SLIDING MODE CONTROL OF PNEUMATIC ARTIFICIAL MUSCLE FOR ROBOT APPLICATION

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ABSTRACT

As an important driver element, the pneumatic artificial muscle (PAM) is widely used in industrial applications for many automation purposes thanks to their variety of advantages. The design of a stable robust position controller for PAM is difficult since it is a very nonlinear time-variant controlled plant because of the compressibility of air, air mass flow rate through the valve, etc. The main contribution of this paper is a robust position control method based on sliding mode for a robot arm, driven by pneumatic muscle actuator. Finally, it presents experimental results.

Keywords: Pneumatic artificial muscles, PAMs, sliding mode control.

1. INTRODUCTION

This work is the first fundamental step of a wider project, aimed at studying the humanoid robot. Muscles only generate a force via contraction, i.e. a muscle can only "pull" and does not "push." One muscle (agonist) contracts and simultaneously the other muscle relaxes (antagonist, which increases in length), thus producing a force and motion on the mass. The same effect can be realized in a rotational sense by generating a rotation or torque on the robotic joint through the contraction of the agonist and relaxation of the antagonist muscle.

Many researchers have investigated the precise position control of pneumatic muscles during the past several years. Most of them dealt with the control of single or antagonistic pneumatic muscles.

Due to the fact that the results obtained with a classical PI controller were not good, robust control techniques were considered. For pneumatic muscles, the application of different control techniques is found in the literature, but a good performance requires the use of robust or non-linear control techniques. A variety of approaches, with varying success, have been attempted. PID control, neural networks, and adaptive control, among others, have been utilized [1, 2, 3, 4]. While PID control is well known, the results are particularly sensitive to errors in the feedforward term. Adaptive and neural network control may be more robust, but suffer from slow convergence and long training sessions respectively. Thus, adaptive control is not well suited for the fast movements required of an orthotic actuator. Analogously, neural control, with its training workspace, does not handle unique or unexpected situations well.

Therefore, a non-linear robust control technique, sliding-mode, was applied to design a position controller.

2. MATERIALS AND METHODS

The pneumatic valve is the key element in the system. There are two types of valves used in the pneumatic positioning, servo-valves and on-off valves. With conventional on-off valves accurate position control is difficult to achieve because of the limitation of the valve response time. In the past few years there has been a wide interest in the use of cheap high speed solenoid valves [7]. The most of applications are on pulse with modulation (PWM). By the advent of DSPs with high computation power, the precise and robust control of pneumatic actuators has become possible.

Sliding mode control was introduced in the late 1970's [8] as a control design approach for the control of robotic manipulators. Among experimental studies, a few succeeded in showing closed-loop system behaviour which was predicted by the theory [9].

Another solution is to employ the advanced nonlinear control strategies developed in recent years (soft computing) [10].

The design of a sliding mode controller consists of three main steps. One is the design of the sliding surface, the second step is the design of the control which holds the system trajectory on the sliding surface, and the third and key step is the chattering-free implementation. The purpose of the switching control law is to force the nonlinear plant's state trajectory to this surface and keep on it. When the plant state trajectory is „above" the surface, a feedback path has one gain and a different gain if the trajectory drops „below" the surface.

Consider a single-input, single-output second-order nonlinear dynamic system:

$$\ddot{x} = f(x, \dot{x}, u) \tag{1}$$

Where x is the output signal (position) of the controlled plant, u is the control signal. If x_d denotes the desired value, then the error between the reference and system states may be defined as

$$e = x_d - x. \tag{2}$$

2.1. Sliding surface design

Classically, a scalar variable s is calculated as a linear combination of the error and its derivative.

$$s = e + \lambda \cdot \dot{e} \tag{3}$$

Let $s(\dot{e}, e) = 0$ define the „sliding surface" in the space of the error state. The purpose of sliding mode control law is to force the state trajectory of the error to approach the sliding surface and then move along the sliding surface to the origin (Fig.1.).

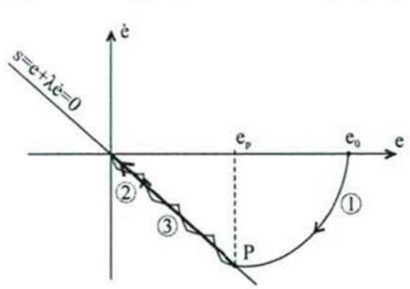

Fig.1. Sliding motion in the state space

The process of sliding mode control can be divided into two phases, that is, the approaching phase with $s(\dot{e},e) \neq 0$ and the sliding phase with $s(\dot{e},e) = 0$. If the system is in sliding mode the error is decreasing exponentially, where λ is a time constant type parameter. If λ is big than the system response is slow but accurate. If it is small than the system response is fast but the system might chatter.

