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# Beyond Obstacle Avoidance: Ultrasonic Wave Diffraction and Multi-Sensor Integration in a Follow-Me Robot

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## ABSTRACT

**Purpose of the study:** This study aimed to design and evaluate a low-cost follow-me robot system based on ultrasonic and infrared sensor integration for object tracking, obstacle avoidance, and indoor autonomous navigation applications.

**Methodology:** The study used HC-SR04 ultrasonic sensors, infrared sensors, Arduino Nano, L298N motor driver, DC motors, and Pulse Width Modulation (PWM) control. Experimental methods were conducted through distance measurement, angular response testing, obstacle avoidance evaluation, payload variation testing, and robot speed analysis under indoor operating conditions.

**Main Findings:** The results showed that the proposed robot achieved stable object-following performance within the range of 40–80 cm. Rectangular objects produced more stable ultrasonic reflections than cylindrical objects because of lower wave scattering. Higher PWM values increased robot speed, while larger payloads reduced movement efficiency. The system also demonstrated effective directional correction and obstacle avoidance capability during indoor navigation experiments.

**Novelty/Originality of this study:** The novelty of this study lies in the integration of ultrasonic and infrared sensors with the analysis of ultrasonic wave diffraction characteristics, object geometry influence, PWM-based motor control, and payload performance within a single follow-me robotic platform. The proposed system provides a comprehensive and low-cost approach for autonomous indoor robotic navigation and lightweight transportation applications.

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## 1. INTRODUCTION

The rapid development of automation technology has accelerated the transformation of conventional devices into intelligent robotic systems. Mobile robots are increasingly utilized to assist human activities in transportation, logistics, and industrial operations [1]-[3]. One important innovation is the development of autonomous follower robots capable of tracking moving objects automatically [4]-[6]. These robots are designed to reduce human effort during carrying and monitoring activities [7]-[9]. Consequently, robotic automation has become an important topic in modern engineering and technology research.

Advances in embedded systems and sensor technology have significantly supported the development of autonomous robots. Ultrasonic sensors are widely applied for distance measurement because they provide stable object detection through ultrasonic wave reflections [10]-[12]. Infrared sensors are commonly integrated into robotic systems for object identification and directional tracking [13]-[15]. In addition, Arduino-based microcontrollers are frequently used because they offer simple programming and flexible hardware integration. Previous studies demonstrated that Arduino and ultrasonic sensors can effectively support robotic navigation and tracking systems [16]-[18].

Human-following robots have attracted considerable attention because of their practical applications in daily life and industrial environments. These robots can be implemented in automatic trolleys, smart carriers, warehouse systems, and assistive transportation devices [19]-[21]. The integration of ultrasonic and infrared sensors enables robots to maintain object distance and determine movement direction more accurately [22]-[24]. Research on intelligent tracking robots also showed that sensor-based control systems improve navigation performance and obstacle avoidance capability [25]-[27]. Furthermore, automated robots contribute to efficiency, safety, and productivity in various operational environments.

The effectiveness of a follow-me robot depends on the synchronization between hardware components and software control systems. Hardware components such as ultrasonic sensors, infrared sensors, DC motors, and motor drivers must operate collaboratively [28], [29]. Meanwhile, software algorithms are responsible for interpreting sensor data and controlling robot movement decisions. An ineffective control mechanism may cause instability in object tracking and movement response. Therefore, designing an integrated robotic control system is essential for improving robot performance and operational stability [30]-[32].

Several previous studies have investigated robotic navigation and object-following systems using Arduino-based platforms. A study entitled Intelligent Tracking Obstacle Avoidance Wheel Robot Based on Arduino discussed intelligent wheel robots integrating infrared tracking and ultrasonic obstacle avoidance [33]. Another study entitled Design of a Robotic Vehicle to Avoid Obstacle Using Arduino Microcontroller and Ultrasonic Sensor focused primarily on obstacle avoidance using ultrasonic sensors [34]. Furthermore, the study Autonomous Human-Following Robot System Using Deep Learning and Sensor Fusion explained that combining multiple sensors improves robot tracking performance in dynamic environments [35]. However, most previous studies mainly emphasized navigation and obstacle avoidance rather than integrating infrared identification with ultrasonic distance calibration for a more stable follow-me mechanism..

This study offers novelty through the integration of HC-SR04 ultrasonic sensors and infrared sensors in a follow-me robot prototype based on Arduino Nano. The ultrasonic sensors are utilized to measure object distance and determine robot movement direction. Meanwhile, the infrared sensor functions as a specific target identifier using infrared signal transmission. The integration of both sensors is expected to improve tracking accuracy and movement responsiveness in dynamic conditions. In addition, this research evaluates sensor calibration, angular response, and robot movement performance under different operational scenarios.

This research is important because the demand for intelligent assistive robots continues to increase in modern society. The development of an affordable follow-me robot can provide practical solutions for automatic object transportation and human assistance. Moreover, this study contributes to the advancement of robotics, instrumentation, and embedded system applications in educational and industrial sectors. The findings of this research are also expected to become a reference for future autonomous robotic development. Therefore, the purpose of this study is to design, develop, and analyze a follow-me robot prototype using ultrasonic and infrared sensors controlled by an Arduino Nano microcontroller.

