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HVAC Duct Monitoring and Cleaning Robot

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Abstract:
The HVAC Duct Monitoring and Cleaning Robot is designed to enhance the inspection and maintenance of Heating, Ventilation, and Air Conditioning (HVAC) systems by automating duct monitoring and cleaning operations. The robot eliminates the need for manual inspection, reduces health risks, and ensures efficient cleaning and maintenance of air ducts. The system comprises two major units: the Robot Unit and the Controller Unit, both powered by Arduino Nano microcontrollers communicating via the RS-485 protocol. The robot uses dual analog cameras, LED illumination, and four DC geared motors for smooth movement inside narrow duct spaces.Externally, a pneumatic cleaning brush can be connected to the robot for effective dust and debris removal during operation. A pressure pipe is fixed on the robot through the provided metal part on the upper side, which supplies the required air pressure to operate the pneumatic brush efficiently. RS-485 communication ensures reliable long-distance data transfer, making the system suitable for industrial environments where wireless communication is ineffective. The 10-core cable simultaneously carries both power and data, supplied through an SMPS that converts 230 V AC to 12 V DC, ensuring stable performance and uninterrupted operation over up to 30 meters without voltage drop or interference. The proposed design provides a cost-effective, compact, and durable solution for real-time HVAC duct inspection, monitoring, and cleaning applications.

Keywords—Robot, HVAC, remote, Wired communication

I. INTRODUCTION
Air quality management plays a crucial role in maintaining healthy environments in residential, industrial, and commercial buildings. HVAC ducts often accumulate dust, microbial contaminants, and grease, leading to decreased airflow, poor energy efficiency, and health risks for occupants. Traditionally, duct inspection and cleaning involve manual labor, which is time-consuming, costly, and hazardous in confined spaces. Robotic duct monitoring systems provide a modern alternative by offering automated visual inspection and remote control. However, most existing systems either rely on wireless communication, which is unreliable inside metal ducts, or complex mechanical systems that increase cost and maintenance. The proposed HVAC Duct Monitoring and Cleaning Robot integrates a wired RS-485 communication network, ensuring reliable and interference-free operation. The robot navigates smoothly through ducts using four DC geared motors, while front and rear cameras transmit real-time video to the operator. The system also includes LEDs for illumination, relay-based camera switching, and SMPS power units to maintain stable voltage throughout operation. This design prioritizes inspection and monitoring rather than cleaning, making it ideal for preventive maintenance applications, especially in environments where wireless transmission is restricted, such as pharmaceuticals, hospitals, and industrial HVAC systems.

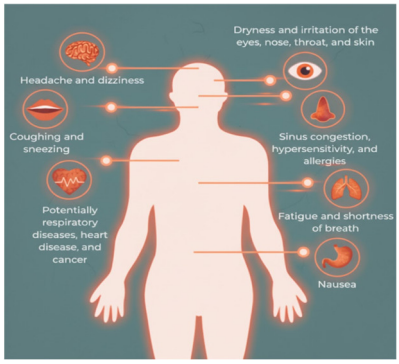

Fig. 1. Impact of low indoor air quality

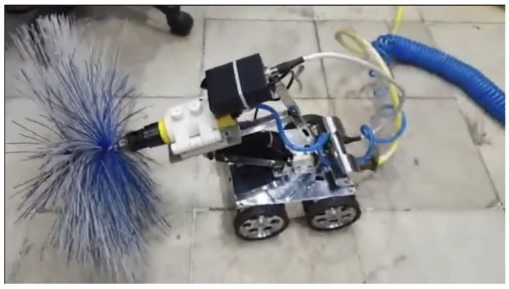

Fig. 2. HVAC Duct Monitoring Robot with Pneumatic Brush System.

For cleaning applications, a pneumatic brush shown in Fig.2. is integrated into the robot, powered by compressed air.This brush efficiently loosens and removes dust and debris from the interior of HVAC ducts.

II.LITERATURE SURVEY

[3] Helan Vidhya T1, Deepak G L2, Amruth K V2 and Ponnarasan D2 , The WALL-E system introduces a compact robot that can clean and monitor air ducts using wireless control. The key components used are ESP32-CAM, RF modules, L293D motor driver, DC motors, cleaning brushes, and rechargeable batteries. The ESP32-CAM captures real-time video inside the duct, which is transmitted to the operator through wireless RF communication. The L293D motor driver controls the rotation of the brushes and the movement of the robot. The RF module enables remote operation, allowing the robot to navigate and clean ducts without direct human contact. The power supply is provided through onboard batteries. The working process involves placing the robot inside the duct, remotely controlling it to clean and inspect the interior, and viewing the live camera feed. The system helps maintain air quality by removing dust and debris. However, the wireless signal becomes weak inside metal ducts, and battery life limits continuous operation, reducing its range and performance.