2.2. Selection of the control law

In order to guarantee that the trajectory of the error vector e will translate from approaching phase to sliding phase, the control strategy must satisfy the sliding condition

$$s(\dot{e},e)\cdot\dot{s}(\ddot{e},\dot{e}) < 0. \tag{4}$$

This means that e will always go toward the sliding surface. A proper control should be selected to satisfy the condition (4) in any time instant. The simplest control law that might lead to sliding mode is the relay.

$$u = \delta \cdot sign(s) \tag{5}$$

2.3. Chattering free implementation

Chattering is the main problem of sliding mode control and chattering free implementation is the key step in design of a sliding mode controller. A quite general solution is that the relay (which changes its output value suddenly) is replaced by a saturation function. There is a boundary layer around the sliding surface where the control signal is changing continuously. If the system trajectory is close to the sliding surface and the control signal is small, than the system might stick before the goal.

To avoid it a modified saturation function shown in Table. 1. is proposed. When the limitation of the position is satisfied, all high-speed on-off solenoid valves are ON to stop the overshoot. The control will be finished when $|e_s|$ is smaller than e.

3. THE SERVOPNEUMATIC POSITIONING SYSTEM

The experimental set-up, is shown in Fig.2. Fig.3. and Fig.4. consists of a slider mechanism. One side of the muscle is fixed to a load cell, while the other side is attached to the movable frame. The load cell (7923 type from MOM) is a 4 bridge element of strain gauges. It is mounted inline to the PAM on the fixed surface. The load cell measures the force exerted by the PAM. The linear displacement of the actuator is measured using a LINIMIK MSA 320 type linear incremental encoder. Velocity and acceleration are obtained by numerical derivation. During each test, slider position, muscle force and applied gauge pressure are recorded. Since PAMs are one-way acting, two are needed to generate bidirectional motion: as one of them moves the load, the other one will act as a brake to stop the load at its desired position. To move the load in the opposite direction the muscles change function. The PAMs were installed horizontally such that the only force present during activation was the small friction force of the slider mechanism. In the test-bed, two DMSP-20-200N-RM-RM type fluidic muscle (from FESTO) can controlled by tree-way and two-way solenoid valves (MATRIX HX 751.102 C 324 3/2 NC and PX 861.9E4C2KK fast switching types in Fig. 3.) and a proportional valve (FESTO MPYE-5-M5-HF-010-B type. in Fig. 4.).

We repeated experiments for several levels of pressures in the range from 0 to 5 bar. To measure the air pressure, two Motorola MPX5999D pressure sensors were plumbed into the pneumatic circuit. A National Instruments data acquisition card (NI 6251/M) reads the signal of force, pressure sensors and incremental encoder into the PC. National Instruments LabVIEW will be used to monitor and collect the data imported through the DAQ card. It will also dispatch the control profiles for the PAMs.

