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Design and Implementation of an IoT- Based Smart Robotic Vacuum Cleaner for Smart Home Environment

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ABSTRACT

This paper presents the design and implementation of a smart robotic vacuum cleaner based on Internet of Things (IoT) technologies, named IO-VAC, specifically developed for smart home environments. The paper covers both the mechanical and electronic aspects of the robot's development. A 2D layout was created using ArchiCAD to define the positioning of components and sensor angles when designing the robot, followed by a 3D model to visualize the final design. The robot chassis was fabricated using reinforced plastic to ensure durability and lightweight structure. The IO-VAC is controlled using an Arduino Mega board programmed in C/C++. Where, the system includes three ultrasonic sensors for obstacle avoidance, along with an infrared (IR) sensor for edge detection to prevent falls. The embedded system of IO-VAC integrates an ESP8266 Wi-Fi module, allowing for remote control via the Blynk IoT platform to enable users to control the robot's movement (forward, backward, left, right), adjust suction power, select the desired cleaning algorithm, and monitor the battery level in real-time. In this paper three movement algorithms were developed: random, spiral and zigzag, and their performance was tested on two types of surfaces smooth and rough to ensure reliability and efficiency in various cleaning conditions after testing the validation of IO-VAC. Based on the test results of robot performance, the zigzag algorithm proved to be the most effective in terms of covered area, cleaning mission time, power consumption and minimizing redundancy. This work demonstrates an effective integration of embedded systems with IoT technologies, offering a smart and cost-efficient solution for automating household cleaning tasks.

Keywords: Smart Home, IoT, Robotic Vacuum Cleaner, Arduino Mega, Spiral.

تصميم وتنفيذ مكنسة روبوتية ذكية تعتمد على إنترنت الأشياء لبيئة المنزل الذكي

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ملخـــــــص البحـــــــث

تعرض هذه الورقة تصميم وتنفيذ مكنسة كهربائية روبوتية ذكية تعتمد على تقنيات إنترنت الأشياء (**IoT**)، أُطلق عليها اسم **IO-VAC**، وقد تم تطويرها خصيصًا لبيئات المنازل الذكية. تغطي الورقة الجوانب الميكانيكية والإلكترونية لتطوير هذا الروبوت.تم إنشاء مخطط ثنائي الأبعاد باستخدام برنامج **ArchiCAD** لتحديد مواقع المكونات وزوايا الحساسات أثناء تصميم الروبوت، تلاه نموذج ثلاثي الأبعاد لتصور الشكل النهائي. وقد صُنع هيكل الروبوت باستخدام بلاستيك معزز لضمان المتانة وخفة الوزن. و يتم التحكم في **IO-VAC** باستخدام لوحة **Arduino Mega** تمت برمجتها بلغة **C/C**++. يتضمن النظام ثلاث حساسات فوق صوتية لتجنب الاصطدام بالعوائق، بالإضافة إلى حساس بالأشعة تحت الحمراء (**IR**) لاكتشاف الحواف ومنع السقوط. حيث يُدمج النظام المدمج للروبوت وحدة **Wi-Fi**

ESP8266، مما يتيح التحكم عن بُعد عبر منصة Blynk IoT، حيث يمكن للمستخدم التحكم في حركة الروبوت (للأمام، للخلف، لليسار، لليمين)، وضبط قوة الشفط، واختيار خوارزمية التنظيف المناسبة، ومتابعة مستوى البطارية لحظيًا. في هذه الورقة، تم تطوير ثلاث خوارزميات للحركة: العشوائية، الحلزونية، والمتعرجة (Zigzag)، وتم اختبار أدائها على نوعين من الأسطح: الملساء والخشنة، للتحقق من موثوقية وكفاءة الروبوت في ظروف تنظيف مختلفة. وأظهرت نتائج الاختبارات أن خوارزمية التحرك المتعرج (Zigzag) كانت الأكثر كفاءة من حيث المساحة المغطاة، ومدة مهمة التنظيف، واستهلاك الطاقة، وتقليل التكرار في الحركة. تُظهر هذه الدراسة تكاملًا فعالًا بين الأنظمة المدمجة وتقنيات إنترنت الأشياء، مقدّمةً حلاً ذكيًا وفعّال التكلفة لأتمتة مهام التنظيف المنزلية.

الكلمات المفتاحية: المنزل الذكي، إنترنت الأشياء، مكنسة كهربائية روبوتية، أردوينو ميغا، حركة حلزونية.

1. INTRODUCTION

In recent years, smart home technologies have witnessed significant advancements, driven by the need to enhance comfort, improve energy efficiency, and provide user-centered automation solutions. Among these technologies, smart cleaning systems particularly robotic vacuum cleaners have emerged as a rapidly evolving field. This development is largely attributed to the integration of Internet of Things (IoT) technologies, which enable real-time communication, remote control, and performance optimization based on data analytics. Although traditional vacuum cleaners have evolved from manual or semi-automatic models into fully autonomous devices equipped with advanced sensors, precise control units, and intelligent navigation systems, several challenges persist. These include limited maneuverability, poor adaptability to dynamic environments, and the lack of seamless integration with internet-based control systems [1][2].

Several studies have addressed these issues. For instance, “Autonomous Multi-Function Floor Cleaning Robot with Zig Zag Algorithm” proposed a cleaning system using a zigzag algorithm to improve area coverage based on embedded navigation capabilities [3]. Another study, “Design and Implementation of a Cost Effective Vacuum Cleaner Robot”, presented the development of a low-cost robotic vacuum cleaner using a simplified structure and practical implementation of basic robotics concepts [4], reflecting continued research interest in enhancing such systems.

Furthermore, recent IoT-based developments have expanded the functionality and connectivity of cleaning robots. Kushwaha (2025), in “Development of an IoT-Based Smart Vacuum Cleaner Controlled via NodeMCU for Autonomous Home Cleaning Solutions”, introduced an intelligent cleaning system that leverages NodeMCU for remote monitoring and control, emphasizing real-time communication and practical challenges in domestic environments [5]. Similarly, Hussin et al. (2024), in “Smart Robot Cleaner Using Internet of Things”, proposed a robot cleaner that integrates IoT control through a mobile application and evaluated its cleaning performance across different types of dirt and surfaces [6]. A comparison among these studies highlights key distinctions: while earlier research [3][4] focused primarily on navigation algorithms and cost-effectiveness, the more recent IoT-oriented works [5][6] concentrated on enhancing user interaction, connectivity, and adaptive performance in real-time environments. This progression underscores a clear research trajectory toward integrating embedded systems with IoT technologies to achieve more intelligent, responsive, and efficient cleaning solutions.

