Design and Performance Optimization of Rectangular Air Duct Cleaning Robot

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Abstract. The widespread adoption of central air conditioning systems has made pipe cleaning a key component in maintaining indoor air quality. However, traditional cleaning robots face numerous challenges that hinder their large-scale deployment. In this study, we designed a rectangular pipe cleaning robot and significantly improved its cleaning efficiency and adaptability by optimizing its motion mechanism, cleaning system, and control strategy. By applying the technical conflict analysis based on TRIZ theory, we abandoned the traditional driving method and adopted a semi-track motion system, ensuring excellent mobility performance. The cleaning system utilized an innovative self-suction technology, eliminating the space limitations associated with external vacuum devices and enhancing the robot's flexibility and cleaning effectiveness in narrow pipes. Additionally, the control system employed a fuzzy PID control strategy, ensuring stability and high efficiency in complex pipe environments. Simulation analysis demonstrated that this design scheme has made significant improvements compared to existing technologies, providing a solid theoretical foundation and technical support for the further development and wide application of related cleaning technologies.

Keywords: air duct; cleaning robot; optimization; PID.

1. Introduction

With the rapid acceleration of urbanization, the frequency of central air conditioning system usage has steadily in-creased. Prolonged operation of these systems leads to the accumulation of various harmful substances within ventilation ducts, posing significant challenges to indoor air quality [1-3]. Currently, robotic systems have emerged as an effective alternative to manual cleaning of central air conditioning ducts. However, the cleaning efficiency of these robots is often constrained by their locomotion methods and cleaning mechanisms.

Presently, central air conditioning cleaning robots are primarily divided into two main components: mechanical structures and control systems [4]. Developed countries, having adopted central air conditioning systems earlier, have advanced research in duct cleaning robotics. For instance, Denmark’s Danduct robot employs a wheeled locomotion system with four-wheel drive, facilitating swift forward and backward movements and steering. Despite these advantages, it suffers from limited passability and stability. Its cleaning mechanism relies on motor-driven front brushes to directly scrub the interior of ducts. Similarly, South Korea’s Hanlin robot, Canada’s Airtox robot, and the United States’ Nikro robot utilize comparable locomotion and cleaning mechanisms. Although these systems are relatively mature, they exhibit numerous issues that significantly impair cleaning efficiency [5,6]. In this study, we design a rectangular duct cleaning robot that synthesizes the strengths and addresses the weaknesses of existing models. By optimizing conventional locomotion methods and cleaning mechanisms, and incorporating a fuzzy PID controller for automated control, the proposed robot achieves enhanced mobility and adaptability within ducts of varying dimensions and operational environments. This innovative design not only improves cleaning performance but also provides a robust theoretical foundation and technical support for the further development and widespread adoption of advanced duct cleaning technologies.

2. Structural design

2.1 Design of the Overall Dimensions.

During internal cleaning operations within ducts, the robot undergoes three primary motion states: linear traversal, turning, and ascending or descending slopes [7]. The designed robot must proficiently execute all fundamental movements to ensure effective cleaning performance. The construction methods, material selection, and dimensional specifications for rectangular ventilation ducts adhere to stringent standards, with common standardized dimensions outlined in Table 1 [8]. Specifically, the general specifications for central air conditioning ventilation ducts must comply with the re-quirements presented in the table. Additionally, the ratio of the longer side to the shorter side (i.e., height) must not exceed 4:1. Consequently, this study establishes the dimensions of central air conditioning ventilation ducts with a minimum long side of 400 mm and a minimum short side of 360 mm. These dimensions ensure that the robot is compatible with the vast majority of duct sizes while preventing maneuvering difficulties in bends that could arise from excessively large robot dimensions. This design consideration enhances the robot's adaptability and operational efficiency across diverse duct environments.

