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Microcontroller applications in autonomous floor cleaning robots: a review of embedded control, navigation, and cleaning technologies

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ABSTRACT

Microcontroller technology has significantly expanded the possibilities for developing affordable autonomous floor-cleaning robots for domestic and commercial environments. These systems integrate embedded controllers, sensors, motor drivers, and cleaning mechanisms to reduce the human effort required for routine floor maintenance. This review examines the application of microcontrollers in autonomous cleaning robots, emphasizing hardware architecture, obstacle detection, navigation strategies, motor control, and cleaning performance. Particular attention is given to Arduino-based platforms, ultrasonic and infrared sensors, wheel encoders, and vacuum-assisted cleaning mechanisms. The operational characteristics of reactive navigation, programmed movement patterns, and sensor-assisted coverage are compared to identify their respective strengths and limitations. Furthermore, the integration of battery monitoring, user interfaces, and wireless communication is discussed in relation to system usability and reliability. The review identifies important challenges involving navigation accuracy, environmental complexity, energy consumption, and cleaning effectiveness. Finally, research opportunities in intelligent navigation, sensor fusion, adaptive cleaning strategies, and low-cost embedded robotics are highlighted. The findings emphasize that successful autonomous cleaning depends on coordinated mechanical design, sensing, control software, and systematic performance evaluation.

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1. INTRODUCTION

Microcontroller-based robotics offers an effective approach to reducing repetitive household cleaning activities through automated movement and cleaning mechanisms. Conventional cleaning equipment frequently requires continuous human operation, whereas autonomous cleaning robots can perform selected tasks with limited intervention. Their affordability and flexibility have encouraged the development of embedded robotic prototypes using accessible microcontroller platforms [1], [2].

The fundamental challenge in autonomous floor cleaning is coordinating locomotion, environmental sensing, and cleaning operations within a compact robotic platform. A robot must detect obstacles, select safe movement directions, maintain appropriate motor operation, and perform cleaning actions without constant human supervision. These requirements make microcontrollers suitable for integrating sensor acquisition, decision-making, and actuator control into a single embedded system [1], [3].

This review examines microcontroller applications in autonomous floor-cleaning robots from an engineering perspective. It emphasizes how controller architecture, sensor selection, navigation methods, and cleaning mechanisms jointly determine practical performance.

2. EMBEDDED ARCHITECTURE AND HARDWARE INTEGRATION

The embedded architecture of a floor-cleaning robot typically consists of a microcontroller, sensor interfaces, motor drivers, a power supply, and cleaning actuators. The microcontroller processes sensor signals and generates commands for locomotion and cleaning operations. Arduino Uno and Mega platforms are frequently used in experimental prototypes because their development environments and peripheral interfaces facilitate rapid implementation [1], [2].

Motor drivers are essential because microcontroller output pins cannot directly supply the current required by wheel motors or vacuum actuators. Driver circuits provide controlled motor direction and speed while separating logic-level signals from higher-power electrical loads. Proper electrical integration also requires attention to battery voltage, current capacity, switching noise, and protection against actuator-related disturbances [2], [3].

The cleaning mechanism determines the type of debris that the robot can effectively remove. Vacuum systems provide suction-based collection, whereas rotating brushes assist in sweeping particles toward collection mechanisms. Some prototypes combine these functions to improve cleaning effectiveness across different floor conditions [2], [4].

3. SENSORS AND AUTONOMOUS NAVIGATION

Sensor integration is a critical component of autonomous floor-cleaning robot design because navigation depends on reliable environmental information. Ultrasonic sensors measure obstacle distance and support reactive avoidance, while infrared sensors can detect nearby objects, boundaries, or wheel-related signals depending on their configuration. Wheel encoders provide movement information that can support distance estimation and improve repeatability of programmed trajectories [1], [3].

Reactive navigation is commonly adopted in low-cost cleaning robots because it requires relatively simple embedded algorithms. The controller may command forward movement until an obstacle is detected, then initiate turning or reversing behavior to avoid collision. Although this method reduces computational requirements, it does not guarantee systematic coverage of the cleaning area [1], [3].

Programmed geometric movement provides another approach to autonomous cleaning. Spiral, zigzag, and rectangular movement patterns can improve coverage under relatively predictable environmental conditions. However, their effectiveness depends on accurate motor control, obstacle handling, and the ability to recover from unexpected interruptions [4], [5]. Table 1 compares common navigation approaches used in microcontroller-based cleaning robots. The comparison illustrates how computational simplicity and coverage efficiency influence the selection of navigation strategies.