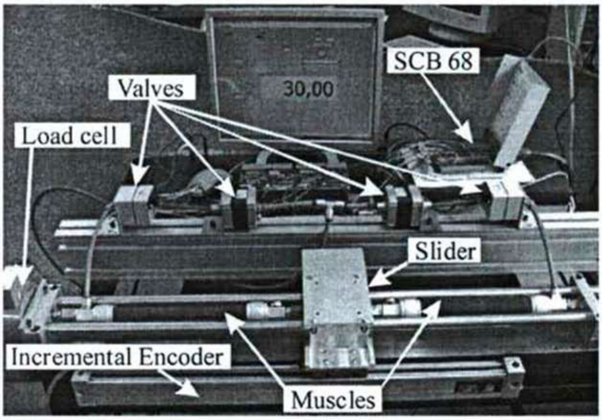

Fig. 2. The photo of the experimental setup

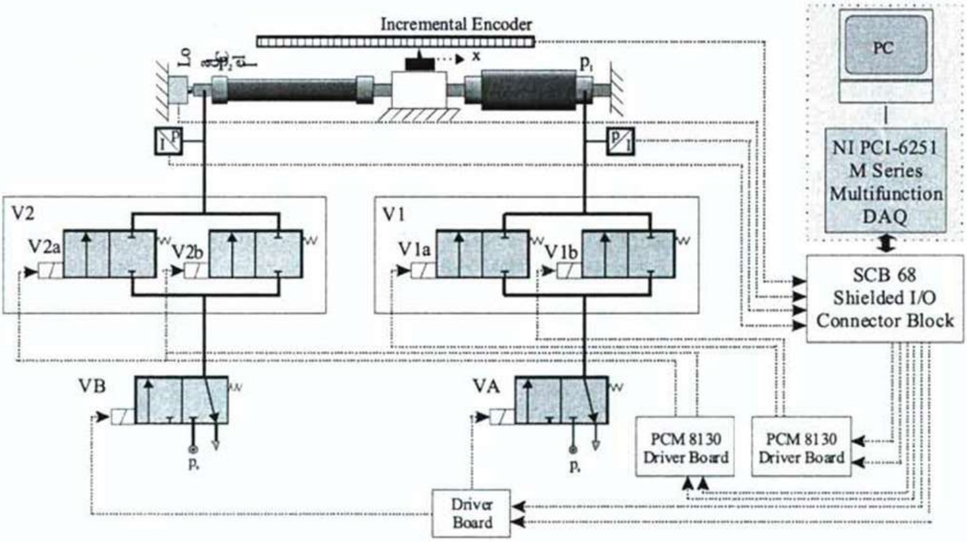

Fig. 3. Configuration of pneumatic positioning system with on-off valves

The system pressure is set to be 6 bar, the sampling time is 10 ms. In order to analyze the positioning methods a real-time data acquisition program was designed. The control program is based on Table1.

Table 1.

		Fast Forward	Slow Forward	In Position	Slow Backward	Fast Backward
VA		1	1	1	0	0
VB		0	0	1	1	1
V1	V1a	1	1	0	1	1
	V1b	1	0	0	0	1
V2	V2a	1	1	0	1	1
	V2b	1	0	0	0	1

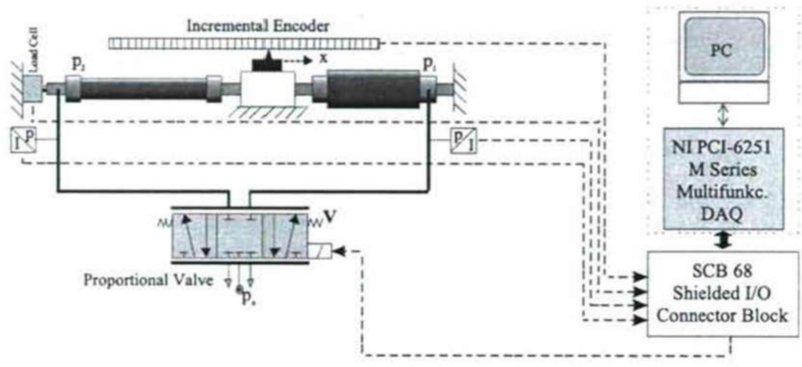

Fig. 4. Configuration of pneumatic positioning system with proportional valve

4. EXPERIMENTAL RESULT

The conventional, single stage solenoid operated on–off valves are very bulky and their dynamic performances are low. With these valves fine motion control is difficult to achieve because of the limitation of the valve response time. With on-off control the system will never reach a steady state value.

The actual position will tend to oscillate around the desired position. The second measurement is a positioning with high-speed on-off solenoid valves. The time functions of the position, and control signal is shown Fig.5. and Fig.6. The position error of the LabVIEW-based relay type sliding mode control is within ±0.02 mm.

This behavior is in absolute contrast to that of a pneumatic cylinder: a cylinder develops a force which depends only on the pressure and the piston surface area so that at a constant pressure, it will be constant regardless of the displacement.

5. CONCLUSIONS AND FUTURE WORKS

This work is the first fundamental step of a wider project aimed at studying the PAMs. With the help of this test-bed we can carried out several static and dynamic investigations and control methods. Based on the laboratory measurements we can conclude that the pneumatic servo-systems can be used for precise robust position control. The sliding mode control is a promising tool for controlling such systems. The proposed modified saturation function can eliminate the chattering, which is the main problem in case of sliding mode control.

Further works we have done with applying the input shaping method. Once the system has reached the setpoint, the residual oscillation will degrade positioning accuracy and may cause a delay in task completion. Input Shaping is a feedforward control technique for reducing vibrations in computer controlled machines. The method works by creating a command signal that cancels its own vibration. That is, vibration caused by the first part of the command signal is canceled by vibration caused by the second part of the command. Input shaping is a command generation technique that is used to reduce command-induced vibration (as opposed to disturbance-induced vibration) [11]. Input shaping is implemented by convolving a sequence of impulses, called an input shaper.

