Simulation-Based Design and Analysis of a Vent Cleaning Robot

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***Abstract*—Air ducts of HVAC systems require regular cleaning to provide proper air circulation and better indoor air quality. However, with the accumulation of dust and debris over time, particles form clogs and clumps inside and their efficiency reduces and poses health risks. This research proposes and develops a robot designed to reach clogs and dust clumps to break them for vacuum to be able to clean air ducts. The robot combines a lightweight body made of aluminium alloy for durability with a wheel-track based locomotion system made of polyurethane for stable movement on dusty or slippery surfaces and allows traveling vertically in vents. A rotary plastic brush effectively scrubs duct surfaces. A sensor module controls the navigation with precision and avoids obstacles. The goal of this air duct cleaning robot is to optimize HVAC performance, conserve energy, and promote cleaner indoor air. A 3D model was built using Solidworks, and Simulink simulations validated the operational dynamics.**

***Index Terms*—Air duct cleaning, HVAC systems, Autonomous robots, SolidWorks, Matlab Simulink**

I. Introduction

In the modern architecture, buildings are designed to accommodate centralized air conditioning and heating systems. Due to global warming, the demand for air conditioning and ventilation systems has increased, making their efficiency and maintenance essential. Air ducts in HVAC (Heating, Ventilation, and Air Conditioning) systems accumulate contaminants over time such as dust, debris, mold, and bacteria.[5] That disturbs the air flow and fails to maintain the desired temperature, affecting the long-term performance and efficiency.

Moreover, contamination in air ducts increases energy consumption and cause fire risks caused by debris buildup. Studies have shown that more than 75% of ventilation systems are highly contaminated, which causes to "sick building syndrome" (SBS), allergies, and respiratory diseases. Polluted air in indoor spaces has been increasing rates of asthma and related diseases. Hence, regular cleaning of air ducts is necessary. It helps with unrestricted airflow, improved energy efficiency, and better indoor air quality.

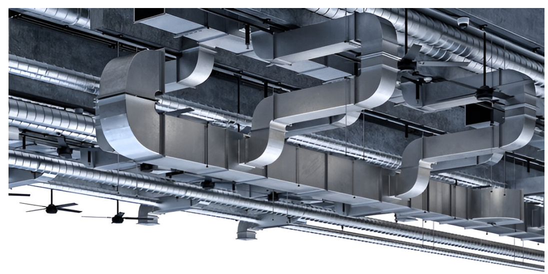

Fig. 1. Vent system of a large building
Image credit: Shutterstock (https://www.shutterstock.com/image-illustration/air-ventilation-pipes-system-hanging-ceiling-2172760893).

To overcome these challenges, vacuum mechanisms are commonly used for air duct cleaning, but there can be clogs and clumps of dust stuck inside vents. Innovating robotic systems to breakdown dust clumps and clogs for air duct cleaning appears to be more relevant. Robots, can be autonomous, semi-autonomous, or remote controlled perform tasks in hazardous or inaccessible areas. Since the 1980s, robotic tools have been used to perform duct cleaning work. Modern robotic systems reduce the labor-intensive nature of duct cleaning and also improve accuracy and efficiency. However, those robots require manual operation and have low autonomous abilities.

The overall work highlights the design, development, and functioning of an advanced air duct cleaning robot with effective cleaning ability. The robot includes automated route guidance, sensor module, and rotating brushes to support cleaning of air ducts. The proposed system is expected to improve HVAC systems, promote better indoor air quality, and reduce health and safety risks due to contaminated air ducts.

II. Literature Review

The air quality in air ducts can shift from being clean to polluted in an instant. The HVAC system plays a crucial role in filtering out harmful substances, but when it accumulates dirt and debris over time, it can become clogged affecting the airflow. That causes HVAC systems to work harder, leading to increased energy consumption and potential health risks from pollutants.

Recently, innovative duct cleaning robots have the capability to address these challenges. By removing obstructions and debris that affect airflow, air duct cleaning robots contribute to energy efficiency and system performance. Maintaining clean air ducts potentially extend the lifespan of their HVAC equipment and minimize repair and maintenance expenses up to 50

Manual air duct cleaning systems rely on direct input from operators for navigation and cleaning, which can be labor-intensive and prone to errors. In contrast, autonomous systems incorporate advanced navigation algorithms, sensors, and machine learning capabilities, enabling them to operate independently. These robots can identify obstacles, adapt to varying duct layouts, and perform thorough cleaning with minimal human intervention.