Table 1. Navigation strategies for autonomous floor-cleaning robots

Navigation strategy	Principle	Advantages	Limitations
Reactive obstacle avoidance	Responds directly to sensor measurements	Simple implementation; low computational demand	Limited systematic coverage
Spiral movement	Moves along expanding or contracting spiral paths	Effective for localized open areas	Sensitive to obstacles and localization errors
Zigzag movement	Repeated parallel passes	Structured coverage of rectangular areas	Requires turning accuracy
Random movement	Changes direction according to programmed rules	Simple and flexible	Coverage efficiency may be unpredictable
Encoder-assisted navigation	Uses wheel movement feedback	Improved trajectory repeatability	Wheel slip and sensor errors accumulate

4. CLEANING PERFORMANCE AND OPERATIONAL RELIABILITY

Cleaning performance depends on the interaction between robot movement and cleaning hardware. A robot may successfully navigate a room without removing sufficient dust if its suction power, brush configuration, or contact geometry is inadequate. Therefore, cleaning effectiveness should be evaluated independently from navigation success [2], [4].

Battery capacity also influences the operational usefulness of autonomous cleaning robots. The energy demand of wheel motors, vacuum fans, and auxiliary actuators determines how long a robot can operate before recharging. Battery monitoring and low-voltage protection can improve operational reliability by preventing unexpected shutdowns and protecting rechargeable cells [2].

Microcontroller-based monitoring can further support user interaction through displays, alarms, and wireless communication. These functions provide information about operating status, battery condition, cleaning duration, and possible system faults. Nevertheless, additional features should be implemented only

when their benefits justify increased hardware complexity and energy consumption [2], [5]. Table 2 summarizes important performance indicators for evaluating autonomous cleaning robot prototypes. These indicators provide a basis for comparing navigation effectiveness, cleaning capability, energy utilization, and operational reliability.

Table 2. Performance indicators for autonomous floor-cleaning robots

Indicator	Evaluation purpose	Example measurement
Cleaning effectiveness	Quantifies debris removal	Removed debris mass or cleaned-area percentage
Coverage efficiency	Measures spatial cleaning performance	Cleaned area relative to total area
Obstacle avoidance	Evaluates safe navigation	Collision frequency and avoidance success
Operating endurance	Measures energy-supported operation	Runtime per battery charge
Navigation repeatability	Evaluates trajectory consistency	Position or distance deviation
Reliability	Assesses operational consistency	Successful cycles before failure

5. LIMITATIONS AND FUTURE RESEARCH

Low-cost microcontroller-based cleaning robots still face important limitations in complex indoor environments. Basic ultrasonic and infrared sensors provide limited environmental information and may be affected by surface characteristics, sensor orientation, and obstacle geometry. More sophisticated navigation requires improved sensing, sensor fusion, and localization techniques [3], [5].

The integration of intelligent navigation algorithms offers opportunities to improve coverage and reduce unnecessary movement. However, computational resources, memory capacity, sensor cost, and energy consumption must be considered when selecting embedded processing approaches. Practical improvements should prioritize measurable cleaning benefits rather than algorithmic complexity alone [3], [5].

Future research should emphasize systematic coverage planning, adaptive cleaning intensity, robust obstacle detection, and improved battery management. Mechanical optimization should also receive attention because cleaning performance cannot be achieved through control software alone. The most effective designs will integrate mechanical engineering, embedded electronics, and experimentally validated navigation strategies.

6. CONCLUSION

Microcontrollers provide an accessible and flexible foundation for autonomous floor-cleaning robots. Their ability to integrate sensor processing, motor control, navigation, and cleaning actuators enables practical automation at relatively low cost. Ultrasonic sensing and reactive navigation support basic obstacle avoidance, whereas encoder-assisted control and structured movement patterns improve trajectory repeatability and coverage. Nevertheless, navigation success does not automatically guarantee effective cleaning, making separate evaluation of debris removal and operational endurance essential. Future development should prioritize reliable sensing, systematic coverage, energy-efficient actuation, and robust embedded control. Integrated mechanical and electronic design remain the key to improving the effectiveness of autonomous floor-cleaning systems.

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