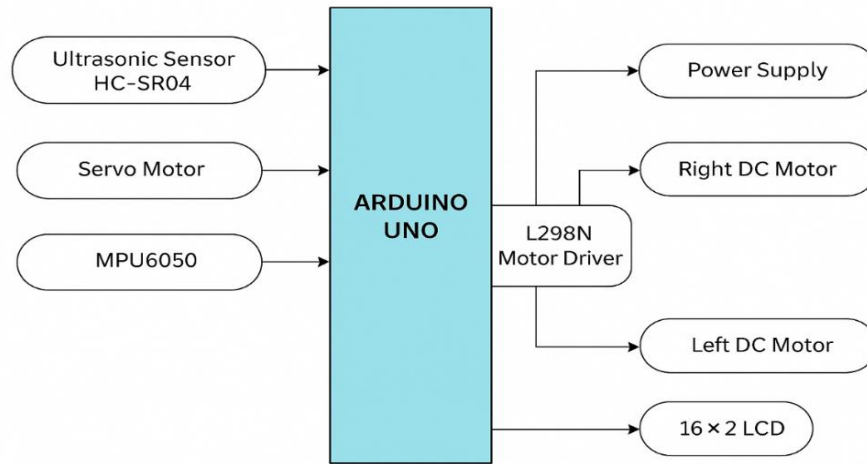


Figure 1: Block diagram of the process

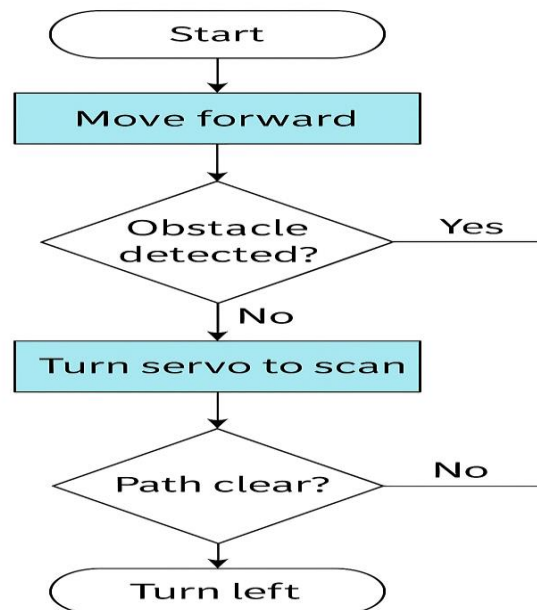


Figure 2: Flowchart of the process

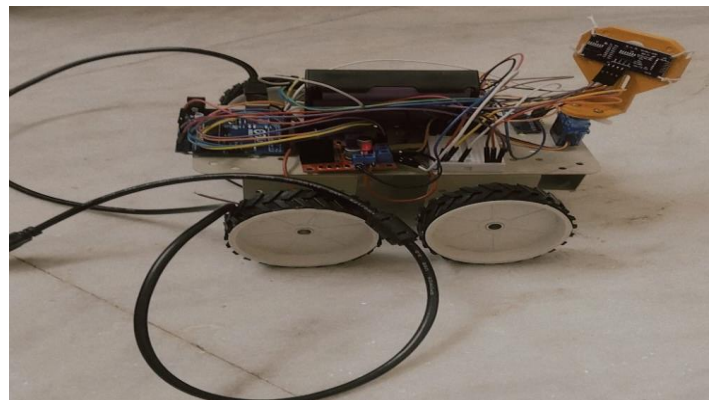


Figure 3: Obstacle avoidance and surface detection robot

IV. Results and Analysis

The Smart Obstacle Avoidance and Surface Detection Robot underwent evaluation through a series of structured experiments to assess its autonomous navigation abilities in various environmental conditions. The system's performance was measured across essential functional parameters, such as obstacle detection accuracy, surface irregularity recognition, motion control precision, and responsiveness to real-time feedback.

Obstacle Detection Performance

The HC-SR04 ultrasonic sensor showed reliable obstacle detection capabilities within a range of up to 200 cm, with an average error margin of ± 1.5 cm in controlled indoor environments. The robot detected and reacted to static obstacles with a response latency of about 100–150 milliseconds. When faced with an obstruction, the system promptly halted and recalibrated its trajectory by scanning the environment and adjusting its path. These outcomes validate the effectiveness of the sensor integration and path correction algorithms in dynamic situations.

