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Omni-Directional Navigation Mobile Robot using Radar Ultrasonic Sensors

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ABSTRACT

Mobile robots often struggle with manoeuvring in confined indoor environments, where conventional wheel configurations limit flexibility and low-cost sensing systems may fail to detect nearby obstacles reliably. This study presents the development of an affordable omni-directional mobile robot equipped with three omni-wheels to achieve seamless 360° holonomic motion. A servo-driven HC-SR04 ultrasonic sensor performs radar-like scanning from 0° to 180°, providing real-time environmental information to an Arduino Uno executing a reactive obstacle avoidance algorithm. The proposed system was evaluated in cluttered indoor environments and demonstrated stable motion with response times below 0.6 s, ultrasonic sensing accuracy improvements exceeding 60% after calibration and autonomous navigation success rates above 90%. The results indicate that low-cost sensing and control hardware can provide reliable autonomous navigation performance for educational, laboratory and small-scale service robotic applications.

Keywords: Omni-Directional Robot, Ultrasonic Radar, Autonomous Navigation, Obstacle Avoidance, Reactive Control

1. INTRODUCTION

Warehouse facilities, hospital corridors and research laboratories often require mobile robots to operate efficiently in confined spaces, avoid obstacles and rapidly change direction while maintaining smooth navigation. Conventional wheeled mobile robots are generally limited by non-holonomic motion constraints, requiring frequent reorientation to achieve directional changes, which reduces manoeuvrability in cluttered indoor environments [1][2]. Furthermore, low-cost sensing systems may exhibit insufficient obstacle detection capabilities, thereby affecting navigation reliability [3]. These limitations pose challenges for practical applications such as autonomous delivery systems, service robotics and educational platforms, where flexibility, responsiveness and operational reliability are essential. Existing solutions frequently rely on either sophisticated sensing and control hardware with relatively high implementation costs or low-cost components that may not provide satisfactory navigation performance, creating a need for affordable and reliable indoor robotic systems [3][4].

In this study, an omni-directional mobile robot was developed to address these challenges. The proposed platform employs three omni-wheels arranged at 120° intervals to provide holonomic motion capabilities, enabling translational and rotational movements without requiring chassis reorientation. Obstacle detection is achieved using an HC-SR04 ultrasonic sensor mounted on a servo motor that performs radar-like scanning between 0° and 180°. Distance measurements are

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processed in real time by an Arduino Uno executing a reactive navigation algorithm to identify collision-free paths and autonomously perform obstacle avoidance manoeuvres. The developed system was experimentally evaluated in indoor environments containing boxes, cylindrical objects and narrow passages. Experimental results demonstrated stable motion with response times below 0.6 s, ultrasonic sensing accuracy improvements exceeding 60% following calibration, and navigation success rates greater than 90% under the tested conditions.

The findings indicate that low-cost, commercially available components, including Arduino-based controllers, DC motors and ultrasonic sensors, can provide reliable autonomous navigation performance when appropriately integrated. The proposed system offers a cost-effective robotic platform suitable for educational institutions, research laboratories and small-scale service applications. Furthermore, this study contributes to the advancement of reactive navigation strategies by demonstrating that the combination of omni-directional mobility and low-cost sensor integration can provide effective indoor navigation capabilities for applications such as education, surveillance and logistics.

1.1 Literature Review

Omni-directional mobile robots with radar ultrasonic sensors provide robust, low-cost solutions for indoor navigation, leveraging holonomic mobility and servo-scanned distance measurement for real-time obstacle avoidance and mapping. This review synthesizes key advancements, emphasizing reactive control in constrained environments.

Omni-wheels enable 360° holonomic motion via inverse kinematics for three wheels at 120° spacing, supporting translation and rotation without steering. A work by Eyuboglu and Atali emphasized a collaborative path-planning algorithm for 3-wheel omnidirectional AMRs, achieving collision-free leader-follower tracking with high accuracy in simulations and tests [5]. This addresses scalability in multi-robot scenarios, though real-world communication remains challenging. Ultrasonic sensors (e.g., HC-SR04) compute distance via time-of-flight, and servo-mounted for 0° to 180° radar scans able to generate polar maps. Another work emphasized the HC-SR04's resolution capability, distinguishing 7 cm separations at 11 cm with Arduino interfacing, recommending aperture enlargement for precision. Limitations include beam divergence and multipath errors on soft surfaces [6].

