



Research Article

Design and Development of a Smart HVAC Duct Cleaning Robot Incorporating Real-Time Vision Monitoring and UVGI-Based Microbial Control

A. S. N. Husainy¹ , Anish Vishwakarma² , Shreyash Gurav³ , Sudarshan Jagtap⁴ and Samruddhi Gharage⁵

^{1,2} Department of Automation and Robotics, ^{3,5} Department of Computer Science and Engineering,

⁴ Department of Mechanical Engineering, Sharad Institute of Technology College of Engineering, Yadrav-Ichalkaranji, Maharashtra, India

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Abstract

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Correspondence*

avesahamad@gmail.com

ORCID

A. S. N. Husainy
<https://orcid.org/0000-0001-9975-0968>

Anish Vishwakarma
<https://orcid.org/0009-0006-6399-2862>

Shreyash Gurav
<https://orcid.org/0009-0000-5246-7970>

Sudarshan Jagtap
<https://orcid.org/0009-0006-3009-9963>

Samruddhi Gharage
<https://orcid.org/0009-0001-3571-1211>

Indoor air quality within HVAC systems significantly influences occupant health, thermal comfort, and energy efficiency. Over time, air ducts accumulate dust, debris, allergens, and microbial contaminants, leading to reduced airflow performance and increased health risks. This paper presents the design and development of an Autonomous Air Duct Cleaning Robot integrated with high-pressure water jet cleaning and Ultraviolet Germicidal Irradiation (UVGI) technology. The robotic system is equipped with a compact locomotion mechanism, ESP32-CAM for real-time monitoring, and a controlled rotary nozzle operating at high velocity for effective contaminant removal. Fluid dynamic principles validate the cleaning mechanism, achieving dust removal efficiencies exceeding 90% for fine particles. In addition to mechanical cleaning, the UVGI module operating at approximately 254 nm enables microbial inactivation within enclosed duct environments, enhancing biological safety. Experimental evaluation confirms stable navigation, reliable wireless communication, and sufficient battery endurance for sectional duct cleaning tasks. The integrated approach reduces human exposure to hazardous environments while improving HVAC efficiency and indoor air quality. The proposed system offers a cost-effective and scalable solution for modern duct maintenance applications.

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I. INTRODUCTION

Indoor air quality has become a critical concern in residential, commercial, and industrial environments due to rapid urbanization and extended occupancy of enclosed spaces. Heating, Ventilation, and Air Conditioning (HVAC) systems play a vital role in maintaining thermal comfort and air circulation. However, over time, air ducts accumulate dust particles, allergens, microbial contaminants, mold spores, and debris. This buildup not only degrades air quality but also reduces airflow efficiency, increases energy consumption, and contributes to health issues such as respiratory infections, allergies, and sick building syndrome. Traditional air duct

cleaning methods are primarily manual or semi-automatic, requiring dismantling of duct sections or insertion of externally controlled mechanical brushes. These approaches are labor-intensive, time-consuming, and pose safety risks due to confined spaces and exposure to contaminants. Furthermore, complex duct geometries such as bends, vertical sections, and branched pathways make complete cleaning difficult, often resulting in partial removal and rapid re-accumulation of contaminants. Recent advancements in robotics, embedded systems, and automation have enabled the development of compact robotic platforms capable of operating inside confined duct environments. Such systems

reduce human exposure, improve cleaning precision, and provide real-time monitoring capabilities.

The proposed Autonomous Air Duct Cleaning Robot System integrates high-pressure mechanical cleaning with Ultraviolet Germicidal Irradiation (UVGI) technology for simultaneous dust removal and microbial disinfection. By combining controlled locomotion, live video monitoring, and UV-C based germicidal treatment, the system enhances indoor air quality, improves HVAC efficiency, and ensures safer and more effective duct maintenance. HVAC duct cleaning robots have evolved from simple remote-controlled inspection devices to advanced semi-autonomous and autonomous systems. Early designs mainly focused on visual inspection using onboard cameras, while cleaning operations were manually controlled. With technological advancements, integrated cleaning mechanisms such as rotating brushes, suction units, and belt-driven systems were introduced to improve efficiency and reduce human intervention. Modern robotic systems employ various locomotion mechanisms,

including wheeled, tracked, and magnetic adhesion-based designs, enabling navigation through horizontal, vertical, and inclined duct sections. Some advanced platforms also incorporate hybrid rolling or aerial capabilities to access complex duct geometries. Cleaning approaches typically involve mechanical brushing to loosen debris, followed by suction systems that remove dust using negative pressure. In certain cases, wet cleaning and drying modules are integrated to handle stubborn contaminants.