Table 1. Ventilation Duct Specification Dimensions [8]

Ventilation Duct Side Lengths (mm)				
120	320	800	2000	4000
160	400	1000	2500	—
200	500	1250	3000	—
250	630	1600	3500	—

2.2 Design of the Locomotion Mechanism.

The locomotion method fundamentally influences a robot’s ability to traverse ventilation ducts and maintain overall stability during the cleaning process. Predominantly, duct cleaning robots employ either wheeled or tracked locomotion systems. Tracked systems offer significant advantages, including high load-bearing capacity, robust adaptability, and low ground pressure. However, extended tracks can lead to increased noise levels and diminished maneuverability. Conversely, wheeled systems provide rapid movement, agile steering, and enhanced operational efficiency but are often constrained by poorer passability and stability [9-11]. Passability is a crucial performance metric for duct cleaning robots, necessitating effective navigation through ducts while maintaining the flexibility to address a variety of complex scenarios. Additionally, it is imperative to minimize the mass of the locomotion mechanism to avoid an excessive increase in the robot’s overall weight. Balancing these factors is essential to ensure that the robot can perform efficiently and reliably in diverse duct environments.

A technical contradiction analysis based on TRIZ theory identifies a pivotal conflict: on one hand, there is a necessity to enhance the robot’s passability and flexibility to effectively navigate complex duct environments; on the other hand, augmenting passability and flexibility typically results in increased complexity and weight of the locomotion mechanism, which directly contradicts the objective of reducing the robot’s overall mass. To resolve this contradiction, a semi-tracked locomotion system was adopted. The semi-tracked configuration successfully maintains high levels of passability and flexibility while effectively controlling the weight and complexity of the locomotion mechanism, thereby achieving a balanced solution that meets multiple performance requirements [12].

The tracked scheme consists of two parts: the front wheeled mechanism and the rear tracked chassis. Carry out the corresponding structural design to the crawler chassis, because the inverted trapezoidal crawler performs well in the aspect of walking speed, passing performance and stability, therefore, the designed crawler chassis selects the metal inverted trapezoidal track, and the track chain link is shown in Fig. 1.

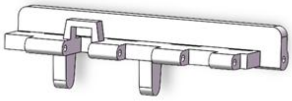


Fig. 1. The selected track links

Track pitch:

$$t_0 = (4 \sim 7.5)\sqrt[4]{M} \tag{1}$$

where t_0 is the track pitch and M is the overall weight.

Since the ratio of the track grounding length L to the track gauge B has a great impact on the steering and stability of the robot, and the L/B is usually between 1.2~1.5 [13], it is determined that the track gauge B between the two tracks is 180mm, and the ground length L is calculated to be between 120~150mm, and the grounding length is 125mm.

Track width b refers to the formula:

$$b = (0.9 \sim 1.1)\text{髟}209\ \ \sqrt[2]{G \quad 10^{-2}} \tag{2}$$

The current robot weighs approximately 15kg, so we set the weight of the designed robot to be 15kg. After calculation, we finally selected a single-sided track width of 44mm. The ground pressure exerted by the track is an important factor in determining the through ability of the designed robot in the ventilation pipe, and is a crucial link in the track design [14]. The formula for calculating the ground pressure is as follows:

$$P = \frac{Mg}{2Lb} \tag{3}$$

where M is the overall dead weight, g is the acceleration of gravity, P is the specific ground pressure,L is the grounding length of the track, and b is the track width.

The design parameters of the robot tracked base are as follows in Table 2.

Table 2. Design parameters

Project	t_0	b	L	P
Setting	8mm	44mm	125mm	0.3MPa

The track chassis is mainly responsible for providing the driving force of the robot, while the wheeled mechanism is responsible for controlling the main direction of movement of the robot, which plays a crucial role in the flexibility of the robot. Fig. 2 shows the design of the wheel mechanism. At the P position, a PWM steering machine is designed to provide the necessary steering force for the steering mechanism through the excellent motion characteristics of the steering machine. Fig. 3 shows the model diagram of the steering mechanism.

