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 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](http://tams-www.informatik.uni-hamburg.de)

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 connects the X and Y cylinders. The waist joint is used for the correction of passive compliance due to the compressibility of the air, thus the movement is smooth and the robot safer than being driven by motors under the situation of interacting with the brittle glass.

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 servos 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 valves. Now a lot of researchers have tried to use on-off solenoid to realize the position control of pneumatic actuators. Among them, the pulse width modulation (PWM) has drawn most attention 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, and 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 large diameter 3-position 5-port solenoid valve (S5) in Fig. 2) is used to bypass the high-speed on-off solenoid valves.

![Figure 2: The scheme of X and Y cylinders](http://tams-www.informatik.uni-hamburg.de)

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 valve 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 non-linear motion using the PWM algorithm through several experiments. Fig. 3a shows the profiles of the influences of the different pressures on the X cylinder. 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: X and Y cylinders profiles](http://tams-www.informatik.uni-hamburg.de)

3. Pneumatic control strategy

Segment and variable bang-bang controller for Sky Cleaner

A 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 over when (6) is satisfied.

\[
\text{U} = U_{\text{MAX}} \ \text{sgn} (y)
\]

Where \( y \) is the position error, \( \varepsilon \) is the limitation between \( U_0 \) and \( U_{\text{MAX}} \), \( U_0 \) is the constructor function synthesizing the position and velocity for moving evaluation. Equation (4) shows that the control signals are computed according to \( \text{sgn} (y) \).

\[
U = \text{sgn} (y) \ \text{sgn} (\epsilon)
\]

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.

\[
U = U_{\text{MAX}} \ \text{sgn} (y)
\]

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

\[
y = y - \epsilon \text{sgn} (y)
\]

(3)

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

1) Firstly, \( \varepsilon = 0 \), \( \epsilon \to \epsilon, y \to y, y_0 : U_0 = U_{\text{MAX}}, U_0 = 0 \), the piston will move to be detected contact at high speed.

2) When the tracking of the constructor function moves from I to II: \( y > 0, U_1 = U_{\text{MAX}}, U_2 = U_{\text{MAX}} \), 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.

4. Open topics

Technical Aspects of Multimodal System
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