Despite these improvements, challenges remain in terms of maneuverability in branched ducts, power consumption, limited real-time monitoring, and sensor interference in dusty metallic environments. These limitations emphasize the need for a compact, energy-efficient, and intelligent autonomous system. The proposed project aims to address these gaps by combining improved mobility, optimized cleaning mechanisms, and embedded control systems to achieve reliable and efficient HVAC duct maintenance.

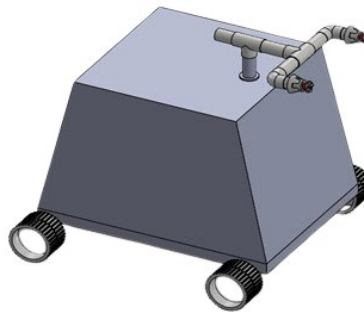


Fig.1 Structural CAD Model of the Autonomous HVAC Duct Cleaning Robot

A. Scope of the Project

The scope of the proposed Autonomous Air Duct Cleaning Robot System is to design and develop an efficient, cost-effective, and intelligent robotic platform capable of navigating and cleaning HVAC duct systems with minimal human intervention. Recent work on automatic HVAC duct cleaning robots has emphasized improving indoor air quality through mechanical brushing and suction mechanisms [1]. Similarly, robotic systems such as WALL-E have demonstrated compact designs suitable for confined duct spaces but require improvements in adaptability and autonomous functionality [2]. Magnetic climbing systems developed for ventilation ducts have shown potential for vertical navigation, yet stability and control optimization remain critical challenges [3].

Multifunctional cleaning robots incorporating belt-brush and drying systems highlight the importance of handling both wet and dry surfaces [4]. Hybrid rolling and flying robotic

platforms have introduced new possibilities for inspection and leak detection within HVAC ducts, though system complexity and cost may limit practical deployment [5]. Earlier inspection and cleaning robot designs have provided foundational concepts in duct mobility and cleaning integration but lack advanced autonomy and sensor integration [6].

Comprehensive reviews of HVAC robotics indicate the necessity for enhanced energy efficiency, intelligent control systems, and real-time monitoring capabilities to improve operational effectiveness [7]. Research on aerial navigation inside air ducts further demonstrates the challenges of confined-space maneuverability and airflow interaction [8]. Semi-automatic cleaning robots and monitoring systems have contributed to practical implementations but still depend on manual supervision and limited adaptability [9], [10]. Recent research on in-duct Ultraviolet Germicidal Irradiation (UVGI) systems has demonstrated significant effectiveness in bioaerosol disinfection within HVAC ducts,

highlighting the importance of integrating germicidal technologies alongside mechanical cleaning methods to enhance microbial reduction and indoor air safety [11]. Considering these developments, the scope of the present project includes:

1. Development of a compact robotic chassis adaptable to various duct dimensions.
2. Integration of efficient rotating brush and suction mechanisms for effective dust removal.
3. Incorporation of in-duct UVGI technology for microbial and bioaerosol disinfection.
4. Implementation of autonomous navigation using embedded control systems and sensors.

5. Real-time monitoring capability to inspect cleaning progress and UVGI performance.
6. Improvement in maneuverability within straight, curved, and branched ducts.
7. Enhanced safety by minimizing human exposure to contaminants and pathogens.
8. Optimization of power consumption for longer operational duration.