Based on these results, this paper identifies the need for an intelligent cleaning system that provides high performance, maneuverability, comprehensive remote control, and real-time adaptability to changing indoor environments. The aim of this paper is to present a functional prototype that demonstrates the potential of integrating embedded systems with IoT technologies in smart cleaning solutions. The proposed system seeks to improve performance, flexibility, and user interaction beyond the capabilities of current robotic vacuum technologies.

In response, this paper proposes the IO-VAC, an intelligent, autonomous smart vacuum cleaner specifically designed to operate efficiently in typical household settings by leveraging advanced IoT technologies, a custom mechanical design, and precise navigation algorithms. The robot system features Mecanum wheels, which allow omnidirectional movement, and an embedded software system that enables full remote control through a mobile application using the Blynk platform. Additionally, the system integrates various sensors, including ultrasonic sensors and infrared sensors, to support real-time decision making, obstacle avoidance, and optimized cleaning performance.

The key contributions of this paper are: designing a robust mechanical structure to enhance navigation in indoor spaces; developing a sensor-based control algorithm optimized for indoor environments; and integrating IoT features such as mobile connectivity and remote command execution.

The paper is organized as follows: an Introduction providing a general background on the development of smart vacuum systems, identifying current limitations, and presenting the proposed IO-VAC system; then the Materials and Methods, which is divided into hardware mechanical design, software architecture, navigation algorithms, and integration with the Blynk application, as well as theoretical models and calculations used in system design, such as data update rates over the Blynk platform. This is followed by a Discussion of system performance in various indoor scenarios, and finally, a Conclusion summarizing key findings and suggesting future directions for system enhancement.

2. MATERIALS AND METHODS

This section focuses on presenting the steps involved in the design and implementation of the smart vacuum cleaner IO-VAC from both hardware and software perspectives. It covers the construction of the mechanical structure and electronic components, followed by programming, control, and the implementation of navigation algorithms.

A) Hardware Design & Implementation

Body Structure: The IO-VAC is designed with a circular The motor speed is managed through an Electronic Speed Controller (ESC), which allows for precise control of the motor's rotational speed, adjusting it according to the cleaning requirements chassis that allows it to move easily in various directions within the home environment. As shown in figure 1, this circular shape helps reduce collisions and eliminate dead corners. Lightweight materials, such as reinforced plastic, were used to ensure flexibility and ease of movement, while maintaining sufficient strength and durability to support the internal components. The design features four Mecanum wheels along with a caster wheel. These advanced wheels enable omni-directional movement, including forward, backward, lateral (sideways) movement, and in-place rotation. This significantly enhances the device's maneuverability, especially in tight or confined spaces.

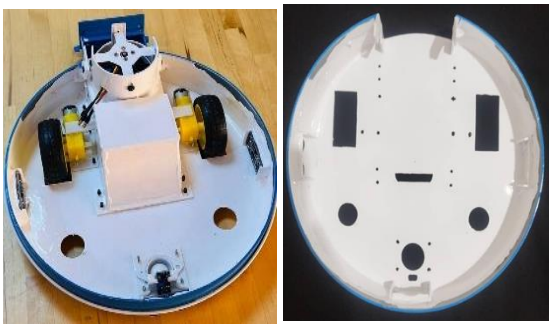


Fig 1. IO-VAC base structure.

- **Electrical & Mechanical Components :**

Suction Motor (BLDC Motor): The system utilizes a Brushless DC (BLDC) motor to operate the suction mechanism efficiently. This type of motor is chosen for its lower power consumption and longer lifespan compared to traditional brushed motors. [7]
Electronic Speed Controller (ESC): The motor speed is managed through an Electronic Speed Controller, which allows for precise control of the motor's rotational speed, adjusting it according to the cleaning requirements. [8]
Ultrasonic Sensors : These sensors are used to detect nearby obstacles and help the device avoid collisions with furniture or walls. [9]
Infrared (IR) Sensors: These are used to detect edges or potential drops such as stairs, ensuring the device operates safely within the environment. [10]
Wi-Fi Module: (ESP8266): Enables internet connectivity and communication with the remote control application. [11]
Arduino Mega: Used as the main controller due to its large number of input/output pins and its capability to support multiple sensors [10]. All components can be shown in figure 2.

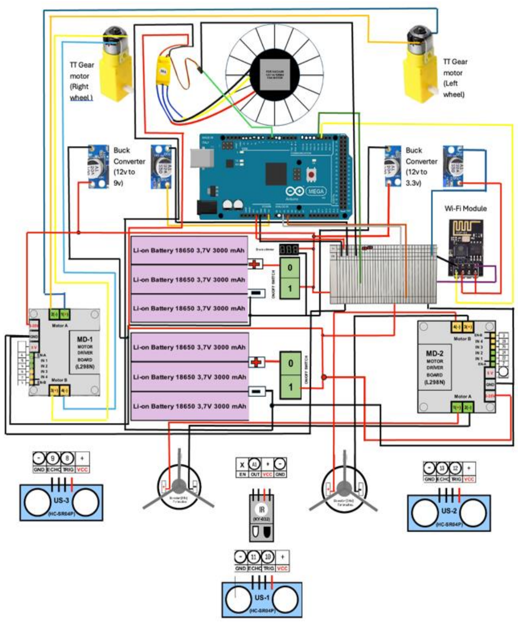


Fig 2. IO-VAC component circuit.

The mechanical structure was initially designed using ArchiCAD for 3D modelling, and the final prototype was then assembled manually. As shown in figure 3, and figure 4.

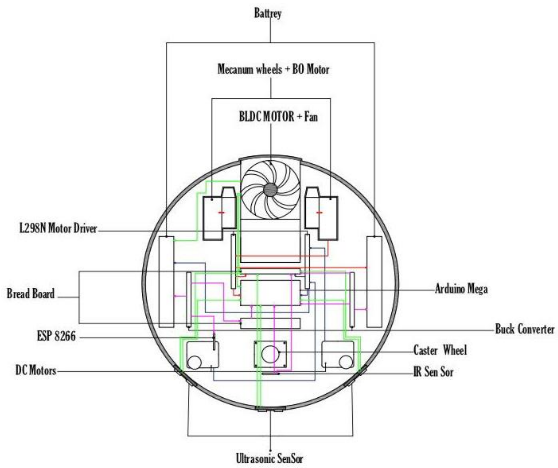


Fig3. 2D Layout Design of IO-VAC.

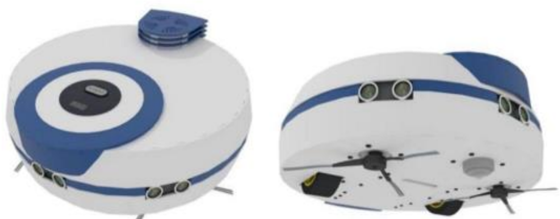


Fig 4. 3D Layout Design of IO-VAC.