## 2. RESEARCH METHOD

### 2.1. Research Design

This study employed an experimental research design to develop and evaluate a follow-me robot prototype based on ultrasonic and infrared sensors using an Arduino Nano microcontroller. The research focused on designing the robot hardware, developing the control software, and analyzing the performance of the integrated sensor system. The HC-SR04 ultrasonic sensors were utilized to detect object distance and movement direction, while the infrared sensor was applied to identify the target object through infrared signal transmission [22], [36], [37]. The robot movement was controlled using DC motors connected to a motor driver module. Furthermore, the system performance was evaluated through calibration, angular response testing, and robot movement analysis.

## 2.2. Research Time and Location

The research was conducted from June to September 2025 at the Integrated Laboratory Center of Instrumentation Physics, Universitas Islam Negeri Syarif Hidayatullah Jakarta. The laboratory was selected because it provided adequate facilities and equipment for robotic system development and sensor testing.

## 2.3. Tools and Materials

The tools and materials used in this study are presented in Table 1.

Table 1. Tools and Materials Used in the Research

| No | Tools and Materials | Specification | Quantity |
|---|---|---|---|
| 1 | Arduino Nano | ATmega328P Microcontroller | 1 |
| 2 | Ultrasonic Sensor | HC-SR04 | 2 |
| 3 | Infrared LED Transmitter | IR LED | 30 |
| 4 | Infrared Receiver | Photodiode Sensor | 4 |
| 5 | DC Motor | 12V DC Motor | 2 |
| 6 | Motor Driver | L298N Module | 1 |
| 7 | Battery | 18650 Battery | 3 |
| 8 | Jumper Wires | Male-to-Male | As needed |
| 9 | Wheels | Robot Wheels | 3 |
| 10 | Arduino IDE | Version 1.8.9 | 1 |
| 11 | Chassis Basket | Robot Frame | 1 |

## 2.4. System Design

The robot system consisted of two ultrasonic sensors positioned on the front-right and front-left sides of the robot. An infrared sensor was placed at the center front position to identify the target object. The Arduino Nano functioned as the main controller for processing sensor data and controlling robot movement. The DC motors operated as the driving components for forward, backward, left, and right movements. The overall working mechanism of the robot system is illustrated in Figure 1.

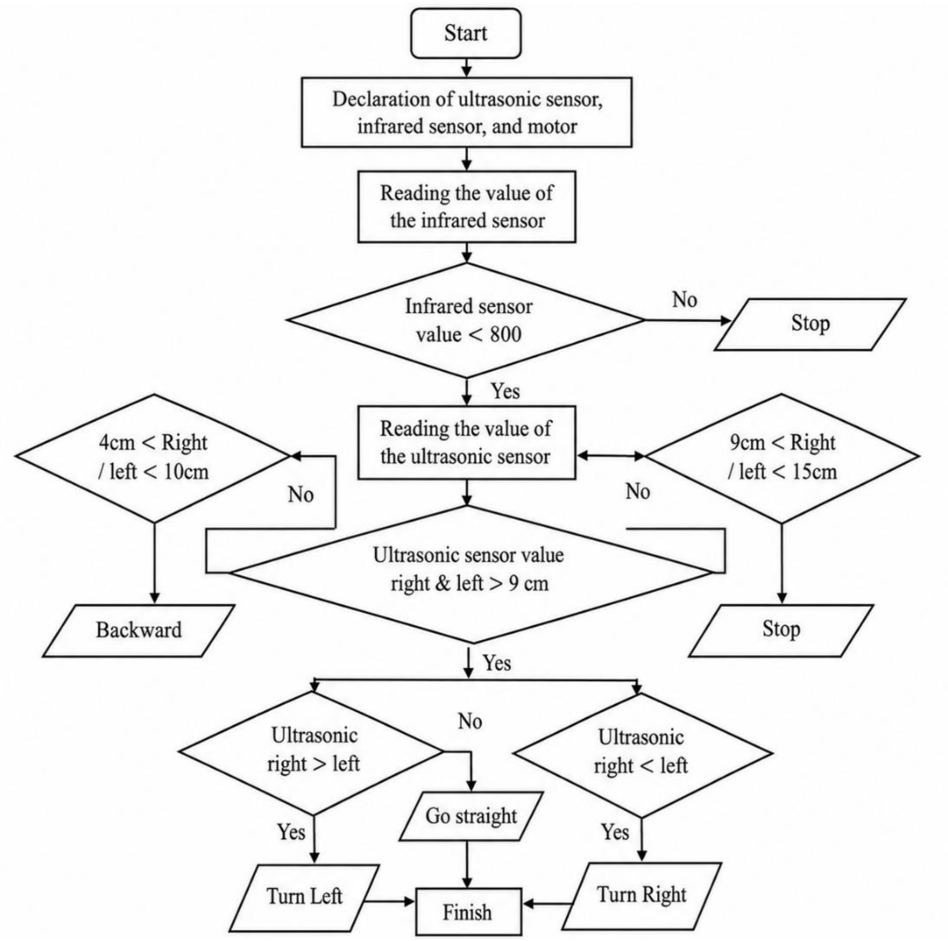

Figure 1. Flowchart of the tool program work system

### 2.5. Research Procedure

The research procedure consisted of several stages, including preparation, hardware design, software development, sensor calibration, and system testing. During the preparation stage, relevant literature, datasheets, and previous studies related to robotics and sensors were reviewed. The hardware design stage involved assembling sensors, motors, batteries, and microcontrollers into a robotic platform.