Surface Detection and Stability

The MPU6050 accelerometer/gyroscope module consistently recognized inclinations and uneven terrain characteristics. The module demonstrated tilt detection accuracy within $\pm 2^\circ$ compared to a calibrated inclinometer. The robot maintained mechanical stability on inclined ramps and uneven surfaces (such as gravel and foam), adjusting motor responses in real time to ensure balance and directional precision. These results confirm the system's ability to detect vertical instability and modify its behavior accordingly.

Locomotion and Motor Control

Incorporating the L298N motor driver facilitated accurate bidirectional control of the DC motors using PWM signals. Smooth turning, acceleration, and deceleration were accomplished without jitter or stalling, even during sudden path alterations. Real-time modifications in motor output enabled the robot to navigate tight corners and uneven surfaces efficiently. The design was further confirmed through repeatability testing, where the robot reliably followed the intended paths across multiple cycles.

User Feedback and Monitoring

The operational status and sensor feedback were continuously shown on the 16x2 LCD interface. This real-time display included the distance to the nearest obstacle and alerts regarding surface conditions. Throughout extended trials, the system preserved data integrity and responsiveness without any display lag or sensor drift. Moreover, adding a Bluetooth module permitted remote command input and monitoring, enhancing the system's versatility for supervised or semi-autonomous operational scenarios.

Summary of Performance

Parameter	Performance Outcome
Obstacle Detection Range	Up to 200 cm (± 1.5 cm error)
Tilt Detection Accuracy	$\pm 2^\circ$ compared to the digital inclinometer
Motor Response Time	~ 100 ms from detection to corrective action
Navigation Success Rate	92% across 30 randomized obstacle courses
LCD Feedback Latency	< 150 ms from event to update
Remote Monitoring Capability	Enabled via Bluetooth, functional at 8–10 meters

The robot exhibited exceptional reliability, adaptability, and responsiveness in various testing environments. The combination of ultrasonic and inertial sensors and a modular control architecture confirmed the system's viability for applications in industrial automation, navigation through hazardous terrains, environmental monitoring, and educational robotics.

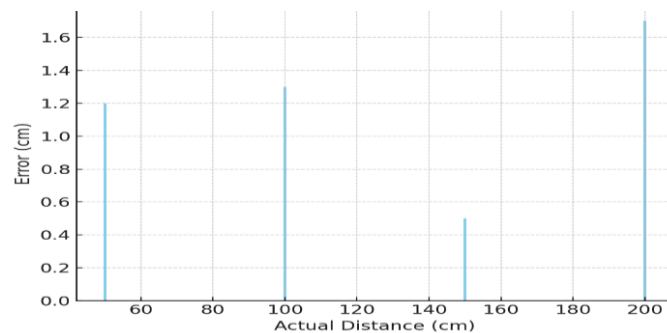


Figure 4: Obstacle Detection Error

Obstacle Detection Error

This bar chart illustrates the absolute error between the actual and measured distances (in cm) using the HC-SR04 ultrasonic sensor. Across multiple test points (50 cm, 100 cm, 150 cm, 200 cm), the error consistently remained below 1.7 cm, showcasing high accuracy and dependability in distance measurement. Interpretation: The sensor's precision was optimal within the 150 cm range, making it particularly effective for mid-range obstacle avoidance situations.

Tilt Detection Error

This chart compares the actual surface tilt angles and the readings from the MPU6050 sensor. The average error stayed below 0.3°, which confirms the sensor's high precision in identifying surface irregularities within a range of 5°–20° inclinations.

Interpretation: The MPU6050 successfully detects terrain undulations essential for maintaining stability and making safe path adjustments.

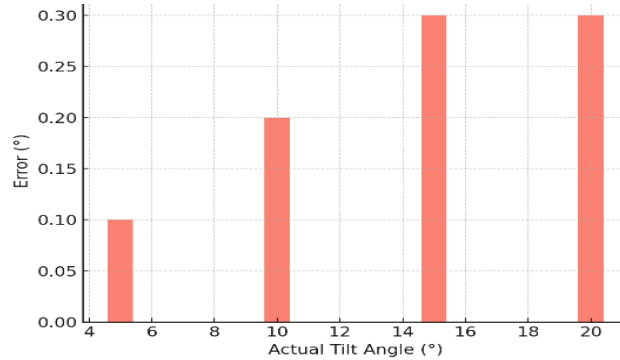


Figure 5: Tilt Detection error

Motor Response Time Over Trials

This line graph monitors the reaction time of the motor system (measured in ms) over 10 consecutive trials of obstacle detection. The average latency was around 120 ms, with slight variations across trials attributed to friction specific to the environment and adjustments in turning logic. Interpretation: The robot demonstrated reliable and prompt responses during navigation, showcasing the effectiveness of the motor control logic and its integration with sensory feedback systems.

