Journal of Basics and Applied Sciences Research (JOBASR)
ISSN (print): 3026-9091, ISSN (online): 1597-9962
Volume 4(2) March 2026
DOI: https://dx.doi.org/10.4314/jobasr.v4i2.37

Enhancement of Obstacle Detection and Avoidance in Smart Cars Using Microcontrollers

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ABSTRACT
This research details the design and implementation of an intelligent, autonomous obstacle-avoiding robotic car designed for collision-free navigation. Several researches were conducted to address gaps such as distance covered by the sensor, power consumption, and mobility of the robot but gaps still exist. The aim of this research is to implement a robot car that, while moving, has the ability to detect obstacles in its path and change direction, the primary objective was to engineer a mobile platform capable of detecting environmental barriers and recalculating its trajectory without external human intervention. By utilizing an HC-SR04 ultrasonic sensor for distance measurement and an Arduino UNO microcontroller as the primary processing unit, the system continuously monitors its path through 40KHz sound wave pulses. Upon detecting an obstacle within a predefined threshold, the robot halts, scans its immediate surroundings via a servo-mounted sensor, and identifies the safest direction based on the maximum clear distance available. Experimental evaluations demonstrate a 90% success rate in navigating controlled environments containing various objects such as desks, chairs, and walls; it also utilized the HC-SR04 sensor to improve detection accuracy and minimise power consumption. This implementation serves as a scalable prototype for enhancing automotive safety and industrial automation, offering a cost-effective alternative to expensive LiDAR-based systems.

Keywords:
Autonomous Navigation,
Obstacle Avoidance,
Ultrasonic Sensors,
Arduino Microcontroller,
Embedded Systems

INTRODUCTION

The quest for autonomous machines dates back to the early 20th century, with the term "Robot" first appearing in Karel Čapek's 1920 play, Rossum's Universal Robots. However, the transition from science fiction to functional engineering began in earnest in 1948 when William Grey Walter produced the first electronic autonomous robots, known as "Machina Speculatrix," in Bristol, England. This was followed by George Devol's 1954 invention of "Unimate," the world's first digital and programmable industrial robot. The specific field of obstacle avoidance saw a major breakthrough in 1988 when Delco System Operations developed the first integrated system designed to detect road obstacles and inform motorists (Garethiya, 2015). Since the late 1980s, global automotive leaders such as Mercedes-Benz, Nissan, and Toyota have continuously refined these models, transitioning from simple proximity warnings to fully self-directed vehicles capable of navigating complex urban environments.

The field of mobile robotics has undergone considerable growth, driven by advancements in sensors, microcontrollers, and communication technologies.

Robots are increasingly deployed in dynamic settings where they must engage with their environment and respond to human commands. Autonomous navigation and remote user control are two critical functionalities for these systems. An obstacle-detecting vehicle can function autonomously by utilizing sensors to perceive its surroundings and make decisions to prevent collisions. This capability is vital for applications such as robotic vacuum cleaners, warehouse automation, and autonomous vehicles (Diksha et'al., 2025).

Researches such as that of (Aniket et.al, 2018) uses the IR sensor, infrared sensors to detect the distance to an object using infrared radiation, in this scenario when the beam detects an object, the light beam returns to the receiver at a certain angle after reflection, therefore there are limitations to this sensor since the performance of IR sensors is limited by their low tolerance to light reflections, such as ambient light or the bright colors of objects. So also, no object recognition is possible within the dead zone; for example, the dead zone of the Sharp GP2D12 IR distance sensor is between 0 and 4 cm. IR sensors also provide inaccurate detection results with transparent or brightly colored materials.

