SLIDING MODE CONTROL IN PNEUMATIC POSITIONING

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ABSTRACT

This paper deals with one of the challenging problems in the field of robot control, namely how to make a pneumatic driven robot manipulator to move as fast as possible without violating the accuracy requirements. The main contribution of this paper is a design of a robust sliding mode controller implemented on a DSP system.
Keywords: Sliding mode control, DSP, chattering, pneumatic system

1. INTRODUCTION

As an important driving element, the pneumatic cylinder is widely used in industrial applications for many automation purposes thanks to their variety of advantages, such as: simple, clean, low cost, high speed, high power to weight ratio, easy maintenance and inherent compliance. The most widely used controller is still the PID (Proportional, Integral, Derivative) controller because of its simplicity and ease of implementation, but it isn't good for nonlinear systems with parameters and load variations. The pneumatic servo-system is a very nonlinear time-variant control system because of the compressibility of air, the friction force between the piston and the cylinder, air mass flow rate through the servo-valve, etc. Because of control difficulties, caused by the high nonlinearity of pneumatic systems, a robust control method must be applied. There are two main classical directions in the field of robust control. One is the H infinite control for linear systems, and the other is the sliding mode control for nonlinear systems. Another solution is to employ the advanced nonlinear control strategies developed in recent years (soft computing) [10][11].

Sliding mode control was introduced in the late 1970's [1][2] as a control design approach for the control of robotic manipulators. In the early 1980's, sliding mode was further introduced for the control of induction motor drives [3]. These initial works were followed by a large number of research papers in robotic manipulator control [4], in motor drive control and power electronics [5]. However, despite the theoretical predictions of superb closed-loop system performance of sliding mode, some of the experimental work indicated that sliding mode has limitations in practice, due to the need for a high sampling frequency to reduce the high-frequency oscillation phenomenon about the sliding mode manifold - collectively referred to as „chattering". In most of the experimental work involving sliding mode, the effort spent on understanding the theoretical basis of sliding mode control is generally minimized, while a great deal of energy was invested in empirical techniques to reduce chattering. Among these experimental studies, a few succeeded in showing closed-loop system behavior which was predicted by the theory [6]. Those who failed to realize, the experimental designs successfully, concluded that chattering is a major problem in realizing sliding mode control in practice.

The connection of sliding mode control to model reference adaptive control introduced some excitement in the research community. In addition, the design of sliding mode observers [7][8], provided additional capabilities to a sliding mode based feedback control loop. Finally, the issue of discrete-time sliding mode was raised from the theoretical perspective, resulting in a number of different definitions of discrete-time sliding mode [9].

2. DESIGN OF A SLIDING MODE CONTROLLER

A good introduction into sliding mode control can be found in [13][14]. 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. The control has discontinuity on this surface that is why some authors call it switching surface. 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.

To introduce the idea of sliding mode control we can consider a single-input, single-output second-order nonlinear dynamic system:

$$\begin{aligned} \ddot{x} &= f(\dot{x},x)+G(x)\cdot u \\ y(t) &= x(t) \end{aligned} \tag{1}$$

Where x is the state variable, y is the output signal (position) of the controlled plant, u is the control signal and G is gain of control signal. If x_d denotes the reference state trajectory, then the error between the reference and system states may be defined as $e=x_d - x$. 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 error vector e approach the sliding surface and then move along the sliding surface to the origin (Fig.1) (where ① denotes the approaching phase, ② denotes the sliding phase and ③ denotes the chattering).

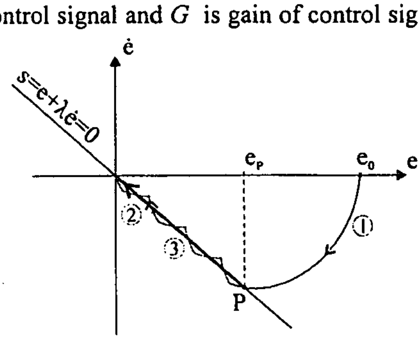

Fig. 1 Sliding motion in the state space

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 $s(\dot{e},e)=0$.

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

$$s(\dot{e},e)\cdot\dot{s}(\ddot{e},\dot{e})<0. \tag{2}$$

This means that e will always go toward the sliding surface. In classical method of sliding mode control the scalar variable is calculated as a linear combination of the error and its derivative.