A "START" button was placed at the centre of the top panel, while the ultrasonic sensor unit was mounted on the front side.
After installing the wheels and motors, the electronic circuits were arranged inside the chassis in a well-organized and secure manner to prevent electrical interference and ensure stable performance as shown in the figure 5.

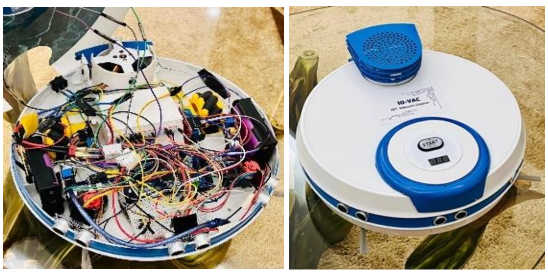


Fig 5. Installation all component.

All sensors were connected to the Arduino Mega through digital pins, and their responsiveness was tested using simple object-detection algorithms. As for, the Wi-Fi module (ESP8266) it was installed and linked to the Blynk application, enabling wireless control of the device and real-time monitoring via a mobile phone. Initial tests were conducted to verify safe movement, sensor responsiveness, and the overall performance of the hardware components.

B) Software Design

Control System: The system is programmed using the Arduino Mega in C/C++, through the Arduino IDE environment. The movement of the Mecanum wheels is controlled Using algorithms based on PWM (Pulse Width Modulation) and signal distribution across the four motors. The Arduino receives data from the sensors and makes real-time decisions to avoid obstacles or prevent falling off edges. The ESP8266 module acts as a Wi-Fi bridge, sending data to the Blynk application and receiving user commands. Figure 6 shows the block diagram of the robot system. The visual representation flowchart of the steps used in the process of programming as main flow chart for IO-VAC, is shown in figure 7.

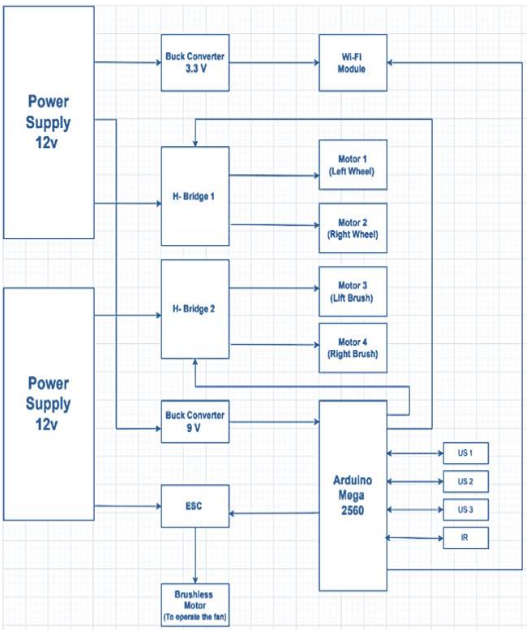


Fig 6. The block diagram for the system.

Algorithmes : They are programmed to ensure effective cleaning coverage in unregulated environments, three different algorithms are programmed to accomplish the task, they are :

- **Random mode algorithm:** It is based on selecting random directions after each collision or after covering a specific distance. Which gives the IO-VAC to choose its smart path automatically while cleaning the specific area. Its flow chart is shown in figure 8.
- **Spiral mode algorithm:** Starts from a specific point in the centre of the target area then moves in a spiral pattern to cover a the area circularly. Its flow chart is shown in figure 9.
- **Zigzag mode algorithm:** Moves in straight parallel lines, while it turns at an 90^0 angle in each line, covering the area in parallel paths. This algorithm flow chart is shown in figure 10.

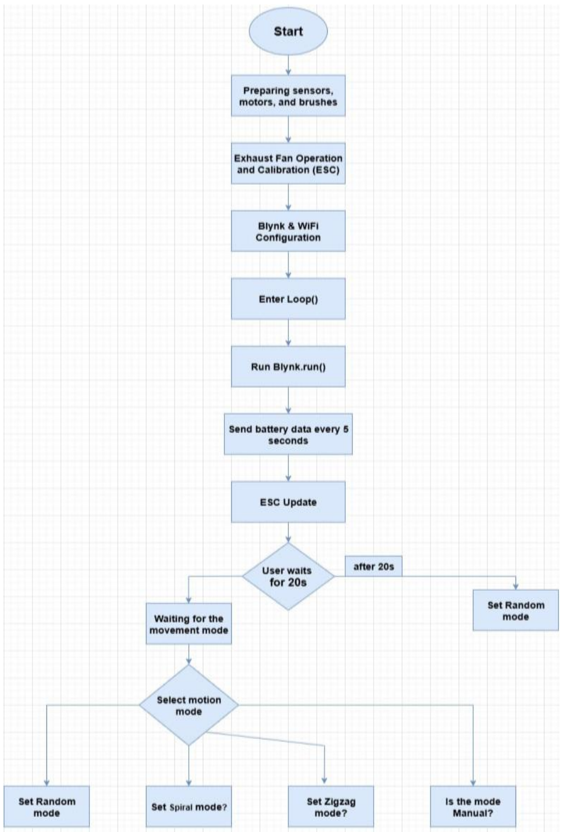


Fig 7. IO-VAC main flow chart.

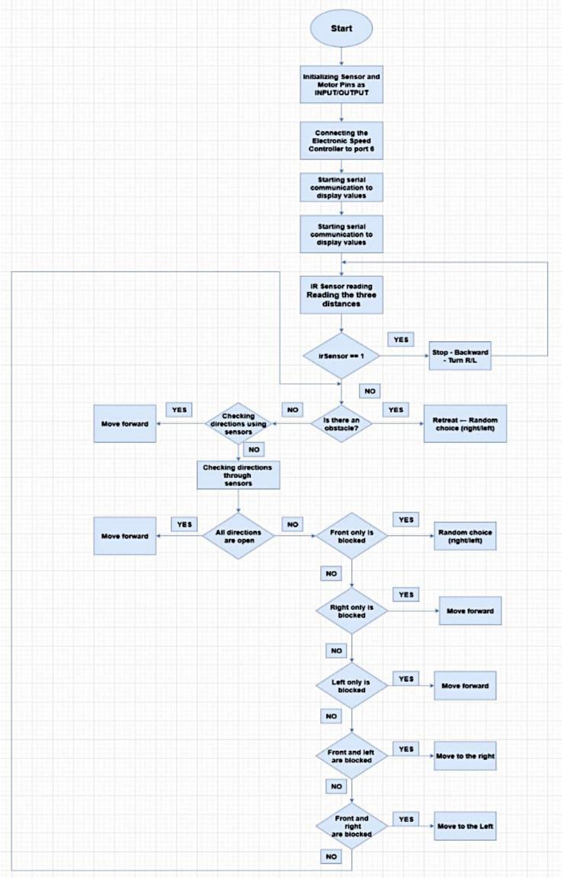


Fig 8. Random mode algorithm flowchart.