Duct cleaning robotics have emerged as innovative solutions transforming the traditional approach. Robotic solutions offer precision, efficiency, and ability to reach inaccessible areas in air ducts. The effectiveness of robotic systems often depends on their cleaning mechanism, navigation method and inspection tools. Advancing of air duct cleaning robotic systems provide a solution to the limitations and offers energy-efficient air ventilation systems.

Duct cleaning robots can be classified into several categories according to their mechanism such as locomotion type, cleaning tools, and inspection tools. For air duct cleaning, locomotion types can vary significantly based on the terrain, geometry, and application requirements. Those types are wheels, track-caterpillar, inchworm, legged, sliding, snakelike, screw drive, wall-pressing and pig-type.

TABLE I
LOCOMOTION TYPES OF VENT CLEANING ROBOTS

Type	Description
A	Wheel type
B	Track-caterpillar type
C	Inchworm type
D	Legged type
E	Sliding type
F	Snakelike type
G	Screw drive type
H	Wall-pressing type
I	Pig-type

Wheeled robots are widely used in consumer market due to the affordability and simplicity. Many of these robots utilize differential steering, using separately driven wheels for movement. By adjusting the speed of each wheel, the robot can change direction effectively. Additional non-motorized wheels are often included to provide balance and stability. Tracked robots rely on their tracks for movement, navigating rough terrain and overcoming obstacles, a challenge that wheeled robots often face. Legged robots, on the other hand, utilize

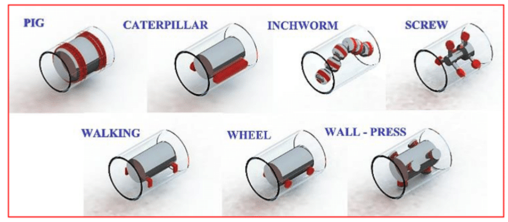

Fig. 2. Locomotion Types

mechanical limbs for mobility. Although they are similar to wheeled robots, their locomotion mechanisms are complex. Legged type robots are adaptable to irregular surfaces since they can step over obstacles but have slower speed. Wall-pressing robots use actuators to press against duct walls, maintaining stability and controlled movement especially in vertical cleaning tasks. Pig-type robot movements rely on external forces and are effective for straight ducts. Wheels are easy to implement and maintain keeping low cost, and also offers quick traversal in horizontal air ducts. Using wider wheels or adding extra support can make the robot more stable, helping it work better even on slightly uneven surfaces.

Based on the cleaning tools, there are several types of air duct cleaning robots as mentioned below.Implementing one method or a combination of multiple methods in the robot design helps to obtain a better cleaning process.

TABLE II
CLEANING MECHANISMS FOR VENT CLEANING ROBOTS

Type	Description
A	Rotary brushes
B	Air jets
C	Vacuum systems
D	UV light disinfection
E	Water jet cleaning
F	Chemical sprays
G	Vibrational cleaning

When designing air duct cleaning robots, there are different types of inspection tools that can be used. These inspection tools handle the robot navigation and identify the areas require cleaning through real time data collection and analysis.
1. High-resolution cameras
2. Thermal imaging cameras
3. Ultrasonic sensors
4. Dust particle detectors
5. Lase distance meters
6. Magnetic sensors
7. LIDAR (Light Detection and Ranging) Sensors
8. Robotic vision with AI processing
These tools detect the presence, size, and concentration of dust, debris, and other contaminants within air ducts.

III. PROBLEM STATEMENT

The traditional technique of cleaning air ducts involves manual chores or invasive procedures that are expensive, time-consuming, and troublesome for businesses. Air duct cleaning robots, which have evolved over the years, now have the capabilities to provide the required solutions timely and with precision. These robotic systems eliminate traditional methods of cleaning pipes, which were costly. Moreover, pipe cleaning robots are excellent devices developed to operate without human intervention in large and multiple duct systems during the cleaning and inspection process. The first step towards cleaning with these robots involves breaching walls designed specifically with advanced sensors that incorporate cleaning mechanisms and locomotion systems. Robots are designed in such a manner as to minimize operational disturbances in the functioning of air ducts while cleaning the dust and debris within them. The application of this cleaning machine is important for many areas, including, but not limited to, manufacturing, healthcare, and commercial properties.

