Effective Pneumatic Scheme and Control Strategy of a Climbing Robot for Class Wall Cleaning on High-rise Buildings

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1. Introduction

Climbing robots are useful devices that can be adopted in a variety of applications such as reliable non-destructive evaluation (NDE) and diagnosis in some hazardous environments, welding and manipulation in the construction industry especially of metallic structures, cleaning and maintenance of high-rise buildings.

In our group, a new kind of pneumatic climbing robots is presented to meet the requirements of glass-wall cleaning for high-rise buildings, which is totally actuated by pneumatic cylinders and attached to the glass wall with vacuum suckers. This project is based on the cooperation between ***Tams group*** at ***Uni-Hamburg*** and ***Arms group*** at ***Beijing University of Aeronautics and Astronautics***.

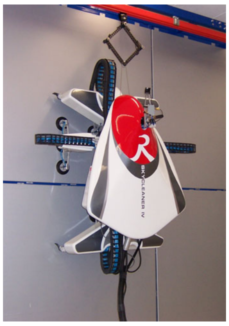

Figure 1: Sky Cleaner Robot

The robot features 14 suction pads which can carry a payload of approximately 60 kg including the body weight. Two cross-connected rodless cylinders which are named X and Y, compose the main body of the robot. A turning waist joint actuated by a pendulum cylinder connects the X and Y cylinders. The waist joint is used for the correction of inclination during the robot's movement. For a turning action, the position-pin cylinder is aired to release the locking pin, so that turning motions can be actuated by the waist pendulum cylinder. At present the robot rotates to a relatively small degree (2°) per step. At the ends of the X and Y cylinders are four connected short-stroke foot cylinders named Z, whose function is to lift or lower the vacuum suckers in the Z direction and support the body on the wall. In order to move from one column of glasses to another in the right-left direction, a specially designed ankle joint gives a passive turning motion to the suckers.

2. Characteristics of pneumatic system

There are two reasons for designing fully pneumatic cleaning robots. Firstly, the climbing robot can be made lightweight and dexterous using the pneumatic actuators. Secondly, the movement driven by pneumatic actuators has the characteristic of passive compliance due to the compressibility of the air, thus makes the robot safer than being driven by motors under the situation of interacting with the brittle glass.

Pneumatic scheme of X and Y cylinders

The pneumatic systems include X, Y and Z cylinders, brush cylinders and the vacuum suckers. The special layout of the vacuum suckers enables the robot to walk freely in the Y direction without attention to seals. But it is important for the control system to detect obstacles on the surface when the robot moves from one column of glass panes to the next in the right-left direction. Therefore, precise position control of the X cylinder is needed. Many of these systems use the proportional servo valve to drive the cylinders to achieve accurate position control. Unfortunately these valves are not only complicated but also very expensive compared with on-off solenoid valve. Now a lot of researchers have tried to use on-off solenoid to realize the position control of pneumatic actuators. Among presented control methods, the pulse width modulation (PWM) has drawn most attentions for its simplicity of hardware construction. However, the benefit of this kind of simple valve is offset by the limitation of the valve response and its discrete on-off nature.

The design of both the X and Y cylinders, to which the vacuum suckers are attached, is cheap, simple and efficient, but the scheme of the X cylinder is even simpler than that of the Y cylinder (shown in Fig. 2). Only one pair of high-speed on-off solenoid valves is used to control the air pressure to the two chambers of the X cylinder. An encoder and a set of gear and rack are used to feedback the position of the piston of the X cylinder. The main reason for this simpler design is that Sky Cleaner mainly moves and cleans along the Y direction, while the movement frequency in the X direction is very low. However, the Y cylinder has to raise a load of 25 kg in order to push the cleaning brushes with a friction force when the robot is cleaning downwards from the top of the building. Moreover, the required cleaning efficiency of the robot cannot be met because the high-speed on-off solenoid valves cannot actuate the cylinder fast enough. In order to accelerate the Y cylinder, a larger ordinary 3-position 5-port solenoid valve (valve 5 in Fig. 2) is used to bypass the high-speed on-off solenoid valves.

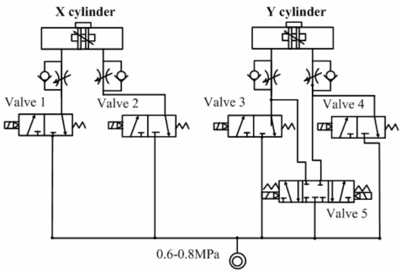

Figure 2: The scheme of X and Y cylinders

Characteristics of the pneumatic cylinders

For our robot, the cylinders will move at full speed with 100% high-speed on-off solenoid valve duty on one side, 0% duty on the other side. When the sensors detect window obstacles, usually duties on both sides will change according to the feedback signals. Here the solenoid valves' delay time to open and close is ignored. A duty of 100% means the solenoid valve is fully open; a duty of 0% means it is fully closed.