How to cite this article: Ismail S., Salisu S. & Shamsuddeen S. (2026). Enhancement of Obstacle Detection and Avoidance in Smart Cars Using Microcontrollers. *Journal of Basics and Applied Sciences Research*, *4*(2), 370-375. https://dx.doi.org/10.4314/jobasr.v4i2.37

Detection results also depend on weather conditions, and the detection reliability of IR sensors decreases in the presence of humidity. Furthermore, IR sensors can detect IR radiation from sunlight, which can lead to correctable or uncorrectable errors in the output. Furthermore, if an analog IR sensor is used, signal loss will occur in the amplifier circuit. At the same time, the PIR motion sensor requires a long calibration time and is sensitive to thermal radiation. Additionally, the PIR sensor is insensitive to very slow movements or stationary objects

To improve novelty of this research we used the HC-SR04 ultrasonic sensor to determine the distance to an object. The sensor used offers excellent non-contact distance detection, ranging from approximately 2 cm to 400 cm, or 1 foot to 13 feet. Its operation is not affected by sunlight or dark materials. The sensor also emits short, high-frequency signals. If it detects an object, the object sends back an echo that is picked up by the sensor via the Echo pin. The research also used Pulse in function to calculate the duration of the signal from the obstacle. Each time the function waits for the pin to go high to start timing, the timer stops when the pin goes low again. It returns the pulse duration in microseconds

Current Challenges in Obstacle Avoidance Systems

Despite decades of progress, several critical challenges persist in the design of robust autonomous avoidance systems. Modern research identifies three primary hurdles:

1. Sensor Reliability and Environmental Interference: Primary sensors like Infrared (IR) and Ultrasonic transducers are highly susceptible to their surroundings. As noted by Kumar (2013), IR sensors often fail to detect dark-colored objects because black surfaces absorb rather than reflect light. Similarly, ultrasonic sensors can be affected by ambient temperature, humidity, and atmospheric pressure, leading to signal attenuation or false readings.
2. Computational Latency: Real-time processing remains a bottleneck. Many existing systems suffer from a "processing gap" where the latency between detection and motor actuation exceeds 200 milliseconds. In high-speed scenarios, this delay can result in collisions before the robot can successfully recalculate its trajectory (Bhagat, 2016).
3. Dynamic Adaptability: While robots perform well in static environments, their success rate drops significantly when introduced to dynamic settings where obstacles are moving or non-linear.

Emerging Technologies and Sensor Fusion

To overcome these limitations, the field has moved toward a hybrid Sensor Fusion model. This approach involves combining different sensing modalities to compensate for individual weaknesses. For example, contemporary designs often pair the long-range capability of HC-SR04 ultrasonic sensors (which offer non-contact measurement up to 400cm with 3mm accuracy) with the high-resolution data of LiDAR or computer vision (Zaki, 2014).

Furthermore, the integration of Artificial Intelligence (AI) and Fuzzy Logic controllers has allowed robots to move beyond "if-then" programming. By utilizing microcontrollers like the Arduino UNO, developers can implement PID (Proportional-Integral-Derivative) control loops that allow for smoother navigation and more sophisticated decision-making in real-time.

Advantages of Autonomous Avoidance Technology

The implementation of this technology offers several transformative advantages across various sectors:

Public Safety and Accident Mitigation: In regions like Nigeria, road accidents are frequently caused by human error or a lack of awareness regarding obstacles like potholes, pedestrians, or animals. Autonomous systems can provide a fail-safe mechanism that alerts drivers or takes automatic corrective action, thereby reducing mortality rates (Waghmare, 2016).

Industrial Efficiency: In factory automation and warehousing, autonomous mobile robots (AMRs) navigate complex floors to transport goods, preventing human workplace injuries and increasing operational throughput.

Assistive Technologies: The principles of obstacle avoidance are fundamental to developing smart wheelchairs and walking aids for the visually impaired, significantly enhancing the independence and quality of life for people with disabilities.

Robotics is one of the new branches of engineering that embraces mechanical engineering, electrical engineering, computer science amongst other disciplines (Zuheng, 2024). Robotics entails the design, specs, operation and convention of robots along with computerized systems for mechanization, sensitized feedback and processing of information. A robotic car is a design in the shape of a car with human –like senses. The robotic car would be able to perform tasks automatically or with the guidance of someone through a control mechanism (resorting from the hardware in place and the software to control). The software involves a pre-existent set of instructions, that gets triggered if and when it receives a signal sensed from the environment through the sensor to perceive the obstacle in its path and by so doing avoid it. The hardware parts are various components of the robot that make up the design of the car (architecture), (Waghmare. 2016).