Shen emphasized omni-directional mobility with ultrasonic positioning for sound-seeking robots, establishing DC motor dynamics to enhance path-tracking over two-wheeled limits [7]. This supports environmental monitoring, but ultrasonic noise reduces accuracy. Ultrasonic-ZigBee positioning was used as a GPS alternative for indoor omni-robots, achieving low-error square/circular trajectories via Visual Basic UI [8], where range and interference constrain larger spaces. Meanwhile, low-cost single-sensor sweeping was utilized for collision avoidance, approximating object shapes with minimal path deviation in dynamic indoor tests [9]; effective as backup, but slow for multiples. For broader radar contexts, mmWave radars' Doppler velocity for odometry/SLAM was used in fog or rain, outperforming LiDAR despite sparse clouds. Ultrasonic hybrids could extend this affordably [10].

In [11], reflective cones were used for 360° beams and trilateration, overcoming directional limits via ToF with fixed receivers. They emphasized weighted sonar grid maps, minimizing erroneous data via morphological reliability. Meanwhile, particle filtering was used with rotating ultrasonics for room-level localization on NXT platforms [9]. Reactive strategies dominate: halt if D_min < 30cm, turn to open ϕ. Cuevas et al. emphasized type-2 fuzzy logic for omnidirectional control, superior to type-1 in uncertainty handling [1], while Palacín et al. emphasized LiDAR self-localization yielding RMSE 0.032 m at 0.3 m/s. They achieved a success of more than 90% in the prototypes [12].

Ultrasonic radars excel in affordability but falter in dynamics and long-range. Fusion with mmWave and artificial intelligence can be the key. This research aligns by calibrating HC-SR04 for >90% avoidance, advancing educational and low-cost autonomy.

2. MATERIAL AND METHODS

This study developed and evaluated an omni-directional mobile robot equipped with a radar-style ultrasonic sensing system for autonomous indoor navigation. The methodology consisted of system design, hardware integration, software development, data collection and experimental evaluation.

2.1 System Design

The robot was designed based on four main subsystems: motion, sensing, control and power. The motion subsystem employed three omni-wheels arranged at 0°, 120° and 240°, each driven by a DC motor through an MD20A motor driver. This configuration enabled holonomic motion, allowing the robot to move forward, backward, laterally and rotationally without changing chassis orientation.

The sensing subsystem used an HC-SR04 ultrasonic sensor mounted on an SG90 servo motor. The servo rotated the sensor from 0° to 180°, creating a radar-like scanning mechanism to detect obstacles across the robot's frontal field. The control subsystem was centred on an Arduino Uno microcontroller, which processed sensor readings, executed the navigation algorithm, and generated motor commands. Power was supplied by an 11.1 V 1300 mAh Li-Po battery, with a buck converter used to regulate the supply to 5 V for logic circuits.

2.2 Hardware Development

The robot chassis was constructed using a two-layer acrylic and plywood frame to provide sufficient structural strength while maintaining a lightweight design. The omni-wheels were mounted symmetrically to ensure stability and balanced motion. The ultrasonic sensor and servo motor were installed at the front of the chassis to provide an unobstructed scanning field. The Arduino Uno, Sensor Shield v5, motor drivers and TFT display were positioned centrally to minimize wiring complexity and improve accessibility.

The HC-SR04 ultrasonic sensor was connected to the Arduino through trigger and echo pins, while the SG90 servo motor was connected to a digital pin for angle control. A TFT ST7735 display was integrated using SPI communication to show radar data and system status in real time. The three MD20A motor drivers received PWM and direction signals from the Arduino to control the speed and rotation direction of each motor. A common grounding scheme was implemented for all modules to ensure stable sensor readings and synchronized operation.