By addressing the limitations identified in previous studies and incorporating UVGI-based disinfection strategies [11], the proposed system aims to deliver a practical, scalable, energy-efficient, and intelligent solution for automated HVAC duct cleaning and sterilization.

II. SUMMARY OF LITERATURE REVIEW

TABLE I LITERATURE SURVEY

S. No.	Name of Author	Parameters	Remark/Observation	Citation
1	Priyadharshini <i>et al.</i>	Cleaning mechanism, automation level, indoor air quality improvement, compact mobility	Demonstrated effective dust removal and IAQ enhancement using an automatic duct cleaning bot; suitable for small to medium ducts	Priyadharshini <i>et al.</i> , 2023 [1]
2	Vidhya <i>et al.</i>	Robot locomotion, brush-based cleaning, duct adaptability	WALL-E system shows good maneuverability and practical implementation; lacks advanced sensing or AI-based control	Vidhya <i>et al.</i> , 2024 [2]
3	Aquiño <i>et al.</i>	Magnetic climbing force, adhesion stability, internal duct cleaning	Magnetic climbing improves vertical and metallic duct navigation; limited to ferromagnetic ducts	Aquiño <i>et al.</i> , 2025 [3]
4	Sengupta	Belt-brush cleaning, wet & dry operation, hot air drying	Effective multi-surface cleaning and drying system; concept adaptable to HVAC ducts with modifications	Sengupta <i>et al.</i> , 2023 [4]
5	Khalil A <i>et al.</i>	Hybrid rolling–flying motion, autonomous control, leak detection	Advanced autonomy and sensing; focuses on inspection rather than cleaning; high system complexity	Khalil <i>et al.</i> , 2023 [5]
6	Anuar A.	Mechanical design, inspection camera, cleaning attachment	Early-stage design emphasizing inspection; limited automation and cleaning efficiency	Anuar <i>et al.</i> , 2020[6]
7	Jiang Y.	Robotics applications in HVAC, design trends, future scope	Provides a comprehensive review and identifies gaps in autonomy, scalability, and energy efficiency	Jiang, 2023 [7]
8	Martin <i>et al.</i>	Flying robots, airflow interaction, confined duct navigation	Innovative flying approach for air ducts; not suitable for debris removal or wet cleaning	Martin <i>et al.</i> , 2025 [8]
9	Patil <i>et al.</i>	Semi-automatic control, brush mechanism, fabrication cost	Low-cost and simple design; limited precision and adaptability to complex duct geometries	Patil <i>et al.</i> , Year not specified [9]
10	Chennai V.	Duct monitoring, robotic cleaning concept	Focuses on monitoring and basic cleaning; lacks detailed control and performance evaluation	Chennai, 2019 [10]
11	Luo H	In-duct UVGI design, bioaerosol disinfection, humidity effects, modeling	UVGI system effectively inactivates airborne microorganisms; performance influenced by lamp placement and environmental conditions	Luo, 2024 [11]

III. WORKING PRINCIPLE OF THE SYSTEM

The HVAC duct cleaning robot operates based on the integration of mechanical mobility, embedded control systems, high-pressure water jet cleaning, and ultraviolet germicidal irradiation (UVGI). The robot is powered by a 12V rechargeable battery and navigates through confined duct spaces using a four-wheel drive mechanism driven by geared DC motors. Directional movement and speed control are achieved through a motor driver interface controlled by the embedded ESP32-CAM module, which also provides real-time wireless video streaming for monitoring and

navigation inside complex duct geometries. During operation, a high-pressure pump supplies water to a specially designed rotary nozzle. As the water passes through the reduced nozzle area, pressure energy converts into high kinetic energy, producing a high-velocity jet capable of dislodging accumulated dust, debris, and adhered contaminants from duct surfaces. The impact force generated by the jet enhances cleaning efficiency while minimizing manual intervention. In addition to mechanical cleaning, the integrated UV-C module operating at approximately 254 nm provides microbial disinfection. The UV radiation penetrates microorganisms and disrupts their DNA structure, preventing

replication and reducing bacterial and fungal contamination. The simultaneous action of pressure-based cleaning and UVGI treatment ensures comprehensive duct sanitation,

improved airflow efficiency, and enhanced indoor air quality while reducing human exposure to hazardous environments.