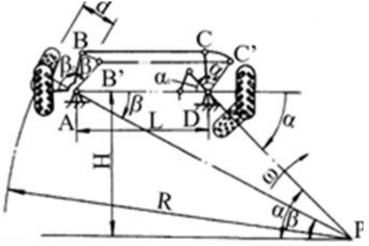


Fig. 2. Wheeled mechanism design scheme

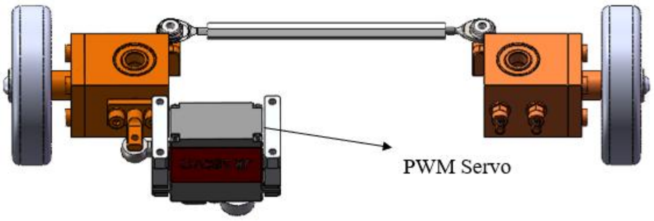


Fig. 3. Steering mechanism model diagram

2.3 Cleaning mechanism design.

The function of the cleaning mechanism includes two parts: dust cleaning and vacuuming. At present, the common central air conditioning duct cleaning robot usually uses the way of cleaning brush dust for dust cleaning, which has a more significant effect and has become the mainstream choice. The robot designed in this research institute also adopts this dust cleaning method. However, the traditional central air conditioning air duct cleaning robot usually needs to be connected separately to the negative pressure fan for vacuuming, which has several disadvantages. The additional negative pressure fan and its connecting pipes increase the structural complexity of the robot. At the same time, the separately connected negative pressure fan limits the robot's range of activity and flexibility, takes up valuable space, and is restricted to move and operate in narrow pipes, reducing the robot's ability to adapt in complex environments. Therefore, it is particularly urgent to design a self-vacuuming mechanism. In this study, a robot self-vacuuming mechanism using vacuum vacuuming scheme is proposed, and the specific principle is shown in Fig. 4. The mechanism is mainly composed of four components, including the negative pressure fan. The suction force is provided by the negative pressure fan, and the dust particles are sucked into the dust collection chamber under the negative pressure fan by rotating with the rolling brush at the dust suction port at a high speed.

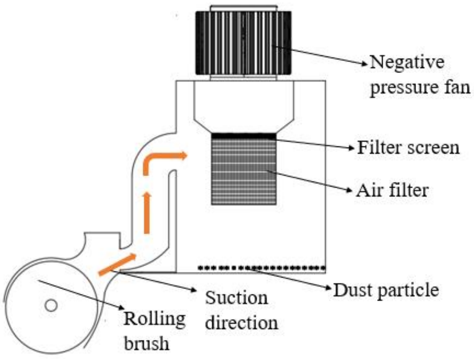


Fig. 4. Schematic diagram of self-vacuuming mechanism

3. Kinematic Simulation

The theoretical driving speed of the robot is slightly different from the actual situation. In order to explore the motion characteristics of the robot, the relevant dynamics simulation of the linear driving process of the robot is carried out. A track-drive wheel model is established. In actual operation, the track and drive wheel teeth mesh together, and the overall force is complicated. In order to carry out the simulation experiment smoothly, Hertz contact theory is adopted for analysis [15], namely:

$$F = K d^{e} + C(d)\dot{d} \tag{5}$$

where F is the normal contact force, K is the Hertz contact stiffness, δ is the normal penetration distance of the contact point, C is the damping coefficient, and e is the force deformation index.

The influence of dust on the damping coefficient and friction coefficient of stainless steel surface should be considered in kinematic analysis. Due to the large density of dust, the damping coefficient and friction coefficient will increase. According to the calculation of the speed of the drive motor, the angular speed of the drive wheel in stable operation is 6.28rad/s. When the robot moves in a straight line in the ventilation duct, its driving wheel rotates at a constant angular speed of 6.28rad/s, and the theoretical calculated speed vw=0.192m/s when the movement is stable. The robot model was imported into Adams for dynamic simulation, and the simulation analysis results were shown in Fig. 5.