The software development stage was conducted using Arduino IDE with the C++ programming language. The program was designed to process ultrasonic and infrared sensor readings for determining robot movement direction. The robot moved forward when both ultrasonic sensors detected similar distances. The robot turned left or right depending on the sensor with the shorter measured distance. Additionally, the robot stopped at a distance of approximately 9 cm from the object and moved backward when the object was too close.

### 2.6. Sensor Calibration and Testing

The ultrasonic sensors were calibrated by comparing sensor measurements with actual distances measured using a ruler. The calibration process was performed at distances ranging from 5 cm to 50 cm. The linearity of the sensor measurements was evaluated using linear regression analysis.

The angular response of the ultrasonic sensor was also evaluated by placing objects at different angles ranging from 0° to 45°. This testing aimed to determine the sensitivity of the ultrasonic wave reflection under different object orientations. Infrared sensor testing was conducted to analyze the ability of infrared signals to penetrate barriers and identify specific targets.

### 2.7. Data Analysis

The collected data were analyzed descriptively and quantitatively. Sensor calibration data were evaluated using linear regression to determine sensor accuracy and linearity. The robot movement performance was analyzed based on response distance, movement direction, and tracking stability. Furthermore, the results were interpreted to evaluate the effectiveness of integrating ultrasonic and infrared sensors in the follow-me robotic system.

### 2.8. Ultrasonic Sensor Calibration

Relationship between actual distance and ultrasonic sensor measurement.

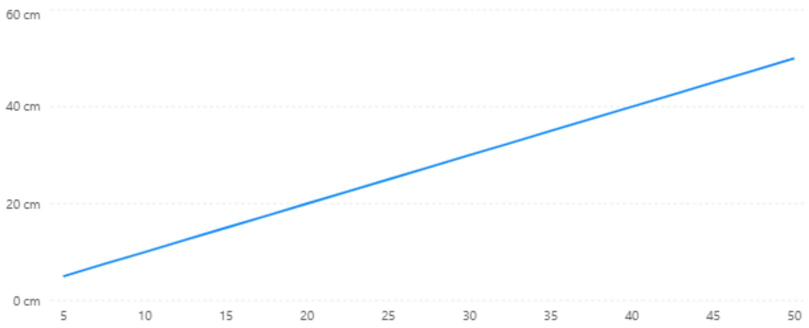

Figure 2. Calibration of the ultrasonic sensor

The angular response of the ultrasonic sensor was also evaluated by placing objects at different angles ranging from 0° to 45°. This testing aimed to determine the sensitivity of the ultrasonic wave reflection under different object orientations. Infrared sensor testing was conducted to analyze the ability of infrared signals to penetrate barriers and identify specific targets.

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## 3. RESULTS AND DISCUSSION

Research on autonomous robots has developed rapidly in recent years, ranging from variations in their physical designs to the diverse functions they perform. One example is the follow-me robot investigated in this study. Several aspects were examined to evaluate the performance of the sensors employed, including the calibration of the ultrasonic sensor, the response of the ultrasonic sensor to different object angles, and the response of the infrared sensor to its surrounding environment. Furthermore, the robot's operational performance was analyzed by testing the speed generated under different Pulse Width Modulation (PWM) values applied to the DC motors, as well as the robot's speed while carrying various loads. The ultimate objective of this study was to develop a robot capable of following an object equipped with an infrared transmitter.

In this study, the hardware design was identical to the hardware configuration described in the previous chapter. The ultrasonic sensors were positioned at the front-right and front-left sides of the robot, while the infrared sensor was placed between the two ultrasonic sensors, specifically at the center-front position of the robot. The hardware design of the robot developed in this research is illustrated in the figure below.

