Accurate Positioning of Pneumatic Artificial Muscle at Different Temperatures Using LabVIEW Based Sliding Mode Controller

J. Sárosi

* Faculty of Engineering, University of Szeged, Szeged, Hungary
sarosi@mk.u-szeged.hu

Abstract—Pneumatic artificial muscles (PAMs) are difficult to control because of their highly nonlinear and time varying nature, thus robust control method is needed. Sliding mode control can be favourably used for accurate positioning of PAMs. In this paper the error of sliding mode control based positioning of a Fluidic Muscle at different temperatures is determined. The controller is developed in LabVIEW and the error of the experiments shows 0.01 mm.

I. INTRODUCTION

Fluidic Muscles produced by Festo Company and Shadow Air Muscle manufactured by Shadow Robot Company are two types of commercially available PAMs. Fluidic Muscles can be characterized such as powerful, dynamic (even 6000 N, 50 m/s²), judder-free and resistant to dirt and dust, therefore these actuators are widely used in industrial environment besides electric motors or hydraulic actuators.

Working principles of different types of pneumatic artificial muscles are well described in [1] and [2]. On the basis of these professional literatures, three types of PAMs can be distinguished: braided muscles (McKibben muscles), netted muscles and embedded muscles. Although the load carrying structure of Fluidic Muscles (Fig. 1) is embedded in its membrane some researches mention the Fluidic Muscles as McKibben type [3], [4].

Figure 1. Structure of Fluidic Muscles

The main disadvantage of PAMs is the highly nonlinear behaviour due to compressibility of air and the viscoelastic material [5], [6]. Choi et al. in [7] highlight to overcome the nonlinearity several easier models have been developed, but the most results are limited and valid only on simulation.

Static and dynamic investigations and modelling of PAMs can be found in [8], [9], [10], [11], [12], [13] and [14]. In these professional literatures the PAMs are analysed in single or antagonistic configuration.

Various control methods have been applied to control PAMs such as classical linear control, adaptive control, fuzzy control, neural network control and sliding mode control. Generally, proportional directional control valves, proportional pressure valves or ON/OFF solenoid valves are used [15]. In this paper a proportional directional control valve and a LabVIEW based sliding mode controller is applied for accurate positioning.

The service life (10⁴-10⁷ cycles for typical applications) of Fluidic Muscles depends on the operating pressure, the contraction (relative displacement) and the temperature. Festo in [16] emphasizes the high loads or the high operating frequencies of Fluidic Muscles lead to a temperature rise. The service life can be improved with reducing the contraction and the applied pressure. The thermal load can be reduced if the pressurisation on one side and the venting on the other side are enabled.

For this study a Fluidic Muscle type DMSP-20-400N-RM-RM is selected which can be characterized with the next technical data:

- inside diameter [mm]: 20,
- nominal length [mm]: 400,
- lifting force [N]: 0…1500,
- maximal permissible pretensioning [%]: 4,
- maximal permissible contraction [%]: 25,
- operating pressure [kPa]: 0…600,
- ideal ambient temperature [°C]: -5…+60,
- DMSP: pressed end caps and integrated air connectors,
- RM: radial pneumatic connection.

This paper can be divided into four sections. After Section I (Introduction), Section II gives the steps of design of sliding mode controller and describes the test bed and the LabVIEW environment. The internal and external temperatures of the PAMs at different operating frequencies are compared and the effect of temperature on the accuracy of the positioning is given in Section III. Finally, conclusion and future work are summarized in Section IV.
II. LABVIEW BASED SLIDING MODE CONTROLLER AND EXPERIMENTAL SETUP

The theory of sliding mode control is well documented in [17], [18], [19], [20] and [21]. Let us consider the next nonlinear system:

\[ x^{(n)} = f(X) + B(X) \cdot u(t) , \]  

(1)

where:

x: state variable,  
X: state vector,

\[ X = \begin{bmatrix} x, \dot{x}, ..., x^{(n-1)} \end{bmatrix}^T , \]  

(2)

u(t): control input,  
f(X) and B(X) are not exactly known, continuous functions.

The tracking error:

\[ \tilde{X} = X - X_d = \begin{bmatrix} \tilde{x}, \dot{\tilde{x}}, ..., \tilde{x}^{(n-1)} \end{bmatrix}^T , \]  

(3)

where:

x_d(t): desired state,  
X_d = \begin{bmatrix} x_d, \dot{x}_d, ..., x_d^{(n-1)} \end{bmatrix}^T . \]  

(4)

Phases of the design of a sliding mode controller:

- design of the sliding surface (sliding mode),  
- design of the control,  
- chattering-free implementation.

The sliding mode can be defined as:

\[ S(t) = \{ x | s(x, t) = 0 \} \]  

(5)

with

\[ s(x, t) = \left( \frac{d}{dt} + \lambda \right)^{n-1} \cdot \tilde{x}(t) , \]  

(6)

where:

\[ \lambda: \text{constant and } \lambda > 0. \]  

If \( n = 2 \):

\[ s = \left( \frac{d}{dt} + \lambda \right) \cdot \tilde{x} = \dot{\tilde{x}} + \lambda \cdot \tilde{x} . \]  

(7)

On the surface \( S(t) \), the error dynamics can be written:

\[ \left( \frac{d}{dt} + \lambda \right)^{n-1} \cdot \tilde{x} = 0 . \]  

(8)

On this surface the error will converge to 0 exponentially.

