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Intelligent Robotic Vacuum Cleaner

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Abstract

This paper presents the design and development of an intelligent robotic vacuum cleaner capable of autonomous navigation and efficient cleaning using embedded systems and machine learning techniques. The system is built around the ESP32-CAM module, which enables real-time image processing and object detection using TinyML. Ultrasonic sensors are used for obstacle detection and distance measurement, allowing the robot to navigate safely in indoor environments. The L298N motor driver controls the movement of DC motors and the vacuum mechanism for dust collection. The integration of Wi-Fi connectivity enables remote monitoring and control through IoT-based applications. The proposed system is cost-effective, energy-efficient, and suitable for applications in homes, offices, hospitals, and public spaces. Experimental results demonstrate improved navigation accuracy, reliable obstacle avoidance, and effective cleaning performance, making it a practical alternative to traditional cleaning methods.

Keywords: Robotic Vacuum Cleaner, ESP32-CAM, TinyML, Ultrasonic Sensor, Internet of Things (IoT), Autonomous Navigation, Smart Cleaning System

Introduction

In recent years, the demand for smart home automation systems has increased significantly due to advancements in embedded systems and the Internet of Things (IoT). Automated cleaning devices, such as robotic vacuum cleaners, have gained popularity as they reduce human effort and improve efficiency in maintaining cleanliness. However, many commercial robotic vacuum cleaners are expensive and lack advanced intelligent features.

This paper presents the design and development of an intelligent robotic vacuum cleaner that utilizes the ESP32CAM module and TinyML for real-time object detection and navigation. The system integrates ultrasonic sensors for obstacle detection, enabling the robot to move autonomously while avoiding collisions. A motor driver module is used to control the movement of the robot and operate the vacuum mechanism effectively.

The proposed system is designed to be cost-effective, energy-efficient, and suitable for indoor environments such as homes, offices, hospitals, and public areas. Additionally, the inclusion of IoT-based connectivity allows users to monitor and control the robot remotely. The main objective of this work is to develop a smart cleaning system that combines automation, intelligence, and affordability, providing a practical alternative to traditional cleaning methods.

Literature Review

Recent advancements in robotic vacuum cleaners have focused on improving navigation, efficiency, and automation. A vacuum cleaner robot with staircase cleaning capability using boustrophedon path planning was proposed. The system utilized Arduino Mega 2560 and mecanum wheels for multi-directional movement. While it achieved high success rates in path planning and staircase climbing, it suffered from weak vacuum suction efficiency due to design limitations(1).

A cost-effective autonomous floor cleaning robot was developed using Raspberry Pi and Arduino Mega. The system incorporated indoor mapping and positioning techniques along with GPS-based navigation. Although the robot demonstrated autonomous cleaning capability, the use of multiple controllers increased system complexity and power consumption(2).

A multi-sensor-based vacuum cleaning robot was presented in, where ultrasonic, infrared, and collision sensors were integrated with a Cortex-M0 controller. The system used a neural network-based algorithm for obstacle avoidance and localization. This approach improved accuracy and robustness; however, it required complex computation and lacked real-time edge AI implementation on lightweight hardware(3).

Yoon, *et al*. introduced a smart window cleaning robot (Windoro) that used magnetic adhesion for navigation on glass surfaces. The system demonstrated energy-efficient cleaning and autonomous operation, but it was limited to specific environments such as window surfaces(4). Rajasekaran and Suresh, highlighted key features such as IoT connectivity, obstacle avoidance, self-docking, and remote control. The study emphasized the importance of integrating multiple technologies but did not propose a specific low-cost implementation(5).

A user-centered approach to path planning was discussed by Gupte, analyzing human cleaning behavior to improve robot navigation. The study suggested adaptive path planning based on environmental characteristics; however, it did not incorporate real-time sensing or AI-based decision-making(6).

From the literature, it is observed that existing systems either focus on advanced navigation techniques, multisensor integration, or IoT-based control, but often lack a balance between cost, efficiency, and intelligent processing. Therefore, there is a need for a system that integrates real-time object detection, efficient navigation, and low-cost hardware. The proposed system addresses this gap by utilizing the ESP32-S3 microcontroller with TinyML, ultrasonic sensors, and IoT connectivity to develop an intelligent and energy-efficient robotic vacuum cleaner.

Methodology

The proposed intelligent robotic vacuum cleaner is designed to perform autonomous cleaning using the ESP32-S3 microcontroller. The system integrates sensing, control, and communication modules to achieve efficient navigation, obstacle avoidance, and cleaning performance.

A. System Architecture

The overall system architecture consists of an ESP32-S3 microcontroller, ultrasonic sensor, motor driver (L298N), DC motors, OV2640 camera module, servo motor, relay module, vacuum motor, GPS tracking module, and lithium ion battery. The ESP32-S3 acts as the central processing unit, receiving inputs from sensors and generating control signals for actuators.