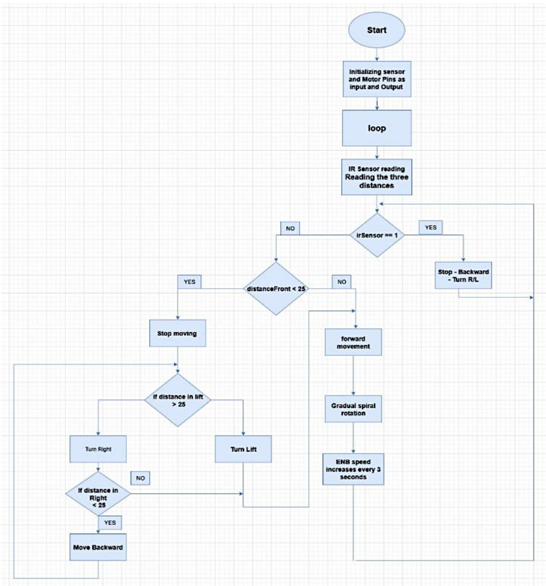


Fig 9. Spiral mode algorithm flowchart.

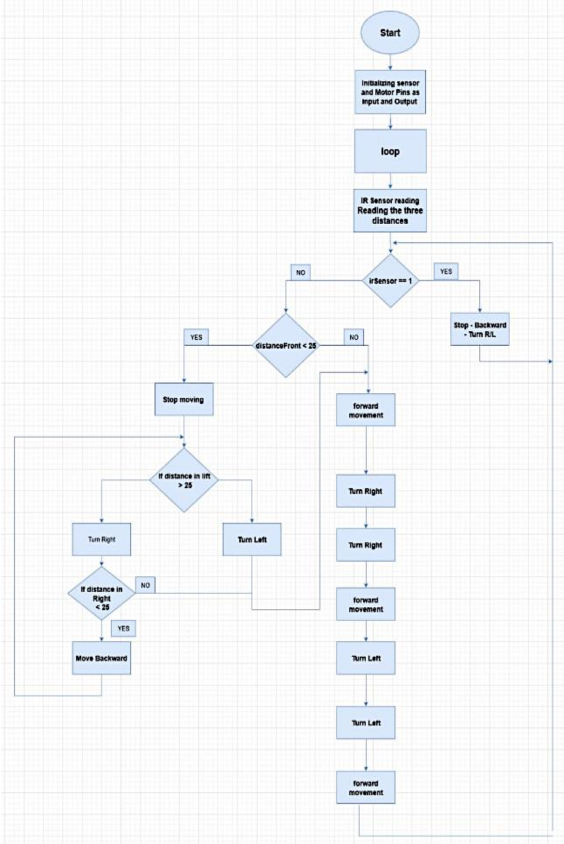


Fig 10. Zigzag mode algorithm flowchart.

Each algorithm is executed based on sensor input, and the system dynamically switches between them depending on the environment or user commands.

Remote Access and Monitoring: The Blynk application was used as a simple graphical user interface (GUI) for the user. The app allows the following functionalities:

- Start or stop the IO-VAC.
- Selecting the movement mode (Random, Spiral, Zigzag, user mode).
- Selecting the speed of suction fan.
- Displaying information such as battery status, and time of task.

3. THEORY AND CALCULATION

The theoretical foundations and mathematical models used to control the performance of the robotic smart vacuum cleaner. The system integrates several digital and physical variables such as suction level, motor speed, and battery percentage, all managed through the Blynk IoT application that enables real-time communication between the robot and the user.

3.1 Suction Level Equation

The suction power is controlled using a PWM signal applied to the BLDC motor through an ESC (Electronic Speed Controller). The relationship between the PWM value and suction power can be expressed as:

$$P(suction) = {}^{(\mathrm{K} * \mathrm{PMW(value)})}/_{255} \quad (1)$$

Where:

P (suction): actual suction level.

PWM (value): PWM duty cycle value sent from the microcontroller.

K: proportional constant based on motor specifications and supply voltage.[12]

The measured suction power is displayed on the Blynk application and can be adjusted according to the selected mode (low, medium, or high).

3.2 Suction Efficiency by Count and Weight

To accurately evaluate suction performance, suction efficiency is defined as follows:

- Count-Based Efficiency:

$$Suction\ Efficiency\ (\%) = (Number\ of\ collected\ cardboard\ pieces / Number\ of\ distributed\ cardboard\ pieces) * 100 \quad (2)$$

This method is used when debris is distributed uniformly, allowing precise measurement based on the number of pieces.

- Weight-Based Efficiency:

$$\text{Suction Efficiency (\%)} = (\text{weight of collected debris (g)} / \text{Weight of distributed debris(g)}) * 100 \quad (3)$$

This method is used when debris is distributed non-uniformly, where counting pieces alone is insufficient, so total weight is considered.

3.3 Power Consumption Calculation

The power consumed by the suction system during operation can be estimated as:

$$\text{Consumed Power (\%)} = 100 - ((\text{Voltage during operation(V)} / \text{Initial Voltage (V)}) * 100) \quad (4)$$

3.4 Battery Percentage Equation

Battery level monitoring is achieved through a voltage divider connected to the analog input of the microcontroller. The measured voltage is converted to a percentage as follows:

$$Battery\% = (\mathrm{V(measured)} - \mathrm{V(min)})/(\mathrm{V(max\,)} - V(\mathrm{min\,})) * 100 \quad (5)$$

Where:

V(measured): actual measured battery voltage.

V(min): minimum safe operating voltage.

V(max): maximum voltage at full charge.[13]

This percentage is transmitted to the Blynk application and displayed in real time on the user interface.

4. RESULTS AND DISCUSSION

The results in this paper will be discussed in two categories, first the results of IO-VAC validation, then the results when testing the robot over different scenarios and cases in term of algorithm mode and floor area type.

4.1 IO-VAC Validation Results & discussion

The validation process aims to test and evaluate the performance of the IO-VAC system to ensure that all its functions operate efficiently and meet the required standards before being implemented in a real-world environment. The validation included the following test cases:

Case 1: IO-VAC Movement

The robot was tested for its ability to move in a straight line as shown in figure 11, using a predefined reference path. The robot successfully followed the line with high precision, confirming its capability to maintain stable and accurate linear motion.

Fig 11. IO-VAC Movement validation.