Bhagat (2016) reviewed existing literature on obstacle avoidance techniques for robot cars, highlighting the strengths and limitations of various approaches. The

review focused on sensor-based, computer vision-based, and machine learning-based approaches.
Sensor-based approaches, such as ultrasonic sensors and infrared sensors, were found to be effective in detecting obstacles but limited by their range and accuracy. Computer vision-based approaches, using cameras and image processing algorithms, offered higher accuracy but were computationally intensive and sensitive to lighting conditions.
The limitation to this research work was the use of the infrared sensor because it's not reliable for precise measurement and only suitable for short distance measurement
Machine learning-based approaches, including neural networks and fuzzy logic, showed promise in improving obstacle avoidance capabilities but required large datasets and computational resources. Bhagat (2016) noted that a hybrid approach combining multiple sensors and techniques could potentially overcome individual limitations and improve overall performance.
The review also highlighted the importance of considering environmental complexity, sensor noise, and real-time processing requirements in designing effective obstacle avoidance systems. Bhagat (2016) concluded that further research was needed to develop robust and efficient obstacle avoidance systems for robot cars.
The research findings on obstacle avoidance systems indicate that a single approach is not effective in all scenarios. Sensor-based approaches have limitations, fuzzy logic-based approaches require expert knowledge, and machine learning-based approaches require large datasets and computational resources. A hybrid approach, combining the strengths of multiple methods, shows promise for improved performance in obstacle avoidance systems.

Theoretical Framework

The foundational theory of this research is rooted in the Closed-Loop Feedback System and the Three Laws of Robotics.
Closed-Loop System: The robot operates on a feedback mechanism where environmental data (distance) is continuously fed into a controller (Arduino), which then adjusts the output (motor movement) to maintain a safe state (no collision).
Asimov's Laws of Robotics: Propounded by Isaac Asimov in 1942, these laws provide the ethical and operational framework for all robotic systems:
A robot may not injure a human being or, through inaction, allow a human being to come to harm.
A robot must obey orders given to it by human beings except where such orders would conflict with the First Law.
A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.
Application: Obstacle avoidance is a direct implementation of the Third Law, ensuring the machine's survival by avoiding physical damage.

Historical Framework

The evolution of robotics has transitioned from simple mechanical labor to complex autonomous decision-making:
Etymology: The term "Robot" was introduced by Karel Čapek in his 1920 play R.U.R. (Rossum's Universal Robots), derived from the Czech word for forced labor.
Early Milestones: The first electronic autonomous robots were created in 1948 by William Grey Walter. This was followed by George Devol's 1954 invention of "Unimate," the first digitally operated and programmable robot.
Obstacle Detection Roots: The first system specifically designed to detect road obstacles was developed by Delco System Operations in 1988. While initially meant to alert motorists, it laid the groundwork for the 1980s emergence of self-directed vehicles by companies like Mercedes-Benz, Nissan, and Toyota.

Analysis of Related Literatures (Recent Trends)

Based on the empirical review of these works, the choice of technology for an obstacle-avoiding robot is a trade-off between cost, complexity, and environment:
Infrared vs. Ultrasonic: IR sensors (Kumar, 2013; Vasavi, 2015) are more affordable but suffer from "black-body absorption," where dark obstacles remain undetected. Ultrasonic sensors (Bhagat, 2016) offer a much higher range (up to 400cm) and 3mm accuracy, making them the standard for robust autonomous navigation.
Computer Vision vs. Sensor-Based: While computer vision (Zaki, 2014) provides higher accuracy, it is computationally intensive and sensitive to lighting. Standard sensors are preferred for real-time processing with low-latency (sub-200ms) requirements.
Recent Developments (Sensor Fusion): The most recent trend is "Sensor Fusion," combining ultrasonic, LiDAR, and cameras to overcome individual sensor failures.

Comparative Analysis of Sensors

- Infrared (IR) Sensors: While cost-effective, IR sensors struggle with dark-colored objects (which absorb light) and have limited ranges.