2.3 Software Development

The control software was programmed in the Arduino IDE using C/C++. A reactive navigation strategy was adopted, in which the robot continuously scanned the environment and responded immediately to nearby obstacles. The software began with initialization of the motors, ultrasonic sensor, servo motor and display module. During operation, the servo swept the ultrasonic sensor across 0° to 180°and back, collecting distance measurements at predefined angular intervals.

The measured distances were compared against a predefined safety threshold of 30 cm. If no obstacle was detected within the threshold, the robot moved forward. When an obstacle was detected, the robot stopped, analysed the radar data and the direction with the largest free space will be selected. Motor commands were then generated to move the robot away from the obstacle. This process repeated continuously in an infinite loop, enabling real-time obstacle avoidance without a predefined map or route.

The inverse kinematic model was revised to incorporate the angular velocity component (Ω) required for rotational motion. For a three-wheel holonomic platform with wheel orientations of 0°, 120° and 240°, the wheel angular velocities were computed as a function of translational velocities (V_x, V_y), angular velocity (Ω), wheel radius (r) and the distance from the robot center to each wheel (R). This formulation enables simultaneous translational and rotational motion, which is consistent with the experimental evaluation presented in this study, as given by Equation (1) to (3):

$$\omega_1 = \frac{-\sin\ \theta_1 V_x + \cos\ \theta_1 V_y + R\Omega}{r} \tag{1}$$

$$\omega_2 = \frac{-\sin\ \theta_2 V_x + \cos\ \theta_2 V_y + R\Omega}{r} \tag{2}$$

$$\omega_3 = \frac{-\sin\ \theta_3 V_x + \cos\ \theta_3 V_y + R\Omega}{r} \tag{3}$$

where:

θ_1 = 0°
θ_2 = 120°
θ_3 = 240°

R = distance from centre to wheel
r = wheel radius
Ω = angular velocity

These values were normalized and converted into PWM signals for the motor drivers.

2.4 Data Collection and Processing

To evaluate the ultrasonic radar system, distance measurements were collected at fixed obstacle distances of 25 cm, 50 cm, 75 cm, 100 cm and 150 cm. For each test distance, 176 samples were recorded across a full radar sweep in both left-to-right and right-to-left directions. Three conditions, half circle, square and obstacle were tested. For half circle and square sweeping, 180° sweeping were done, while for obstacle sweeping, 80° were done. Multiple servo delay settings of 0 ms, 20 ms, 30 ms, 40 ms, 50 ms and 80 ms were examined to assess their effect on measurement stability.

The radar data were analysed using Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and bias. These metrics are expressed as in Equation (4) until (6):

$$MAE = \frac{1}{n}\sum_{i=1}^{n} \mid y_i - \hat{y}_i \mid \tag{4}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{5}$$

$$Bias = \frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i) \tag{6}$$

where $y_i$represents the actual distance and $\hat{y}_i$ represents the measured distance.

To reduce systematic measurement error, a linear correction model obtained from regression analysis was applied to the ultrasonic sensor readings, as expressed in Equation (7):

$$D_{\{corrected\}} = 0.913D_{\{measured\}} + 1.276 \tag{7}$$

where $D_{\{corrected\}}$ is the calibrated distance and $D_{\{measured\}}$ is the raw distance measured by the HC-SR04 sensor. The regression coefficients were determined as (a=0.913) and (b=1.276) through linear fitting of the experimental calibration data. In addition, a Simple Moving Average (SMA) filter was employed to reduce random fluctuations in the sensor output. Missing angular readings were reconstructed using linear interpolation to obtain a complete scan profile. Directional fusion averaging was subsequently performed by combining left-to-right and right-to-left scans to further improve measurement accuracy and suppress noise.

2.5 Experimental Procedure

The prototype was tested in a controlled indoor environment on a flat surface. Three sets of experiments were performed. First, omnidirectional movement tests evaluated the robot's ability to move forward, backward, sideways and rotate. Response time and stability were recorded for each motion type. Second, radar accuracy tests assessed the performance of the ultrasonic sensor at the five fixed distances. Third, autonomous navigation tests were conducted in a 2 m × 2 m space with different obstacle arrangements, including straight paths and corner layouts.