IV. System Overview

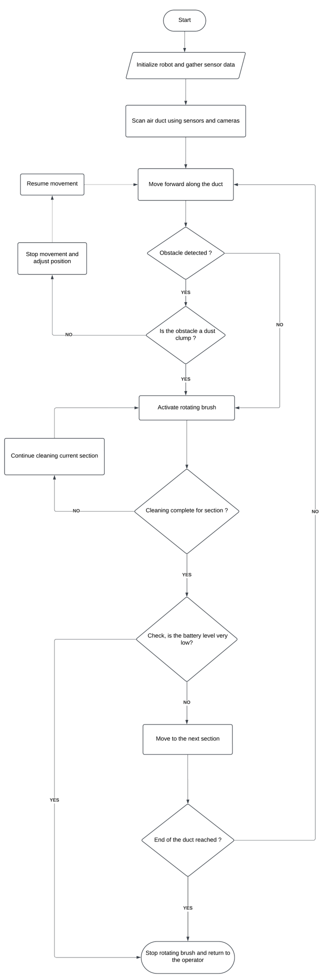

Fig. 3. Flow Chart of the process tree

The air duct cleaning robot is mainly composed of several parts: a rotating brush, a moving unit that comprises the body, magnetic wheels, and a motor, a sensor module, and a control system. First, it depends on its sensor module to detect dusty or debris-loaded (clogs and dust clumps) portions within the duct. This detection is based on variations in sensor readings or visual data from the camera system. Upon detecting dirt in the duct, the robot stops its movement and activates its brush rotation. When the robot reaches the clogs and dust clumps, the rotating brush breaks them and removes accumulated dust and debris by external vacuum system, ensuring efficient cleaning of the duct's interior. The identified area will be cleaned by the above approaches. When the cleaning process in the identified dirt spot is completed, the robot stops its cleaning procedures at the moment (rotating the brush). Thereafter, it continues to move and accelerate forward until it detects another dirty area section requiring cleaning within the air duct. This cycle is repeated until the entire air duct has been thoroughly cleaned.

V. System Design

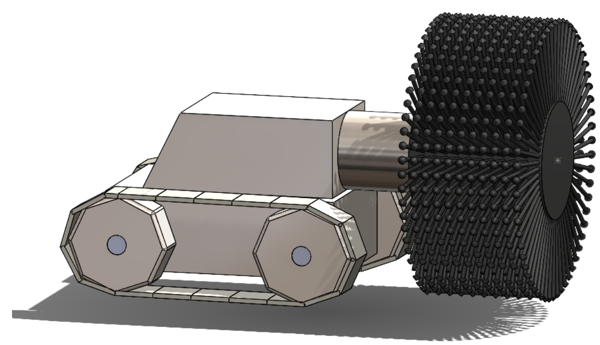

Fig. 4. Isometric view of the robot design with a chain track mechanism for enhanced mobility inside vents

SolidWorks was used to model every part of the pipe cleaning robot, ensuring exact measurements to satisfy unique cleaning specifications. The Dust Collection Unit, Rotating Brush, and Sensor Module are the three main modules that are integrated into the design. These elements were assembled into the finished design using a bottom-up assembly method. A table of the robot's components and accompanying images is included, along with illustrations of the finished robot in various operation settings.

A – Body
B – Wheels and Tracks
C – Rotating brush
D – Sensor module
E – Power Supply
F – Controller System

VI. Parts Description

A. Body

The body of the air duct cleaning robot is formed of aluminium, which is robust and lightweight, making it easier to move during cleaning operations. The body is small enough to fit through tight ducts and still include necessary parts,

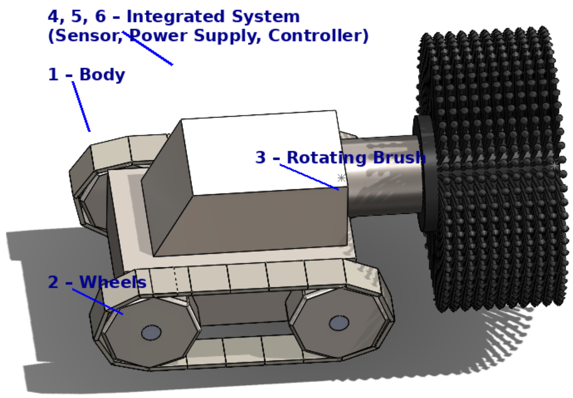

Fig. 5. Design of the robot with labeled components

comprising 200 mm in width, 300 mm in length, and 220 mm in height.