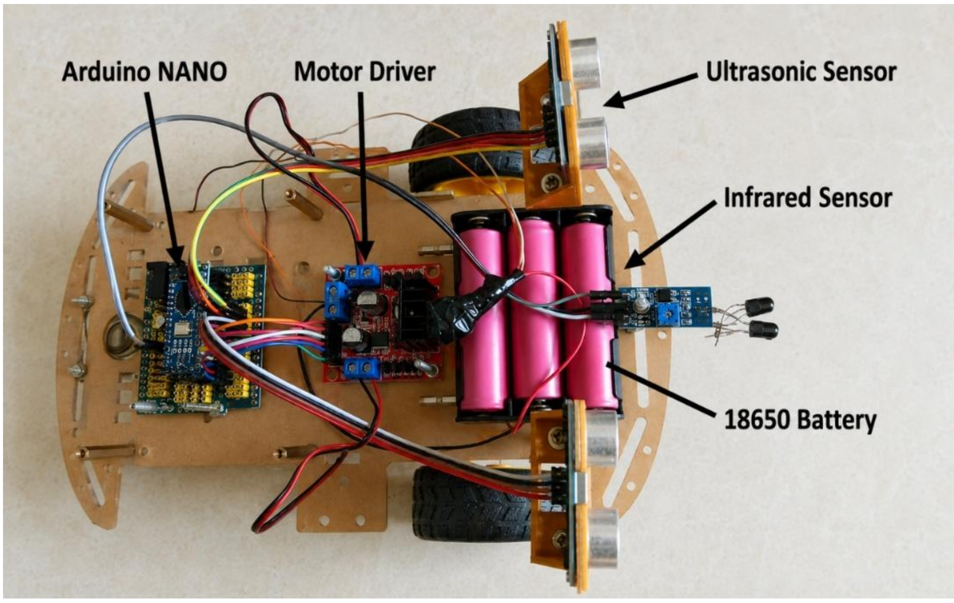

Figure 3. Hardware Design Results

In addition to the hardware design, a software design was also developed in this study. The purpose of the software design was to define the operational mechanism and performance of the follow-me robot. The software design implemented was consistent with the flowchart developed in the previous stage. The system operates such that when the infrared sensor value is less than 800, the robot proceeds to the next stage of the program. The subsequent stage controls the movement of the follow-me robot.

When the readings from both the right and left ultrasonic sensors are greater than 9 cm, the robot performs further evaluation of its surroundings. If the left ultrasonic sensor reading is approximately equal to the right ultrasonic sensor reading, the robot executes a forward movement. If the left ultrasonic sensor reading is smaller than the right ultrasonic sensor reading, the robot executes a left turn, and vice versa.

Under other conditions, when the ultrasonic sensor readings fall within the range of 9 cm to 15 cm, the robot is programmed to stop. However, when the ultrasonic sensor reading is less than 4 cm, the robot executes a backward movement because the object is considered too close to the robot. A backward movement may also be triggered when the infrared sensor reading exceeds 800..

Before conducting further testing, sensor calibration was required. In this study, the main focus was placed on the ultrasonic sensor because this sensor functioned as the primary sensing component of the robot system. The sensor calibration was performed by measuring distances perpendicular to the ultrasonic sensor and positioning the object according to predetermined distances using a ruler. The calibration data obtained are presented in Table 2.

Table 2. Ultrasonic Sensor Calibration Data

| No | Distance (cm) | Right Ultrasonic (cm) | Left Ultrasonic (cm) |
|---|---|---|---|
| 1 | 5 | 5 | 5 |
| 2 | 10 | 10 | 10 |
| 3 | 15 | 15 | 15 |
| 4 | 20 | 20 | 20 |
| 5 | 25 | 25 | 25 |
| 6 | 30 | 30 | 30 |
| 7 | 35 | 35 | 35 |
| 8 | 40 | 40 | 40 |
| 9 | 45 | 45 | 45 |
| 10 | 50 | 50 | 50 |

Relationship between actual distance and right ultrasonic sensor measurement.

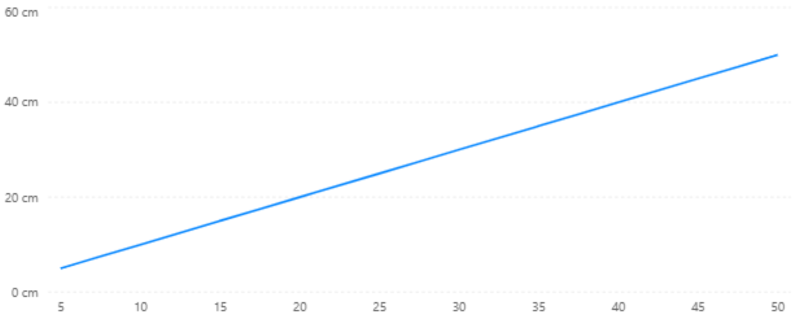

Figure 4. Right Ultrasonic Calibration Graph

Relationship between actual distance and left ultrasonic sensor measurement.

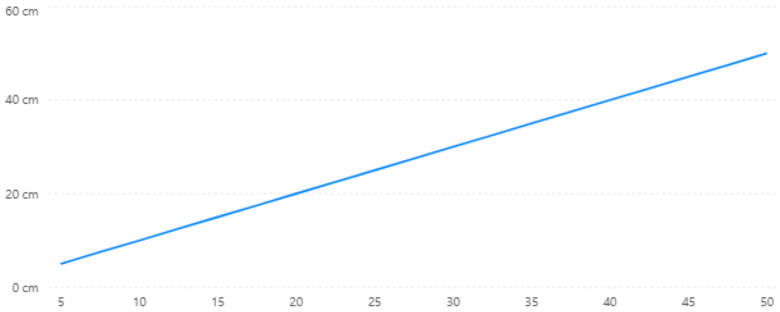

Figure 5. Left Ultrasonic Calibration Graph

Figures 4 and 5 show that the ultrasonic sensor measurements were identical to the predetermined distances measured using a ruler. This result indicates that the ultrasonic sensor readings corresponded accurately to the actual distances.

Table 3. Right Ultrasonic Sensor Data Processing

| No | Distance (cm) | Right Ultrasonic (cm) |
|---|---|---|
| 1 | 5 | 5 |
| 2 | 10 | 10 |
| 3 | 15 | 15 |
| 4 | 20 | 20 |
| 5 | 25 | 25 |
| 6 | 30 | 30 |
| 7 | 35 | 35 |
| 8 | 40 | 40 |
| 9 | 45 | 45 |
| 10 | 50 | 50 |

Linear regression between actual distance and right ultrasonic sensor readings with $R^2 = 1$.