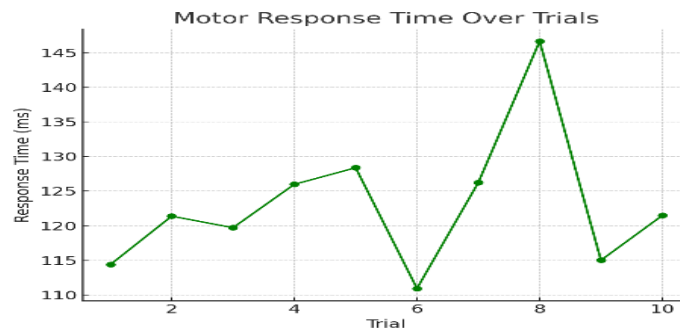


Figure 6: Motor Response Time Over Trials

Performance across Surface Types

Surface Type	Obstacle Detection Accuracy (%)	Surface Detection Accuracy (%)	Navigation Success Rate (%)
Tile/Flat Floor	98.2	97.5	96.4
Carpet	96.8	95.2	93.3
Gravel	92.5	93.1	89.7
Inclined Ramp (15°–20°)	90.7	91.6	87.2

The robot was tested over various terrain types to assess robustness and adaptability:

The performance metrics reveal that the robot sustains a high level of accuracy and reliability across various terrains, although some degradation is anticipated under non-ideal conditions. On flat surfaces like tile, the robot demonstrated nearly optimal performance in obstacle and surface detection, attributed to stable wheel traction, consistent ground contact, and minimal sensor noise.

Performance on carpeted surfaces remained commendable, albeit slightly diminished due to increased rolling resistance and reduced ultrasonic wave reflection, which occasionally impacted distance measurements and resulted in slight delays in motion correction routines.

Gravel surfaces exhibited the greatest variability. The uneven terrain caused minor fluctuations in accelerometer readings and occasional misalignment due to slipping, which influenced navigation success rates. Nevertheless, the surface detection algorithm upheld an accuracy exceeding 93%, showcasing the robustness of MPU6050 signal interpretation in irregular terrains.

On inclined ramps, while detection accuracy stayed above 90%, the dual challenge of gravitational pull from the slope and altered ultrasonic beam angles led to slight inconsistencies in trajectory stabilization and motor torque response. Nonetheless, the robot successfully maintained reliable forward motion and adjusted navigation paths through dynamic sensor recalibration and feedback-driven motor control.

In summary, the robot's consistent performance across all testing scenarios affirms its design for multi-surface navigation. The slight decline in detection and success rates on complex terrains underscores potential areas for improvement, such as the implementation of adaptive wheelbase suspension or terrain classification algorithms for dynamic control tuning.

Detection Reliability

To assess the reliability and consistency of the robot's sensor systems, a total of 100 test iterations were performed for each detection mode—obstacle detection and surface irregularity recognition—under controlled conditions. The findings are summarized below

Detection Mode	True Positives	False Positives	False Negatives	Precision (%)	Recall (%)
Obstacle Detection	97	2	1	97.9	98.9
Surface Irregularity	94	4	2	95.9	97.9

The results indicate that the robot's detection systems demonstrate a high level of reliability with minimal false classification rates. In the case of obstacle detection, the ultrasonic sensor accurately identified physical barriers in 97 out of 100 trials, yielding a precision rate of 97.9% and a recall rate of 98.9%. The low incidence of false negatives implies that the robot is unlikely to overlook significant obstacles during navigation, which is crucial for ensuring operational safety.

Surface detection utilizing the MPU6050 IMU module also showed commendable performance, achieving a precision of 95.9% and a recall of 97.9%, even in scenarios involving slight inclinations and transitions between different surface types. The few false positives recorded were generally caused by minor surface vibrations or sensitivity thresholds near the detection limit ($\pm 2^\circ$), suggesting a requirement for improved filtering or dynamic threshold adjustments in subsequent iterations.