[14] Amirah ‘Aisha Badrul Hishama , Wong Liang Xuana , Mohamad Hafis Izran Ishaka , Nurul Hawani Idrisb , Abdullah Mohd Nawic, This project presents a robotic system designed for inspection and monitoring of HVAC ducts. The main components used are Arduino Uno, Raspberry Pi, camera, LED lights, gripper mechanism, DC motors, and a LAN-based communication setup. The Raspberry Pi is responsible for capturing and transmitting video images, while the Arduino controls the robot’s motion and lighting system. The camera provides a live video feed of the duct interior, and the LED lights help to illuminate dark sections. The robot communicates with the control station through UDP protocol over a LAN cable. The gripper mechanism can be used to pick up dust samples or small objects inside the duct. In operation, the robot moves inside the duct while sending live footage to the operator for inspection. This helps identify blockages, dirt buildup, or structural issues. However, the system faces communication delays and power loss over long cables, limiting its inspection range and efficiency.

[12] Seung Woo Jeon1, Wootae Jeong2, Duckshin Park2 and Soon-Bark Kwon2, This research work focuses on the development of an intelligent robotic system capable of cleaning HVAC ducts automatically. The system uses components such as a force-compliant brush, ultrasonic sensors, IMU (Inertial Measurement Unit), DC motors, and a microcontroller. The ultrasonic sensors help in detecting the distance between the duct surface and the robot, while the IMU maintains balance and orientation during movement. The force-compliant brush adjusts its pressure automatically to remove dirt and debris effectively without damaging the duct walls. The microcontroller acts as the main control unit, processing sensor data and controlling the motors and brushes. The working process involves the robot moving inside the duct, sensing the walls, and cleaning the interior surfaces using

the brush mechanism. This project reduces manual effort and improves cleanliness in air ducts. However, it is mechanically complex, costly, and focused only on cleaning, with no real-time inspection or monitoring capability.

II.EXISTING SYSTEM

In existing HVAC duct cleaning and inspection solutions, various robotic systems have been designed with a focus on either cleaning or short-range visual inspection. Early systems such as the *[6]* employed ultrasonic sensors, IMUs, and a pressure-controlled brush mechanism to clean ducts. Although effective in removing debris, the system was mechanically complex, bulky, and expensive, with no real-time inspection or monitoring capabilities. Subsequent models like the *[10]* used Arduino and Raspberry Pi boards, integrating cameras and gripper mechanisms to capture and transmit live video. However, communication was established through a UDP-based LAN connection, which resulted in signal delays, voltage drops, and limited range. This restricted its ability to operate over long duct lengths.

More recent designs, such as *[2]*, utilized ESP32-CAM modules with RF-based wireless communication and battery power. Although this system offered portability and simple operation, it suffered from severe signal attenuation and interference inside metallic ducts, leading to unreliable control and limited operating time due to battery constraints. Moreover, these systems were designed mainly for cleaning rather than continuous monitoring, which limits their applicability in environments like pharmaceutical industries or HVAC systems that require strict hygiene compliance and regular inspection.

III.PROPOSED SYSTEM

The proposed HVAC Duct Monitoring and Cleaning Robot presents a stable, long-distance, and reliable solution to overcome the limitations of existing systems. It employs a robust wired communication network that ensures uninterrupted data transmission and control, even within metallic ducts where wireless signals fail. he design emphasizes continuous visual inspection, stable power delivery, and operational safety, making it suitable for sensitive environments such as pharmaceutical industries, hospitals, and industrial HVAC networks. This system promotes efficiency, hygiene, and ease of maintenance through its modular design and centralized control architecture. It enables real-time duct monitoring without dismantling ceiling structures or disrupting normal operations. Overall, the proposed robot provides a cost-effective and industry-compliant solution for continuous air duct inspection, offering a dependable alternative to wireless systems in environments that demand non-invasive and uninterrupted monitoring.