1) Benefits of aluminium: Lightweight and Strong-Aluminium profiles are light but sturdy, allowing them to resist massive weights. This minimises the weight of body, conserves energy, and lowers expenses.
Corrosion Resistance and Longevity: Anodised aluminium profiles are corrosion resistant, enabling robot to survive longer and require less maintenance, especially in challenging environments such as rain, snow, and salt.
Non conductive : Industrial aluminium profiles are insulating the robot body and preventing electrical contact with other components, hence lowering possible dangers.

B. Wheels and Tracks

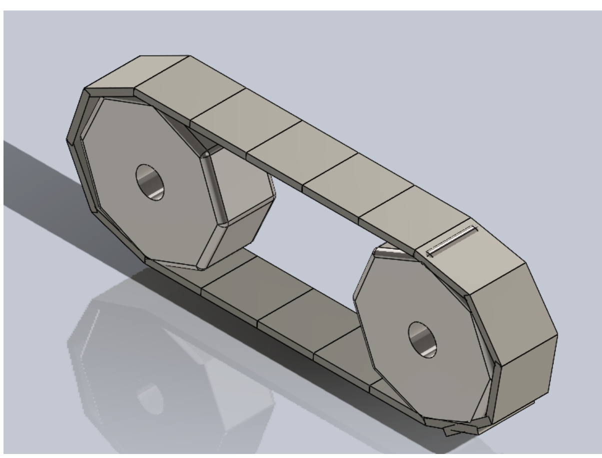

Fig. 6. Solidworks Model of the Wheels and Tracks

Given the tight, sticky and frequently dusty circumstances inside air ducts, the air duct cleaning robot's wheel design has an important effect on its flexibility and effectiveness. In addition to offering stability and mobility, the wheels guarantee that the robot may move over various duct surfaces without slipping or losing contact. The important features when selecting wheels includes,

1) Material: Polyurethane is used here. Polyurethane tracks are sturdy, flexible, and resistant to abrasion, making them suitable for air duct cleaning robots to travel vertically in vents. Their flexibility decreases noise, promotes smooth navigation, and gives a firm grip while resisting oils, greases, and cleaning chemicals.

2) Specifications and profile: The wheels have a diameter of 100 mm and are designed to be magnetic and stable within typical duct sizes.

3) Drive Mechanism: dc motor feeds two rear wheels to propel the vehicle forward.

4) Advanced grip: To minimise slippage and ensure steady contact with duct surfaces, the wheels' outer surface has a gear-like design.

C. Rotating Brush

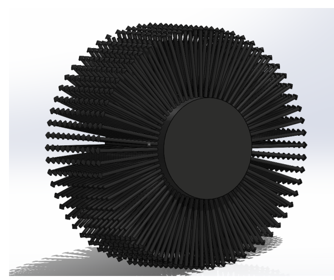

Fig. 7. Solidworks Model of The Brush

This air duct cleaning robot's revolved brush is made to effectively remove trash and clean surfaces. Plastic is used here to make synthetic bristles, which are highly effective and durable. Typically, brushes have stronger bristles for stability and thinner ones for fine dust, connected to metal or plastic wire frames.. Cleaning effectiveness is enhanced by thicker and stiffer bristles because they create stronger contact pressures and are more susceptible to deflection. The study also demonstrates that there are diminishing returns when the rotation speed is increased beyond a certain point because the bristle straightens and only bends close to the tip, preventing further increases in contact force. The robot goes within the vents to break down dust clumps and clogs to clean.

D. Sensor Module

The sensor module, which is in charge of navigation, obstacle recognition, and cleaning process monitoring, is an important component of the air duct cleaning robot. It has camera sensors to identify obstructions and air ducts, ensuring accurate alignment and movement inside the duct. The module maximises the robot's performance in various kinds of duct environments by enabling real-time feedback for adaptive control.

E. Power Supply

The air duct cleaning robot's power source can use a Battery Management System (BMS) and high-performance Li-ion battery modules to provide stable, long-lasting power. These modules, that utilise popular 18650 cells such as Sony/Murata VTC6, Samsung 30Q, and LG HG2, offer high energy density, compact size, lightweight design, and a long cycle life. This enables the robot to operate efficiently for long periods of time, powering hard tasks such as rotating brushes and dust collecting, while automatically returning to its charging station when the battery level drops, assuring uninterrupted operation.

