POSITION CONTROL ALGORITHM FOR ANTAGONISTICALLY DRIVEN PNEUMATIC MUSCLE ACTUATORS

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Abstract: Pneumatic artificial muscles (PAM) have many useful properties (low cost, high power to weight ratio, flexibility...), but present a challenge if we want to achieve accurate position control due to their nonlinear characteristics. In this paper we present the development of the new control algorithm for the accurate position control of two antagonistically coupled PAM’s. We tested the algorithm on an experimental setup (rotational one-DOF pneumatic actuator with two PAM’s) for measuring muscles’ response. Newly developed control algorithm is an upgraded A-PID (Adaptive PID) control algorithm (by M. Pipan), that was developed for a linear actuator with only one pneumatic artificial muscle. The final part of this paper contains the comparison of experimental results to two other similar systems.

Keywords: PNEUMATIC MUSCLE, ANTAGONISTIC SYSTEM, CONTROL ALGORITHM, POSITION AND PRESSURE CONTROL, FAST-SWITCHING VALVES

1. Introduction

Pneumatic artificial muscles (PAMs) are known for high contraction speeds, fast response, simple design, flexibility, high force to weight ratio and their possible use in micro and macro applications [1], [2]. However, due to the problems with accurate position control, accurate dynamic and static modelling and their nonlinear characteristics, the use of PAMs in industrial and biomechanical applications is still limited [3]. Developed control algorithms for position control of PMA are usually based on advanced PID control algorithms coupled with neuron networks, fuzzy logic, predictive control, SMC, nonlinear control, hybrid and other methods [4]-[7]. Until the development of fast-switching valves with faster response times (under 10 ms) [8], [9] servo – pneumatic [10], [11] and proportional – pneumatic valves [4], [12] with high accuracy but slow response were mostly used for pressure control. In this paper, we present pressure control with fast-switching valves controlled with PWM modulation, and position control of an antagonistic system of two pneumatic muscles based on a discreet PID control algorithm. The developed control algorithm is based on the A-PID (Adaptive PID) control algorithm, developed by M. Pipan [13].

2. Prerequisites and means for solving the problem

Testing setup that we designed for measuring muscles’ response is illustrated in Fig. 1 and Fig. 2. In the above-mentioned diagrams, A stands for Beckhoff controller, B is the rotary encoder, C is the antagonist muscle, D are the force sensors, E is the pressure regulator, F is compressed air network, G is the agonist muscle, H are the pressure sensors, I is the control computer and J is the arm of the actuator, K are the valves MHJ10-MF and L are the valves MHJ10-LF.

Fig. 1 Experimental setup

Fig. 2. Components of the testing rig

The setup consists of two FESTO pneumatic muscles configured in an antagonistic setup (type DMSP-20-200N RM-RM acting as an agonist and type DMSP-10-200N RM-RM acting as an antagonist). FESTO fast-switching valves (a pair of in/out valves MHJ10-S-2.5-MF for muscle DMSP-20 and a pair of in/out valves MHJ10-S-2.5-LF for muscle DMSP-10), controlled by PWM modulation, were used for pressure control in the muscles. For feedback in the pressure control loop, we used two pressure sensors (FESTO SDET-22T-D10-G14-U-M12) mounted after muscles’ outlets. For connecting the muscles to the frame of the testing rig, two coupling adapters were designed. They connected the ends of both muscles to the load cells (ELANE ELC-L116), which were fixed to the support frame of a testing setup. The antagonistic setup or a rotary joint was created by connecting both muscles with a steel rope, which was wrapped two times around their axis with two supporting bearings, and fixed with a screw. The distance (31 mm) between axes was calculated as a minimal possible distance if both muscles were fully contracted. The rotation of the joint was measured by an incremental rotary encoder (HEIDENHAIN ROD 426E.004 1080). The »arm« of a pneumatic actuator was mounted on the rotating axis. The I/O information was processed with a Beckhoff industrial controller CX 5010. It allows connection with sensors via corresponding modules (shown in Table 1.)

Table 1. Specifications of used modules

<table>
<thead>
<tr>
<th>Description</th>
<th>Specifications</th>
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<tbody>
<tr>
<td>CX5010 [14]</td>
<td>Controller, 1,1 GHz Intel Atom Z510 processor</td>
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<tr>
<td>EL5101 [15]</td>
<td>Encoder module, 5 V DC, 0,5 A, 32 bit, 1 MHz</td>
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Controller was connected to a real-time desktop PC by GigE ethernet connection. The control cycle was 1 ms. The control algorithms were developed using Structured Text (ST) programming language in a Twin Cat 2 software environment. Important I/O parameters were analyzed using Scope View 2, Matlab and Microsoft Excel.

