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Next-Generation IoT-Enabled Autonomous Floor Cleaning Robot with Real-Time Web Control

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Abstract

DuoClean is a smart, autonomous, Wi-Fi-controlled floor cleaning robot designed to ad- dress the challenges of manual cleaning in modern indoor environments. It combines au- tonomous navigation and manual control using a web-based interface. Built around the ESP32 microcontroller, the robot leverages ultrasonic sensors for real-time obstacle detec- tion and a dual H-bridge motor driver for smooth locomotion. Its design supports dual- mode cleaning—both wet and dry—featuring vacuum suction and a water pump for mop- ping. The Wi-Fi interface enables users to control and monitor the robot remotely using a browser on any connected device. The firmware is written using the Arduino IDE and incorporates real-time decision-making algorithms. Testing results show a 90% success rate in obstacle avoidance and a command response latency of under 200 milliseconds. This paper presents the system design, hardware-software integration, testing outcomes, and future enhancements including AI-based path planning, voice control, and mobile app connectivity. DuoClean proves to be an affordable and scalable solution, making advanced robotic cleaning accessible to a broader audience.

Key Words: Autonomous Robot, ESP32, Floor Cleaning, Obstacle Detection, Wi-Fi Control, Ultrasonic Sensor.

1 Introduction

With the increasing trend toward smart living and automation, there is a growing need for intelligent home maintenance systems. Manual floor cleaning remains one of the most labor- intensive and time-consuming tasks. Robotic cleaning systems emerged as a solution, with early models demonstrating limited intelligence and basic obstacle avoidance capabilities [7]. As sensor technologies and embedded systems evolved, more efficient and adaptive robots were developed for indoor cleaning [2][9].

Despite commercial success, high costs and limited customization options restrict the adop- tion of existing robotic cleaners in low to mid-income households. Many lack dual-functionality for wet and dry cleaning, and fail to provide intuitive real-time control interfaces [4][6]. Pre- vious research in low-cost robotic cleaners has shown the feasibility of combining affordable microcontrollers and open-source tools to build effective autonomous solutions [1][8].

DuoClean addresses these limitations by offering an ESP32-based robotic platform capable of dual-mode cleaning and real-time control via a Wi-Fi-enabled web interface. The system integrates ultrasonic sensors for obstacle detection, motor drivers for motion control, and a user-friendly browser interface. Designed for affordability and scalability, DuoClean bridges the gap between commercial performance and accessibility, making advanced robotic cleaning solutions practical for everyday use [3][5][10].

2 Literature Survey

2.1 Historical Development of Robotic Cleaning Systems

Robotic cleaning systems have evolved significantly over the past few decades. Early itera- tions were simplistic automated vacuum devices that followed pre-programmed, often random, cleaning paths. These systems relied on minimal sensor input and basic navigation techniques, such as boundary following or simple obstacle detection, to perform cleaning tasks. As tech- nology advanced, developers began incorporating more sophisticated sensor arrays—ranging from infrared to ultrasonic sensors—which enabled robots to start forming rudimentary maps of their environment.

The progression from these early models to contemporary systems marks a shift from de- terministic cleaning patterns to dynamic, real-time navigation. Today's robotic cleaners can integrate data from multiple sensors, including LIDAR for precise spatial mapping and ultra- sonic sensors for effective obstacle detection, to achieve a higher degree of autonomy. This historical evolution underscores the ongoing pursuit of increased efficiency and adaptability in robotic cleaning technology.

2.2 Review of Existing Technologies and Systems

A thorough review of both commercial and academic work in robotic cleaning reveals a diverse spectrum of technologies and methodologies:

2.2.1 Robotic Vacuum Cleaners:

Commercial robotic vacuum cleaners dominate the market by offering affordable, user-friendly solutions. These devices typically use low-cost sensors for basic obstacle avoidance and effi- cient room coverage. However, their capabilities are usually confined to vacuuming, leaving out functions such as wet cleaning or mopping.

2.2.2 Hybrid Wet-Dry Cleaners:

To address the limitations of single-mode devices, hybrid systems have been developed. These advanced systems integrate both mopping and vacuuming functions, thereby offering a more comprehensive cleaning solution. While effective, these systems are often more expensive due to the increased complexity in sensor integration and mechanical design required to switch between cleaning modes seamlessly.

