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Design And Development of a Wireless Air Duct Cleaning and Inspection Robot for HVAC Systems

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Abstract
Heating, Ventilation, and Air Conditioning (HVAC) systems are critical for maintaining indoor air quality and thermal comfort in hospitals, industries, and commercial infrastructures. Over time, dust accumulation, microbial growth, and corrosion inside air ducts reduce airflow efficiency and increase health risks. Conventional cleaning methods are labor-intensive and often ineffective in confined duct environments. This paper presents the design, development, and experimental validation of a wireless air duct cleaning and inspection robot for rectangular HVAC ducts. The system integrates a four-wheel drive mechanism, rotating brush assembly, ESP8266-based wireless control, and live-streaming inspection. Mechanical calculations were performed for motor selection, and experimental evaluation demonstrated a 50% reduction in bacterial colony count after cleaning. The proposed system provides a cost-effective and efficient alternative to conventional duct maintenance techniques.
Keywords: *HVAC, Duct Cleaning Robot, ESP8266, Indoor Air Quality, Wireless Control, Mechanical Brushing.*

I. Introduction

HVAC systems are widely used in hospitals and industries to maintain controlled environmental conditions. Air ducts serve as distribution channels; however, prolonged use results in dust accumulation, fungal growth, bacterial colonies, and corrosion. These contaminants reduce system efficiency and compromise indoor air quality. Manual inspection is difficult due to confined duct geometry. Robotic cleaning systems provide a safer and more efficient alternative.

This study focuses on designing a wireless mobile robot capable of cleaning and inspecting rectangular ducts typically used in hospital installations.

II. Duct Specifications and Design Parameters

The duct dimensions were measured before fabrication. The recorded values are shown in Table 1. These dimensions were used to determine robot chassis size.

Table 1. Measured HVAC Duct Dimensions

Parameter	Symbol	Value	Unit
Thickness	t	1.6	mm
Width	W	600	mm
Height	H	300	mm
Cross Section	—	Rectangular	—

III. Mechanical Design Calculations

Step 1:
Measurements of air duct laid in hospital and industries; the following dimensions are to be recorded by actual inspection of the air duct.

A) Thickness of air duct: 1.6 mm
B) Width of air duct: 600 mm
C) Height of air duct: 300 mm

This information is used to determine the travel of the robot inside the duct and selection of the dimensions of the robot body and arm which carry the cleansing brush.

Step 2:
The motors used for the promotion of the robot have been selected based on the following design criteria,

i) Speed of robot required.
ii) Gross weight of the robot.

Gross weight of the robot = pay load on the robot + weight of the robot

$$Wg = Wp + Wr \quad \text{---------3.1}$$
$$= 0.12\ kg + 3kg$$
$$= 3.12\ kg$$

Torque required,

$$T = f * r \quad \text{---------3.2}$$
$$= m * g * r \quad \text{---------3.3}$$
$$= 3.12 * 9.8 * 0.053$$
$$= 1.622\ Nm \quad \text{(For one motor)}$$

$$T = 1.622 * 4 = 6.4887\ Nm \quad \text{(For 4 motor)}$$

Speed required,

$$Speed = power / Torque \quad \text{---------3.4}$$
$$Power = V * I \quad \text{---------3.5}$$
$$= 12 * 1.3$$
$$= 15.6\ W$$
$$Speed = 15.6 * 9.54 / 6.488$$
$$= 22.95\ rpm$$
$$\sim 23\ rpm$$

Therefore, the speed required for carrying the weight of 3.12 Kg is 23 rpm for each wheel. Table 2 summarizes robot parameters. Motor specifications are summarized in Table 3.

Table 2. Robot Physical Parameters

Parameter	Symbol	Value	Unit
Payload Weight	W_p	0.12	kg
Structural Weight	W_r	3.00	kg
Gross Weight	Wg	3.12	kg
No. of Motors	—	4	—

Table 3. Motor Design Parameters

Parameter	Value
Torque per Motor	1.622 Nm
Total Torque	6.488 Nm
Required Speed	23 RPM
Voltage	12 V
Current	1.3 A

IV. System Architecture

The robot integrates mechanical and electronic subsystems. Figure 1 shows the interconnection between battery, motor drivers, ESP8266 module, DC motors, DC–DC converter, and camera.

