Design and research on the adsorption system for self-regulating unmanned cleaning aircraft

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Abstract. Cleaning robot is one of the main research directions in the field of glass curtain wall cleaning at present. It has important theoretical research significance and practical application value in high altitude work tasks such as glass curtain wall cleaning and crack detection. At present, cleaning robots are prone to reduce their working stability due to the dynamic uncertainty of the high-altitude wind field environment, and even fall from the sky in serious cases, which greatly affects the safety of high-altitude operation. Therefore, an adsorption system applied to unmanned cleaning aircraft is proposed in this paper. The system has two advantages: (1) through the adjustment of the center controller, the system can be detected in dynamic environment according to the parameters change, the influence of adsorption force to adjust output parameters, the corresponding mechanism, control the automatic adjusting system surface adsorption, are keeping their reasonable adsorption range, thus ensuring the system stability; (2) When the adsorption force adjustment parameter exceeds the adjustment threshold, the system will automatically start the motor to make the rotor work and prevent the cleaning equipment from falling, so as to improve the safety performance of the system.

1. Introduction

In recent years, with the continuous development of urban economy, the number of high-rise buildings has gradually increased. Since the 1980s, glass curtain wall has been widely used in the exterior decoration of high-rise buildings such as shopping malls and office buildings because of its advantages of light material quality and good lighting effect. However, the curtain wall glass is stained with dust due to long-term exposure to the environment, which greatly affects the aesthetics of high-rise buildings. At the same time, it is easy to burst due to aging or dislocation and deformation of the stress structure, which leads to a series of safety accidents. Therefore, in order to improve the aesthetics of glass curtain wall and reduce the safety risks caused by curtain wall glass, a series of urgent problems have emerged in the field of glass curtain wall cleaning, including glass curtain wall cleaning, glass crack detection, etc. [1]-[3]. At present, because manual operation can ensure the cleanliness and detection accuracy of glass curtain wall, the cleaning, inspection and maintenance work in the field of glass curtain wall cleaning is mainly completed by traditional manual work. However, as manual operation relies on safety rope, auxiliary rope and winch system (as shown in Figure 1), and the operation height usually varies from tens of meters to hundreds of meters, resulting in frequent aerial operation accidents in recent years, the cleaning efficiency of this operation method is low and the risk is high. At the same time, manual work has a high demand on employees, so labor shortage is also a critical social problem.
In order to improve the operation status of high-altitude glass curtain wall, many relevant studies have been carried out [4]. For example, a built-in-guide type building maintenance robot system using additional module is proposed such as guidance mullion to the facade. In specific, this paper proposes robotic building façade cleaning system which is directly subjected to minimize human labor; that improves the process efficiency and economic feasibility. The sensor for detecting contamination of building’s outer-wall glass is proposed; Kalman filter was used for estimating robots’ status with the contamination of the window glass. Through the simulations, an effective way of task execution is introduced and the feasibility was verified with the proposed sensor based motion control algorithm [5]. In [6], the small window climbing robot with pneumatic suction cups mentioned can automatically perform and complete the task of window cleaning in a predefined mode.

It is well known that the complex wind environment in high altitude has the characteristics of time-varying and nonlinear. As a result, there will be unpredictable risks when working at high altitude. Especially for the cleaning robot working on the high glass curtain wall, it will be difficult to ensure the stability of the system. For the adsorption of glass curtain wall, vacuum sucker is usually selected as the adsorption tool [7]-[9]. Although the interference of the environment on the cleaning robot can be effectively reduced by unilaterally enhancing the adsorption force between the vacuum sucker and the wall surface, when the adsorption force is too large, the mobility of the cleaning robot will be reduced, thus reducing the working efficiency of the system. In order to improve the stability, safety and working efficiency of the system, an adsorption system which can dynamically adjust with the environmental disturbance is proposed and applied to the rotary-wing unmanned cleaning aircraft. Since the high altitude operation efficiency of the UAV is closely related to the stability of the system, it is of great significance to design and study the adsorption system in the uncertain high altitude environment.

2. Structure and overall structure of the unmanned cleaning aircraft

2.1. Mechanical structure of the unmanned cleaning aircraft
CATIA software is used to conduct 3D modeling of the unmanned cleaning aircraft, as shown in Figure 2.

![3D model of unmanned cleaning aircraft](image)

Figure 2. 3D model of unmanned cleaning aircraft
2.2. Overall architecture of the unmanned cleaning aircraft

The overall design of the unmanned cleaning aircraft is divided into five modules, including monitoring module, control module, cleaning module, driving module and adsorption module. The specific architecture is shown in Figure 3.