IV.SYSTEM ARCHITECTURE

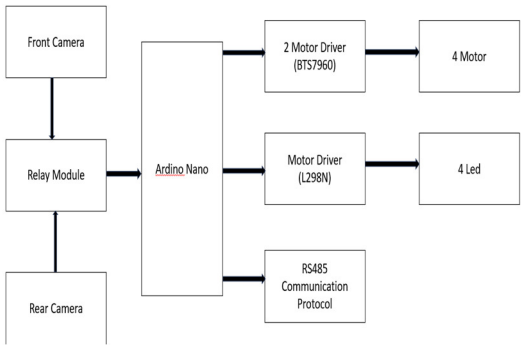

Fig. 3. Robot Unit

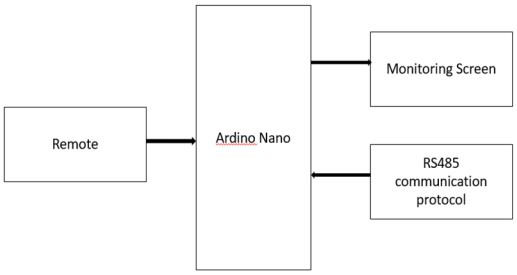

Fig.4 . Controller Unit

The provided system is comprised of two distinct units: the Robot Unit and the Controller Unit. The Robot Unit serves as the mobile component, centered around an Arduino Nano that manages sensing, movement, and communication. It receives visual input from a Front Camera and a Rear Camera via a Relay Module that switches between them. The Nano controls the robot's movement through a 2

Motor Driver (BTS7960) which powers 4 Motors, and it illuminates the path using a separate Controller Unit to operate 4 LEDs. All communication with the operator is handled by an RS485 communication protocol module for stable, long-distance data exchange. The Controller Unit acts as the operator's ground station, also utilizing an Arduino Nano to process commands sent from the Remote. This unit communicates with the robot using its own RS485 communication protocol module, and it displays the video feed and robot status on a Monitoring Screen, allowing the operator to control and inspect the duct interior remotely.

Methodology

A. Hardware Selection

Sr. No	Name of the Component	Function
1.	Arduino Nano	The central brain that processes commands and controls all robotic functions.
2.	RS485 Communication Module	Provides stable, long-range wired communication between the robot and controller unit.
3.	Wheels	Provides the mobility necessary for the robot to move inside the duct.
4.	Relay Module	An electronic switch used to toggle between the front and rear camera feeds.
5.	BTS7960 Motor Driver	Controls the speed and direction of the robot's main locomotion motors.
6.	L298N Motor Driver	Controls the power for secondary motors or the LED illumination unit.
7.	Camera	The visual sensor capturing the interior images of the duct
8.	LED	Provides illumination for the camera in the dark duct environment.
9.	Monitoring Screen	The display for the operator to view the real-time video feed.
10.	Remote	The operator's interface for sending movement and control commands.
11.	SMPS	Regulates and converts power to stable voltages required by the electronics.
12.	10 Core Cable	The physical medium transmitting power and RS-485 signals over distance.
13.	Motors	Supplies mechanical power to rotate the wheels for propulsion and steering.
14.	Power Supply Cable	Brings electrical power from the external source to the SMPS.

B. PCB Design and Layout

1.Controller PCB:

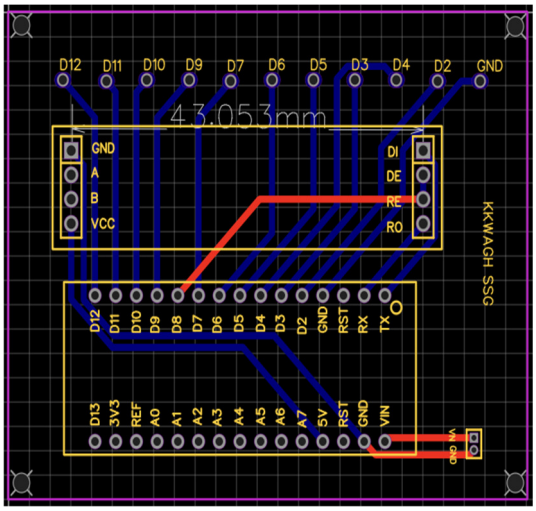

Fig.5. Controller PCB Design

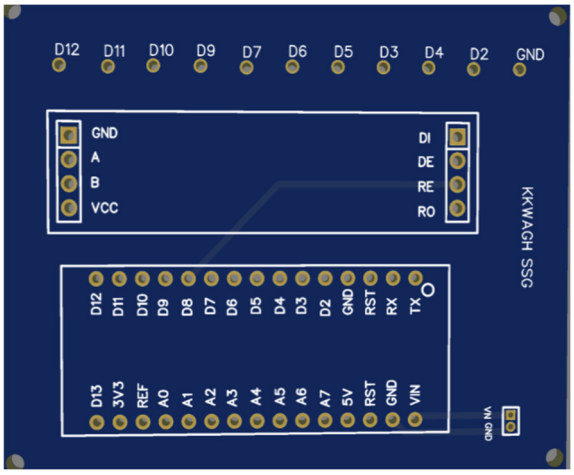

Fig.6. Controller PCB Layout(Top View)