3. PAM operating range

The maximum rotation angle of the pneumatic actuator is 140°. The initial position of the pneumatic actuator is at an angle 0 at the lowest position of the arm as it is shown in Fig. 5. Initial position was achieved manually, by increasing the pressure in the antagonist muscle to 6 bar and keeping the pressure agonist muscle at 0 bar. Required contraction of the agonist muscle for reaching a rotation angle $\theta = 140^\circ$, can be calculated as shown:

$$h = \frac{\pi \times d \times \theta}{360^\circ} \times 100\% = \frac{\pi \times 32.5 \text{ mm} \times 140^\circ}{360^\circ} \times 100\% = 19.86\%$$  

where $h$ is the contraction of the pneumatic muscle, $d$ is the muscle’s diameter, $\theta$ is the rotation angle and $L$ is the pneumatic muscle’s length.

Required contraction of the agonist muscle must therefore be at least 19.86 % or 20 %, which is the main parameter that defines the working area of the pneumatic actuator, as illustrated in Fig. 3. Diagrams of generated force vs. contraction with different pressures were put on the same diagram, where black pressure curves represent the antagonist muscle and red pressure curves represent the agonist muscle. The working area is limited on the x axis by the calculated contraction ratio of the agonist muscle. Due to the same contraction capability (25 %) the agonist muscle is also limited by the same calculated contraction. The working area (B) is also limited by the 6 bar pressure curve of each muscle. The pressure limitation was chosen due to the fact that 6 bar is the maximum operating pressure of MHJ10-S-2.5-MF valves, as specified in respective datasheet.

4. Control method

From Fig. 3, it was concluded that there are two possible control methods:

- control with reference position and reference pressure
- control with reference position and reference force.

Because of the capability to generate higher force in the same work area the first method was chosen. Firstly, the pressure in the antagonist muscle is kept constant at 6 bar. Control algorithm then follows the reference position by increasing pressure in the agonist muscle until it reaches the limit pressure 6 bar in point A (curve between point 1. and 2.), where pressures of both muscle are equal (6 bar). After reaching point A, the pressure in the agonist muscle stays constant at 6 bar while the pressure in the antagonist muscle is decreasing (curve between point 2. and 3.). The course of control method is illustrated in Fig. 4. Point A was achieved programmatically, by pressurizing both muscles to 6 ± 0,25 bar and saving the value of the rotation angle as $\theta_A$.

5. Control algorithm

The control algorithm presented in this paper consists of four separate PID algorithms, one for each valve. That configuration allows for the separate control of air input and output for each muscle and increases the control accuracy. Additionally, it consists of the valve control algorithm (which was adapted to the antagonistic system) and PID algorithm modification from A-PID control algorithm. For the determination of PID parameters Ziegler-Nichols method was used, adapted for discreet systems by Patki et al. [19].

As proved by Pipan in [13], the fast-switching valve starts to open only when the PWM signal reaches the smallest needed pulse width, which means that the error is present and the system doesn’t respond to it. Control algorithm for fast-switching valves enables faster valves response time and consequently smaller position error (which is calculated as the difference between reference and actual position). Due to the nonlinear muscles’ characteristics and consequent changes in rigidity and damping in the structure of the pneumatic muscles, the developed control algorithm optimizes PID parameters according to the reference position (due to the unequal pressure in the agonist muscle in different positions, inner structure of muscles deforms differently and consequently changes its rigidity). The block diagram of the developed control algorithm is illustrated in Fig. 5, where $\theta_A$ is the rotation angle in point A, $\theta_{ref}$ is the reference rotation angle, $\theta$ is the actual measured rotation angle, $e_p$ is the pressure difference (calculated as the difference between reference pressure 6 bar and measured pressure in the antagonist muscle) and $e_{pos}$ is the position difference (calculated as $\theta_{ref} - \theta$), PID-1/2-10/20 is PID algorithm of antagonist/agonist muscle, control algorithm 1/2-10/20 is the control algorithm of inlet/outlet valve of the agonist/agonist muscle and EL2502 1/2-1/2 is first/second module and first/second channel of the module.
6. Results and discussion

The control algorithm analysis was performed using three step functions in a sequence with different amplitudes. The PID values were optimized with regard to stiffness and dampness in the muscle and the planned trajectory. Fig. 6 illustrates the system response to step function with amplitude 60°. Due to the same pressure difference between inlet and outlet valve the response speed of both valves is approximately the same. It is also evident that the inlet valve leak is present. The system continuously compensates that by switching the outlet valve on/off.