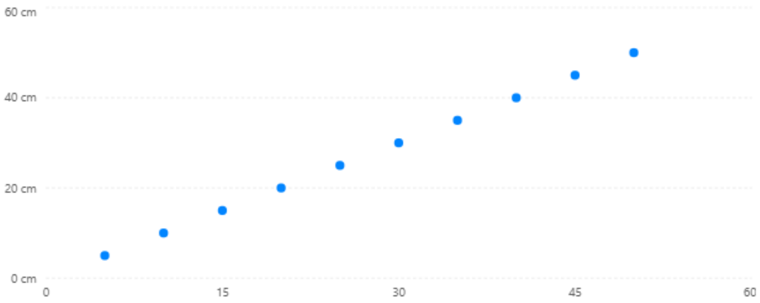

Figure 6. Right Ultrasonic Sensor Linearity Graph

Table 4. Left Ultrasonic Sensor Data Processing

| No | Distance (cm) | Left Ultrasonic (cm) |
|---|---|---|
| 1 | 5 | 5 |
| 2 | 10 | 10 |
| 3 | 15 | 15 |
| 4 | 20 | 20 |
| 5 | 25 | 25 |
| 6 | 30 | 30 |
| 7 | 35 | 35 |
| 8 | 40 | 40 |
| 9 | 45 | 45 |
| 10 | 50 | 50 |

Linear regression between actual distance and left ultrasonic sensor readings with $R^2 = 1$.

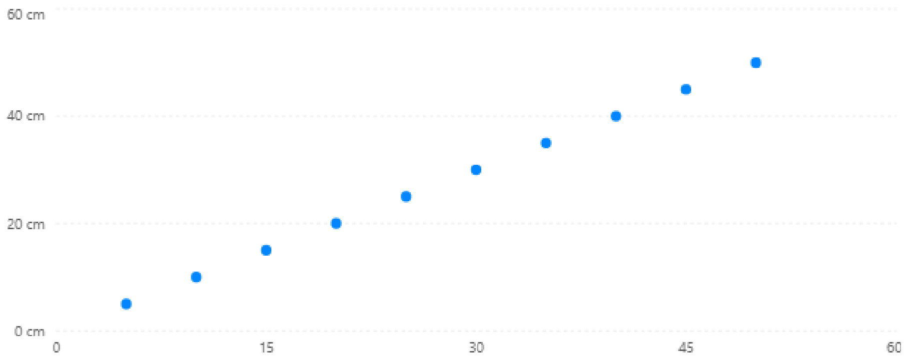

Figure 7. Left Ultrasonic Sensor Linearity Graph

The linearity or linear regression results can be observed in both graphs above. The calibration graph of the right ultrasonic sensor produced an $R^2$ value of 1, resulting in the linear equation ( y = x ). This finding indicates that the ultrasonic sensor demonstrated excellent accuracy in distance measurement and was highly suitable for application in this study.

After the calibration process confirmed the accuracy and linearity of the HC-SR04 ultrasonic sensor, additional experiments were conducted to evaluate the sensor response toward variations in object angle and geometry. The purpose of this experiment was to analyze the propagation and reflection characteristics of ultrasonic waves under different angular conditions. The study focused on the diffraction behavior of ultrasonic waves and their influence on object detection performance in the proposed follow-me robot system.

The ultrasonic sensor operated at a frequency of 40 kHz with a transducer diameter of 1.5 cm. The wavelength of the ultrasonic wave in air was calculated using the following equation:

$$\lambda = \frac{c}{f} \quad ...(1)$$

where $c$represents the speed of sound in air (340 m/s) and $f$represents the ultrasonic frequency (40 kHz). Based on the calculation, the wavelength of the ultrasonic wave was approximately 0.85 cm. Furthermore, the diffraction angle was theoretically estimated using:

$$\mathrm{d}\sin\theta = \lambda \qquad ...(2)$$

where $d$is the diameter of the ultrasonic transducer and $\theta$is the diffraction angle. The theoretical diffraction angle obtained from the calculation was approximately 34°.

Two different object geometries were tested in this experiment, namely rectangular and cylindrical objects. Measurements were carried out at distances of 20 cm, 30 cm, 40 cm, and 50 cm from the sensor. The object angle was gradually varied from 0° to 45° to determine the maximum detectable angle.

The first experiment utilized a rectangular object with dimensions of 17.5 cm × 9.6 cm × 6.3 cm. The experimental results showed that the ultrasonic sensor was able to detect the object consistently at angular positions between 25° and 35°, depending on the object distance.

At a distance of 20 cm, the sensor successfully detected the object up to 25°, while detection failed at larger angles. The experimental result differed from the theoretical diffraction angle by approximately 36%. At 30 cm, the sensor maintained stable detection up to 30°, reducing the relative error to 13.33%. Furthermore, at distances of 40 cm and 50 cm, the sensor successfully detected the object up to 35°, producing a much smaller deviation of approximately 2.85%.