Case 2: Sensor Response

The Ultrasonic Sensors: These sensors were evaluated for real-time obstacle detection. They demonstrated immediate responsiveness; its movement decisions were made according to the following rules:

- If no obstacle is detected in front: the device moves forward.
- If an obstacle is detected in front: it checks the left sensor.
- If the left side is clear: it turns left.
- If the left side is blocked: it turns right.
- If all directions are blocked: the device moves backward and reassesses the side sensors.

This logic highlights the system's ability to adapt effectively in complex environments and avoid collisions dynamically.

The Infrared (IR) Sensors: These sensors were tested after installation to prevent the device from falling off elevated surfaces such as stairs. When IO-VAC approaches an edge, the IR sensor immediately stops the device, which then reverses and checks the right-side sensor:

- If the right side is clear: the device turns right.
- If an obstacle is detected: it turns left.

The test confirmed effective edge detection and avoidance.

Case 3: Waste Suction Unit

This unit, performance was tested in an environment with light debris. The unit as shown in figure12, operated efficiently, collecting waste without delay. The test confirmed the system's ability to successfully carry out its primary cleaning function.

Fig. 12. IO-VAC Waste Suction Unit.

Case 4: Mobile Application Interface

The mobile app was enhanced using the Blynk platform with several control and monitoring features:

• **Movement Control**: Directional buttons (forward, backward, left, right) allowed smooth and accurate control of the robot's motion. As shown in figure 13.

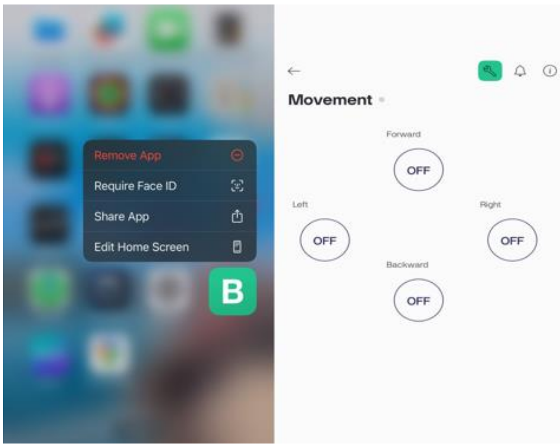


Fig 13. IO-VAC mobile App**.**

• **Suction Level Selection**: A menu widget was added to choose suction power (Low, Medium, High). The Arduino processed these commands successfully. Shown in figure 14.

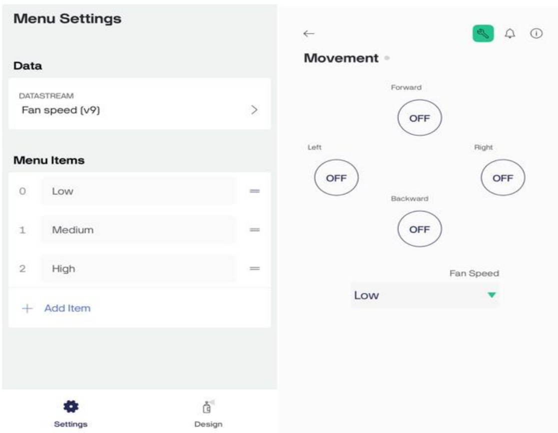


Fig 14. IO-VAC App user Interface suction level

• **Movement Mode Selection**: Another menu enabled switching between movement patterns (Manual, Zigzag, Spiral), with correct system responses to each mode. Shown in figure 15.

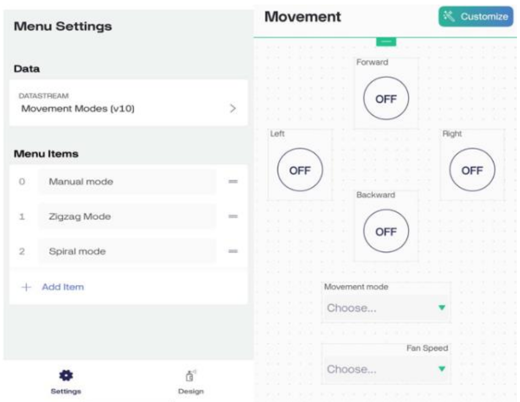


Fig 15. IO-VAC App Interface for movement mode.

• **Battery Monitoring**: A voltage divider circuit connected to analog pins (A2 and A3) was used to calculate and display the battery charge percentage via the app. Additionally, a low battery alert was implemented to notify the user when charge drops to 25%. Shown in figure 16.

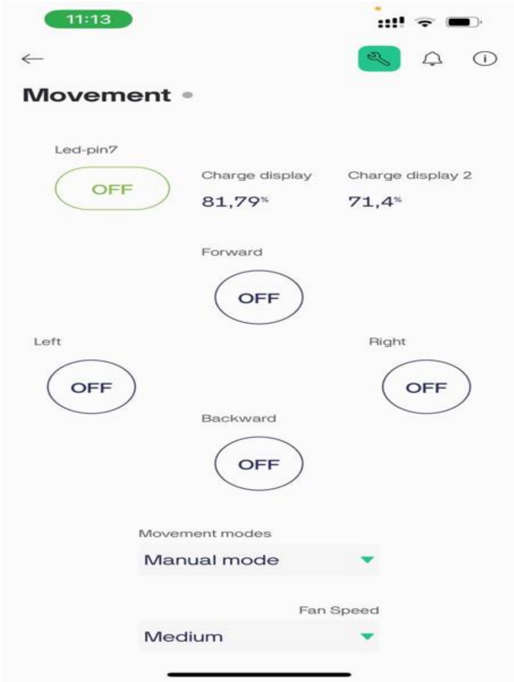


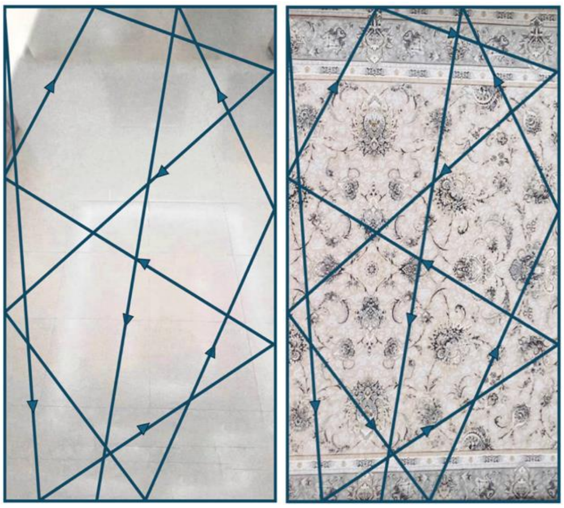
Fig 16. Final IO-VAC App Interface.