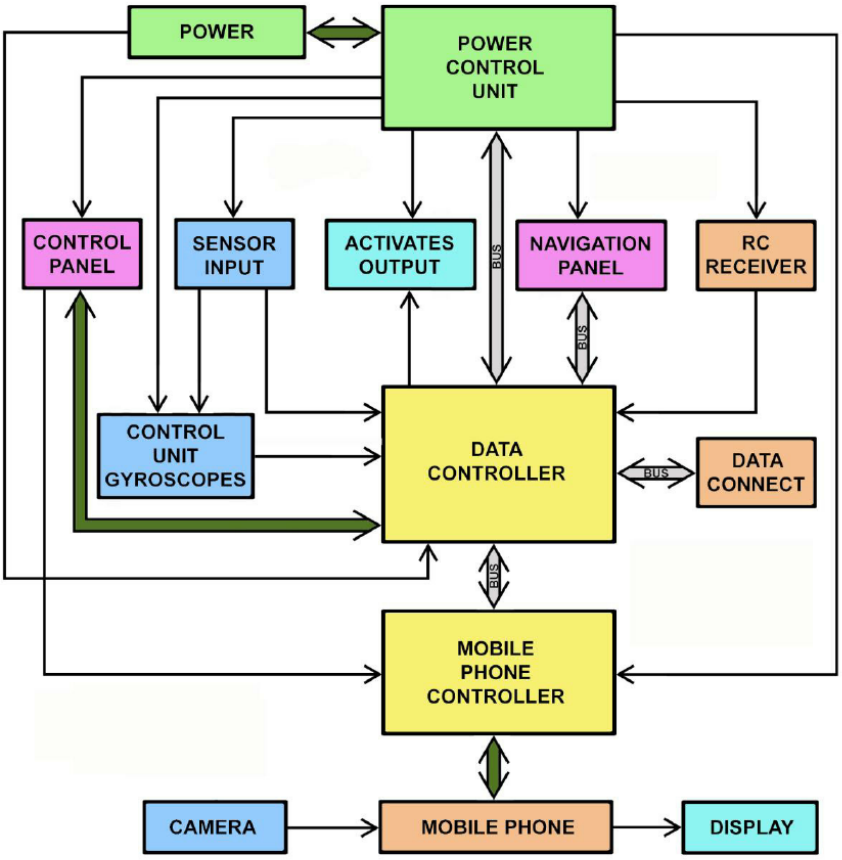

Figure 1. Overall System Block Diagram

V. Prototype Development

The fabricated prototype includes four drive wheels and a centrally mounted rotating brush. The model is shown in Figure 2.