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

Where λ is a time constant type parameter. The simplest control law that might lead to sliding mode is the relay.

$$u=\delta\cdot sign(s) \tag{4}$$

The relay-type controller does not ensure the existence of sliding mode for the whole state space, and relatively big value of δ is necessary, which might cause a big chattering phenomenon. If the sliding mode exists ($s=0$ and $\dot{s}=0$), then there is a continuous control, know as equivalent control u_{eq} which can hold the system on the sliding surface.

In practice, there is no perfect knowledge of the whole system and parameters, so, only $\hat{u}_{eq}$, the estimate of u_{eq} , can be calculated. Since $\hat{u}_{eq}$ does not guarantee convergence to the switching surface, in general, a discontinuous term is usually added to $\hat{u}_{eq}$, thus,

$$u = \hat{u}_{eq} + \delta \cdot sign(s). \tag{5}$$

The role of the discontinuous term in the control law is to hide the effect of the uncertain perturbations and bounded disturbance. The more knowledge is implied in the control law, the smaller discontinuous term is necessary. Usually, all state variables are not measurable, the system parameters are not known and the unmodeled dynamics may cause chattering.

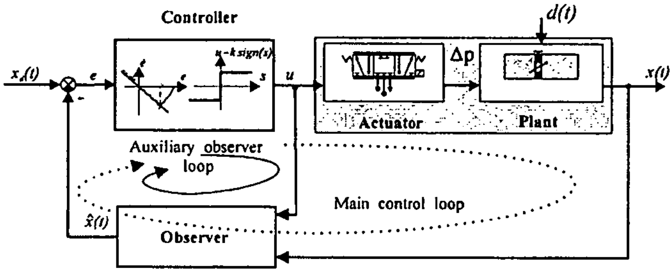

Fig. 2 Observer-based solution

The most commonly cited approach to reduce the effects of chattering has been the so called boundary layer control. The discontinuous control law is replaced by a saturation function which approximates the *sign(s)* term in a boundary layer of the sliding manifold *s(t)=0*.

To solve the chattering problem, another solution is the asymptotic state observer. An asymptotic observer can eliminate chattering despite discontinuous control laws. The key idea as proposed by Bondarev et al. (1985) is to generate ideal sliding mode in an auxiliary observer loop rather than in the main control loop (Fig. 2).

3. THE SERVOPNEUMATIC POSITIONING SYSTEM

The system is shown in Fig. 3 Fig. 4 and Fig. 5 (details can be found in [12]).

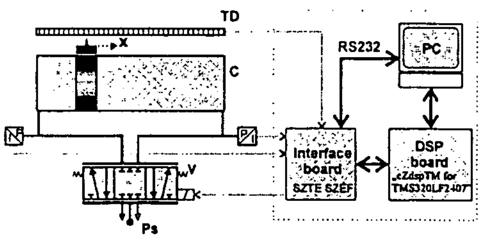

Fig. 3 Configuration of pneumatic positioning system

It consists of a double-acting pneumatic rodless cylinder (MECMAN 170 type) with bore of 32 mm, and a stroke of 500 mm, controlled by a five-way servo- distributor (FESTO MPYE-5-1/8 HF-010B type). A linear encoder (LINIMIK MSA 320 type) gives the position. Velocity and acceleration are obtained by numerical derivation. Pressure sensors (Motorola MPX5999D) are set in each chamber.

Because of control difficulties caused by the high nonlinearity of pneumatic systems a nonlinear control method must be applied. So we will deal with robust control and a DSP based sliding mode control was designed. We have used the „eZdspTM for TMS320LF2407" DSP target board from Spectrum Digital.

The control goal is to move the piston from any initial position to the target position. Using the sliding approach it is possible to minimize the positioning errors.

In order to design an optimal controller and predict the control performance for the pneumatic test rig, a theoretical and practical modeling of the rig is needed (Fig. 6). The equations derived are based upon Burrows.

Motion equation:

$$p_a \cdot A_a - p_b \cdot A_b - m \cdot \ddot{x} - k \cdot \dot{x} - c \cdot x - sign(\dot{x}) \cdot F_f = 0 \qquad (6)$$

Pressure build-up equations:

$$\dot{p}_{apol} = \frac{n_a}{V_a} \cdot \left(\dot{m}_{in} \cdot R \cdot T_{in} - p_a \cdot A_a \cdot \dot{x} \right) \qquad (7)$$

$$\dot{p}_{bpol} = \frac{n_b}{V_b} \cdot \left(p_b \cdot A_b \cdot \dot{x} - \dot{m}_{out} \cdot R \cdot T_b \right)$$