4.2 Scenarios & Challenges results discussion

This section presents a set of real-world scenarios in which the IO-VAC was tested, along with the challenges it encountered during operation. The aim is to assess the efficiency of the algorithms used in handling different environments in term of quality-of-service QoS such as: time consumed, power consumption and the rate of total suction within a limited area. These evaluations help identify the strengths and weaknesses of the current system and provide insights for future performance improvements. However, the scenarios were carried out on two different layout surfaces: smooth surface and rough surface (carpet in this case), within a 3×6-meter area, to ensure consistent and controlled testing conditions. Also each algorithm was tested on each surface for a uniform distribution debris 5 times trial, and another 5 times trial for a non-uniform distribution debris. Reporting the average and standard deviation for time of action, dissipated power, and suction efficiency.

1) Scenario 1: Random Mode

This scenario examines the performance of the IO-VAC system when operating under the Random Mode Algorithm. The robot moves without following a fixed path, allowing for the evaluation of its ability to navigate unpredictably, avoid obstacles, and perform cleaning tasks in a dynamic environment.



(a) (b)

Fig 17. Random mode algorithm (a) Layout 1 (b) Layout 2

Layout1: Smooth surface

During this test, IO-VAC moved smoothly and randomly on the flat surface, with mostly stable navigation, as shown in figure 17 (a). While the ultrasonic sensors helped avoid obstacles, occasional collisions occurred due to limited sensor accuracy. The task was completed in an average of 5:54 minutes with an estimated 72% suction efficiency. Battery voltage dropped moderately from 11.7V to 11.2V, indicating average power usage.

Layout 2: Rough surface

In this test, IO-VAC operated on a rough surface using the Random Mode Algorithm as shown in figure 17 (b), resulting in less smooth movement due to higher friction. The robot completed the task in an average of 7 minutes and 34 seconds, with some minor collisions from sensor limitations. Suction efficiency was reasonable at approximate 63%. Where the battery voltage dropped from 11.7V to 11.0V, indicating higher power consumption due to the rough terrain.

2) Scenario 2: Spiral Mode

The IO-VAC was tested using the Spiral Mode algorithm on both smooth and rough surfaces to evaluate the system's performance in different operating environments with structured movement paths. During testing, a challenge was encountered regarding the distance between the spiral loops during movement, which slightly affected the robot's overall performance.

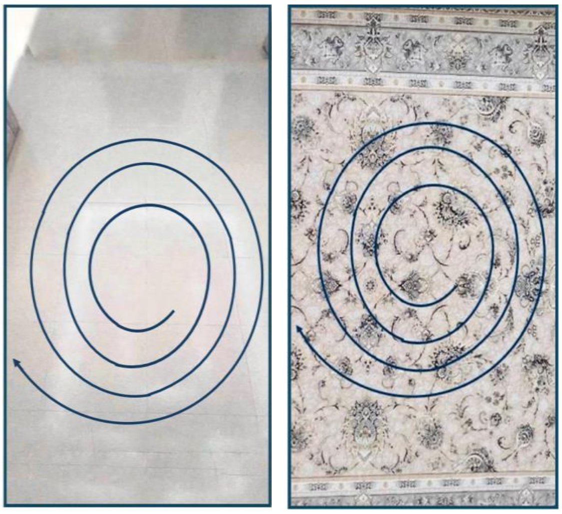
Layout 1: Smooth surface

The robot demonstrated smooth and efficient movement, completing the task in 5 minutes average. The battery voltage dropped from 11.7 volts to 11.4 volts, indicating relatively low power consumption. The suction efficiency reached approximately in average 74% when tested with regular and cardboard paper distributed uniformly and non-uniformly, reflecting good capability in collecting debris in a low-friction environment, as shown in figure 18 (a).

Layout 2: Rough surface

The movement was less smooth due to increased friction, which led to a longer task duration of 8 minutes and 37 seconds. The battery voltage dropped from 11.7 volts to 11.0 volts, indicating higher power consumption compared to the smooth surface. The average suction efficiency was recorded at approximate

65%, which is relatively lower due to the surface texture and its impact on the robot's ability to clean effectively. Figure 18 (b) shows the used Layout.



(a) (b)

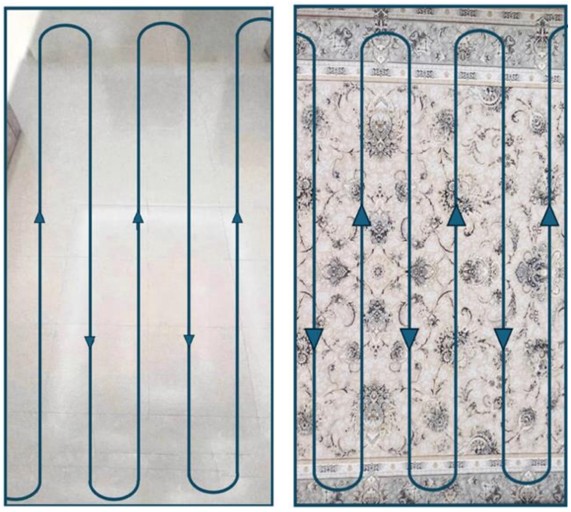
Fig 18. Spiral mode algorithm (a) Layout 1 (b) Layout 2.

3) Scenario 3: Zigzag Mode

The IO-VAC was tested using the Zigzag Mode algorithm on both smooth and rough surfaces to evaluate movement accuracy and performance efficiency under a relatively structured navigation pattern. The system faced certain challenges during these tests, as the zigzag pattern requires precise readings from distance sensors to determine the correct direction of movement. Nevertheless, the following results were achieved after several attempts to fine-tune the performance and obtain the best possible navigation response.

Layout 1: Smooth surface

The IO-VAC demonstrated fairly precise movement and completed the task in 4 minutes and 19 seconds. The battery voltage dropped from 11.7 volts to 11.5 volts, indicating low power consumption. The mean value of suction efficiency reached 85% when tested with both uniform and non-uniform of debris distribution, which reflects excellent performance in a low-friction environment. As in figure 19 (a).



(a) (b)

Fig 19. Zigzag mode algorithm (a) Layout 1 (b) Layout 2.

Layout 2: Rough surface

The task took 6 minutes and 57 seconds to complete, with the battery voltage dropping from 11.7 volts to 11.2 volts a, indicating relatively higher power consumption due to surface resistance. Despite the challenges, the system achieved a good suction rate of 81% in average, demonstrating adequate efficiency in collecting debris even in a more complex environment. Figure 19 (b) shows the Layout.

Scenario 4: User/ Wi-Fi Mode

In this scenario, the IO-VAC was operated manually via the user interface using Wi-Fi mode, where the user controls the robot's movement through the available interface buttons. It is noted that the performance in this mode depends heavily on the user's speed and responsiveness during navigation, which directly impacts the efficiency of movement, suction, and task completion time.