For the navigation tests, the robot's detection distance, travel time and success rate were measured. A successful trial was defined as the robot completing its movement without colliding with any obstacle. This experimental setup allowed evaluation of both subsystem performance and overall robot functionality in real-time navigation tasks.

3. RESULTS AND DISCUSSION

The developed omni-directional mobile robot (as shown in Figure 1) was evaluated in terms of motion performance, radar ultrasonic sensing accuracy, and autonomous navigation capability. The results confirm that the integrated system achieved the intended objectives of smooth holonomic movement, reliable obstacle detection and reactive indoor navigation.

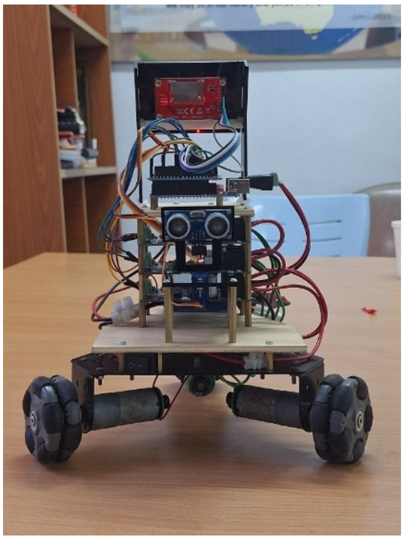

Figure 1. The developed robot used in this study

3.1 Omni-Directional Movement Performance

The first evaluation focused on the mobility performance of the three-wheel omni-directional platform. The robot was tested for forward, backward, sideways and rotational motion on a flat indoor surface. Each movement was repeated five times, and the response time from command activation to wheel actuation was recorded.

The robot demonstrated fast and stable movement in all tested directions, with average response times below 0.6 s. Forward motion showed the shortest response time at 0.42 s, followed by backward motion at 0.45 s. Sideways motion to the left and right recorded 0.47 s and 0.46 s, respectively, while rotational movement required 0.51 s. Stability ratings indicated that forward and backward movement were the most stable, each achieving a score of 5, whereas sideways and rotational motions received a score of 4 due to slight traction imbalance during lateral displacement and turning. Stability scores were assigned based on visual observations of chassis vibration, trajectory deviation, and wheel slippage during repeated motion tests. A five-point scale was adopted, where 5 represented highly stable motion with negligible deviation, and 1 represented severe instability.

These findings indicate that the selected three-wheel holonomic configuration provided sufficient manoeuvrability for indoor use. Although minor instability was observed during sideways and rotational movements, the robot remained controllable and responsive. This confirms that the mechanical design and motor control strategy were suitable for omni-directional navigation in confined environments.

3.2 Radar Ultrasonic Sensing Performance

The second evaluation examined the radar-style ultrasonic sensing subsystem. The HC-SR04 sensor mounted on the servo motor was tested at fixed obstacle distances of 25 cm, 50 cm, 75 cm, 100 cm and 150 cm. Three conditions were tested as shown in Figure 2, Figure 3 and Figure 4, which represent the sample radar mapping for half circle, square and obstacle, respectively. The raw data were processed using filtering and calibration techniques to reduce measurement noise and systematic error. Table 1 shows the ultrasonic radar accuracy by set distance.

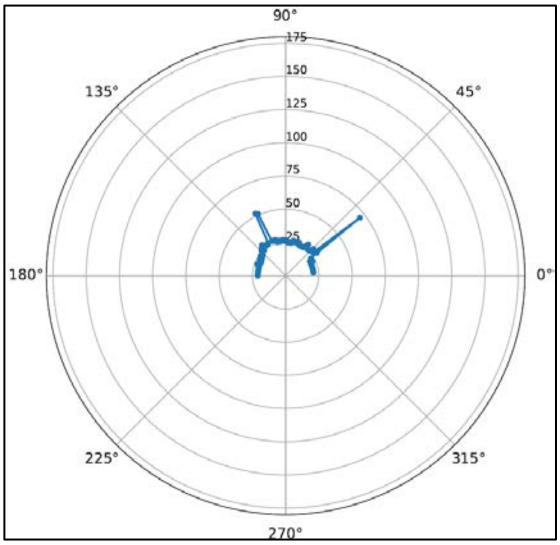

Figure 2. 180° ultrasonic half circle sweeping from right to left at 25 cm distance