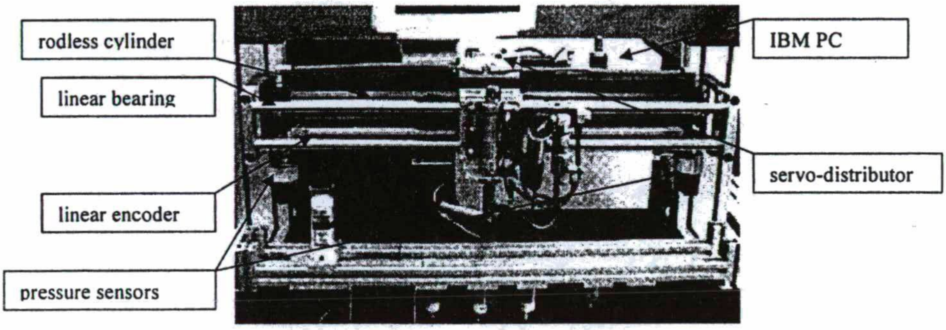

Fig. 4 The experimental positioning system

Mass flow rate equations:

$$\dot{m}_{in} = \mu_{oa} \cdot A_{oa} \cdot p_e \cdot \sqrt{\frac{2}{R \cdot T_e}} \cdot \Psi \qquad (8)$$

$p_a / p_{in} \leq 0.528$ $\qquad \Psi = 0.484$

$p_a / p_{in} > 0.528$

$$\Psi = \sqrt{\frac{\chi}{\chi - 1} \left[\left(\frac{p_a}{p_{in}} \right)^{\frac{2}{\chi}} \cdot \left(\frac{p_a}{p_{in}} \right)^{\frac{\chi+1}{\chi}} \right]}$$

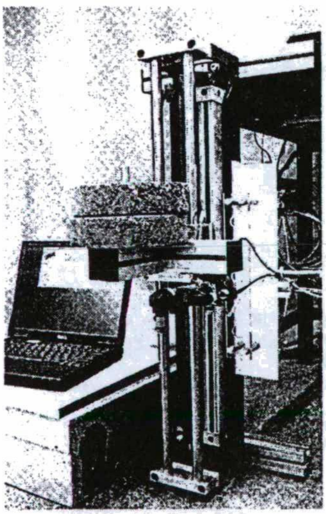

Fig. 5 Positioning with mass load disturbances

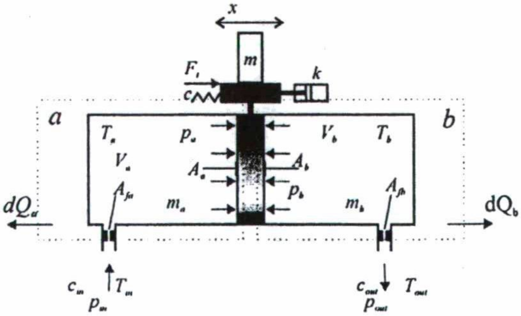

Fig. 6 Analysis model

The paper [12] utilities MATLAB and SIMULINK in order to investigate the basic properties of pneumatic actuators.

For flexibility, the design includes an extra interface board to fit I/O ports, to support both of the two main types of position encoder and providing two analog outputs for the servo-valves and serial communications link to a host computer. In this application, the second board can be plugged.

In our experiments, we use D/A channel (Analog Devices AD420) for control and incremental encoder channel for position measurements. The two boards contain a DSP controller (TMS320LF240) and its oscillator, a JTAG and an RS232 link and the necessary inputs and outputs. The system pressure is set to be 6 bar, the sampling time is 2 ms. In order to analyze the positioning methods a real-time data acquisition program was designed for a PC to capture the system output data through the communication interface between the PC and the DSP controller. The control program is in the DSP program memory. So the DSP controller can operate independently. The DSP Starter Kit (DSK) enables the user to connect the DSP to the parallel port on a PC and download code using a DOS interface. This interface allows the programmer to step through the code on the DSP and check the values of registers and memory locations while debugging.

The control algorithm is written in "C" language, and compiled into assembly language and downloaded into the DSP board.

4. EXPERIMENTAL RESULT

First, the performance of a well tuned PID controller and SMC are compared in case of a step change in the position reference signal (Fig. 7 – Fig.8). Because of the well known stick-slip phenomenon, the steady state error is alternating with the value of 3.8 mm. The position error of the DSP based sliding mode control is within ±0.01 mm. It is less then 1% of the steady state error of a well tuned PID controller.