F. Controller System

The mechanism ensures that the air duct cleaning robot runs efficiently and functions properly. The joystick controller provides precise control over the robot's four-wheel drive, allowing for very simple navigation and manoeuvrability. The control box's LCD screen displays live video footage from the attached camera, allowing operators to watch the robot's progress and record the cleaning procedure. Pneumatic brush rotation: Uses compressed air provided by a typical single-phase compressor to ensure efficient brush cleaning performance.

VII. Simulink Model and Simulation Results

A. Obstacle Detection

Fig. 8. Plot: Simulation of the Obstacle detecting Sensor

In this system, the robot is equiped with an Ultrasonic sensor that can detect the obstacles in the path upto 1 meter . The system can seperate obstacles and dust clumps using the ultrasonic sensor. In the above figure the noise is identified as the individual small dust collections and the area with over an amplitude of over 10 is taken as solid obstacles. The peaks below the amplitude of 10 are identified as clusters of dust.

B. Infrared Camera Module

To further clarify the detected obstacle is a dust clump we have used a infrared camera module. This module confirms the obstacle ahead as dust and inputs the signal for the activation of the motor of the Rotating Brush.

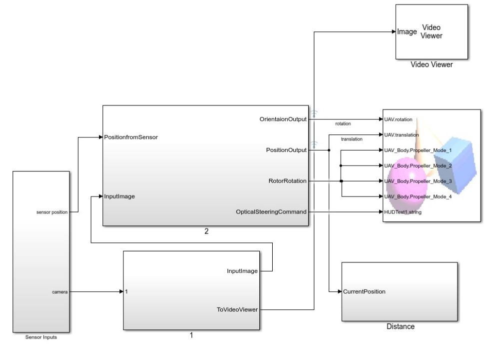

Fig. 9. Design of the Infrared Camera Module in Simulink

C. DC Motor Module

A DC motor model is designed and implemented as a subsystem within the vent cleaning robot's control system. This module simulates the behavior of the motor responsible for driving the cleaning and moving mechanism of the robot. There are 2 motor modules included in the robot for the wheels and track module and the rotating brush module.

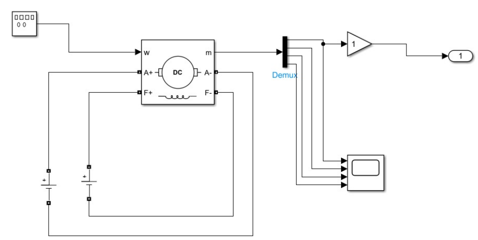

Fig. 10. Design of the DC Motor Module Module in Simulink

D. Simulink Model of the Solidworks Design

The solidwork design was imported to Simulink through Simscape for the simulation of sensors.

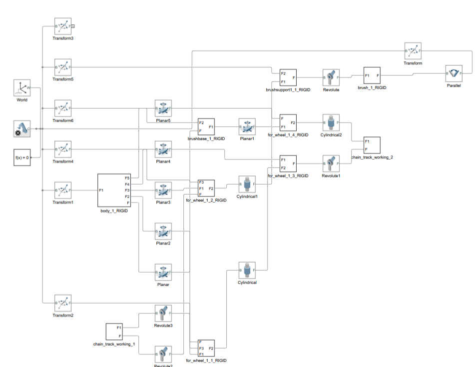

Fig. 11. Simulink Model

VIII. Conclusion

The vent cleaning robot system is designed to detect and break clusters of dust collected in vents where human can not reach. The robot has been simulated in Simulink to for the capabilities of the sensor systems. The robot demonstrates high efficiency and automation capabilities. Projected benefits includes reduction of human labor, better ventilation system that would lead to healthier living environments. Future improvements include autonomous vacuum system, system that monitors the quality of the air and a higher capacity power supply.

IX. Individual Contribution

Author Contributions

- **Samarawickrama K.N.(220559R):** Abstract, Introduction and Literature review
- **Sampavi(220561P):** System design and parts description
- **Sandaru U.A.C.(220566K):** 3D Modelling in Solidworks and importing to Simulink, Matlab code for UltraSonic sensor
- **Sandeepa H.W.P. (220569X):** Designing the robot and 3D model designing of the robot in SolidWorks, Designing the camera module in Simulink, and writing the MATLAB code for the camera module
- **Sanujan K. (220581C):** Designing flowchart for system overview

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