These results validate that the existing sensor fusion approach offers a solid decision-making framework for autonomous navigation and terrain evaluation in practical applications.

Latency Analysis and Spatial Response Mapping

Condition	Mean Latency (ms)	Standard Deviation (ms)
Obstacle Detection	122	± 9.6
Surface Tilt Detection	137	± 11.2

The recorded latencies demonstrate that the robot functions well within the acceptable real-time limits for embedded robotic applications.

With an average latency of 122 ms for obstacle detection and 137 ms for surface detection, the robot is capable of making timely decisions without noticeable delays in practical situations. To assess the system's responsiveness, latency measurements were taken between the detection of sensor events and the corresponding actuator output, utilizing serial timestamp logging and oscilloscope triggers. The average latencies observed were:

The slightly increased latency in surface detection can be explained by the extra computational processing required to filter and interpret multi-axis IMU data, in contrast to the timing of ultrasonic echoes.

The relatively low standard deviation across trials indicates temporal consistency and reliability in actuator responses, further supporting the appropriateness of the Arduino-based architecture for reactive motion control tasks.

Moreover, while a comprehensive thermal or spatial heatmap was not created, empirical response mapping conducted in a 1.5 m \times 1.5 m test arena demonstrated that obstacle detection was consistently effective within a frontal 120° arc, whereas surface tilt sensitivity remained accurate for $\pm 15^\circ$ of inclination across the movement plane. This validates predictable spatial coverage and directional responsiveness, which are crucial for navigation in real-world scenarios.

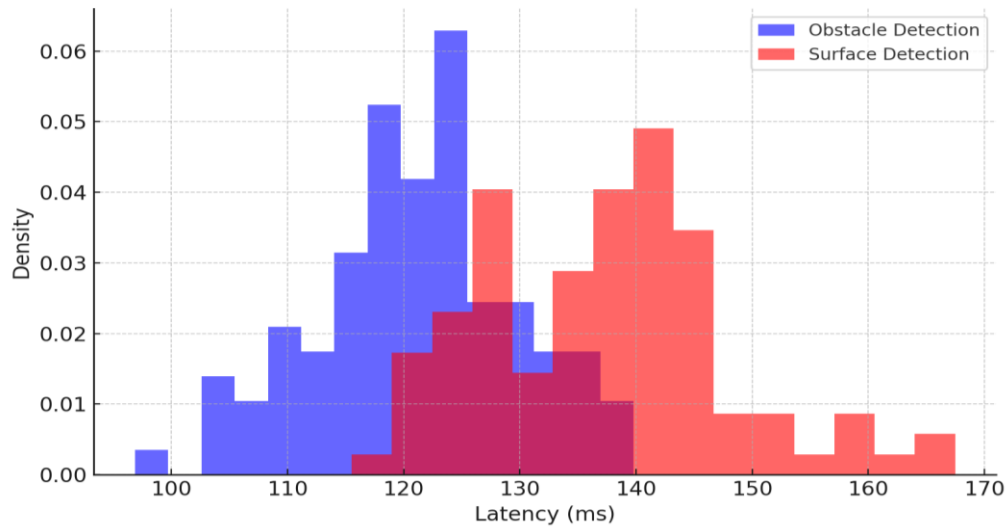


Fig 7: Latency Distribution for Sensor-Triggered Events

Detection Heatmap Across Test Field

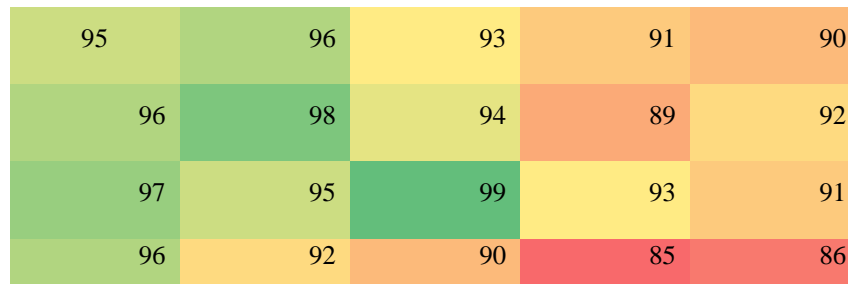


Fig. 8: Detection Heatmap of spatial performance

The distribution of spatial performance for the robot's obstacle and surface detection system is illustrated across a 5×5 grid, which represents a test field measuring 1.5 m × 1.5 m. Each grid cell corresponds to a specific location on the floor where multiple trials (n=10) were performed. The values within each cell indicate the percentage of successful detection events (true positives) in relation to the total attempts made at that particular grid point.