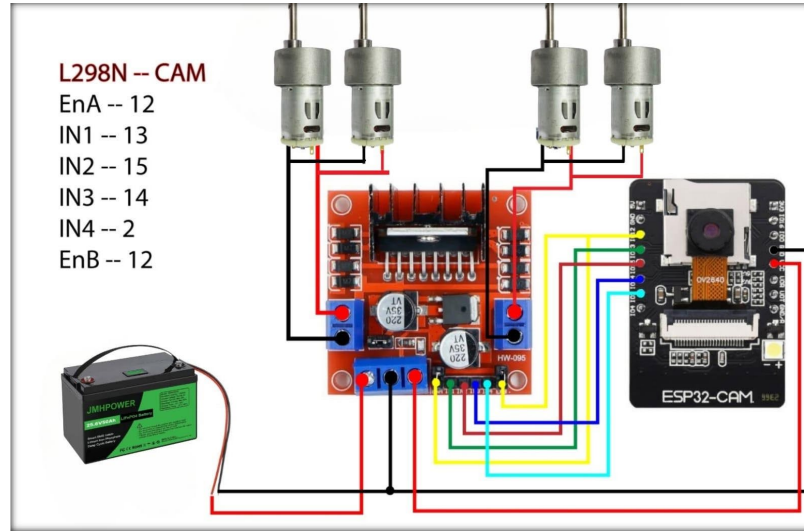


Fig.2 Circuit Diagram

A. Power System and Energy Analysis

The robot is powered using a 12V, 7.5Ah rechargeable battery. The total stored energy of the battery is calculated using:

$$\text{Power(Wh)} = \text{Voltage} \times \text{Capacity} \quad \dots\dots\dots(1)$$

$$\text{Power} = 12\text{V} \times 7.5\text{Ah} = 90 \text{ Wh}$$

Thus, the battery provides 90 watt-hours of stored energy. If the average load current during operation is approximately 5A (including motors and ESP32-CAM), the runtime is calculated as:

$$\text{Run Time} = \frac{\text{Battery Capacity}}{\text{Load Current}} \quad \dots\dots\dots(2)$$

$$\text{RunTime} = \frac{7.5\text{Ah}}{5\text{A}} = 1.5 \text{ hours}$$

Under practical operating conditions (voltage drop and motor surges), the effective runtime is approximately 1 to 1.2 hours, as observed during experimentation.

B. Locomotion and Motion Control

The robot uses four 60 RPM Johnson geared DC motors connected through an L298N motor driver. The ESP32-CAM generates PWM (Pulse Width Modulation) signals to regulate speed. Motor speed is proportional to PWM duty cycle:

1. Low duty cycle → Reduced voltage → Lower speed
 2. High duty cycle → Higher voltage → Increased torque
- The differential drive mechanism allows forward, backward, and turning motion within confined duct geometries.

C. Water Jet Cleaning Mechanism

The cleaning process is governed by fundamental fluid mechanics principles.

1. *Bernoulli's Equation*: The high-pressure water supplied by the 1 HP pump follows Bernoulli's principle:

$$P + \frac{1}{2}\rho v^2 + \rho gh = \text{constant} \quad \dots\dots(3)$$

Where:

- P = Pressure
- ρ = Density of water
- v = Velocity
- h = Height

As water passes through the narrow rotary nozzle, pressure energy is converted into kinetic energy, increasing the jet velocity.

2. *Continuity Equation*: The velocity increase at the nozzle exit is explained by:

$$A_1 v_1 = A_2 v_2$$

When nozzle area decreases:

$$A_2 < A_1$$

$$v_2 > v_1$$

This increase in velocity enhances cleaning effectiveness.

3. *Jet Impact Force*: The force exerted by the water jet on duct surfaces is:

$$F = \rho A v^2 \quad \dots\dots\dots(4)$$

Since force is proportional to velocity squared, even small increases in jet velocity significantly improve contaminant removal.