The monitoring module mainly includes environmental wind monitor, image collector, etc., in which the environmental wind monitor is mainly used for data collection of high-altitude wind and wind direction, and the image collector will send the collected working picture to the database, so that users can view the working condition of the unmanned clean aircraft. The control module is composed of a central controller and a database, which plays a key role in the unmanned cleaning aircraft. Before the system starts to work, the user inputs the cleaning path information into the database. After the analysis and processing of the database, the central controller controls the start and work of other modules respectively. The cleaning module includes client signal input, booster pump, rotating brush, detergent nozzle and water purification nozzle, which can complete the cleaning task under the control of the central controller. The drive module has wall movement function and safety protection function. The adsorption module can complete the adsorption between the unmanned cleaning aircraft and the working wall under the control of the central controller. This article will introduce the adsorption module in detail.

3. Adsorption module discussion and theoretical modeling

3.1. Working principle of adsorption module

Adsorption module is one of the core modules to make the system work stably, and its working principle is shown in Figure 4. When the system enters the normal working state, the suction monitoring sensor can feed back the suction information in the vacuum sucker to the central controller, and then the central controller can judge the current suction state of the vacuum sucker and issue control instructions to the corresponding adsorption unit. The specific steps are as follows:

Step 1: Before the system starts to work, the user needs to input the adsorption adjustment margin into the database, and the system will adjust the adsorption capacity of the adsorption module according to the margin. If the margin value is too small, the adsorption module will be in the real-time adjustment state and too sensitive, resulting in the static stability of the system, thus affecting the work efficiency; on the contrary, the system is too slow to adjust the adsorption module, which will reduce the safety performance of the system. Therefore, according to the condition of the glass curtain wall that needs to be cleaned and the working environment, it is very important to adjust the appropriate adsorption adjustment margin.

Step 2: When the system starts to work normally, the suction monitoring sensor will feed back the suction information in the corresponding vacuum sucker to the central controller, and then the central controller will compare with the adsorption adjustment margin input by the user. If it is judged that the suction of the vacuum sucker is within the set range, no control command will be issued. Otherwise you will proceed to step 3.

Step 3: First, the central controller judges whether the suction value is too large. If so, it will issue instructions to control the pressure relief of the vacuum pump. Otherwise, judge whether the current
suction has disappeared. When the central controller judges that the suction value is too small instead of disappearing, it will issue an instruction to open and pressurize the vacuum pump; Otherwise go to Step 4;

Step 4: If the system judges that the suction has disappeared and the suction provided by all the vacuum suckers is insufficient to maintain the adsorption of the unmanned cleaning aircraft, the central controller will start the rotor and stop the operation of the cleaning module; Otherwise, it indicates that the vacuum sucker fails, and the vacuum safety valve is directly controlled to stop the vacuum sucker from working.

![Flow chart of adsorption module](image)

**Figure 4. Flow chart of adsorption module**

### 3.2. Theoretical modeling of adsorption states

The adsorption state of the unmanned cleaning vehicle on the vertical wall is shown in Figure 5, which shows the distribution of the upper force of the unmanned cleaning vehicle under the action of vacuum suction cup adsorption.

![Distribution of forces during operation of unmanned cleaning aircraft](image)

**Figure 5. Distribution of forces during operation of unmanned cleaning aircraft**

In the normal working state (no overturning), the stress condition of the whole system shall meet the following conditions:

\[
\sum F_x = 0, \quad \therefore Q_1 + Q_2 = F_N \tag{1}
\]

\[
\sum F_y = 0, \quad \therefore Q + f = G \tag{2}
\]

\[
\sum M = 0, \quad \therefore Q \cdot x_1 + Q_1 \cdot h_1 = G \cdot x_1 + Q_2 \cdot h_2 \tag{3}
\]

Where, Equation (3) is a necessary and sufficient condition to prevent the system from overturning. Wall friction is considered in the following two cases:
when the sliding critical condition is not reached.

\[ f = \begin{cases} G & \text{when the sliding critical condition is not reached} \\ \mu \cdot F_N & \text{when the capsizing condition has not been met and is about to skid} \end{cases} \]

Where, the parameter is the equivalent friction coefficient between the wall surface and the vacuum chuck.