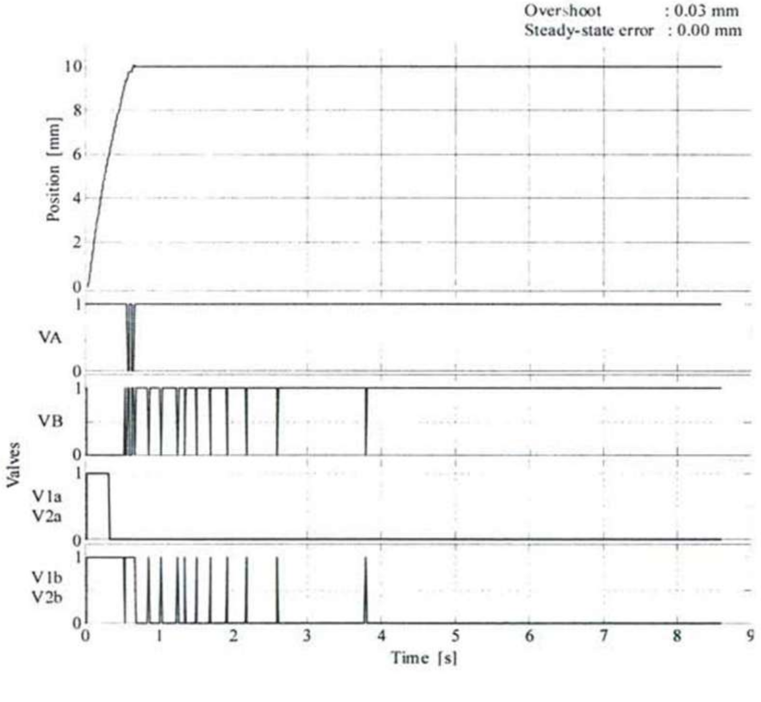

Fig. 5. The time functions of the position and control signal

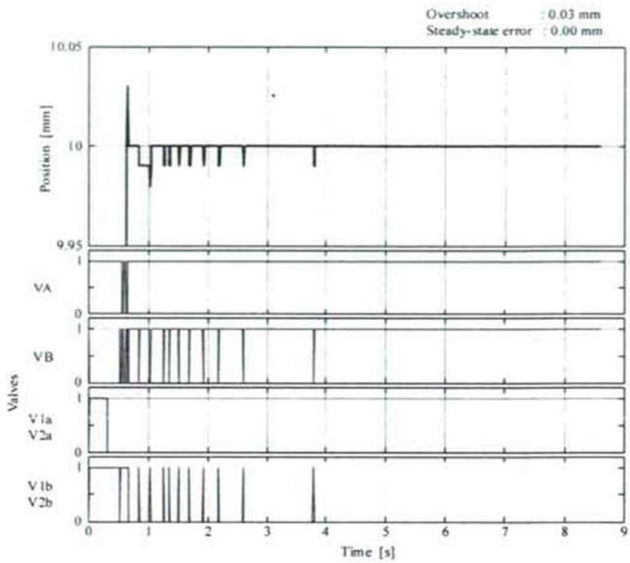

Fig. 6. The time functions of the position and control signal (enlarged)

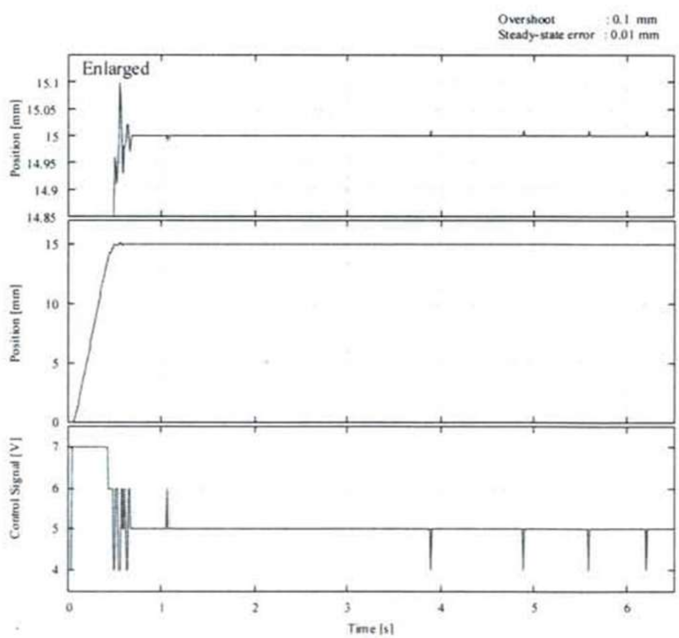

Fig. 7. The time functions of the position and control signal (with proportional valve)

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