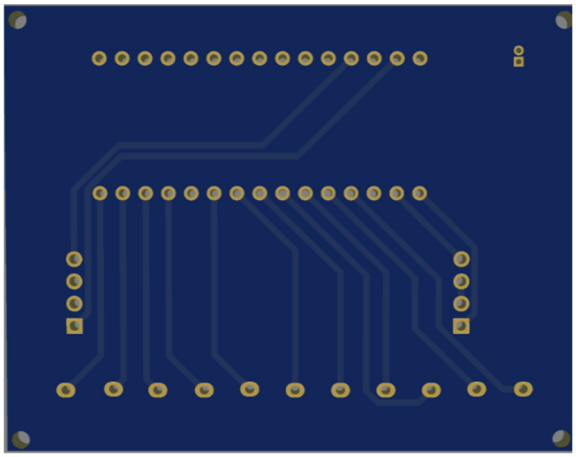

Fig.7. Controller PCB Layout(Bottom View)

2.Robot PCB:

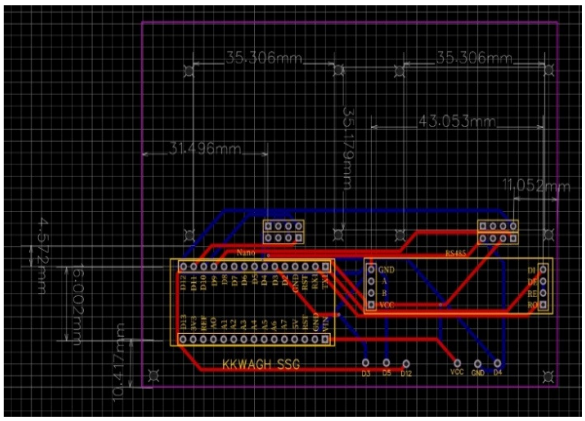

Fig.8. Robot PCB Design

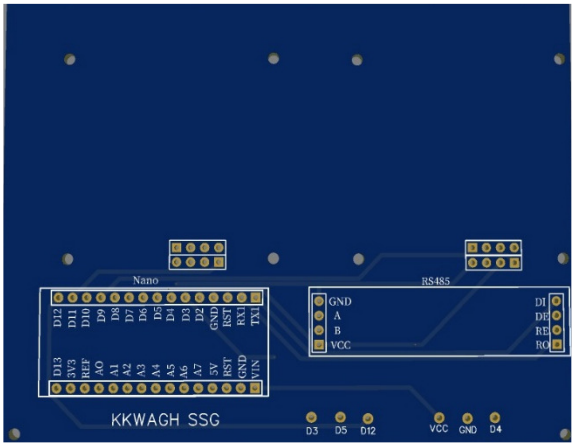

Fig.9. Robot PCB Layout(Top View)

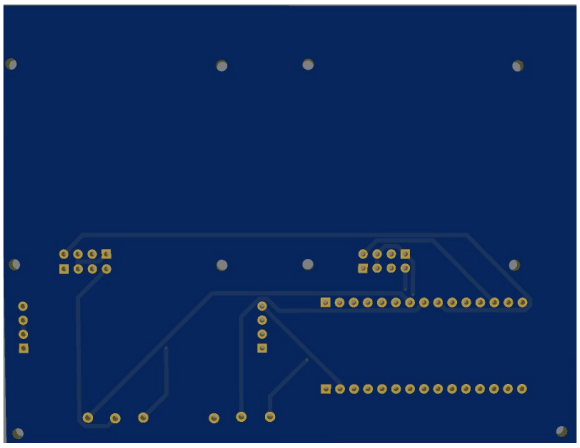

Fig.10. Robot PCB Layout(Bottom View)