The tracking problem can be reduced to that of keeping the scalar \( s \) at zero. It can be achieved with the next sliding condition:

\[ \frac{1}{2} \frac{d}{dt} s^2 \leq -\eta \cdot |s| , \]  

(9)

where:

\[ \eta: \text{constant and } \eta > 0. \]  

Using a relay (as a controller) is a simple way that can lead to sliding mode:

\[ u = k \cdot \text{sign}(s) , \]  

(10)

where:

\[ k: \text{gain and } k > 0. \]  

The discontinuity creates an unfavourable dynamic behaviour in the environment of the surface that is called chattering. It is the main problem of sliding mode control, therefore an important phase in the design of a sliding mode controller is the chattering free implementation. To avoid the chattering the signum function can be replaced by a saturation function (Fig. 2). Then inside a boundary layer \( H \) the control signal changes continuously:

\[ u' = k \cdot \text{sat}(s) = \begin{cases} k \cdot \text{sign}(s), & \text{if } |s| > \varepsilon \\ \frac{k}{\varepsilon} \cdot s, & \text{if } |s| \leq \varepsilon \end{cases} , \]  

(11)

\[ H(t) = \{ X, |s(X, t)| \leq \varepsilon \} . \]  

(12)

Figure 2. Signum and saturation functions

In this study the chattering-free implementation of the sliding mode controller was developed in Formula Node of LabVIEW (Fig. 3). Despite the graphical programming, the Formula Node is a text-based environment in LabVIEW using the C/C++ syntax structure that can be applied to execute mathematical operations or statements and loops (e.g. if, while, for) on the block diagram. LabVIEW is widely used for measurement and control applications [22], [23].

The controller responds to the error of the system that can be measured without knowing \( f(X) \) or \( B(X) \) in (1). The next input signals were used to control the 5/3 proportional directional control valve type MPYE-5-1/8 HF-010B made by Festo Company: 4 V (fast backward), 4.65 V (slow backward), 5 V (in position), 5.35 V (slow forward) and 6 V (fast forward) (Fig. 4).
Fig. 5 shows the Fluidic Muscle was built horizontally into the test bed. Another LabVIEW program was used for periodic movement of PAM and monitoring of internal and external temperatures (Fig. 6). The internal and external temperatures were measured using thermocouples type K. In all cases before the operation the PAM was cooled with a compressed air spray (Novasol M5) to -10 °C and the moved load \( m \) was 20 kg. The position of slider was determined by an incremental encoder with 0.01 mm resolution type LINIMIK MSA 320.

### III. EXPERIMENTAL RESULTS

The changing temperature of Fluidic Muscle type DMSP-20-400-RM-RM was determined by the test bed presented in Fig. 5 and the LabVIEW program presented in Fig. 6. The air temperature entering the PAM was 24 °C, the pressure was 600 kPa, the sampling time was 250 ms and the proportional directional control valve was operated by sinusoidal signals with different frequencies (0.1 Hz, 0.25 Hz, 0.5 Hz, 0.75 Hz and 1 Hz) for periodic movement. The temperature changes can be observed at varying frequencies in Fig. 7, Fig. 8, Fig. 9, Fig. 10 and Fig. 11. As shown in these figures, inside the PAM the temperature varied with the airflow, but increasing the frequency caused higher steady-state internal temperatures. Outside the PAM the temperatures stabilised, furthermore higher external temperatures were measured away from the pneumatic jack. Thermocouple 1 determined the same temperatures (24 °C) at all frequencies, while thermocouple 3 measured the highest temperature values. The highest external temperature (70 °C) at a frequency of 0.5 Hz was noticed. This temperature value can negatively affect the service life of Fluidic Muscle. At 0.5 Hz the temperature trend changed: external temperatures show similar results at 0.1 Hz and 1 Hz as well as 0.25 Hz and 0.75 Hz.
The investigations of positioning error at several temperatures were carried out at a pressure of 600 kPa. The sliding surface gradient was 0.35 and the sampling time was 10 ms. Thermocouple 2 was used as reference sensor and thus the slider was positioned at temperatures of -10 °C, 0 °C, 10 °C, 20 °C, 30 °C and a maximum of 39 °C.

Fig. 12 and Fig. 13 depict reaching the desired position of 40 mm the positioning lasted for 1.4 s at a temperature of -10 °C and an overshoot of 0.02 mm and a steady-state error of 0.01 mm were experienced. Fig. 14 presents the positioning lasted for 1.2 s at a temperature of 39 °C and the overshoot and steady-state error remained within 0.01 mm.

It is important to note that at all temperatures the steady-state error was within 0.01 mm and by increasing the temperature the positioning time decreased.
the position error will be investigated using increased temperature can shorten the positioning time. In the temperatures inside and outside the PAM and was proved that the frequency of input signal influences encoder. The controller was designed in LabVIEW that is favourable because of the resolution of incremental steady-state error was achieved. The error cannot be using sliding mode controller was described and 0.01 mm

CONCLUSION AND FUTURE WORK

In this paper accurate positioning of Fluidic Muscle using sliding mode controller was described and 0.01 mm steady-state error was achieved. The error cannot be favourable because of the resolution of incremental encoder. The controller was designed in LabVIEW that is capable of eliminating the influence of temperature. It was proved that the frequency of input signal influences the temperatures inside and outside the PAM and increased temperature can shorten the positioning time. In the future the position error will be investigated using Balluff incremental encoder with 0.001 mm resolution.

REFERENCES


Figure 13. Positioning at a temperature of -10 °C (enlarged)

Figure 14. Positioning at a temperature of 39 °C (enlarged)