Ultrasonic Sensors: These are superior for this application due to their high ranging capability (up to 400cm) and non-contact measurement accuracy within 3mm

MATERIALS AND METHODS

The motor driver unit will be used as an Integratation to the microcontroller, the unit gets input from the comparator to gives some output to the motor driver (L298N dual H-bridge motor driver are used in controlling motor direction and speed. The Arduino board is connected with a DC Motor and through motor driver board (pin10, pin11, pin12, pin13) which provides power to the actuators. Actuators are used to move robot in Forward, Backward, Left and Right directions. -The motor driver unit drives the motor in the left or right, slow or fast as the case may be; a decision determined by the microcontroller signals being received. The motor driver unit has a sufficient current to drive the two side motors (left and Right motors). This unit also incorporates a caster wheel which acts as a wheel steering for the robot.

System Design and Architecture

This is an electronic/robotic system, This system was design using the following components, Arduino UNO, Ultrasonic sensor, Motor Driver modules, 5V DC Motors, Batter, Caster wheel, Wheels, Chassis, integrated using C programming language

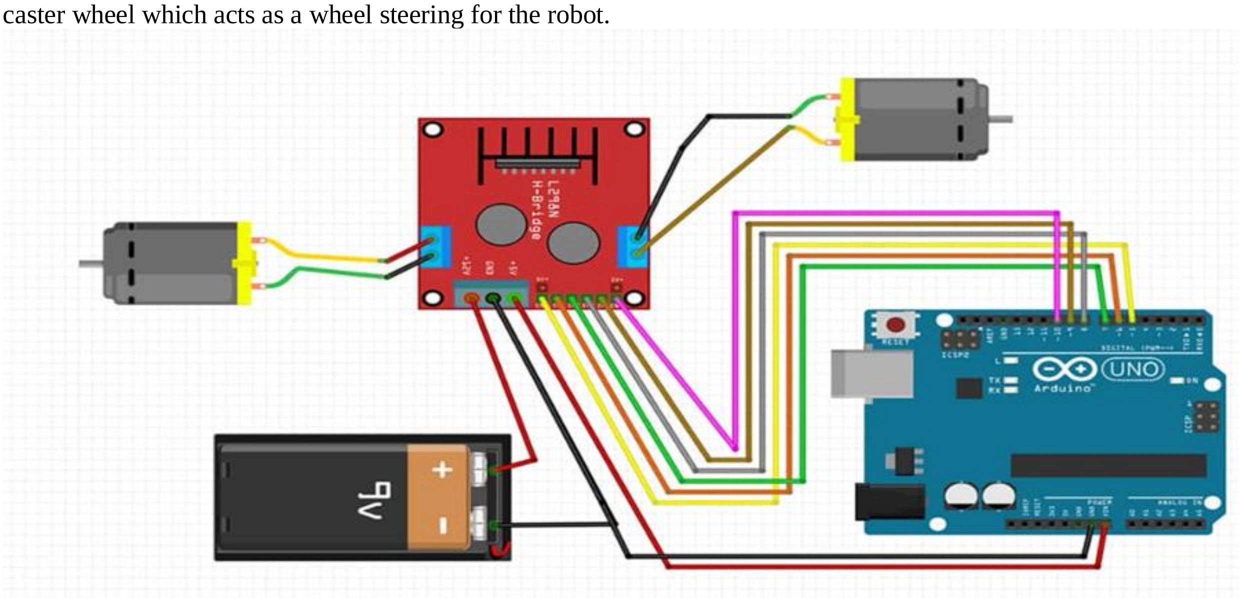


Figure 1: System design

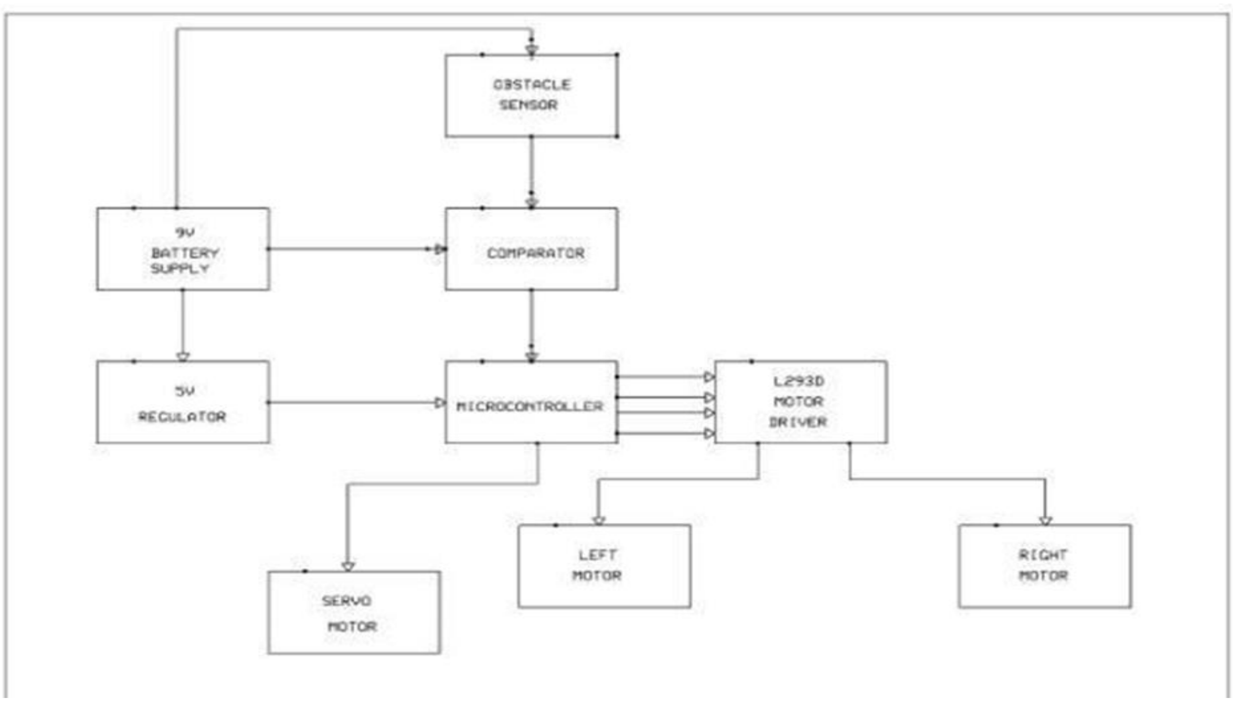


Figure 2: System Workflow

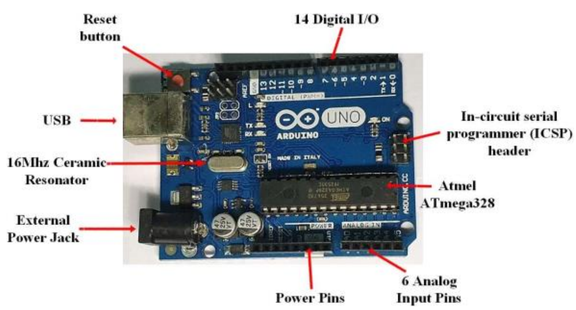
System Implementation

This system was design using the following components, Arduino UNO, Ultrasonic sensor, Motor Driver modules, 5V DC Motors, Batter, Caster wheel, Wheels, Chassis, integrated using python programming language

The robot's design is divided into five specialized units:

1. **Sensing Unit:** HC-SR04 Ultrasonic sensor converts sound waves into electrical signals to gauge distance.

2. **Angle Scanning Unit:** An SG-90 Servo motor rotates the sensor 180 degrees to achieve a precise angular view of surroundings.
3. **Processing Unit:** An Arduino UNO (microcontroller) acts as the decision-maker, interpreting sensor input to control movement.



4. **Motor Drive Unit:** An L293D/L298N shield provides the current necessary to drive motors in various directions based on microcontroller signals.
5. **Actuation Unit:** DC Gear motors translate electrical power into mechanical movement for the chassis.