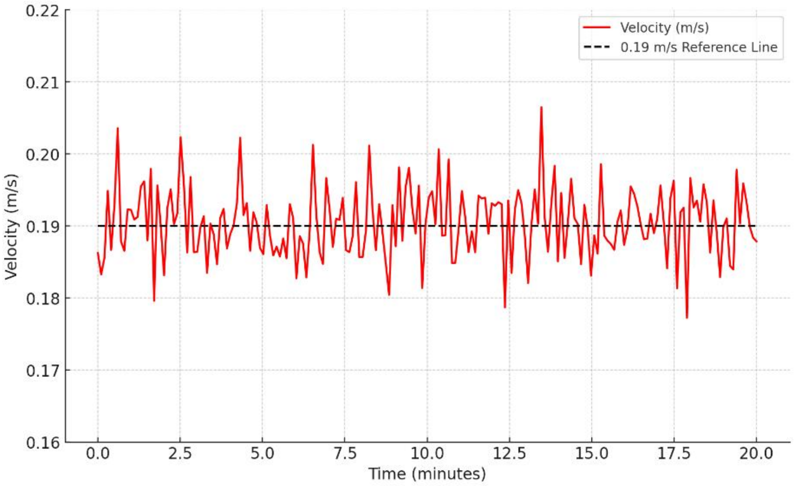


Fig. 5. Curve when the robot travels in a straight line

According to the simulation results, the robot travels in a straight line on a dusty stainless steel plane at a speed of about 0.19m/s. Compared with the theoretical calculation results, the error is as follows:

$$D = \frac{v - v_W}{v_W} = \left|\frac{0.19 - 0.192}{0.192}\right| = 1.04\% \tag{6}$$

The calculated error is only 1.04%. The main reason for the error is that the friction between the track and the air duct and the skid between the track and the driving wheel are not considered in the theoretical calculation. At the same time, the analysis of Figure 8 shows that the robot speed fluctuates between 0.17m/s and 0.21m/s, and the stable speed is about 0.19m/s. Most points are distributed in the range of 0.18m/s to 0.20m/s, and the average value is about ≈0.19m/s. The fluctuation range of the speed is about 0.01m/s above and below the mean value, and the standard deviation ≈0.01m/s. The coefficient of variation CV is calculated by (7), and the coefficient of variation CV is about 0.05, which is relatively small, indicating that the speed fluctuates relatively low and the speed is relatively stable during this period.

$$CV = \frac{SD}{\left|\overline{v}\right|} = \frac{0.01}{0.19} \approx 0.05 \tag{7}$$

4. Robot Control Scheme Design

4.1 Control Strategy

The control system of a robot is an important factor affecting its cleaning ability, and a reasonable control scheme can significantly reduce the difficulty of operation and improve the cleaning efficiency. The robot walking mechanism is driven by a permanent magnet brushless DC motor. By changing the PWM trigger signal duty cycle of the inverter power device, the voltage is adjusted to realize the speed regulation of the brushless DC motor. Traditional control theory is difficult to achieve satisfactory control for highly nonlinear, time-varying or uncertain complex systems. Therefore, the designed robot control system adopts the fuzzy control method to control by simulating the fuzzy thinking mode of human beings, so as to realize the effective management and adjustment of the control object [16,17]. The principle of the basic fuzzy control method is shown in Fig. 6.

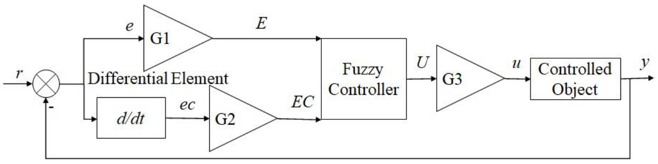


Fig. 6. Schematic diagram of basic fuzzy control method

4.2 Control System

In order to improve the motion performance of the robot and realize the operation of fast start, braking, load snap and dynamic rapid drop, a three-ring control structure is adopted, namely the current ring, the speed ring and the position ring. The speed adjustment of the designed robot adopts the general PID algorithm, and the three parameters of ratio (P), integral (I) and differential (D) can quickly respond to errors, eliminate steady-state errors and improve dynamic performance, with good stability and anti-interference ability [18]. The overall structure of the control system is shown in Fig. 7.

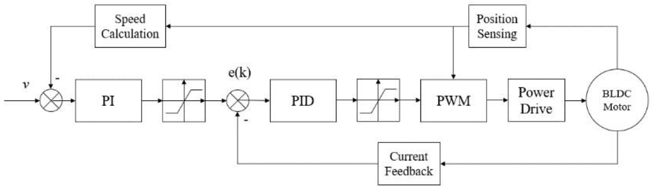


Fig.7. Block diagram of control principle

4.3 Matlab Simulation

The optimal control strategy is to adopt PD control in the rising time stage and PI control in the stable stage of the system. Based on this idea, a fuzzy PID control scheme which can adjust the scale factor, integral factor and differential factor in real time is selected in this study. The scheme adopts Mandri fuzzy model, in which the fuzzy process is based on two input signals, error and error rate of change. The simulation principle diagram is shown in Fig. 8. The traditional PID controller and the fuzzy PID controller were simulated respectively, and the step response curves of the two different algorithms were obtained, as shown in Fig. 9. The simulation results show that the fuzzy PID controller can effectively eliminate the static error, and the system has no overshoot in the steady state [19]. Because of the cooperative work of differentiation and integration, the output oscillation is effectively suppressed when the system approaches steady state. This control strategy provides excel-lent control for the brushless DC motor with strong nonlinear, ensures the stability and flexibility of the robot walking mechanism, and significantly improves the cleaning efficiency of the robot.

