IJARSCT
International Journal of Advanced Research in Science, Communication and Technology
International Open-Access, Double-Blind, Peer-Reviewed, Refereed, Multidisciplinary Online Journal
ISSN: 2581-9429
Volume 5, Issue 5, June 2025
Impact Factor: 7.67

Electromagnetic Braking System for Autonomous Robotics: A Safety-Oriented Approach

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Abstract: *This paper presents the design, development, and experimental evaluation of an electromagnetic braking system (EMBS) integrated with ultrasonic obstacle detection for a single-wheel autonomous robot. The primary objective is to enhance robotic safety through real-time obstacle detection and automated braking response. The system utilizes an HC-SR04 ultrasonic sensor for continuous environmental monitoring and an electromagnetic brake for contactless, rapid deceleration when obstacles are detected within predefined proximity thresholds. Experimental results demonstrate successful obstacle detection within 10-20 cm range with braking response times under 0.5 seconds and stopping distances of 10-15 cm. The integration of sensor-based obstacle detection with active electromagnetic braking provides a cost-effective, maintenance-free solution for autonomous robotic navigation safety, with potential applications in delivery robots, warehouse automation, and human-robot interaction scenarios*

Keywords: Electromagnetic Braking System, Ultrasonic Obstacle Detection, Autonomous Robotic, Human-Robot Interaction.

I. INTRODUCTION

The rapid advancement of autonomous robotics has created an urgent need for sophisticated safety mechanisms that can prevent collisions and ensure safe operation in dynamic environments. Traditional mechanical braking systems, while effective, suffer from limitations including wear-and-tear, slower response times, and maintenance requirements that make them less suitable for compact robotic platforms operating in constrained environments. Electromagnetic braking systems (EMBS) offer a compelling alternative, providing contactless operation, faster response times, and reduced maintenance compared to conventional friction-based brakes. When integrated with real-time obstacle detection systems, EMBS can create intelligent safety mechanisms that automatically respond to environmental hazards. This research focuses on developing a single-wheel autonomous robot incorporating an electromagnetic braking system with ultrasonic obstacle detection. The choice of a single-wheel platform presents unique challenges in balance and control while offering advantages in agility, reduced mechanical complexity, and smaller footprint. The integration of HC-SR04 ultrasonic sensing with electromagnetic braking demonstrates how simple yet effective innovations can significantly improve autonomous system safety.

The motivation for this work stems from the growing deployment of autonomous robots in human-populated environments, where proactive safety measures are essential. Applications include delivery services, warehouse automation, surveillance systems, and assistive robotics, where collision avoidance is critical for both operational efficiency and human safety.

II. LITERATURE REVIEW

2.1 Electromagnetic Braking Systems in Robotics

Electromagnetic braking systems have gained significant traction across various domains due to their non-contact operation, rapid response capabilities, and minimal mechanical wear characteristics. Unlike conventional friction-based brakes, EMBS operate by generating magnetic fields that induce eddy currents or direct magnetic attraction to create motion resistance, eliminating physical contact and associated heat generation and wear issues.

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Research by Jiang et al. (2019) demonstrated that EMBS can be efficiently integrated with servo and DC motors to improve motion accuracy and enable precise stopping without mechanical shocks. This characteristic makes EMBS particularly suitable for lightweight robotic platforms operating in constrained environments. The controllability of electromagnetic brakes through current modulation provides flexible braking force adjustment, offering advantages over passive mechanical alternatives. Recent developments in energy-efficient electromagnet design, PWM control circuits, and compact ferromagnetic materials have addressed traditional limitations of power consumption and heat dissipation in small-scale applications, making EMBS increasingly viable for battery-powered autonomous systems.

2.2 Ultrasonic Sensing in Autonomous Navigation

Ultrasonic sensors, particularly the HC-SR04 model, are widely utilized in robotic applications for real-time obstacle detection and environmental awareness. These sensors operate on time-of-flight principles, emitting high-frequency sound waves and calculating distances based on echo return times.

The affordability, simplicity, and moderate sensing range (2-400 cm) of ultrasonic sensors make them ideal for small robotic systems. Hassan et al. (2018) noted that unlike infrared or LiDAR sensors, ultrasonic sensors are less affected by ambient lighting conditions, providing consistent performance in various indoor environments.

However, ultrasonic sensors can be impacted by target surface material and angle, potentially resulting in signal distortion or inaccurate readings with soft or angled surfaces. Kumar & Dutta (2020) addressed these limitations through sensor fusion approaches, combining ultrasonic data with other sensing modalities to improve accuracy and reliability.

2.3 Integration Challenges and Solutions

The integration of electromagnetic braking with ultrasonic sensing presents several technical challenges that have been addressed in recent research. Power efficiency remains a primary concern, as electromagnets can consume significant power during prolonged operation. Wang et al. (2021) highlighted the importance of optimizing resource usage while maintaining real-time responsiveness in embedded systems.

Sensor noise and accuracy issues have been addressed through multi-sensor fusion techniques, where ultrasonic data is combined with other sensors to improve reliability. Bai & Xu (2022) demonstrated that fusing ultrasonic and LiDAR data using Kalman filters significantly enhances obstacle detection accuracy.