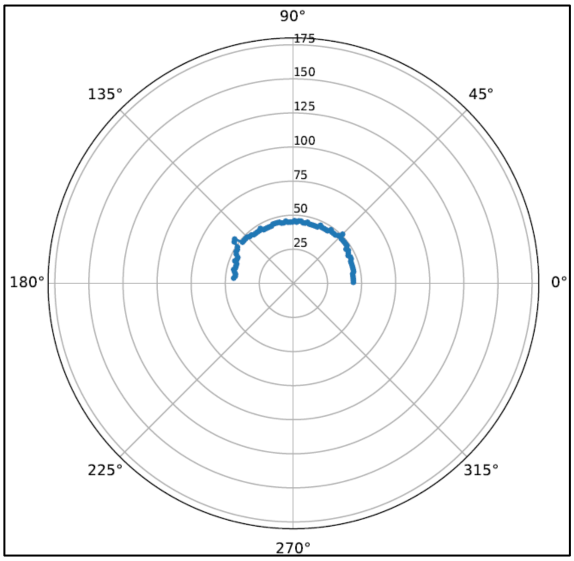

Figure 3. 180˚ ultrasonic square sweeping from left to right at 50 cm distance

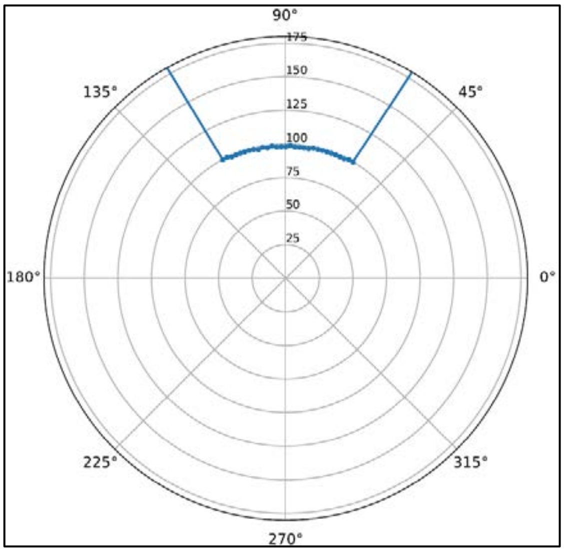

Figure 4. 180˚ ultrasonic obstacle sweeping from right to left at 100 cm distance

Table 1 Ultrasonic radar accuracy by set distance

Distance (cm)	MAE			RMSE		
	Before (cm)	After (cm)	Improvement (%)	Before (cm)	After (cm)	Improvement (%)
25	5.14	1.62	68.5	5.67	1.98	65.1
50	10.26	2.76	73.1	11.35	3.57	68.5
75	14.89	5.73	61.5	17.01	6.83	59.8
100	16.72	8.83	47.2	19.75	10.71	45.8
150	22.65	13.34	41.1	27.94	16.27	41.8

The results showed that the radar subsystem achieved its highest accuracy at short and medium ranges. At 25 cm, the Mean Absolute Error (MAE) was reduced from 5.14 cm before calibration to 1.62 cm after calibration, corresponding to an improvement of 68.5%. At 50 cm, the MAE improved from 10.26 cm to 2.76 cm, representing the highest improvement of 73.1%. Similarly, the Root Mean Square Error (RMSE) decreased substantially across all tested distances, with improvements above 65% at shorter ranges.