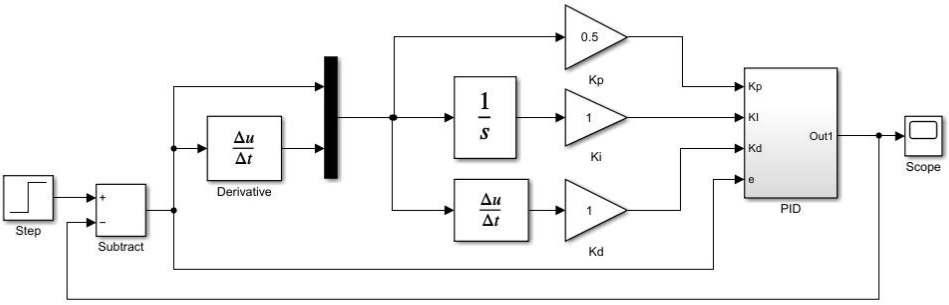
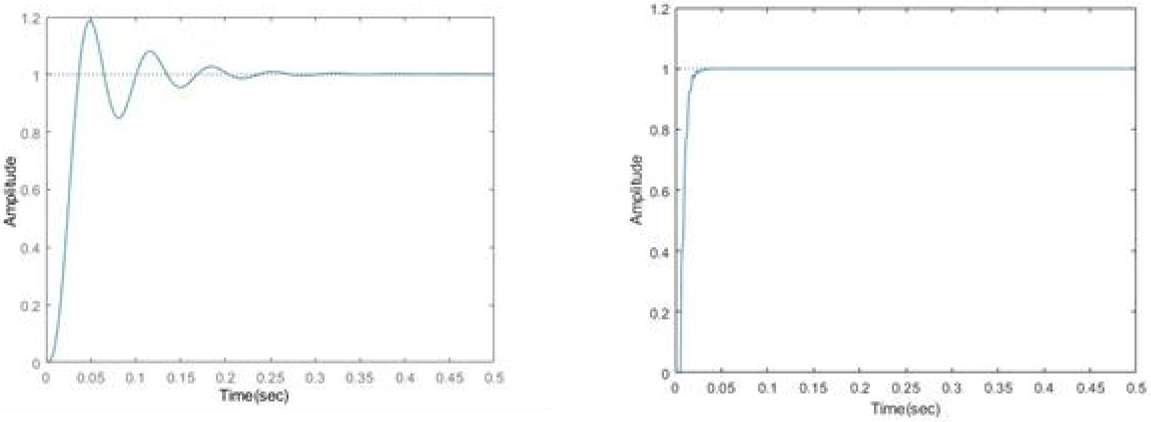


Fig. 8. Schematic diagram of simulation



(a) (b)

Fig. 9. Step response curve. (a) conventional PID and (b) fuzzy PID

5. Summary

This paper presents the design of a rectangular air duct cleaning robot that significantly improves the efficiency and adaptability of HVAC duct cleaning through optimization of its locomotion mechanism, cleaning system, and control strategy. The robot adopts a semi-tracked locomotion mechanism, which offers both excellent maneuverability and flexibility, effectively overcoming the limitations of traditional wheeled and fully-tracked systems. In terms of the cleaning system, an innovative self-suction technology is introduced to eliminate the spatial constraints of external vacuum devices, thereby enhancing the robot’s flexibility and cleaning efficiency in narrow ducts. Moreover, a fuzzy PID control strategy is employed to ensure stable operation and effective cleaning performance in complex duct environments. In the future, integrating intelligent algorithms and sensing technologies is expected to further enhance the robot's autonomy and intelligence, promoting broader application of this technology in real-world scenarios.

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