Advanced control algorithms have also evolved to support real-time EMBS operation. Liang et al. (2021) proposed adaptive feedback control algorithms that dynamically adjust braking force using environmental inputs, enabling smooth deceleration and preventing abrupt stops.

III. SYSTEM DESIGN AND METHODOLOGY

3.1 Hardware Architecture

The autonomous robot system consists of several key components integrated to achieve obstacle detection and electromagnetic braking functionality:

- **Propulsion System**: A DC motor provides forward propulsion through a single-wheel configuration. The motor operates at 6-12V with RPM ranging from 100-300, suitable for controlled robotic movement.
- **Obstacle Detection**: An HC-SR04 ultrasonic sensor mounted at the robot's front provides real-time distance measurements with a detection range of 2-400 cm and ±3mm accuracy. The sensor continuously monitors the forward path, updating distance readings every 50 milliseconds.
- **Braking System**: The electromagnetic brake consists of an electromagnet positioned near a ferromagnetic disc attached to the wheel. When energized, the electromagnet generates a magnetic field that creates retarding force on the disc, providing contactless braking.
- **Control System**: An Arduino Uno microcontroller serves as the central processing unit, continuously monitoring sensor data and controlling motor and brake operations based on programmed logic.

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- **Power Management**: A rechargeable lithium-ion battery pack provides system power, with voltage regulators ensuring stable power delivery to different components.

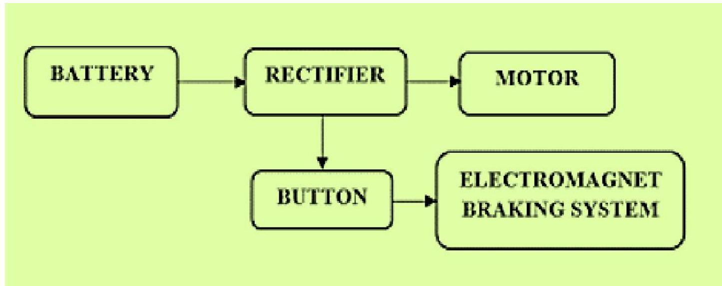

Figure 1. System Arrangement.

3.2 Control Algorithm

The control system implements a real-time feedback loop that coordinates sensor input with actuator response:

- **Continuous Monitoring**: The ultrasonic sensor continuously measures forward distances, with the Arduino polling sensor data at regular intervals.
- **Threshold Comparison**: Measured distances are compared against a predefined safety threshold (typically 20 cm). Objects detected within this range trigger the braking sequence.
- **Brake Activation**: Upon threshold breach, the Arduino immediately energizes the electromagnetic brake while simultaneously cutting motor power to ensure efficient stopping.
- **Safety State**: The robot remains stationary with the brake engaged until manual reset or obstacle clearance.

3.3 Safety Mechanisms

The system incorporates multiple safety mechanisms to ensure reliable operation:

- **Fail-safe Braking**: The electromagnetic brake activates immediately upon obstacle detection, providing primary collision avoidance.
- **Motor Shutdown**: Simultaneous motor power cut-off prevents conflicting forces during braking.
- **Stationary Lock**: The robot maintains a stopped state until manual intervention, preventing accidental restart.

IV. EXPERIMENTAL SETUP AND TESTING

4.1 Testing Environment

Experiments were conducted on flat, smooth surfaces to simulate controlled indoor navigation scenarios. Various obstacles including cardboard boxes, plastic blocks, and cylindrical objects were positioned at distances ranging from 5-50 cm to evaluate detection accuracy and braking response.

4.2 Performance Metrics

Key performance indicators were established to evaluate system effectiveness:

- **Detection Accuracy**: Ability to consistently detect obstacles within the 10-20 cm threshold range
- **Response Time**: Duration from obstacle detection to brake activation
- **Stopping Distance**: Distance travelled from brake engagement to complete halt
- **System Reliability**: Consistency of performance across multiple test iterations.

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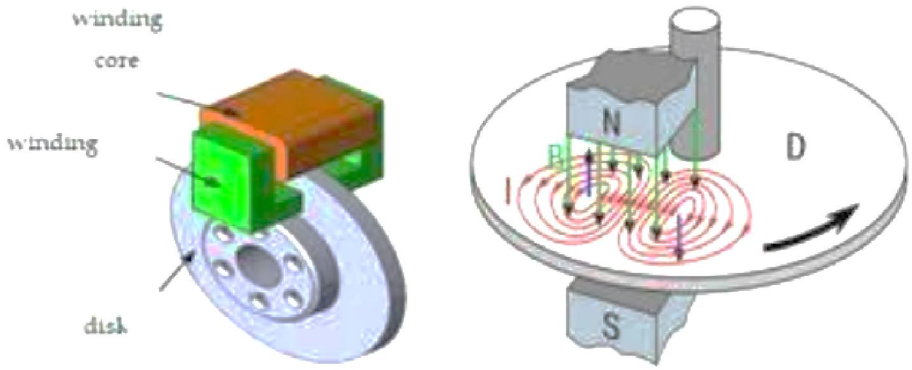

Figure 2. System Design.