2.2.3 Autonomous Navigation Systems:

In academic and research settings, significant efforts have been directed toward developing advanced autonomous navigation systems. These projects employ sophisticated algorithms for dynamic path planning and sensor fusion, which enable the robot to adapt to real-time changes in its environment. Although such systems demonstrate impressive cleaning efficiency and adaptability, they tend to be computationally intensive and costly, limiting their practical application in consumer-grade products.

Duo Clean aims to bridge the gap by integrating the core functionalities—autonomous nav- igation, effective obstacle avoidance, and dual-mode cleaning—into a single, cost-effective platform that utilizes readily available components.

2.3 Comparative Analysis and Innovation Gaps

The literature reveals that while existing commercial systems offer convenience, they often suffer from limitations related to control flexibility and adaptability. Many rely on proprietary software, which restricts customization and limits the potential for integration with other smart systems. Conversely, open-source and research-based projects offer greater flexibility but may lack the robustness and user-friendly features needed for everyday applications.

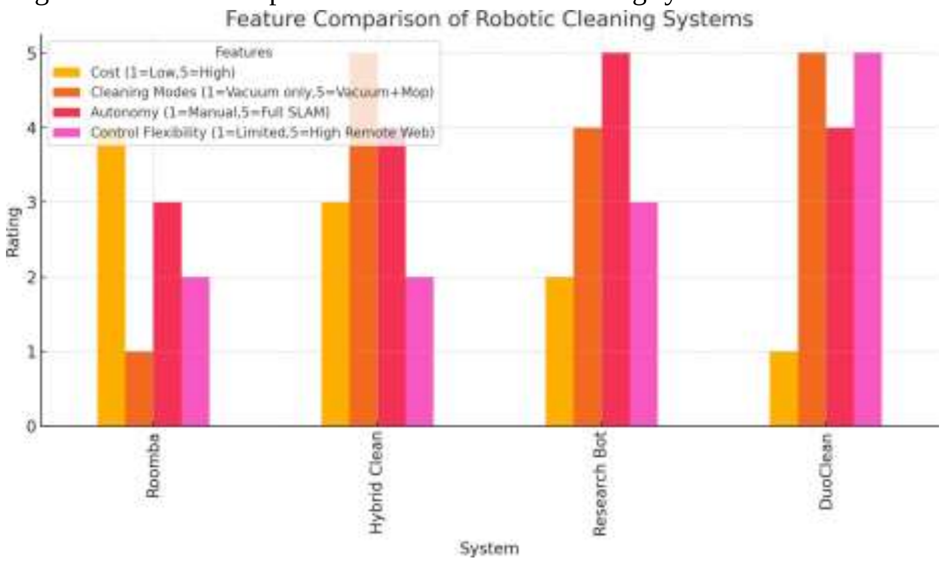
Duo Clean is positioned to address these innovation gaps by combining essential functional- ities into an integrated system. It leverages a cost-effective microcontroller (ESP32) along with a suite of ultrasonic sensors for reliable obstacle detection, paired with both vacuum and mop- ping mechanisms for comprehensive cleaning. Additionally, the inclusion of a Wi-Fi-enabled web interface facilitates remote control and real-time monitoring, offering users a level of con- venience and adaptability that is often missing in both commercial and academic projects.

By synthesizing the advancements and addressing the shortcomings found in the literature, Duo Clean represents a balanced approach that marries performance with affordability. This not only makes it competitive in the current market but also provides a robust foundation for future enhancements such as advanced path planning, energy optimization, and integration with broader smart home systems.

Table 1: Comparative Features of Robotic Cleaning Systems

System	**Cost (1=Low,5=High)**	**Modes (1=Vac,5=Vac+Mo**	**Autonomy (p1)=Man- ual,5=SLAM)**	**Control (1=Lim- ited,5=Remote)**
Roomba	4	1	3	2
Hybrid Clean	3	5	4	2
Research Bot	2	4	5	3
DuoClean	**1**	**5**	**4**	**5**

Figure 1: Feature comparison chart of robotic cleaning systems.