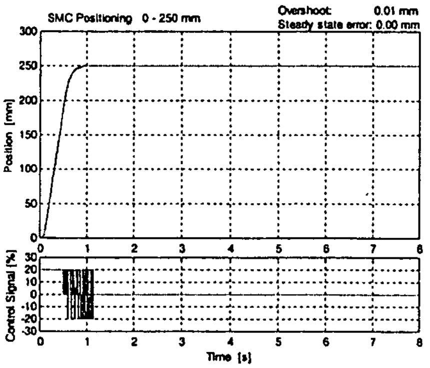

Fig.7 Positioning result with SM controller

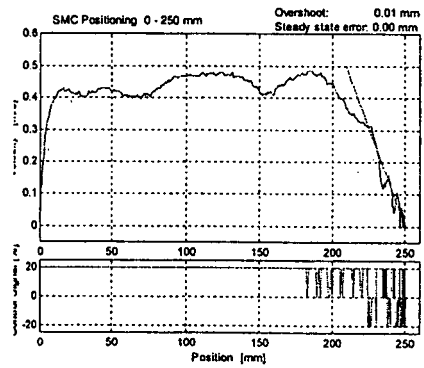

Fig.8 Phase plane trajectory with SM controller

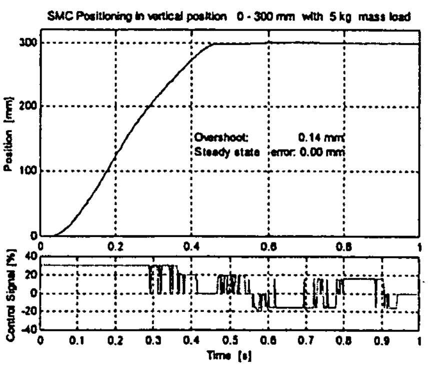

Fig. 9 Positioning result in vertical position

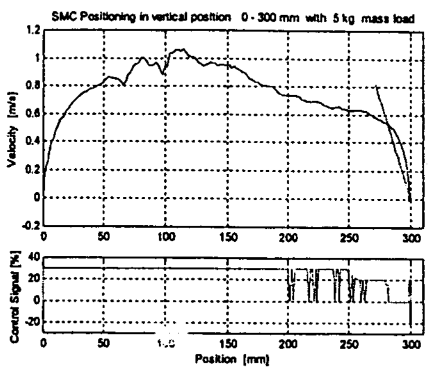

Fig. 10 Phase plane trajectory in vertical position

Since the DSP has a fast operation speed and a large memory, it can be applied in the control loop to increase the sampling frequency and the control accuracy.

The robustness of the proposed SMC is also tested on the vertical position cylinder with mass load disturbances (Fig. 9 and Fig. 10).

For the purpose of measuring the tracking error of the piston, a sinusoidal (amplitude of 200 mm) desired input position trajectory is used. The experiment is repeated for 4 different frequencies (1/30, 1/10, 1/5 and 1/2 Hz).

We can see the tracking errors are smaller (less then ± 5 mm) at low frequencies, mainly in the points where there is inversion in the direction of movement.

The experimental results indicate that the proposed sliding mode controller gives also fast response, good transient performance and it is robust to variations of system parameters and external disturbances, and they do not require accurate modeling.

Further works we have done with applying the BTL5-S101 type Micropulse Linear Transducer with 1 μm resolution from Balluff (Fig. 11).

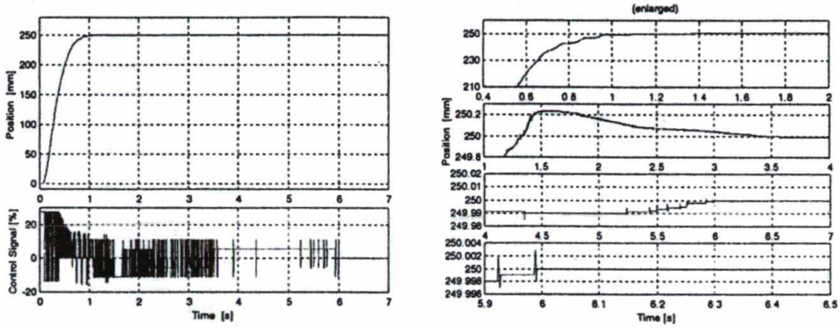

Fig. 11 Performance of the SM controller with boundary layer

5. CONCLUSIONS AND FUTURE WORK

This paper presents a brief introduction to sliding mode control theory and takes the first step toward the practical Based on the laboratory measurements, we can conclude that the DSP based Sliding Mode Control is suitable and effective for the position control. Furthermore we interested in trying out several methods with simulation and on "real world" systems. So, further experiments were carried out to compare the simulation results with experimental results.

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