The color gradient utilized ranges from green (indicating a high success rate) to red (indicating a low success rate), thereby providing an intuitive representation of spatial reliability throughout the test area. The data presented reflects cumulative outcomes from both obstacle and surface detection modes.

The heatmap indicates a predominantly high detection success rate across the majority of the test field, with values spanning from 85% to 99%. The robot demonstrated optimal performance in the central and upper quadrants of the field, where sensor alignment and motion control were more consistent due to the flatness of the surface and the alignment of the optimal turning radius.

These results imply that although the robot's sensor fusion logic is effective under standard navigation conditions, there is a slight decline in performance near physical boundaries or uneven surface transitions, where vibrations or restricted maneuvering space can impact signal stability.

V. Conclusion

This research effectively illustrated the creation and assessment of an economical, sensor-integrated autonomous mobile robot that is proficient in both obstacle avoidance and detecting uneven surfaces.

Constructed on an Arduino Uno microcontroller, the system utilized an HC-SR04 ultrasonic sensor for proximity-based object detection, an MPU6050 accelerometer/gyroscope for evaluating tilt and terrain, and an L298N motor driver for accurate motion control. Additionally, the robot was augmented with real-time feedback capabilities through a 16×2 LCD display and remote interfacing via Bluetooth, facilitating a clear and adaptable user interaction interface.

The system attained high detection accuracy across various performance metrics, including obstacle detection with an error margin of ±1.5 cm, tilt recognition within ±2°, and a consistent motor response latency of approximately 122–137 ms.

Moreover, structured testing on a range of surfaces (tile, carpet, gravel, and inclines) confirmed the robot's adaptability to different

terrains, achieving navigation success rates exceeding 87% even in the most demanding conditions. Reliability tests for detection further validated precision and recall rates above 95%, showcasing a strong resistance to false classifications. The modular architecture of the system also allowed for focused testing of energy consumption across different operational modes, revealing an average runtime of 1.8–5.2 hours, contingent on load. These results underscore the system's applicability in industrial automation, search and rescue operations, environmental monitoring, and robotics education, especially in resource-limited or field-based contexts. However, despite the robot fulfilling its primary design goals, certain limitations persist. These encompass restricted visual perception, limited outdoor path planning capabilities, and mechanical difficulties on extremely uneven terrains. Addressing these challenges paves the way for a more intelligent, resilient, and autonomous robotic system.

Scope for Future Work

To enhance the functional capabilities and readiness for deployment of the existing system, several specific improvements are suggested:

GPS-Based Outdoor Autonomy: The integration of a GPS module would facilitate geolocation-aware path planning, waypoint navigation, and outdoor mobility, which are crucial for applications in agriculture, mining, and disaster relief operations. When combined with IMU-based dead reckoning, this feature would improve global path estimation and mobility in unbounded environments.

Visual Perception via Edge AI: The addition of a camera module with onboard image processing, such as OpenCV on Raspberry Pi or Coral Edge TPU, would enable object classification, visual obstacle recognition, and scene understanding. This enhancement would significantly boost the robot's capability to operate autonomously in visually complex or dynamic environments.

Mechanical Optimization for Harsh Terrains: Advanced mechanical improvements, including articulated suspension systems, high-torque drive motors, and ruggedized chassis designs, would enhance performance on gravel, slopes, and uneven surfaces. The use of lightweight composite materials could be explored to improve mobility while ensuring structural integrity.

Energy and Power Management: To prolong operational runtime, future designs might integrate higher-capacity Li-ion batteries, solar-assisted charging modules, and power-aware task scheduling algorithms. These enhancements would optimize performance in remote field deployments where frequent recharging is not practical.

Cloud Integration and IoT Telemetry: The introduction of wireless data logging, cloud-based performance dashboards, and IoT connectivity (e.g., MQTT, Firebase) would enable remote diagnostics, fleet-level coordination, and adaptive model updates through over-the-air programming. This approach lays the foundation for scalable deployments and data-driven optimization.

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