Operational Algorithm

The robot follows a systematic four-stage navigation cycle:

1. **Forward Traversal:** The robot moves straight while emitting 40KHz ultrasonic pulses.
2. **Detection:** If an obstacle is detected within the threshold, the robot stops and moves back slightly.
3. **Scanning:** The servo rotates the sensor left and right to compare clear distances.
4. **Avoidance:** The robot turns toward the direction with the maximum distance and resumes forward motion.

```
// Logic for Forward, Stop, and Scan
void loop() {
distance = readUltrasonic();
if (distance <= 20) { // Threshold in cm
stopRobot();
delay(500);
moveBackward();
delay(500);
stopRobot();
lookLeft = scanLeft();
lookRight = scanRight();
if (lookLeft >= lookRight) {
turnLeft();
} else {
turnRight();
}
} else {
moveForward();
}
}
```

Program Code

Hardware Integration

The system uses a 4WD chassis with the ultrasonic sensor mounted on the front-facing servo. The Arduino executes the control code, managing the H-bridge logic of the motor driver to navigate around obstacles.

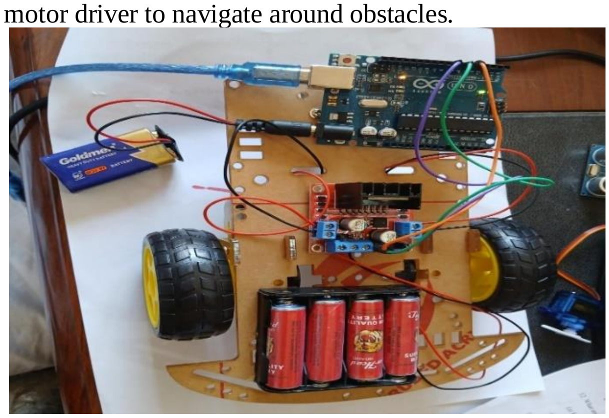


Figure 3: Designed system

RESULTS AND DISCUSSION

Performance Evaluation

Tests conducted in a controlled environment showed a 90% success rate in navigating around common obstacles such as chairs and desks. The system had an average response time of 0.5 seconds between detection and maneuver. However, reliability tended to decrease as the complexity of the environment and the density of obstacles increased

Test Parameter	Result Range	Observations
Detection Range	2cm–400cm	Accuracy is highest between 10cm and 100cm.
Distance Error	2% – 5%	Errors increase with soft surfaces (foam, cloth).
Avg. Response Time	50ms-0.5s	Significantly higher than the distance the robot travels
Collision-Free Rate	85% – 95%	Lower in complex environments with many tight corners.

CONCLUSION

The research successfully demonstrated an autonomous vehicle capable of real-time environmental perception and decision-making. The use of ultrasonic sensing paired with Arduino provides a robust, low-cost platform for developing automotive safety systems.
The research successfully achieved its goal: to design and build an autonomous robotic car capable of avoiding obstacles. Thanks to the integration of a suite of sensors and real-time processing logic, the prototype achieved a 90% success rate when navigating controlled environments. The implementation of dual power rails and priority-based scheduling effectively addressed common hardware instabilities and system latency. While the current model operates reliably at moderate speeds, its 0.5-second response time highlights a trade-off between mechanical inertia and sensor data processing that defines the limits of the current prototype.

Recommendations

we recommend the following for future work:

i. **Sensor Fusion:** Future work should combine ultrasonic sensors with LiDAR or cameras to overcome limitations in range and detection of varied materials.
ii. **Machine Learning:** Integrating AI would allow the robot to adapt to dynamic or unknown environments more efficiently.

IoT Connectivity: Implementing a Wi-Fi or Bluetooth module to provide **Real-Time Telemetry** would allow researchers to monitor sensor data and battery levels remotely on a smartphone or computer dashboard, for IIoT primarily focus on detection accuracy while offering limited interpretability, thereby reducing their practical trustworthiness and deployment in real-world industrial environments (Idris Y.S et'al., 2026).

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