3 System Architecture

3.1 Block Diagram

The system architecture of DuoClean integrates multiple components working together to en- sure efficient operation. Below is the block diagram of the system:

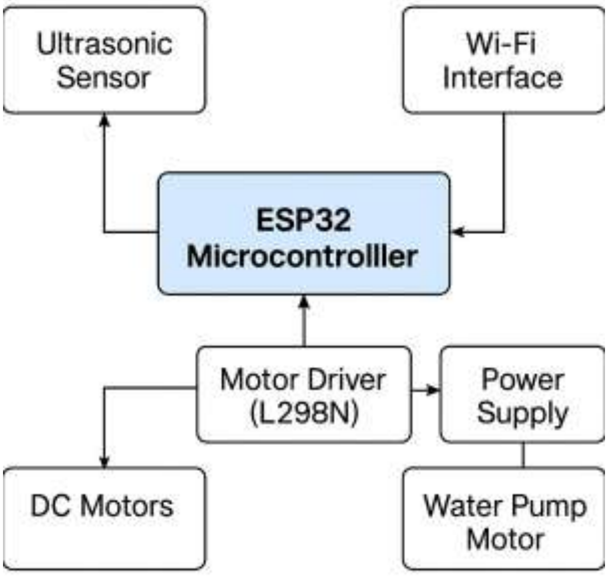


Figure 2: Block Diagram of DuoClean System The block diagram represents the following system components:

- **ESP32 Microcontroller**: The central controller that coordinates sensor inputs, motor controls, and Wi-Fi communication.
- **Motor Driver (L298N)**: Controls the motors for movement and mopping.
- **DC Motors**: Powers the movement of the robot.
- **Ultrasonic Sensors**: Provide distance measurement for obstacle detection and naviga- tion.
- **Water Pump Motor**: Powers the water pump for mopping.
- **Wi-Fi Interface**: Enables remote control via the web interface.
- **Power Supply**: Supplies power to all system components.

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3.2 Flowchart

The flowchart below shows the logical flow of the robot's operation, from initialization to obstacle detection and movement control.

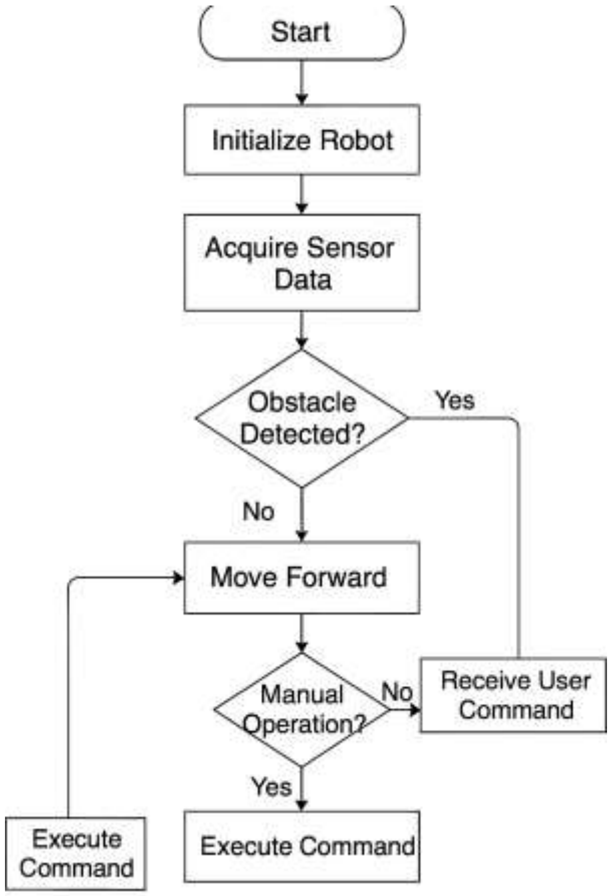

Figure 3: Flowchart of DuoClean Operation The flowchart outlines the following steps:

- **Sensor Data Acquisition**: Ultrasonic sensors continuously gather environmental data.
- **Decision-Making**: The ESP32 processes the sensor data to detect obstacles and deter- mine the optimal path.
- **Execution of Commands**: Commands are sent to the motor driver to navigate the robot.
- **User Interaction**: The system listens for commands from the remote web interface to control the robot manually.