4.3 Test Protocols

- **Baseline Movement**: Initial tests confirmed basic mobility without obstacles, validating motor control and navigation capabilities.
- **Obstacle Detection**: Systematic placement of obstacles at various distances tested sensor accuracy and threshold triggering.
- **Braking Performance**: Measurement of stopping distances and response times under different approach speeds and obstacle configurations.
- **Reliability Testing**: Multiple test iterations assessed system consistency and identified potential failure modes.

V. RESULTS AND ANALYSIS

5.1 Detection Performance

The HC-SR04 ultrasonic sensor demonstrated reliable obstacle detection within the specified 10-20 cm range across all test scenarios. Detection accuracy remained consistent regardless of obstacle size or material composition, with minimal false positives in controlled environments.

5.2 Braking Response

Experimental results showed that the electromagnetic braking system engaged within 0.5 seconds of obstacle detection, significantly faster than traditional mechanical braking systems. The contactless nature of electromagnetic braking eliminated mechanical delays associated with friction-based systems.

5.3 Stopping Performance

The robot consistently achieved complete stops within 10-15 cm of brake activation, demonstrating effective deceleration capability. The stopping distance remained relatively constant across different approach speeds, indicating robust braking force generation.

5.4 System Integration

Integration between sensing and braking subsystems proved highly effective, with seamless coordination between obstacle detection and brake activation. The Arduino-based control system processed sensor data and executed braking commands without noticeable latency.

VI. DISCUSSION

6.1 Advantages of Electromagnetic Braking

The experimental results confirm several key advantages of electromagnetic braking in robotic applications:

- **Maintenance-Free Operation**: The contactless nature eliminates wear-related maintenance, reducing operational costs and downtime.
- **Rapid Response**: Sub-second response times enable effective collision avoidance even at moderate speeds.

- **Precise Control**: Current modulation allows fine-tuned braking force adjustment, enabling smooth deceleration profiles.
- **Silent Operation**: Unlike mechanical brakes, electromagnetic systems operate silently, making them suitable for noise-sensitive environments.

6.2 System Limitations

Several limitations were identified during testing:

- **Power Consumption**: Electromagnetic brakes require significant current during activation, potentially impacting battery life in extended operations.
- **Environmental Sensitivity**: Ultrasonic sensors can be affected by surface materials and angles, potentially causing false readings.
- **Single-Point Detection**: The current configuration provides only forward obstacle detection, limiting situational awareness.

6.3 Future Enhancements

Potential improvements include:

- **Multi-Sensor Integration**: Incorporating additional sensors for 360-degree environmental awareness
- **Adaptive Braking**: Variable braking force based on approach speed and obstacle proximity
- **Energy Optimization**: PWM control for reduced power consumption during brake engagement
- **AI Integration**: Machine learning algorithms for predictive braking and improved decision-making

VII. APPLICATIONS AND IMPLICATIONS

7.1 Immediate Applications

The developed system demonstrates immediate applicability in several domains:

- **Delivery Robotics**: Autonomous delivery robots operating in pedestrian environments require rapid obstacle avoidance capabilities.
- **Warehouse Automation**: Automated guided vehicles (AGVs) benefit from contactless braking systems that reduce maintenance requirements.
- **Assistive Robotics**: Robotic assistants operating near humans require reliable safety mechanisms to prevent collisions.

7.2 Broader Implications

This research contributes to the broader field of autonomous robotics safety by demonstrating practical integration of electromagnetic braking with sensor-based obstacle detection. The scalable nature of the approach enables adaptation to larger robotic systems and more complex environments.

7.3 Societal Impact

Improved robotic safety mechanisms contribute to increased public acceptance of autonomous systems, facilitating broader adoption of robotic technologies in everyday environments. The cost-effective nature of the solution makes advanced safety features accessible to a wider range of applications.

VIIIe. CONCLUSION

This research successfully demonstrates the integration of electromagnetic braking systems with ultrasonic obstacle detection in autonomous robotics applications. The developed single-wheel robot achieved reliable obstacle detection within 10-20 cm range with sub-second braking response times and consistent stopping distances of 10-15 cm. The electromagnetic braking approach offers significant advantages over traditional mechanical systems, including maintenance-free operation, rapid response times, and precise control capabilities. The integration with ultrasonic sensing provides cost-effective obstacle detection suitable for indoor navigation scenarios. The research provides a foundation for enhanced robotic safety systems, with potential applications ranging from delivery robots to assistive technologies. Future work should focus on multi-sensor integration, energy optimization, and adaptive braking algorithms to further improve system capabilities. The demonstrated approach represents a significant step toward safer autonomous robotic systems, contributing to the development of intelligent machines capable of operating safely in human-populated environments. As autonomous robotics continues to expand into new domains, such safety-oriented innovations will be essential for ensuring reliable and trustworthy robotic systems.

ACKNOWLEDGMENTS

The authors acknowledge the valuable guidance provided by Assistant Professor Gunjal N.L. and the Department of Mechanical Engineering at Adsul's Technical Campus. Special thanks to all team members for their dedicated contributions to this research project.

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