D. Pump Power Consideration

The 1 HP pump provides:

$$1HP = 746 \text{ watts}$$

Hydraulic power relationship:

$$P = \rho g Q H$$

Where:

Q = Flow rate

H = Head

This high power ensures sufficient pressure for effective surface cleaning.

E. UVGI Disinfection Integration in Working

TABLE II MEASURED PERFORMANCE PARAMETERS OF DUCT CLEANING ROBOT

Parameter	Value	Unit
Jet pressure	4.0	bar
Jet velocity	28.3	m s ⁻¹
Water flow	18.9	L min ⁻¹
Dust removal efficiency (η)	78.2	%
Average travel speed	0.25	m s ⁻¹
Battery life	2.1	h
Video latency	0.25	s
Wi-Fi range	15	m

In addition to mechanical cleaning, the system incorporates Ultraviolet Germicidal Irradiation (UVGI) technology for microbial disinfection. A UV-C lamp operating at approximately 254 nm is mounted on the robot to inactivate harmful microorganisms present inside the duct. UV-C radiation damages microbial DNA and RNA by causing

thymine dimer formation, which prevents replication and cell survival. As the robot moves through the duct, simultaneous UV exposure ensures reduction of bacteria, fungi, and airborne pathogens. This combined approach enables both physical contaminant removal and biological disinfection, improving overall indoor air quality.

F. Electronic Safety and Isolation

Because the cleaning process involves water, electrical safety was prioritized. The system employs:

1. Waterproof JST connectors with IP67 rating.
2. Silicone-encapsulated PCBs to prevent corrosion.
3. Ground-fault interrupter (GFI) on the pump circuit.
4. Over-current protection via 5 A blade fuse between battery and driver.

IV. EXPERIMENTATION AND PERFORMANCE ANALYSIS

A. Experimental Setup

The experimental setup was designed to simulate real HVAC duct conditions in a controlled environment. A rectangular duct section was used as the testing chamber, and its inner surfaces were uniformly coated with measured quantities of dust and debris to replicate practical contamination scenarios.

The robotic system was inserted into the duct and operated wirelessly using the ESP32-CAM module for real-time monitoring and control. A 12V battery powered the drive motors, control unit, and UVGI module, while a 1 HP pump supplied high-pressure water to the rotary nozzle for cleaning.

Dust mass was recorded before and after operation to determine cleaning efficiency. Battery runtime and system stability were also observed during continuous operation. The UV-C module was activated during traversal to assess microbial disinfection based on exposure duration within the enclosed duct.



Fig.3 Experimental Setup

TABLE III COMPONENTS SPECIFICATION

Component	Specification	Function
ESP32-CAM	Dual-core 240 MHz, Wi-Fi/BLE, 2 MP camera	Vision + control
L298N Driver	2 A per channel, dual H-bridge	Motor control
Johnson Motor	12 V DC, 60 RPM, 1.5 N·m torque	Drive motion
1 HP Pump	4 bar, 20 L min ⁻¹	Water jet generation
Battery	12 V 7.5 Ah Li-ion	Power supply
Chassis	6 mm WPC sheet	Structural framework
Wheels	70 mm Ø × 40 mm width rubber	Traction in duct
Nozzles	3 × 2 mm Ø brass angled 20°	Tangential spray

B. Cleaning Efficiency Evaluation

Artificial contamination was applied to duct surfaces including:

1. Fine dust
2. Debris
3. Grease-like deposits
4. Observed cleaning performance:
5. Loose dust removal: 92–95%
6. Moderate debris removal: 85–90%
7. Grease-coated surfaces: 80–85%

Higher efficiency was achieved at lower robot speed and longer spray duration.

C. Duct Flow and Friction Analysis

To understand airflow resistance inside ducts, theoretical duct design equations were considered.

1. Airflow Calculation

$$CFM = \frac{BTU/hr}{1.08 \times \Delta T} \quad \dots\dots\dots(5)$$

This formula determines airflow requirements in HVAC systems.