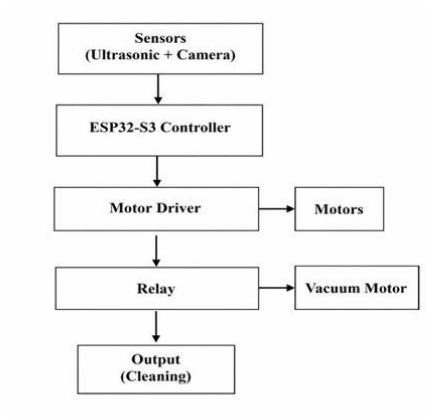

Fig. 1: System Architecture

B. System Block Diagram

(Fig. 1) illustrates the system block diagram of the proposed robotic vacuum cleaner. All components are interfaced with the ESP32-S3, which controls the overall operation of the system.

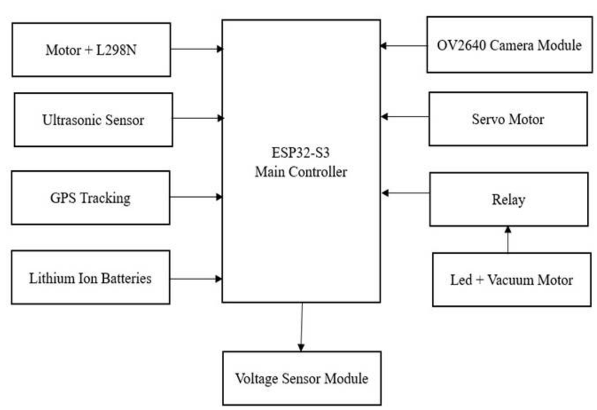

Fig. 2: Block Diagram

C. Components Description

1. ESP32-S3 Microcontroller:

The ESP32-S3 serves as the main controller of the system. It processes sensor data, executes control algorithms, and manages communication between all components. It also supports Wi-Fi connectivity and TinyML-based processing for intelligent decision making.

2. Ultrasonic Sensor:

The ultrasonic sensor is used for obstacle detection. It continuously measures the distance between the robot and nearby objects, enabling the system to avoid collisions during movement.

1. Motor Driver (L298N) and DC Motors: The motor driver controls the DC motors based on signals from the ESP32-S3. It allows the robot to move in different directions such as forward, backward, left, and right.
2. OV2640 Camera Module:

The camera module is used for capturing images and enabling object detection. It supports real-time processing and enhances the robot's navigation using TinyML.

3. Servo Motor:

The servo motor is used to control directional movement of components such as the camera or sensor positioning.

4. Relay Module:

The relay module is used to control high-power devices like the vacuum motor and LED. It acts as a switch to turn these components ON or OFF.

5. Vacuum Motor and LED:

The vacuum motor generates suction to collect dust and debris, while the LED provides visual indication of system operation.

6. GPS Tracking Module:

The GPS module enables tracking of the robot's location, which can be useful for monitoring and navigation.

7. Lithium-Ion Battery:

The lithium-ion battery provides power to all components, ensuring portability and efficient energy usage.

D. Working Principle

The system starts by initializing all components connected to the ESP32-S3. The ultrasonic sensor continuously scans the surroundings to detect obstacles. When an obstacle is detected within a predefined distance, the controller processes the data and changes the direction of the robot to avoid collision.

The robot moves autonomously using a predefined navigation logic to cover the cleaning area efficiently. The motor driver controls the movement of the wheels based on commands from the ESP32-S3.

The OV2640 camera module captures images, and TinyML models running on the ESP32-S3 help in object detection and intelligent decision-making. The servo motor adjusts the orientation of components when required.

The relay module controls the operation of the vacuum motor, which performs the cleaning by generating suction. The system is powered by a lithium-ion battery, and the GPS module provides location tracking for monitoring purposes.

Overall, the integration of sensing, processing, and actuation enables the robot to perform autonomous and efficient cleaning with improved intelligence and low power consumption.

Hardware Implementation

The hardware implementation of the intelligent robotic vacuum cleaner is designed using efficient and low-cost components integrated with the ESP32-S3 microcontroller. The system combines sensing, processing, and actuation units to achieve autonomous cleaning.

A. ESP32-S3 Microcontroller

The ESP32-S3 serves as the central control unit of the system. It processes sensor data and generates control signals for actuators. It features built-in Wi-Fi and Bluetooth, enabling wireless communication and remote operation. Its dual-core architecture ensures real-time processing and efficient multitasking.

B. Sensors and Vision Module

An ultrasonic sensor (HC-SR04) is used for obstacle detection by measuring distance using sound waves. Additionally, the OV2640 camera module provides visual input for enhanced navigation and monitoring. The combination of these sensors improves environmental awareness and navigation accuracy.

C. Motor Driver and Locomotion

The L298N motor driver module is used to control the speed and direction of DC motors. It acts as an interface between the ESP32-S3 and the motors. The DC motors enable movement of the robot in multiple directions such as forward, backward, and turning.