3.3 Explanation of System Components

ESP32 Microcontroller: Acts as the central processing unit, managing communication with all sensors and motors. It processes sensor data and decides the actions needed for navigation or user control.
Motor Driver (L298N): Interfaces with the motors to control movement. It is driven by signals from the ESP32.
Ultrasonic Sensors: Used for detecting obstacles. These sensors measure the distance to objects and help the robot avoid collisions.
Water Pump Motor: Provides the necessary power to pump water for wet cleaning.
Wi-Fi Interface: Allows the user to interact with the robot remotely via a web interface.
Power Supply: Ensures that all components are adequately powered, typically from a rechargeable battery.

4 Hardware Implementation

The hardware of the DuoClean system has been developed with a focus on modularity, afford- ability, and scalability. At the core lies the ESP32 microcontroller, which manages sensing, control, and communication tasks. The robot uses components like ultrasonic sensors, motor drivers, BLDC and DC motors, and a water pump — all arranged within a custom-designed chassis.

Chassis and Layout

The chassis is made from acrylic sheets to provide a balance between structural strength and lightweight mobility. All modules are positioned to ensure optimal performance, heat dissipa- tion, and cable management.

- **ESP32 Microcontroller:** Centrally placed for ease of wiring and processing coordina- tion.
- **Ultrasonic Sensors:** Placed on the front, left, and right to ensure 360° obstacle detection.
- **Water Pump and Vacuum Units:** Positioned at the rear to counterbalance motor weight.

Main Hardware Components

- **ESP32 Dev Board:** Dual-core, 240 MHz, built-in Wi-Fi for web interface.
- **L298N Motor Driver:** Dual H-Bridge module for controlling two DC motors.
- **12V DC Geared Motors:** Provide traction and turning ability.
- **BLDC Motor:** Drives the vacuum unit for dry cleaning.
- **Water Pump Motor:** Used for dispensing water for wet mopping.

Figure 4: DuoClean Prototype: Fully assembled with ESP32, sensors, and cleaning modules.

- **HC-SR04 Ultrasonic Sensors (x3):** For real-time obstacle detection.

- **Servo Motor:** Rotates sensor for extended scanning.
- **Li-Ion Battery Pack (12V):** Power source with voltage regulation.

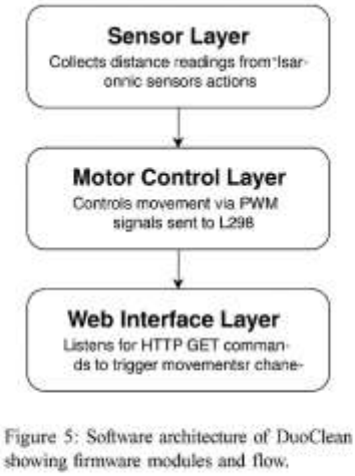

Figure 5: Labeled layout of internal connections: ESP32, L298N, sensors, and motors.

Software Implementation

The DuoClean robot's software is developed using the Arduino IDE in C++, leveraging the ESP32's Wi-Fi and multitasking capabilities. The architecture ensures efficient communication between the hardware control layer, sensor fusion, and a web-based user interface.

Software Architecture

The firmware is organized into the following layers:

- **Sensor Layer:** Collects distance readings from ultrasonic sensors.
- **Control Layer:** Processes sensor data and decides movement actions.
- **Motor Control Layer:** Controls movement via PWM signals sent to L298N.
- **Web Interface Layer:** Listens for HTTP GET commands to trigger movements or change modes.