Fig. 7 illustrates system response to step function with amplitude 100°. The initial deviation of the position is partly due to the indication of the inlet valve, the residual muscle tension, and the excessive value of the proportional parameter (at a lower value, the reaction speed of the system is significantly reduced). The system fixes the position by switching on the outlet valve, which works at a higher pressure difference than the input valve, which means that its response is slower. The pressure graph shows that the pressure initially rises to the point where the system reaches the reference position, and then slowly falls. The DMSP20 muscle inlet valve is switched off at this moment, but because the muscle is deformable, it continues to contract (internal strain and inner tension deformation occurs). Due to the formation of internal, residual stresses, and friction between the hardening fibers and the rubber jacket, when the DMSP20 output valve is switched on, the muscle does not extend in proportion to the pressure drop, which the system solves by reducing the pressure in the muscle.

Fig. 8 illustrates system response to step function with amplitude 140°. Since the pressure in the muscle DMSP10, when raising over point A, falls almost to 0 bar (as a consequence of a larger proportional member value, to achieve a significantly shorter response time of the system), the DMSP20 muscle is not limited for a short time by the force produced by the smaller muscle, which consequently, in addition to the indentation of the inlet valves and the deformation of the inside of the muscle, means a much larger deviation at the moment when the system reaches the reference position.
Since the pressure in the muscle DMSP20 in the area above point A increases slowly to 6 bar, and because the DMSP20 muscle in this state generates greater force than the DMSP10 muscle, it also affects the increase in the position error in addition to the leakage of the output valve of the muscle DMSP10. The system attempts to compensate this by turning on the input valve of the DMSP10 muscle.

Experimental results are compared to two similar systems. Although the response time of the first compared system is for 32.6 % faster than the response time of our algorithm with step function 60°, it has to be mentioned that since the step function of our algorithm is bigger than the step function of the first compared system, it is logical its response time is longer, but it also must be emphasized that the position error of our algorithm is smaller for 87.5 %. The second system has in comparison to our algorithm with step function with amplitude 60°, for 27 % longer response time and for 89.7 % bigger position error. The reason for much smaller position error of our algorithm is probably the use of fast-switching instead of proportionals for faster pressure control and the use of fast-switching valves’ control algorithm which was adapted from A-PID algorithm. Therefore, we can conclude that considering the comparison to the algorithm made by Ahn et. al. [12] In the future we will focus on upgrading the developed control algorithm in such a way, that it will compensate for different actuator loads and further stabilize the actuator.

8. References

[17] Beckhoff: Documentation for EL3104, 4-channel analog input terminal -10...+10 V. Beckhoff, 2017.

Table 2. Comparison of results

<table>
<thead>
<tr>
<th>Control</th>
<th>Muscles</th>
<th>Reference function sequence</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Self-organizing fuzzy control (SOFC) [20]</td>
<td>Pair of Festo MAS-10-260N- AA-MC-O-ER muscles</td>
<td>Step function from 0° to 18°</td>
<td>t_{0} = 0.6 s \text{ \ l_{max} = 0.6 s} \text{ \ e =</td>
</tr>
<tr>
<td>Intelligent switching control by LVQ network [12]</td>
<td>Pair of Festo MAS-10-N-220- AA-MCFK muscles</td>
<td>Linear function at 45°</td>
<td>t_{0} = 3.5 s \text{ \ l_{max} = 4.3 s} \text{ \ e = ±0,39°} \text{ \ \h_{0} = 2,5°}</td>
</tr>
<tr>
<td>Our algorithm</td>
<td>Pair of Festo DMSP-20-200N RM-RM muscles and a pair of Festo DMSP-10-200N RM-RM muscles</td>
<td>Step from 0° to 60°</td>
<td>t_{0} = 0.89 s \text{ \ l_{max} = 0.89 s} \text{ \ e = -0.038° ± 0.002°} \text{ \ \h_{0} = 0°}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Step from 0° to 100°</td>
<td>t_{0} = 0.76 s \text{ \ l_{max} = 0.76 s} \text{ \ e = -0.085° ± 0.003°} \text{ \ \h_{0} = 0°}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Step from 0° to 140°</td>
<td>t_{0} = 1.23 s \text{ \ l_{max} = 1.23 s} \text{ \ e = -0.184° ± 0.011°} \text{ \ \h_{0} = 0°}</td>
</tr>
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</table>

7. Conclusion

This paper presents the development of the control algorithm for two antagonistically coupled pneumatic muscles, based on the adaptive PID (A-PID) control algorithm for one pneumatic muscle developed by M. Pipan in [13]. With our newly developed control algorithm we can accurately control position and pressure using fast-switching pneumatic valves controlled with PWM modulation. Developed control algorithm response was analyzed using three step functions in sequence with different amplitudes (from 0° to 60°, 100° and 140°) and the results were compared to two other control architectures: the PAM actuator control system. The static position error of our algorithm was in comparison to the first control algorithm by Chang et. al. [20] smaller for 87.5 % and for 89.7 % smaller in comparison to the algorithm made by Ahn et. al. [12] In the future we will focus on upgrading the developed control algorithm in such a way, that it will compensate for different actuator loads and further stabilize the actuator.