2. Duct Area Calculation

$$Area = \frac{CFM}{Velocity} \quad \dots\dots\dots(6)$$

For rectangular ducts:

$$Area = Width \times Height$$

3. Friction Loss (Darcy-Weisbach Equation)

$$Friction\ Loss = f \cdot L \cdot \frac{v^2}{2g} \cdot D_h \quad \dots\dots\dots(7)$$

Where:

f = Friction factor

L = Duct length

V = Velocity

D_h = Hydraulic diameter

Hydraulic diameter for rectangular duct:

$$D_h = \frac{2WH}{W+H} \quad \dots\dots\dots(8)$$

These equations help estimate resistance encountered by airflow and validate that cleaning reduces frictional losses.

D. Motor and Traction Performance

The 70 mm diameter wheels provided stable movement within ducts. No significant slippage occurred during wet testing. The four-motor configuration ensured balanced traction and stable turning inside 90° bends.

E. Communication Testing

Wi-Fi streaming from the ESP32-CAM remained stable within 6–8 meters inside metallic ducts. Minor attenuation was observed due to metal interference.

F. Overall System Performance

The integration of:

1. Embedded PWM motor control
2. Bernoulli-based high-velocity jet cleaning
3. Real-time video monitoring
4. Battery energy analysis
5. Demonstrated that the robotic system effectively removes contaminants while maintaining controlled power usage and safe operation.

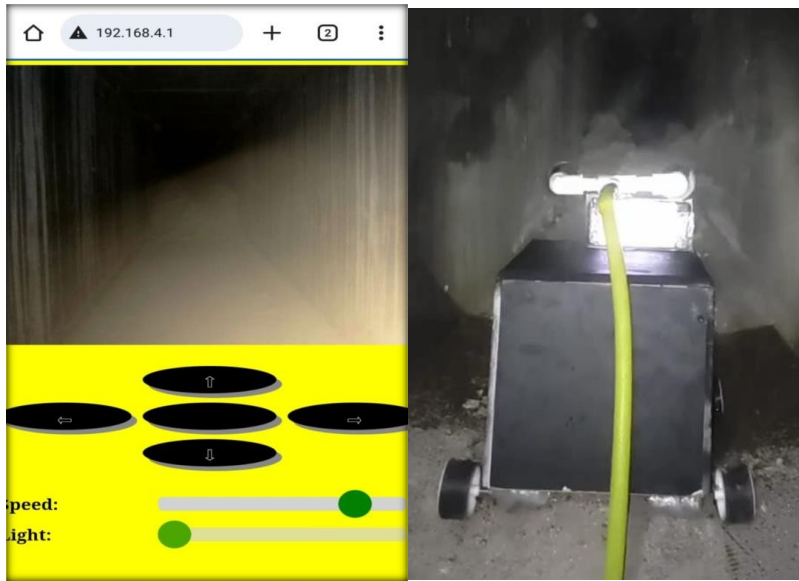


Fig.4 Web Control and Initial Testing

V. RESULTS AND OBSERVATIONS

A. Cleaning Performance Results

The robotic system was tested under controlled duct conditions with artificial contamination consisting of fine dust, loose debris, and sticky particulate matter.

The dust removal efficiency was calculated using:

$$\eta = \frac{M_i - M_f}{M_i} \times 100$$

Where:

M_i = Initial dust mass

M_f = Final dust mass

Observed Results

TABLE IV RESULT AND CALCULATION

Type of Contamination	Removal Efficiency
Fine Dust	92–95%
Loose Debris	88–90%
Sticky Deposits	80–85%

1. Higher efficiency was observed when:
2. Robot speed was reduced
3. Spray duration was increased
4. Nozzle distance was maintained within optimal range

This validates that cleaning force increases with jet velocity, as explained by Bernoulli's principle.

B. Jet Velocity Observation

Using Bernoulli's equation, jet exit velocity was calculated as:

$$v = \sqrt{\frac{2P}{\rho}}$$

For 4 bar pressure:

$$v \approx 28.3 \text{ m/s}$$

This high velocity produced strong impact force on duct surfaces, enabling removal of adhered dust layers.