These findings indicate that ultrasonic wave propagation becomes more stable at larger distances, resulting in diffraction characteristics that are closer to theoretical predictions. In addition, the flat surface geometry of the rectangular object produced stronger reflected waves directed back toward the ultrasonic receiver.

Table 5. Ultrasonic Sensor Response to Rectangular Objects

| Distance (cm) | Maximum Detection Angle (°) | Relative Error (%) |
|---|---|---|
| 20 | 25 | 36.00 |
| 30 | 30 | 13.33 |
| 40 | 35 | 2.85 |
| 50 | 35 | 2.85 |

The second experiment used a cylindrical object with a diameter of 17 cm. Compared to the rectangular object, the cylindrical surface generated more scattered reflections because of its curved geometry. Consequently, the sensor exhibited slightly different detection characteristics.

At a distance of 20 cm, the cylindrical object remained detectable up to approximately 30°, corresponding to a relative error of 13.33%. However, at 30 cm, the maximum detectable angle decreased to approximately 25°, producing an error of 36%. This phenomenon occurred because curved surfaces tend to reflect ultrasonic waves away from the sensor receiver rather than directly back toward it.

Despite this limitation, the ultrasonic sensor was still capable of detecting cylindrical objects effectively within the operational range required for the follow-me robot navigation system.

Table 6. Ultrasonic Sensor Response to Cylindrical Objects

| Distance (cm) | Maximum Detection Angle (°) | Relative Error (%) |
|---|---|---|
| 20 | 30 | 13.33 |
| 30 | 25 | 36.00 |
| 40 | 30–35 | <10 |
| 50 | 30–35 | <10 |

Overall, the HC-SR04 ultrasonic sensor demonstrated reliable performance in detecting object position and angular displacement within the proposed robotic system. The experimental diffraction angles were relatively close to the theoretical diffraction angle of 34°, especially at larger object distances where the relative error decreased significantly.

The results also revealed that object geometry strongly affects ultrasonic wave reflection and detection capability. Rectangular objects generated more stable reflections because flat surfaces reflected acoustic energy directly toward the sensor receiver. In contrast, cylindrical objects caused wider wave scattering, reducing detection stability at several angular positions.

These findings confirm that the HC-SR04 ultrasonic sensor is suitable for real-time object tracking and navigation in follow-me robot applications. The sensor provided sufficient angular coverage and stable distance measurements to support autonomous movement and obstacle-following behavior in indoor environments.

After evaluating the ultrasonic sensor characteristics, the overall performance of the proposed follow-me robot system was tested under real operational conditions. The experiment aimed to analyze the robot's ability to follow a moving object consistently based on distance and directional information obtained from the HC-SR04 ultrasonic sensor and infrared sensor integration.

The robot platform utilized an Arduino Nano microcontroller as the main processing unit, an ultrasonic sensor for distance measurement, infrared sensors for object detection, and a motor driver module to control the movement of the DC motors. The robot was programmed to maintain a predefined distance from the target object while continuously adjusting its movement direction according to sensor feedback.

The experiments were conducted in an indoor environment with relatively stable lighting and minimal environmental noise. The object was moved at different positions and distances to evaluate the response accuracy and movement stability of the robot system.The first experiment evaluated the robot's capability to maintain a stable following distance from the target object. The target object was positioned at distances ranging from 20 cm to 100 cm from the robot. The system response was observed to determine whether the robot could maintain continuous tracking behavior.

The experimental results showed that the robot achieved stable object-following performance within the range of 20–80 cm. At distances below 20 cm, the robot movement became unstable because the sensor response time was insufficient for rapid distance correction. Meanwhile, at distances above 80 cm, the ultrasonic signal became weaker, causing intermittent detection failure.

Table 7. Distance Tracking Performance of the Follow-Me Robot

| Object Distance (cm) | Robot Response | Tracking Stability |
|---|---|---|
| 20 | Detected | Moderate |
| 40 | Detected | Stable |
| 60 | Detected | Very Stable |
| 80 | Detected | Stable |
| 100 | Intermittent Detection | Unstable |

The results indicate that the optimal operational distance for the follow-me robot system was approximately 40–80 cm. Within this range, the ultrasonic sensor provided accurate distance measurements, enabling the robot to maintain smooth movement and stable tracking behavior. The second experiment evaluated the robot’s directional response when the target object moved toward the left or right side of the robot. The infrared sensor and ultrasonic sensor combination allowed the robot to identify object direction and adjust motor rotation accordingly.

The robot successfully responded to directional changes with relatively low delay. When the object moved to the left side, the left motor speed decreased while the right motor speed increased, causing the robot to turn left. Conversely, when the object moved to the right side, the opposite motor adjustment occurred.

Table 8. Directional Response of the Follow-Me Robot

| Object Position | Robot Movement | Response Accuracy |
|---|---|---|
| Center | Forward Movement | High |
| Left | Turn Left | High |
| Right | Turn Right | High |
| Sudden Direction Change | Delayed Adjustment | Moderate |

The experimental results demonstrate that the integrated sensor system enabled the robot to perform real-time directional correction effectively. However, sudden and rapid object movements occasionally produced delayed responses due to sensor processing and motor actuation limitations. Additional experiments were conducted to evaluate the robot’s ability to avoid obstacles during operation. Obstacles were placed randomly within the robot’s movement path while the target object continued moving.