C. Internal Circuitry

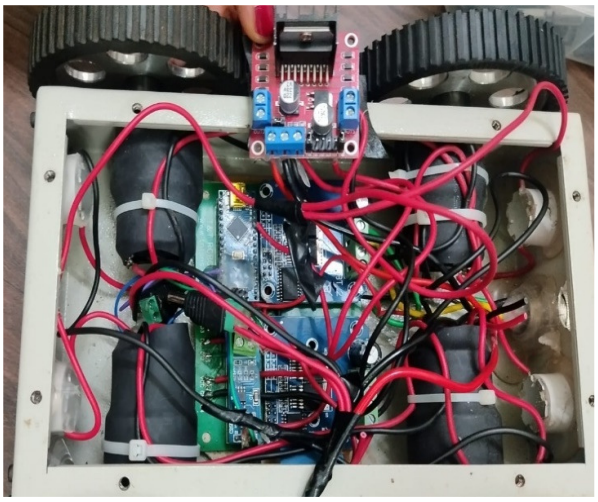

Fig.11. Internal Electrical Circuitry of the Robot

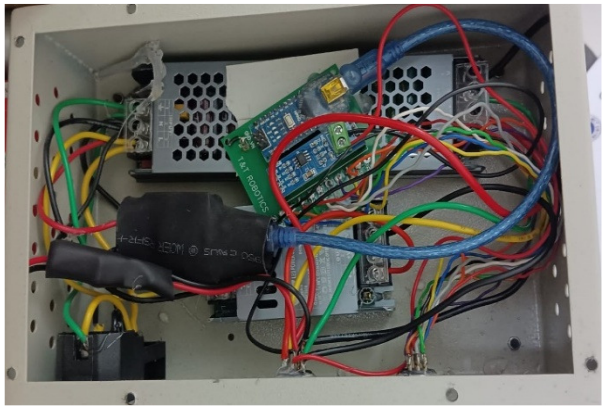

Fig.12. Internal Electrical Circuitry of the Controller

V.RESULTS AND DISCUSSION

The testing of the robotic system confirmed its foundational viability as a duct inspection platform, with results primarily focusing on mobility, camera switching, and communication stability. The Robot Unit successfully demonstrated navigation through typical duct geometries, with the 4 Motors providing adequate power for movement. The core innovation of integrating dual cameras via the Relay Module proved effective, enabling the operator to swiftly switch between forward and backward views, which is critical for maneuvering and inspection. Crucially, the RS-485 communication protocol delivered on its promise of stability over long distances, maintaining a reliable data link for the real-time video feed and control commands far exceeding the typical range of wireless alternatives in metallic duct environments.

While the Arduino Nano efficiently managed all integrated components, future iterations could benefit from optimizing the motor control for smoother transitions. Overall, the system met the primary goals of providing real-time visualization and remote control over a significant range, positioning it as a robust solution for enhancing HVAC maintenance accessibility and safety.

Aspect	HVAC Duct Monitoring and Cleaning Robot (Our Project, 2025)	Design of an Intelligent Duct Cleaning Robot with Force-Compliant Brush (2012)	Mobile Inspection Robot for HVAC Ducting Systems (2015)	WALL-E: A Robotic Duct Cleaning System (2024)
Main Objective	To design a wired robotic system that can inspect and monitor HVAC ducts without dismantling ceilings.	Developed an automatic cleaning robot that adjusts brush pressure to clean ducts efficiently.	Designed a mobile robot for duct inspection using a camera and gripper mechanism.	Built a wireless cleaning robot equipped with cameras and brushes for duct maintenance.
Communication Used	RS-485 wired communication between Arduino Nano units.	Wired communication with feedback sensors.	UDP-based wired communication using LAN cable.	RF (wireless) control and ESP32-CAM for camera feed.
Major Components	Dual cameras with relay switching, LEDs, Arduino Nano, RS-485 modules, 10-core cable, SMPS.	Force-controlled brush, ultrasonic sensor, IMU module.	Camera, LED lights, mechanical gripper, Arduino and Raspberry Pi.	ESP32-CAM, RF module, motor driver (L293D), cleaning brushes.
Power Source	230 V AC to 12 V DC SMPS, power sent through single 10-core cable.	Wired connection with internal supply.	Power through control cable (voltage drop over long distance).	Battery powered.
Operating Range	Reliable operation up to about 30 meters inside ducts.	Suitable for small duct areas.	Works for moderate distances.	Limited range due to wireless signal loss.
System Focus	Real-time visual inspection and monitoring.	Cleaning only.	Inspection and sample collection.	Cleaning and partial monitoring.
Drawbacks / Gaps	If any obstacle is detected inside the duct, the robot must be moved back, and the obstacle needs to be removed manually before proceeding.	Heavy and complicated design, expensive, no inspection ability.	Communication delay, voltage drop, limited coverage.	Wireless interference inside metal ducts, short battery life.
Improvements in Our Work	Stable wired communication, long-distance power supply, two-camera system, suitable for restricted areas, low-cost and easy maintenance.	Light, simple structure with inspection focus and stable RS-485 link.	Replaced UDP with RS-485, added SMPS for power stability.	Used wired control instead of wireless, added dual cameras and relay system.
Best Application Area	Industrial, residential, and pharmaceutical areas where wireless is restricted.	Industrial and subway ducts.	Commercial and residential ducts.	Small-scale duct cleaning.