Layout 1: Smooth surface

The robot completed the task in 6:20 minutes average time, with the battery voltage dropping from 11.7 volts to 11.3 volts, indicating moderate power consumption. The suction efficiency reached almost 83% when tested with both debris distribution, which is a good result that reflects the system's effectiveness under proper guidance in a low-friction environment.

Layout 2: Rough surface

The task took 8 minutes and 23 seconds to complete, with a greater drop in battery voltage from 11.7 volts to 11.0 volts, due to the additional effort required to move across an uneven surface. Despite the challenges, a suction rate up to 79% as an average, which is a good result considering the surface complexity and the reliance on the user's performance in manual control.

These results indicate that the manual control mode offers a high level of flexibility for the user; however, its efficiency is directly tied to the user's level of interaction and the accuracy of robot navigation during operation.

4.3 Comparison of Results

When implementing the IO-VAC on four different modes (Random, Spiral, Zigzag, and User mode), it showed noticeable variations in performance due to the nature of each algorithm and its adaptability to different operating environments. However, the performance was evaluated on both smooth and rough surfaces in terms of task consumed time, suction efficiency and power consumption. The figure 20 shows a comparison of consumed time results in both smooth and rough layouts for each algorithm.

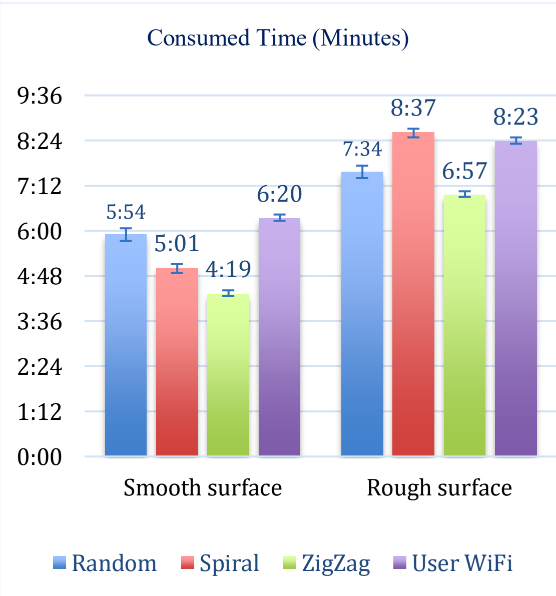


Fig 20. Results of Average & Standard Deviation of Consumed Time.

From figure 20, it can be obvious that the Zigzag Mode achieved the most balanced performance in both layouts, especially on the smooth surface with the shortest completion time of 4:19 minutes. While the spiral mode reaches the highest score with 8:37 minutes on rough surface. On the other hand, its seen that the user WiFi got the highest time in Layout 1.

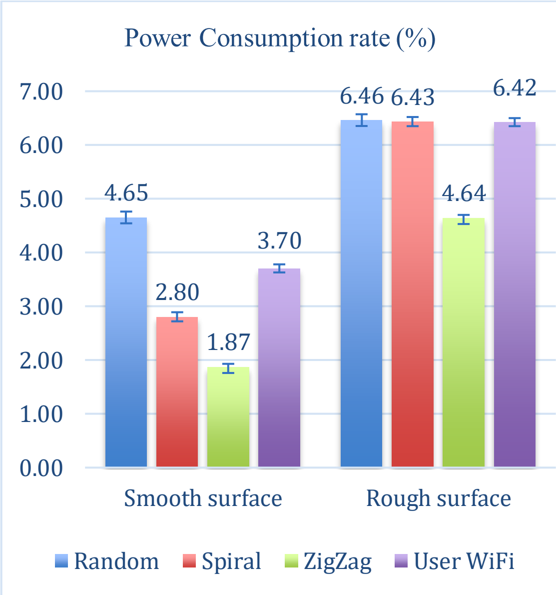


Fig 21. Results of Average & Standard Deviation of Power Consumption rate.

As for the performance of Io-VAC in term of power consumption at both smooth and rough surfaces, it was found that Zigzag Mode also achieved the best performance on saving power on both layouts, having a 1.87% from total power to achieve full mission in smooth surface and 4.64% at rough surface, as shown in figure 21. While all other algorithms score almost the same high-power rate in the rough surface even when compared to layout 1, leaving random algorithm with highest consumption in smooth surface. On the other hand, the Random Mode performed well on the smooth surface with a suction rate of 72% and lower efficiency on the rough surface at 62.6%, due to irregular motion and occasional difficulty in accurately avoiding obstacles. While user-Wi-Fi mode delivered stable results on both surfaces, with performance depending largely on the user's responsiveness and control accuracy. It recorded 82.7% suction on the smooth surface and 78.3% on the rough surface, as shown in figure 22.

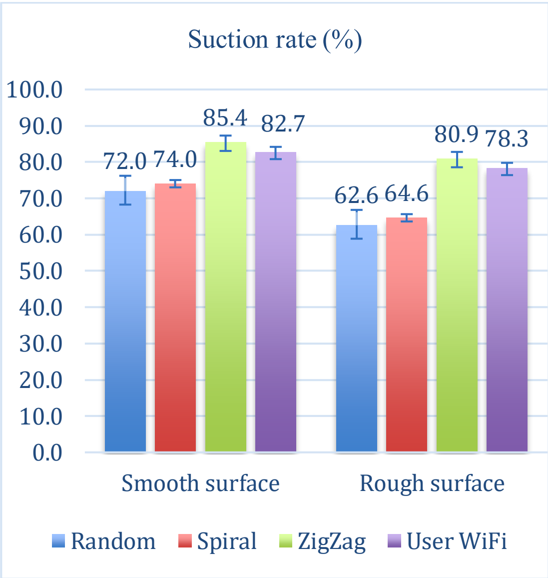


Fig 22. Results of Average & Standard Deviation of Suction rate

Overall, the results indicate that structured movement modes (such as Zigzag mode) tend to deliver better performance in organized environments, whereas less structured modes (like Random mode) may experience reduced efficiency, particularly in complex or uneven terrains. Therefore, selecting the most suitable mode depends on the surface type and specific requirements for coverage and accuracy. Table 1, shows a summary of all results obtained for the various algorithms on two different surfaces when the debris are distributed uniformly and non-uniformly, given the mean values and standard deviation in all cases.

Table 1. Summary of all scenarios results for different mode algorithms in each layout over an area $18m^2$.