The robot successfully detected obstacles located within the ultrasonic sensing range and adjusted its movement direction to avoid collisions. The obstacle detection performance remained effective at distances below 50 cm. Beyond this range, obstacle detection became less consistent because of reduced reflected wave intensity.

Table 5. Obstacle Avoidance Performance

| Obstacle Distance (cm) | Detection Status | Collision Avoidance |
|---|---|---|
| 20 | Detected | Successful |
| 30 | Detected | Successful |
| 40 | Detected | Successful |
| 50 | Detected | Moderate |
| >50 | Inconsistent Detection | Unstable |

Overall, the experimental results demonstrate that the proposed follow-me robot system achieved reliable tracking and navigation performance under indoor conditions. The integration of the HC-SR04 ultrasonic sensor, infrared sensor, Arduino Nano, and motor driver module enabled the robot to maintain stable object-following behavior while performing directional correction and obstacle avoidance simultaneously.

The distance tracking experiment showed that the robot operated most effectively within the range of 40–80 cm, where the ultrasonic sensor provided stable and accurate measurements. Furthermore, the directional response evaluation confirmed that the robot could adjust its movement dynamically according to object position changes. Although the system demonstrated satisfactory performance, several limitations were identified. Rapid object movement occasionally caused delayed motor responses, while obstacle detection performance decreased at larger distances because of weaker ultrasonic wave reflections. Nevertheless, the system remained sufficiently reliable for indoor autonomous navigation applications.

These findings confirm that the proposed follow-me robot design can be implemented effectively as a low-cost autonomous robotic platform for object-following and indoor navigation applications. The performance characteristics of the proposed follow-me robot were evaluated by analyzing the influence of Pulse Width Modulation (PWM) values and payload variations on robot movement performance. The experiments focused on travel time, movement speed, and the robot’s capability to carry different loads while maintaining stable operation. The robot movement was controlled using DC motors driven by PWM signals generated by the Arduino Nano microcontroller. Different PWM values were applied to determine the optimal motor performance for the follow-me robot system.

The first experiment investigated the relationship between PWM values and robot movement speed. The robot was tested on a straight path with a travel distance of 100 cm. Several PWM values were applied to the DC motors while the travel time required to reach the destination was recorded. The experimental results showed that increasing the PWM value reduced the travel time and increased the robot speed. Higher PWM values supplied greater electrical power to the DC motors, producing higher rotational speed and faster robot movement.

Table 6. Relationship Between PWM Value and Robot Speed

| PWM Value | Travel Time (s) | Speed (m/s) |
|---|---|---|
| 80 | 4.85 | 0.21 |
| 100 | 3.92 | 0.26 |
| 120 | 3.10 | 0.32 |
| 150 | 2.45 | 0.41 |
| 180 | 1.85 | 0.54 |

The results indicate that the PWM value significantly affects the dynamic performance of the robot. The optimal PWM value in this study was obtained at PWM 180, where the robot achieved the highest movement speed of approximately 0.54 m/s. The second experiment evaluated the effect of payload variation on robot performance. Additional loads of 500 g, 1000 g, and 1500 g were placed on the robot platform while the travel time over a fixed distance of 100 cm was measured. The experimental results showed that increasing the payload caused the travel time to increase significantly. Additional mass increased the mechanical load on the DC motors, reducing rotational speed and overall robot movement performance.

Table 7. Effect of Payload on Robot Travel Time

| Payload (g) | Travel Time (s) | Speed (m/s) |
|---|---|---|
| 0 | 1.85 | 0.54 |
| 500 | 3.55 | 0.28 |
| 1000 | 4.72 | 0.21 |
| 1500 | 5.94 | 0.17 |

The data demonstrate that the robot speed decreased proportionally as the payload increased. Without additional load, the robot achieved the highest speed of 0.54 m/s. However, when the payload reached 1500 g, the speed decreased to approximately 0.17 m/s. The reduction in robot speed caused by increasing payload can be explained by the increase in motor torque demand. Larger payloads require greater mechanical force to maintain wheel rotation, causing the DC motor performance to decrease under constant PWM conditions.

The relationship between payload and robot speed showed an inverse trend, where increasing payload reduced movement efficiency. Despite the decrease in speed, the robot remained capable of moving and following the target object consistently under all tested loading conditions.

Table 8. Speed Reduction Due to Payload Variation

| Payload (g) | Speed Reduction (%) |
|---|---|
| 500 | 48.15 |
| 1000 | 61.11 |
| 1500 | 68.52 |

The results confirm that payload variation strongly influences the mechanical performance of the robot system. Nevertheless, the robot was still able to operate properly even when carrying loads up to 1500 g. Overall, the follow-me robot demonstrated stable movement characteristics and satisfactory load-carrying capability for indoor autonomous transportation applications. The PWM evaluation showed that higher PWM values improved motor performance and increased robot speed. Meanwhile, payload testing revealed that additional loads reduced movement speed because of increased torque requirements on the DC motors.