Fig. 13. Robot Front View

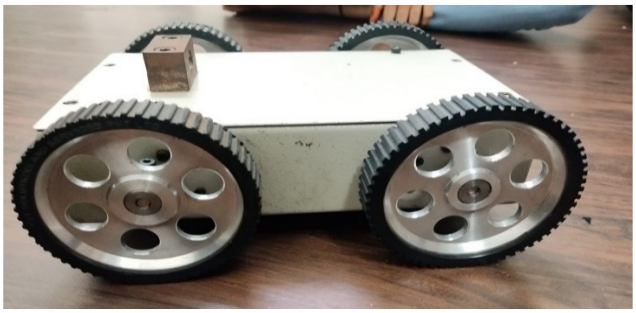

Fig. 14. Robot Side View

Fig. 15. Controller Front View

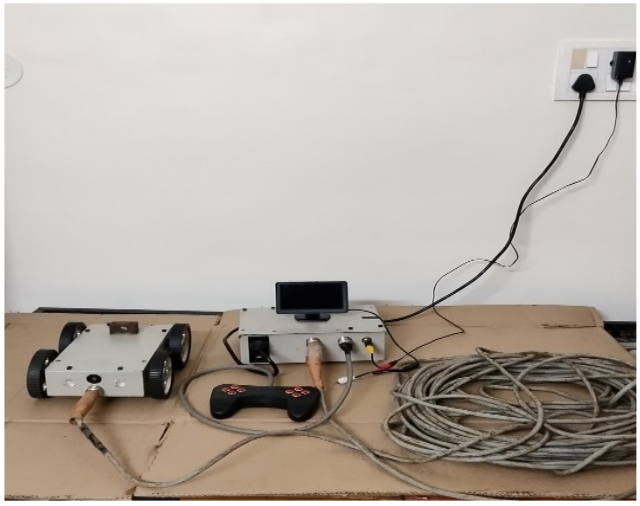

Fig. 16. Complete Project Setup

VI.CONCLUSION AND FUTURE WORK

The HVAC Duct Monitoring and Cleaning Robot has been successfully designed and developed to provide a practical, stable, and efficient solution for inspecting and maintaining HVAC ducts. The system effectively eliminates the drawbacks of previous methods that relied on wireless communication and complex mechanical cleaning mechanisms. By integrating a wired RS-485 communication network with centralized control and power delivery, the robot achieves reliable long-distance operation, consistent power performance, and real-time video monitoring, even inside metallic ducts where wireless systems typically fail. The results obtained during testing validate that the system offers stable signal transmission, clear visual feedback, and efficient power management over distances up to 30 meters. The robot's modular structure ensures ease of assembly, low maintenance requirements, and adaptability to different duct dimensions. Its use minimizes manual inspection, improves operator safety, and enhances maintenance efficiency, especially in pharmaceutical and healthcare industries where maintaining clean, sterile, and dust-free air ducts is essential for ensuring product quality and meeting regulatory standards. Overall, the proposed system demonstrates that a wired communication-based robotic monitoring solution can significantly improve duct inspection processes in terms of reliability, performance, and cost-effectiveness. It represents an important step toward safer and more hygienic HVAC maintenance practices in industrial and commercial applications.

In future developments, the robot can be upgraded with autonomous navigation capabilities using ultrasonic, infrared, or LiDAR sensors to allow self-directed movement and mapping of complex duct layouts. The incorporation of AI-based fault detection algorithms can enable automated identification of defects, cracks, or contamination within the duct system. Moreover, integrating UV-C sterilization or air purification modules could extend its function beyond monitoring to include active cleaning and disinfection.

These advancements will transform the HVAC Duct Monitoring and Cleaning Robot from a manually operated inspection device into a fully autonomous and intelligent maintenance system, promoting cleaner, safer, and energy-efficient air circulation — particularly in pharmaceutical, industrial, and healthcare HVAC environments that demand continuous hygiene monitoring and precision control.

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