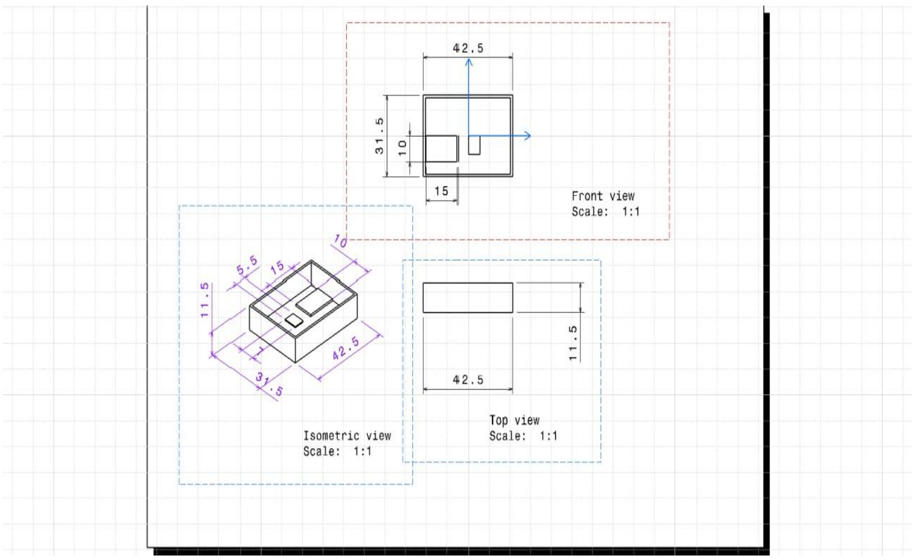

Figure 2. CAD Model of Proposed Robot

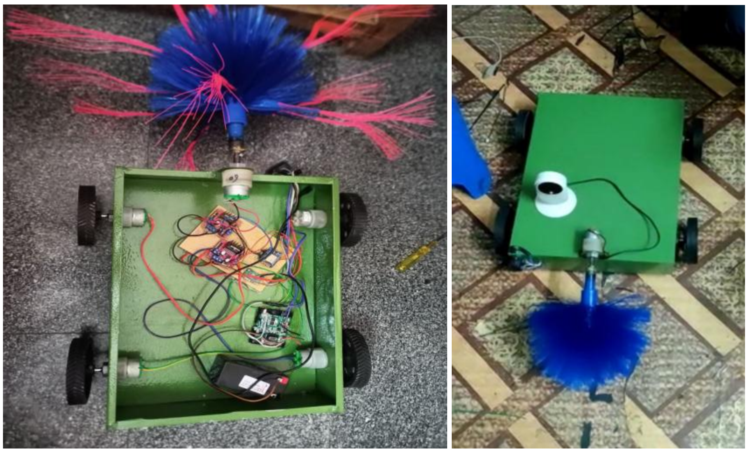

Figure 3. Fabricated Working Prototype

VI. Results and Discussion

The robot was tested inside a rectangular duct. Locomotion was stable, and the calculated motor speed of 23 RPM was sufficient for smooth traversal. The rotating brush effectively removed dust deposits from the inner duct surface. Microbial analysis was conducted using bacterial colony count (CFU). The acceptable limit was set at CFU < 10. During Week 3, the colony count reached 14 CFU, indicating contamination. After robotic cleaning, the value reduced to 7 CFU.

Table 4. Bacterial Colony Count Analysis

Week	CFU Before Cleaning	CFU After Cleaning
1	6	—
2	8	—
3	14	7
4	9	—

The percentage reduction is calculated as:

Reduction= (14−7) ×100 / 14 = 50% which confirms effective microbial removal.

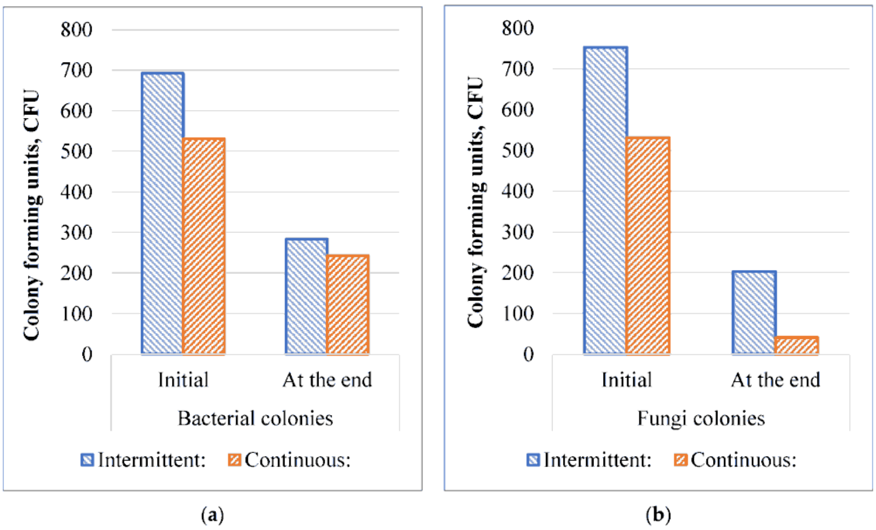

Figure 4 illustrates microbial reduction trend.

VII. Conclusions

A wireless air duct cleaning and inspection robot was successfully designed and validated. Mechanical calculations ensured appropriate motor selection, and experimental testing confirmed stable operation and effective cleaning. The system achieved a 50% reduction in bacterial contamination, demonstrating significant improvement in indoor air quality. Compared to existing complex autonomous systems, the proposed robot offers reduced cost, simplified architecture, and ease of operation.

Future improvements may include autonomous navigation, obstacle detection sensors, antimicrobial spray systems, and adaptability to circular ducts.

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