As the object distance increased, the sensing accuracy decreased gradually. At 150 cm, the MAE was reduced from 22.65 cm to 13.34 cm, while the RMSE improved from 27.94 cm to 16.27 cm. Although calibration still improved performance at longer distances, the results suggest that the ultrasonic sensor was less reliable beyond 100 cm due to weaker echo reflections and longer propagation times.

Overall, the sensing results demonstrate that the radar ultrasonic system was effective for near-field obstacle detection, which is the most critical range for reactive indoor navigation. The application of linear correction, smoothing and directional fusion significantly enhanced the quality of the radar data, making the subsystem sufficiently reliable for real-time decision-making.

3.3 Autonomous Navigation Performance

The autonomous navigation algorithm was tested in a controlled indoor area measuring 2 m × 2 m, with obstacles arranged in different layouts including straight path, right corner and left corner scenarios. The robot used continuous radar scanning to detect nearby obstacles, and when an object was identified within the safety threshold of 30 cm, the control algorithm selected a safer movement direction based on the available free space.

The results indicate that the robot successfully navigated through all test scenarios with success rates ranging from 89.6% to 93.8%. The highest success rate was obtained in the straight path environment, where the robot recorded a detection distance of 43.5 cm and completed the navigation in an average of 18.7 s. In the right corner and left corner environments, the success rates were 91.2% and 89.6%, respectively, with slightly longer travel times of 20.4 s and 21.3 s.

The reduced performance in corner scenarios can be attributed to the limited sensing field during turning manoeuvres and the additional time required for rescanning before selecting a new path. Nevertheless, the detection distance remained above the 30 cm threshold in all cases, indicating that the robot was able to identify obstacles early enough to execute safe avoidance actions.

These findings confirm that the reactive navigation strategy was effective for simple indoor obstacle avoidance tasks. While the navigation performance was adequate for structured and semi-structured environments, tighter corners and more dynamic obstacle arrangements may require faster scanning or a wider sensing field for improved responsiveness.

The overall system performance demonstrates that the integration of omni-directional locomotion with a radar ultrasonic sensing mechanism can provide an effective low-cost solution for indoor autonomous robots. The omni-wheel platform offered flexible movement, which is advantageous in narrow or cluttered spaces where conventional differential-drive robots may require more complex steering actions.

The radar subsystem, despite relying on a low-cost HC-SR04 sensor, provided sufficiently accurate distance information within the critical obstacle avoidance range. The significant improvement in MAE and RMSE after calibration shows the importance of data preprocessing in ultrasonic sensing applications. This also suggests that low-cost hardware can still achieve acceptable navigation performance when combined with appropriate filtering and correction techniques.

From the navigation perspective, the reported success rate above 90% indicates that the robot was able to make timely and reliable movement decisions in real time. However, the results also reveal several limitations. First, ultrasonic accuracy deteriorated at longer distances, limiting the robot's awareness of far obstacles. Second, the servo-based scanning method introduced a delay, which reduced responsiveness in cornering situations. Third, the navigation algorithm was based on a simple reactive rule set and did not incorporate mapping, path planning, or prediction.

For future enhancement, the sensing subsystem could be improved by integrating multiple ultrasonic sensors or combining ultrasonic sensing with infrared or LiDAR modules. Faster servo motors or fixed multi-sensor arrangements may also reduce scanning delay. In addition, more advanced navigation algorithms, such as fuzzy logic, simultaneous localization and mapping (SLAM), or machine learning-based decision-making, could further improve performance in dynamic and complex environments.

4. CONCLUSION

This study presented the development of an omni-directional mobile robot using a radar ultrasonic sensing system for autonomous indoor navigation. The results showed that the robot was able to perform smooth 360° movement, detect obstacles reliably at short and medium distances and navigate autonomously using a reactive obstacle avoidance algorithm. The integration of omni-wheels, an HC-SR04 ultrasonic sensor with servo scanning and Arduino-based control provided a low-cost yet effective robotic platform. Overall, the proposed system demonstrates strong potential for indoor applications such as educational robotics, automation and small-scale delivery. Future improvements may focus on enhancing sensing accuracy, reducing scanning delay and integrating more advanced navigation methods.

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