Layout	Debris distribution	Trails	Random mode algorithm			Spiral mode algorithm			Zigzag mode algorithm			User-WiFi mode algorithm		
			Consumed time (Minutes)	Consumed Power (%)	Suction rate (%)	Consumed time (Minutes)	Consumed Power (%)	Suction rate (%)	Consumed time (Minutes)	Consumed Power (%)	Suction rate (%)	Consumed time (Minutes)	Consumed Power (%)	Suction rate (%)
Smooth Surface	Uniform	1	5:40	4.54	68	4:55	2.70	74	4:10	1.80	86	6:14	3.60	83
		2	5:45	4.60	80	4:56	2.75	74	4:11	1.82	87	6:15	3.63	84
		3	5:50	4.52	75	4:57	2.71	74	4:12	1.81	88	6:16	3.66	85
		4	5:44	4.55	77	4:55	2.74	74	4:10	1.83	87	6:15	3.62	84
		5	5:47	4.53	72	4:58	2.72	74	4:13	1.80	86	6:14	3.64	83
	Non-Uniform	1	6:00	4.70	67	5:05	2.85	72	4:25	1.90	83	6:25	3.75	80
		2	6:05	4.75	70	5:10	2.90	74	4:28	1.95	85	6:28	3.78	82
		3	6:02	4.72	72	5:08	2.88	75	4:26	1.92	84	6:27	3.80	83
		4	6:07	4.80	68	5:06	2.86	73	4:27	1.94	82	6:29	3.76	81
		5	6:03	4.78	71	5:09	2.91	76	4:29	1.93	86	6:26	3.79	82
Average			**5:54**	**4.65**	**72**	**5:01**	**2.80**	**74**	**4:19**	**1.87**	**85.4**	**6:20**	**3.70**	**82.7**
S. deviation			**0:10**	**0.11**	**4.22**	**0:06**	**0.09**	**1.05**	**0:08**	**0.06**	**1.9**	**0:06**	**0.08**	**1.49**
Rough Surface	Uniform	1	7:20	6.30	60	8:30	6.30	64	6:52	4.50	82	8:18	6.30	79
		2	7:25	6.40	70	8:32	6.36	65	6:54	4.54	83	8:20	6.36	80
		3	7:30	6.38	65	8:34	6.42	66	6:56	4.58	84	8:22	6.42	81
		4	7:28	6.35	66	8:31	6.38	65	6:53	4.52	82	8:19	6.35	80
		5	7:26	6.37	64	8:33	6.33	64	6:55	4.55	83	8:21	6.38	79
	N	1	7:40	6.50	58	8.40	6.45	63	6.58	4.70	78	8:25	6.45	76

		2	7:45	6.55	60	8.45	6.50	64	7:00	4.74	80	8:28	6.48	78
		3	7:42	6.60	63	8.43	6.55	66	6:59	4.76	79	8:30	6.50	77
		4	7:48	6.52	59	8.46	6.52	65	7:02	4.72	77	8:27	6.46	75
		5	7:44	6.58	61	8.42	6.48	64	7:01	4.75	81	8:29	6.49	78
Average			**7:34**	**6.46**	**62.6**	**8:37**	**6.43**	**64.6**	**6:57**	**4.64**	**80.9**	**8:23**	**6.42**	**78.3**
S. deviation			**0:10**	**0.11**	**3.72**	**0:06**	**0.08**	**0.97**	**0:03**	**0.11**	**2.33**	**0:04**	**0.07**	**1.89**

5. CONCLUSIONS

The conclusion when comparison with previous works, the results of this paper show clear progress compared to other research papers. Unlike many previous systems that relied on a single algorithm or neglected the variations in surface conditions, this paper implemented multiple movement algorithms (Random, Spiral, Zigzag, and User-WiFi mode), allowing for a broader performance evaluation. Additionally, the focus was placed on reducing power consumption and improving obstacle handling by integrating sensors in a more practical manner. As for the conclusion of Performance comparison through different scenarios over different debris distribution, by conducting various scenarios on both smooth and rough surfaces within a defined 3×6 m^2 area, the system was evaluated in terms of completion time, suction efficiency, and power consumption. Structured algorithms such as Zigzag demonstrated the best performance in stable environments, while less organized modes like Random faced significant challenges, especially on high-friction surfaces. These experiments helped identify the strengths and weaknesses of each mode and provided insights into how environmental conditions affect the overall performance of the system. However, the Zigzag algorithm outperformed other modes in overall performance in terms of suction efficiency, energy consumption, and task completion time. This superiority is attributed to the systematic and organized movement pattern adopted by this algorithm. It moves in straight, parallel lines that cover the entire area in a sequential and organized manner, ensuring that the device passes over all points without repetition or leaving uncleaned areas. This mode reduces path overlap and limits excessive random movement that consumes time and energy without added benefit, as commonly occurs in the Random mode.

Moreover, the Zigzag algorithm optimizes the mechanical energy usage of the motors because its path is consistent and directionally stable, minimizing sudden stops and repeated turns that increase energy consumption. As a result, the algorithm achieves high suction efficiency (*≈ 86% on smooth surfaces and ≈ 81% on rough surfaces*), with the shortest completion time among all modes and the lowest energy consumption (≈1.87%).

Overall, the Zigzag algorithm combines coverage efficiency and energy economy, making it most suitable for regular spaces that can be cleaned with a gradual linear path without many obstacles.

6. LIMITATIONS & FUTURE WORK

Although the proposed IO-VAC system presents an integrated model combining advanced mechanics (Mecanum wheels) and Internet of Things (IoT) technologies for remote control, several limitations have been identified during testing:

Dependence on Internet Connectivity: The system heavily relies on continuous Internet access via the Blynk platform, which may lead to performance degradation or loss of control in cases of weak or interrupted Wi-Fi signals.

Limited Artificial Intelligence and Self-Analysis: The current version lacks advanced machine learning or computer vision algorithms to analyze the environment or classify dirt types, limiting its ability to make autonomous complex decisions.

Restricted Navigation Range in Large or Multi-Room Environments: The system currently relies on ultrasonic and infrared sensors, which are effective in small spaces but struggle to generate accurate maps of larger or multi-floor environments.

As for future development directions:

Integration of Artificial Intelligence and Machine Learning (AI & ML): Future versions can include AI-based algorithms that enable floor-type recognition (carpet, tile, wood) and automatic adjustment of motor speed or suction power. The system could also learn from previous cleaning patterns to plan more efficient routes.

Implementation of Computer Vision Systems: Adding cameras and image processing modules such as Raspberry Pi or Jetson Nano would allow for precise mapping (SLAM) and recognition of dynamic obstacles or sensitive areas (e.g., wires, glass furniture).

Enhanced Smart Home Integration: The system can be expanded to integrate with voice assistants like Google Home or Amazon Alexa, enabling voice-based commands and scheduling through interconnected smart home applications.

Addition of Multifunctional Cleaning Features: Incorporating extra modules such as a small water tank and mopping system, or UV-based sterilization unit, would make the system more versatile and capable of performing multiple cleaning tasks.

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