Firstly, we should discover the characteristics of the nonlinear motion using the PWM algorithm through several experiments. In Fig.3a, PWM duty cycles of 20%, 40%, 60%, 80% and 100% during the Y cylinder going down are displayed. The fastest motion was obtained when the duty was 100%. But the steady-state errors of the different motions were not improved accordingly. Furthermore, the duties below 40% are not strong enough to drive the robot upwards.

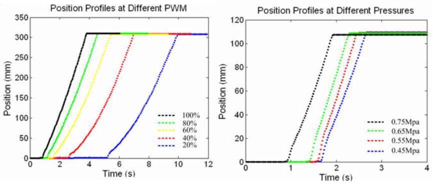

Figure 3: Y and X cylinders profiles

Fig.3b shows the profiles of the influences of the different pressures on the X cylinder. The fastest motion was obtained when a pressure of 0.75 Mpa was applied to the system. As the pressure dropped, the time to reach the desired position increased.

3. Pneumatic control strategy

Segment and variable bang-bang controller for Sky Cleaner

A method of segment and variable bang-bang controller is proposed to implement the accurate control of the position servo system for the X cylinder during the sideways movement. Generally, the conventional bang-bang controller for the pneumatic system is described with (1) (2). The control will be finished when (2) is satisfied.

$$U_i = -U_{MAX}(e_s) \qquad \text{i=1, 2} \qquad (1)$$

$$|e_s| < \varepsilon \qquad (2)$$

Where e_s is the position error, ε is the limitation to the position error, U_1 and U_2 are the control signals for the two chambers of the X cylinder and U_{MAX} is the maximum of the control signals. Only the position error is used as the switch to change the control without considering the factor of velocity. However, the velocity of the piston is not zero even if the piston is just at the ideal point. The movement will not be finished and the control function will have to act for the system because of the overshooting, which in the end will cause oscillations. Based on this consideration, an improved variable bang-bang controller is proposed described with the following (3) and (4). Where e_v is the velocity error, **c** is a constant, ***sgn ()*** is the signal function and y is the constructor function synthesizing the position and velocity for movement evaluation. Equation (4) shows that the control signals are computed according to ***sgn (y)***.

$$y = e_v + c e_s^2 \operatorname{sgn}(e_s) \qquad (3)$$

$$U_i = -U_{MAX} \operatorname{sgn}(y) \qquad (4)$$

Fig. 4 shows that there are four areas named I, II, III and Ⅳ which are formed by y and the axes in the phase plane. The control signals will change if the tracking of y changes from Ⅰ to II or from III to Ⅳ. Here (5) is satisfied.

$$U_1 + U_2 = U_{MAX} \qquad (5)$$

The control will be over when (6) is satisfied.

$$\sqrt{e_s^2 + e_v^2} \le \varepsilon \qquad (6)$$

Starting from the beginning of precise position control, the whole process includes two parts:

1) Firstly, $e_s < 0$, $e_v > 0$, $y \le 0$, $\therefore$ $U_1 = U_{MAX}$, $U_2 = 0$, the piston will move to the desired position at high speed.

2) When the tracking of the constructor function moves from Ⅰ to II: $y > 0$, $U_1 = 0$, $U_2 = U_{MAX}$, the piston will still move towards the ideal point while the piston velocity is decreasing. The following parts are similar. So the position error and the velocity error are approaching zero at the same time because the constructor function is used as evaluation.

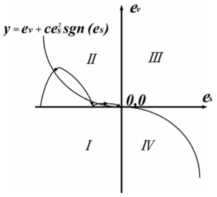

Figure 4: The phase plane

Segment strategy

Furthermore, a segment strategy has been devoted to this method in order to improve the stiffness and eliminate the system nonlinearities. Here two different control strategies are needed. Firstly, when window obstacles are detected, the robot should begin to control according to (5), (6) while the distance to obstacles is larger than e_b. Where e_b is the limitation between the first step and the second step. In the second, the absolute value of e_s is smaller than e_b. The initial pressure will be applied to the chambers during this phase. The chamber which was open to the air is under initial pressure. The goal of the measure is to increase the pressure in the chambers when the piston is close to the desired position. Fig. 5 shows the profiles of position and velocity using the method of segment and variable bang-bang controller. The e_s and e_v approach zero together. It is seen that the movement is smooth and the maximum of the velocity is 680 mm/s.

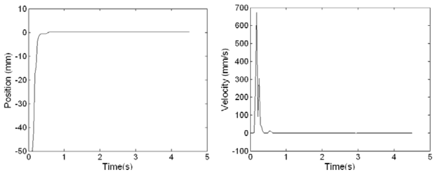

Figure 5: 50mm-movement position and velocity profiles of the improved bang-bang controller

Open topics

At present the activities are extended to enable new features, especially concerning a more intelligent, i.e. flexible and learning system behavior. Here the pneumatic climbing robot is used as target and as a demonstration system. Research hence features an integrated-systems view and focuses on engineering and intelligent control as well as on a robust perception of the environment, respectively.

Technical Aspects of Multimodal System
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