4. Exploring the adjustment margin of adsorption force

As mentioned above, the adjustment margin of adsorption force is an important parameter of the adsorption module. Therefore, it is very important to explore the influence of the adjustment margin of adsorption force on the adjustment of adsorption force of the system when the external environment interferes with the system. Here, we define in detail the said adsorption force regulation margin. Suppose that the lower limit of the adsorption force required by the system without overturning at some point is \( Q_{\text{down}} \). At the same time, in order to maintain the flexibility of system movement, the upper limit of adsorption force required is set as \( Q_{\text{up}} \), then the adjustment margin of adsorption force \( V \) must meet

\[ V = \left[ V_{\text{down}}, V_{\text{up}} \right] = \left[ Q_{\text{down}}, Q_{\text{up}} \right]. \]

The material of vacuum sucker is rubber. According to literature [10], the equivalent friction coefficient \( \mu \) between vacuum sucker and curtain wall glass is set as 0.48. According to [11], \( Q_{\text{down}} = 2.2G \) and \( Q_{\text{up}} = 3.2G \) are set here, and the variation range of external interference \( Q \) is assumed to be \(-0.5G \sim 0.5G\). Then, combined with the static model in Section 3, the adsorption force adjustment overflow rate \( \lambda \) is calculated, and its calculation formula is as follows:

\[ \lambda = \begin{cases} \frac{R - V_{\text{up}}}{Q_{\text{up}} - Q_{\text{down}}} \times 100\% & \text{(I)} \\ \frac{V_{\text{down}} - R}{Q_{\text{up}} - Q_{\text{down}}} \times 100\% & \text{(II)} \end{cases} \]

Wherein, the holding condition of Equation (I) is that the adsorption force \( R \) required for system equilibrium is greater than the upper limit \( V_{\text{up}} \) of the adjustment margin of adsorption force \( V \) when the interference force exists. And (II) the establishment of the condition that exists when interference force and the adsorption force \( R \) is less than the adsorption force required for balance of the system and the adjustment allowance \( V \) the lower limit value of \( V_{\text{down}} \), in particular, if \( R < Q_{\text{down}} = 2.2G \) directly to \( R = 2.2G \) (due to the system to provide the minimum adsorption force for \( Q_{\text{down}} \), if in the presence of disturbance force makes \( R < Q_{\text{down}} \), then system adsorption force is enough to make the system maintain good adsorption state without falling).

After calculation, we obtained the influence of external interference force within a certain range on the adjustment margin \( V \) of different adsorption force of the system, as shown in Figure 6.
5. Conclusions

In this paper, a self-regulating adsorption system is proposed. Compared with the existing impedance control methods, the system is not only simple to implement, but also strong robust to the disturbance caused by external factors such as wind field environment change. By exploring the influence of external interference force on the adjustment margin of different adsorption force in a certain range, we conclude that when the adjustment time of the system reaches the requirement, the adjustment margin of adsorption force should be increased as much as possible to make the system stable performance better.

References

[1] Choi, Young-Ho, et al. "SMART WINDORO V1.0: Smart window cleaning robot." 2012 9th International Conference on Ubiquitous Robots and Ambient Intelligence (URAI). IEEE, 2012.
[2] Mir-Nasiri, Nazim, Hudyjaya Siswoyo, and Md Hazrat Ali. "Portable autonomous window cleaning robot." Procedia computer science 133 (2018): 197-204.
[3] Kouzehgar, Maryam, et al. "Self-reconfigurable façade-cleaning robot equipped with deep-learning-based crack detection based on convolutional neural networks." Automation in Construction 108 (2019): 102959.
[4] TOCUȚ, Dănuț Pavel. "Design of Cleaning Robot System to External Glass Walls of Buildings." Fascicle of Management and Technological Engineering 1 (2013): 423-426.
[5] Kim, D. H., et al. "Proposal of built-in-guide-rail type building façade cleaning robot and its motion planning algorithm." IEEE International Conference on Automation Science & Engineering IEEE, 2012.
[6] Mn, A., B. Hsj, and A. Mha. "Portable Autonomous Window Cleaning Robot." Procedia Computer Science 133(2018):197-204.
[7] Vega-Heredia, M., et al. "Design and modelling of a modular window cleaning robot." Automation in Construction 103 JUL.(2019):268-278.
[8] Liu, J., et al. "Analytical modelling of suction cups used for window-cleaning robots." Vacuum 80.6(2006):593-598.
[9] Wang, K., et al. "Suction force of vibrating suction method based on pi theorem: Analysis and experiment." Vacuum 86.12(2012):1783-1788.
[10] Bani-Hani, Ehab Hussein, Jessica Lopez, and Girish Mohanan. "Data on the coefficient of static friction between surfaces coated with different sizes of rubber granules produced from used tires." Data in brief 22 (2019): 940-945.
[11] Ren Zhiqi. Design and Research of Negative Pressure Adsorption Walling Robot. MS Thesis. North China Electric Power University, 2018.