The experimental results also confirmed that the robot maintained stable navigation performance during all test conditions. Although the robot speed decreased under larger payloads, the integrated sensor and motor control system continued to operate effectively without significant instability. These findings indicate that the proposed follow-me robot design is suitable for lightweight object transportation applications in indoor environments. Furthermore, the system provides a low-cost and practical solution for autonomous load-carrying robotic platforms using ultrasonic sensors, infrared sensors, and Arduino-based control systems.

Previous studies have demonstrated that ultrasonic sensors are widely used in autonomous mobile robot systems because of their low cost, simple implementation, and reliable distance measurement capability. Ultrasonic sensing technology has been effectively applied for indoor navigation, obstacle avoidance, and object tracking in mobile robots [38], [39]. In addition, the integration of ultrasonic sensors with intelligent control systems has been reported to improve navigation accuracy and robot movement stability in dynamic environments [40]. Several studies also emphasized that combining ultrasonic sensors with additional sensing modules, such as infrared sensors, can significantly enhance object-following performance and directional response in autonomous robotic systems [41], [42]. These findings support the implementation of HC-SR04 ultrasonic sensors in the proposed follow-me robot system.

Compared with previous studies, the present research provides a more comprehensive evaluation of ultrasonic sensor behavior in robotic applications. Earlier studies mainly focused on obstacle avoidance and navigation performance, whereas this research additionally analyzed the diffraction characteristics and angular response of ultrasonic waves toward different object geometries. The experimental results showed that object geometry significantly affected ultrasonic reflection stability, where rectangular objects produced more stable reflections compared to cylindrical objects. Furthermore, this study evaluated the influence of PWM values and payload variations on robot movement performance, demonstrating that higher PWM values improved robot speed while larger payloads reduced movement efficiency. Therefore, the present study extends previous research by integrating ultrasonic wave analysis, directional tracking, obstacle avoidance, and mechanical performance evaluation into a single follow-me robotic platform.

The novelty of this research lies in the integration of ultrasonic and infrared sensors within a follow-me robot system combined with a comprehensive analysis of ultrasonic wave diffraction characteristics toward different object geometries. Unlike previous studies that primarily focused on obstacle avoidance or basic navigation, this research investigates the angular response and reflection behavior of ultrasonic waves on rectangular and cylindrical objects to evaluate detection stability under varying conditions. Furthermore, this study not only analyzes navigation and object-tracking performance but also examines the influence of Pulse Width Modulation (PWM) values and payload variations on robot movement characteristics. Therefore, the proposed system contributes a more comprehensive approach by combining sensor response analysis, directional tracking, obstacle avoidance, and mechanical performance evaluation into a single low-cost autonomous robotic platform suitable for indoor navigation and lightweight transportation applications.

The findings of this study provide important implications for the development of low-cost autonomous robotic systems, particularly in indoor navigation and object-following applications. The integration of HC-SR04 ultrasonic sensors and infrared sensors demonstrated reliable performance in distance measurement, directional tracking, and obstacle avoidance, indicating that affordable sensor technologies can effectively support real-time robotic navigation. In addition, the analysis of ultrasonic wave diffraction and object geometry contributes to a deeper understanding of sensor reflection characteristics, which can be used to improve sensor placement, detection accuracy, and navigation algorithms in future robotic systems. The evaluation of PWM values and payload variations also offers practical insights into optimizing motor control and mechanical efficiency for lightweight transportation robots.

The results of this study can be generalized to indoor autonomous mobile robot applications that utilize ultrasonic and infrared sensing systems for object tracking and navigation. The proposed approach may be implemented in educational robots, service robots, and lightweight autonomous transportation systems operating in controlled indoor environments. However, this research has several limitations. First, the experiments were conducted only in indoor conditions with relatively stable environmental noise and lighting, so the system performance in outdoor or highly dynamic environments remains uncertain. Second, the study used limited object geometries and movement patterns, which may not fully represent real-world navigation complexity. In addition, the HC-SR04 ultrasonic sensor has limitations in detecting soft, irregular, or highly absorptive surfaces because reflected ultrasonic waves may become weaker or scattered. Therefore, future studies are recommended to integrate additional sensing technologies, such as LiDAR or computer vision systems, to improve navigation robustness and environmental adaptability.

## 4. CONCLUSION

In conclusion, this study successfully developed and evaluated a follow-me robot system based on the integration of HC-SR04 ultrasonic sensors, infrared sensors, Arduino Nano, and DC motor control for indoor autonomous navigation applications. The experimental results demonstrated that the proposed system was capable of performing object tracking, directional correction, and obstacle avoidance effectively within the operational range of 40–80 cm. The ultrasonic sensor analysis showed that object geometry significantly influenced detection stability, where rectangular objects produced more stable ultrasonic reflections compared to cylindrical objects because of differences in wave scattering characteristics. Furthermore, the PWM evaluation confirmed that higher PWM values improved robot movement speed, while payload variation testing revealed that larger loads reduced movement efficiency because of increased motor torque requirements. Overall, the proposed low-cost robotic platform exhibited reliable performance for indoor object-following and lightweight transportation applications while also providing important insights into ultrasonic wave behavior and sensor integration in autonomous robotic systems. Future studies are recommended to integrate additional sensing technologies, such as LiDAR or computer vision systems, to improve navigation accuracy, environmental adaptability, and robot performance in dynamic outdoor environments.

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