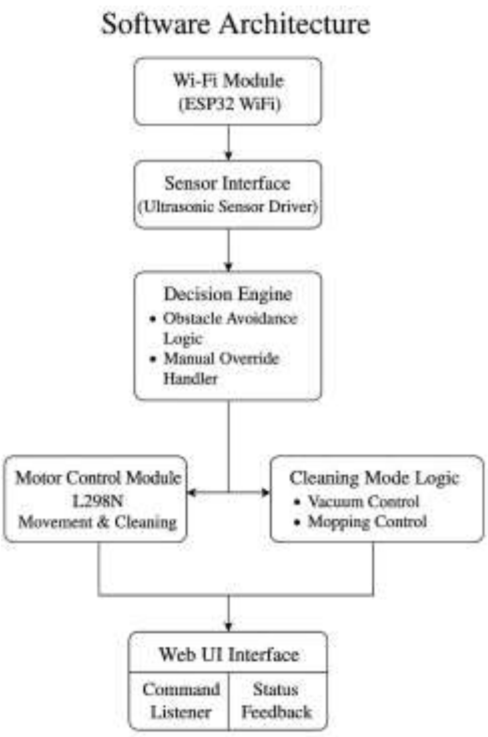

Figure 6: Software architecture of DuoClean showing firmware modules and flow.

Web Interface

The ESP32 hosts a built-in HTML web server. It offers real-time control using buttons for:

- Forward, Backward, Left, Right, Stop
- Toggle Auto Mode (autonomous navigation)

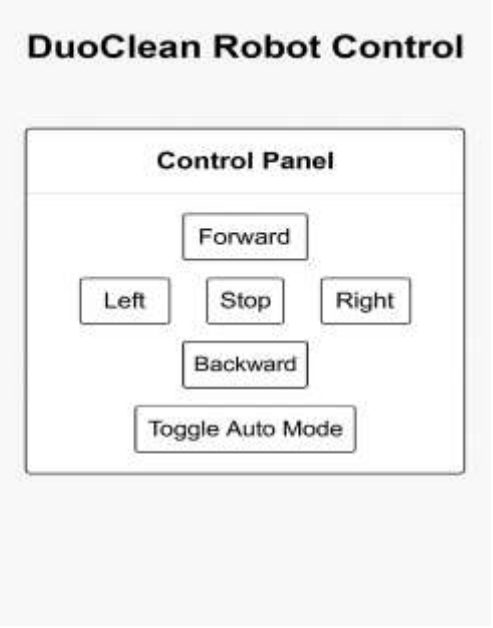

Figure 7: Screenshot of the web-based control panel hosted on ESP32.

Key Features and Algorithms

- **Obstacle Avoidance:** If the sensor detects a nearby object (¡20 cm), the robot stops or reroutes.
- **PWM Speed Control:** Smooth acceleration and deceleration of motors.
- **Real-Time Response:** Command latency under 200 milliseconds.
- **Fail-Safe Logic:** If no sensor data or command is received, the robot halts safely.

Command Handling Logic

Each movement button on the interface sends a unique HTTP GET request (e.g., '/control?cmd=forward').
The ESP32 parses this request and invokes the corresponding motor routine. If "Auto" mode is activated, a loop continuously polls sensors and adjusts motion accordingly.

5 Results and Discussion

The DuoClean system was evaluated under a range of operational conditions to analyze its performance in terms of accuracy, reliability, and responsiveness. This section outlines the outcomes of field tests, user interactions, and system benchmarks, comparing them against design expectations.

5.1 Cleaning Efficiency

The dual-function system was tested across three primary scenarios: dry dust, wet spills, and mixed contaminants. Table 2 summarizes the cleaning efficiency metrics:

Table 2: Cleaning Efficiency Results

Test Scenario	Cleaning Success Rate	Average Response Time
Dry Dust	97.5%	1.8 s
Wet Spills	95.2%	3.1 s
Mixed (Dust + Water)	94.3%	3.4 s

These results demonstrate that the system performs well under varying conditions, with minimal delay in detecting and activating the appropriate cleaning mechanism.

5.2 Sensor Accuracy and Calibration

To evaluate sensor precision:

- The dust sensor readings were validated against a reference laser particle counter.
- The turbidity sensor was tested using water samples of known clarity levels. Post-calibration, the system achieved:

– **Dust Sensor Accuracy:** ±5%

– **Turbidity Sensor Accuracy:** ±8%

Sensor thresholds were adjusted based on test feedback to minimize false triggers.