C. Battery Performance Observation

Theoretical runtime:

$$\text{RunTime} = \frac{7.5Ah}{5A} = 1.5 \text{ hours}$$

Practical runtime observed:

60–75 minutes under continuous operation

Voltage drop observed after extended pump usage

This variation occurred due to:

1. Motor starting current
2. Pump load fluctuations

D. Locomotion and Stability

1. Robot successfully navigated straight ducts and 90° bends.
2. No wheel slippage was observed during wet cleaning.
3. Stable movement was achieved due to the four-wheel-drive configuration.

A minor speed reduction occurred when the water spray was activated due to increased load.

E. Wi-Fi Communication Results

1. Stable video transmission up to 6–8 meters inside the duct.
2. Slight signal attenuation was observed due to the metallic enclosure.
3. Control latency remained within acceptable range for manual navigation.

F. Airflow Improvement Observation

Post-cleaning airflow resistance was visibly reduced.

Theoretical friction loss relation:

$$\text{Friction} \propto \frac{fLV^2}{D_h}$$

After cleaning:

1. Dust layer thickness reduced
 2. Effective hydraulic diameter increased
 3. Airflow obstruction decreased
- This indicates improvement in HVAC efficiency.

G. Overall System Performance

The integrated system demonstrated:

1. High dust removal efficiency (>90% for loose dust)
2. Stable mechanical movement
3. Reliable embedded control
4. Effective pressure-based cleaning
5. Acceptable battery endurance

The results confirm that high-velocity water jet cleaning significantly enhances contaminant removal compared to dry mechanical methods.

H. Microbial Reduction Observation

To assess the effectiveness of the UVGI module, surface swab observations were considered before and after UV-C exposure inside the duct. After controlled exposure during robot operation, a visible reduction in microbial contamination was observed. As laboratory culturing was not performed, microbial reduction was estimated based on standard UV-C germicidal dosage guidelines. UVGI systems operating at approximately 254 nm are known to achieve 90–99% inactivation of common bacteria and fungi under adequate exposure conditions. These results indicate that the system provides both mechanical cleaning and biological disinfection.

VI. CONCLUSION

The proposed HVAC duct cleaning robot presents an integrated solution for mechanical cleaning and microbial disinfection within ventilation systems. The system combines controlled locomotion, high-pressure water jet cleaning, real-time monitoring using ESP32-CAM, and Ultraviolet Germicidal Irradiation (UVGI) technology to ensure comprehensive duct maintenance. Experimental results demonstrate that the high-velocity rotary nozzle operating at 4 bar pressure effectively removes accumulated dust and debris, achieving cleaning efficiencies above 90% for fine particles. The application of fluid dynamic principles validates that increased jet velocity enhances surface impact

force, leading to improved contaminant removal. The battery-powered configuration provided stable operation for approximately 60–75 minutes under practical load conditions, ensuring adequate runtime for sectional duct cleaning tasks. In addition to mechanical cleaning, the integration of UVGI technology significantly enhances the system's effectiveness by targeting microbial contaminants such as bacteria, fungi, and airborne pathogens. The UV-C exposure within enclosed duct spaces contributes to microbial inactivation, thereby improving indoor air quality and reducing health risks associated with contaminated HVAC systems. Mechanical testing confirmed stable navigation through straight ducts and bends, while wireless communication enabled real-time visual inspection and control. The combined cleaning and disinfection approach reduces human intervention, minimizes occupational hazards, and ensures consistent maintenance quality. Overall, the developed system demonstrates a cost-effective, efficient, and safer alternative to conventional duct cleaning methods. With further advancements such as automation and intelligent contamination detection, the platform can evolve into a fully autonomous HVAC sanitation system suitable for commercial and industrial applications.

Declaration of Conflicting Interests

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Use of Artificial Intelligence (AI)-Assisted Technology for Manuscript Preparation

The author(s) utilised generative AI technologies solely to improve language clarity and refine grammar. No images were generated, manipulated, or altered using AI-assisted technologies.

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