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Optimized Obstacle Avoidance in Low-Cost Autonomous Robots Using Sensor Fusion

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Abstract:
Autonomous robots require robust obstacle avoidance systems to navigate dynamic environments and handle unpredictable obstacles. This research presents a low-cost, sensor fusion-based approach integrating ultrasonic and infrared sensors to enhance detection accuracy and reliability. Ultrasonic sensors perform well across diverse conditions but struggle with small or sound-absorbing objects, while infrared sensors work effectively in well-lit environments but fail in darkness. By combining their data, the system mitigates individual sensor limitations, ensuring consistent obstacle detection. The hardware framework employs a Raspberry Pi for high-level decision-making and data processing, while an Arduino handles real-time sensor acquisition and motor control, balancing computational efficiency and responsiveness Experimental results indicate an obstacle detection accuracy of 96% in optimal lighting and 88% in darkness, demonstrating adaptability. Across varied conditions. Compared to previous studies that rely on single-sensor approaches or expensive LiDAR-based solutions, this system provides an optimal balance between affordability and performance. The system's cost-effectiveness, enabled by open-source components, makes it ideal for small-scale robotics and educational applications.

Keywords: Autonomous Robots, Obstacle Avoidance, Sensor Fusion, Ultrasonic Sensors, Infrared Sensors, Raspberry Pi, Arduino, Real-Time Processing, Low-Cost Robotics, Machine Learning, Adaptive Algorithms, Dynamic Environments, Object Detection.

1. Introduction

Autonomous robotic systems have gained significant traction in industrial and domestic applications, particularly for tasks such as warehouse automation, smart navigation, and assistive robotics. Obstacle avoidance is a critical component of autonomous robot navigation, ensuring smooth movement and collision prevention. While high-end solutions like LIDAR and computer vision offer excellent performance, their high cost and computational requirements make them unsuitable for small-scale, low-cost applications. This paper presents a low-cost, sensor fusion-based approach to obstacle avoidance, integrating ultrasonic and infrared sensors to enhance detection accuracy and system reliability. The proposed system is designed for affordability, making it accessible for educational, industrial, and domestic use.

Key Contributions: Design and implementation of an Arduino-Raspberry Pi-powered robot. Fusion of ultrasonic and infrared sensors to improve obstacle detection. Performance analysis under various environmental conditions. Comparative evaluation with existing systems (LIDAR, computer vision).

2. Methodology

A. Sensor Fusion Strategy

Obstacle avoidance in autonomous robots requires precise and reliable detection of environmental obstacles. However, single-sensor systems often suffer from limitations such as false positives, poor accuracy under varying environmental conditions, and slow response times. To overcome these issues, the proposed system integrates ultrasonic and infrared (IR) sensors using a sensor fusion approach.

1. Need for Sensor Fusion

Ultrasonic Sensors: These sensors operate by emitting high-frequency sound waves and measuring the time taken for the echo to return after hitting an obstacle. While effective in detecting most objects, they struggle with small or sound-absorbing surfaces (such as fabric or foam). Infrared Sensors: These sensors detect obstacles based on reflected infrared light. While highly responsive and energy-efficient, they are affected by environmental factors such as ambient light and reflective surfaces. By combining the strengths of both sensors, the system improves overall accuracy, reduces false detections, and ensures reliable performance in dynamic and unpredictable environments.

2. Implementation of Sensor Fusion

The fusion strategy follows a multi-stage process: Data Acquisition: The Arduino collects raw sensor data from both ultrasonic and infrared sensors. Noise Filtering: A Kalman filter is applied to minimize inaccuracies caused by sensor noise and external disturbances. Data Weighting & Reliability Calculation: The system assigns reliability weights to each sensor's output based on environmental conditions. For example: If the infrared sensor detects an obstacle but the ultrasonic sensor does not, the system considers the possibility of interference (such as strong ambient light) and adjusts its confidence in the IR sensor data accordingly. If the ultrasonic sensor detects an obstacle at a certain distance but the IR sensor detects it much closer, the system resolves inconsistencies by cross-referencing historical data. Decision-Making & Action Execution: The Raspberry Pi processes the weighted sensor data, determines the most probable obstacle location, and adjusts the robot's movement accordingly.

3. Modelling and Analysis

The modeling of the proposed system is structured into three key phases: Simulation Testing, Prototype Development, and Performance Analysis. These stages ensure that the obstacle avoidance system is both efficient and reliable in real-world conditions.

A. Simulation Testing

Before deploying the physical system, the obstacle avoidance algorithm is tested in a simulated environment. Simulation helps identify potential issues in sensor response, algorithm efficiency, and

motor control logic before hardware implementation.

1. Virtual Environment Setup:

A 2D/3D simulation is created using software like Gazebo, ROS (Robot Operating System), or MATLAB. Virtual sensors mimic the behavior of real ultrasonic and infrared sensors. The robot model is placed in various obstacle configurations, including static (walls, furniture) and dynamic.

2. Algorithm Validation:

The sensor fusion algorithm processes simulated sensor data and generates appropriate avoidance responses. Collision detection techniques ensure the robot adjusts its path before impact. Various path-planning strategies (e.g., A* algorithm, potential fields) are tested.

B. Prototype Development

Once the simulation is successful, a physical prototype is developed using real hardware components.

1. Hardware Integration:

Microcontrollers: Arduino Uno for real-time sensor data processing and Raspberry Pi for decision-making. Sensors: Ultrasonic and infrared sensors are mounted on the front and sides of the robot. Motors: Two DC motors with motor driver circuits control movement and direction. Power Source: A rechargeable battery supplies power.

2. Software Implementation:

The sensor fusion algorithm is implemented in Python (on Raspberry Pi) and C++ (on

Arduino). Serial communication between Arduino and Raspberry Pi ensures smooth data transfer. The system is tested in real-world indoor and outdoor environments.

C. Performance Analysis

The performance of the system is evaluated under different conditions, including varying light levels, obstacle types, and sensor placements

Future work will focus on:

- Integrating machine learning models for dynamic obstacle prediction.
- Expanding the sensor array with LiDAR or vision-based systems.
- Improving energy efficiency through optimized power management.

Figure 1: Autonomous Robot with Sensor Fusion for Obstacle Avoidance

Table 1: Sensor Performance in Different Conditions

	Detection	**Detection**	**Fused**
Condition	**Accuracy**	**Accuracy**	**Accuracy**
	(Ultrasonic)	**(Infrared)**	
Well-lit	90%	92%	96%
Low-light	85%	78%	91%
Complete	70%	80%	88%

4. Conclusion

This research presents an optimized, low-cost obstacle avoidance system using sensor fusion techniques. By integrating ultrasonic and infrared sensors, the system compensates for individual sensor limitations, significantly improving detection accuracy and reliability. The use of an Arduino-Raspberry Pi hybrid architecture ensures efficient data processing while maintaining cost-effectiveness. Compared to existing studies that rely solely on ultrasonic, infrared, or vision-based systems, our approach demonstrates superior adaptability in diverse environments, reducing false detections and blind spots. Unlike high-cost LiDAR-based solutions, our system achieves a balance between affordability and performance, making it accessible for small-scale robotics applications. whereas this study integrates both aspects for a more holistic improvement in real-time obstacle detection and avoidance.

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