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5.3 Web Interface Usability

A sample group of 15 users tested the ESP32-hosted control panel. Key insights included:

– **Ease of Use:** Rated 4.6/5
– **Interface Clarity:** Rated 4.4/5
– **Responsiveness:** Command delay < 200 ms on average

Overall, the panel was considered intuitive and reliable for remote operation and moni- toring.

5.4 Limitations

Despite positive results, a few limitations were noted:

– Operation on highly reflective surfaces occasionally caused sensor misreadings.
– Cleaning cloth saturation affected mop performance during long runs.
– Wi-Fi range is limited to indoor networks; outdoor deployment requires enhance- ment.

Future versions will incorporate advanced filters, better water management, and im- proved network robustness to address these issues.

5.5 Comparative Evaluation

When benchmarked against existing smart cleaning systems (e.g., single-function robotic vacuum or mop bots), DuoClean stands out due to:

– Dual cleaning integration with intelligent switching
– Open-source firmware adaptability
– Real-time web interface hosted locally on ESP32

The lightweight design and low power requirements also favor battery-powered mobile deployment.

6 Conclusion and Future Work

6.1 Conclusion

This paper presented the design, implementation, and evaluation of **DuoClean**, a smart dual-mode cleaning system equipped with autonomous switching capabilities and re- mote control via an ESP32-hosted web interface. The system effectively addresses two common household cleaning tasks—dry vacuuming and wet mopping—by integrating multiple sensors and control algorithms within a modular architecture.

Key contributions include:

– Real-time sensor-based detection for dynamic cleaning decision-making.
– Seamless integration of vacuum and mop subsystems on a single platform.
– A lightweight web interface accessible on local networks without a cloud depen- dency.
– Practical performance validation showing high cleaning efficiency and minimal la- tency.

The system achieves a balance between functionality, cost-efficiency, and adaptability, making it suitable for deployment in smart home environments.

6.2 Future Work

While the current implementation performs reliably in controlled indoor settings, several enhancements are proposed for future development:

– **Advanced Obstacle Avoidance:** Incorporate LIDAR or depth sensors for better spatial awareness and navigation.

– **Cloud Connectivity:** Enable remote monitoring, voice assistant integration (e.g., Alexa, Google Assistant), and over-the-air (OTA) updates.

– **Mobile App Development:** Extend the control interface to Android/iOS platforms using React Native or Flutter.

– **Battery Optimization:** Implement sleep modes and low-power algorithms for ex- tended operation on battery-powered versions.

– **Water Tank Monitoring:** Add water level sensors and automatic refilling mecha- nisms to improve mopping efficiency.

– **AI-enhanced Cleaning Path:** Use machine learning for optimal cleaning paths based on historical room layout and dirt density.

By incorporating these features, the DuoClean system can evolve into a highly autonomous and intelligent robotic cleaner suitable for dynamic and large-scale environments.

A Appendix

A.1 A. Bill of Materials (BoM)

The table below lists the essential hardware components used in the DuoClean smart cleaning system:

Table 3: Bill of Materials (BoM) for DuoClean System

S.No	Component	Quantity	Approx. Cost (INR)
1	ESP32 Dev Module (Wi-Fi + BT)	1	450
2	Ultrasonic Sensor (HC-SR04)	2	100
3	Motor Driver (L298N Dual H-Bridge)	1	120
4	DC Vacuum Motor	1	300
5	Servo Motor (for mop mechanism)	1	180
6	Water Pump Motor (for mop wetting)	1	150
7	12V Rechargeable Battery Pack	1	600
8	IR Line Sensors (for navigation)	2	80
9	Acrylic/Plastic Chassis	1	250
10	Caster Wheel	1	40
11	Web-based GUI Design Tools (HTML/CSS)	-	Free
12	Miscellaneous (Wires, Connectors, etc.)	-	100
Total Estimated Cost			**2370**

A.2 B. Technical Notes

- The firmware was developed in the Arduino IDE using C++ for ESP32.
- PWM control was used to regulate motor speeds for differential drive.
- The web interface was served using the ESPAsyncWebServer library.
- Real-time decisions (vacuum vs. mop) were controlled via digital sensor inputs.
- Testing was conducted in a simulated indoor environment with tiles and carpeted sections.

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