D. Suction Mechanism

A high-speed brushless DC motor (drone motor) is used to generate suction. It is controlled via a relay module, allowing the ESP32-S3 to switch the vacuum motor ON or OFF efficiently.

E. Power Supply

The system is powered by rechargeable lithium-ion batteries, providing stable voltage and portability. A voltage sensor module is used to monitor battery levels and ensure safe operation.

F. Mechanical Structure

The chassis frame provides structural support for all components, including motors, sensors, and control units. A circular design is preferred for smooth navigation and better area coverage.

G. Supporting Components

Additional components such as a servo motor (for camera orientation), zero PCB (for circuit assembly), jumper wires, and switches are used for system integration and control.

Software Implementation

The software architecture of the proposed intelligent robotic vacuum cleaner is designed to ensure efficient control, real-time data processing, and wireless communication. It consists of embedded programming using the Arduino IDE and a web-based user interface for monitoring and control.

1. Arduino IDE

The Arduino Integrated Development Environment (IDE) is utilized for programming the ESP32-S3 microcontroller. It supports C/C++ based development and provides necessary libraries for interfacing with sensors, actuators, and communication modules.

In the proposed system, the Arduino IDE is used to implement motion control, obstacle detection using ultrasonic sensors, and control of peripheral devices such as the motor driver and relay module. It also facilitates wireless communication via Wi-Fi and Bluetooth, enabling remote operation and real-time data transmission. Furthermore, the IDE provides essential functionalities such as code compilation, uploading, and debugging through the serial monitor, ensuring reliable system performance.

2. Components of Arduino IDE

The Arduino IDE comprises several functional components that assist in program development and debugging. The code editor is used for writing and modifying the program, while the toolbar provides quick access to compile and upload functions.

The menu bar enables configuration of board selection, port settings, and library management. The output console displays compilation results and error messages, aiding in debugging. The serial monitor allows real-time visualization of sensor data and system status. Additionally, the board and port selection feature ensures proper communication between the ESP32-S3 and the development environment.

3. Web Dashboard

A web-based dashboard is developed using HTML, CSS, and JavaScript to provide an interactive interface for system control and monitoring. The dashboard communicates with the ESP32-S3 over Wi-Fi, enabling remote access through a web browser.

It allows the user to control robot movement (forward, backward, left, and right) and adjust camera orientation using a servo motor. The interface also displays real-time parameters such as obstacle distance, battery status, and overall system condition.

The ESP32-S3 operates as a web server, receiving user commands and executing them while simultaneously transmitting sensor data back to the dashboard. This integration enhances system usability, enables real-time monitoring, and supports efficient wireless control.

Results and Discussion

The performance of the proposed intelligent robotic vacuum cleaner was evaluated based on cleaning efficiency, obstacle detection capability, and overall system functionality.

The robot was able to perform cleaning operations effectively on flat surfaces by removing dust and small debris using the suction mechanism. The brushless DC motor generated sufficient airflow to ensure proper suction, resulting in satisfactory cleaning performance in indoor environments.

The obstacle detection system using ultrasonic sensors functioned reliably within its operating range. The robot was capable of detecting obstacles and altering its path to avoid collisions. Additionally, the integration of the camera module improved environmental awareness and supported better navigation in complex scenarios.

The system demonstrated stable wireless communication through Wi-Fi, enabling real-time monitoring and control via the web dashboard. User commands were executed with minimal delay, and sensor data such as distance and battery status were accurately displayed.

In terms of efficiency, the robot operated continuously for a reasonable duration based on battery capacity. The overall system showed good coordination between hardware and software components, ensuring smooth operation.

However, minor limitations were observed, such as reduced performance on uneven surfaces and limited suction power compared to commercial vacuum cleaners. Future improvements can focus on enhancing navigation algorithms and increasing suction efficiency.

Application:

- Home Automation
- Offices and Commercial Buildings
- Hospitals and Healthcare Facilities
- Educational Institutions
- Park and Garden

Conclusion

The proposed intelligent robotic vacuum cleaner system successfully demonstrates the integration of embedded systems, IoT, and basic artificial intelligence for autonomous cleaning applications. The use of the ESP32S3 microcontroller enables efficient control, real-time data processing, and wireless communication within a compact and cost-effective design.

The system is capable of performing autonomous navigation, obstacle detection, and cleaning operations with satisfactory performance. The integration of ultrasonic sensors and a camera module improve environmental awareness, while the web-based dashboard allows convenient remote monitoring and control.

Experimental results indicate that the robot can effectively clean indoor surfaces and avoid obstacles with reliable accuracy. The system also maintains stable communication and coordinated operation between hardware and software components.

However, certain limitations such as moderate suction power and reduced performance on uneven surfaces were observed. Future enhancements can focus on improving suction efficiency, optimizing navigation algorithms, and incorporating advanced machine learning techniques for better decision-making.

Overall, the proposed system provides a low-cost, efficient, and scalable solution for intelligent robotic cleaning, making it suitable for modern smart home applications.

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