Control of Pneumatic Artificial Muscles with Enhanced Speed Up Circuitry.

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ABSTRACT

The power to weight ratio of the actuators is an important design factor for running robots. Therefore pleated pneumatic artificial muscles are optimal actuators. Obviously the weight of the pressure control valves has to be taken into consideration as well. For this application, standard pressure regulating valves are rather heavy and slow. An intelligent controlled number of fast switching on-off valves was tested as an alternative. Ways to decrease the opening and closing times of the valves are discussed in this paper. The pressure control is used to control the angle of a joint actuated by two antagonistic pneumatic muscles. Results will show that this solution has satisfactory speed and accuracy, and reduces the weight of the pressure control significantly.

Keywords: On-Off Valves, Bang-bang Algorithm, Pneumatic Artificial Muscles

1. BACKGROUND

During the last decades research groups working on walking robots have increasingly focused on developing dynamically balanced robots in order to increase speed and smoothen motion. For these robots, all parts, but especially the actuators, need to be lightweight in order to limit inertia and motion power. Since electric motors are quite heavy, some research groups started to work with other actuators.

In the research lab of the mechanical department of the Vrije Universiteit Brussel, where the Pleated Pneumatic Artificial Muscle (PPAM) has been developed [1], one is building a dynamically controlled biped robot with PPAMs [2]. The robot is build to run dynamically, requiring a lightweight design. The frame of the robot is made of a high-grade aluminium alloy. PPAMs—which are used as actuators for the robot—have a very high power to weight ratio and an inherent and adaptable compliance which is important for energy recuperation in faster gaits. Their generated force can be as high as 4000 N at a gauge pressure of 3 bar, while the device itself weighs only 100 g. To power a joint bi-directional, two muscles have to be antagonistically coupled. This way, the angle of the joint depends on the ratios of both muscle gauge pressures while its compliance is determined by the sum of pressures.

As is the case for all pneumatic actuators, the pressure in the PPAMs needs to be controlled by pneumatic valves. This can be done by off-the-shelf pressure regulating servo-valves, either continuously or on-off controlled. The former type was found to be too heavy and too slow for our application. Therefore fast switching on-off valves have been used to make fast and lightweight proportional pressure servo-valves. By making them ourselves, full control over the servo-valve control system was gained, which is usually concealed in commercial valves. The control system can be tuned and adapted for a specific application—e.g. in order to use the springiness of the muscles to bend the knee after touchdown and jump back up again and thereby save valuable energy it must be able to close the muscles completely which cannot be done by all commercial valves.

2. THE VALVES

In order to realize a fast and accurate pressure control, fast on-off valves are used. Since the pressure control is designed for the dynamically balanced biped, the weight should be restricted. The pneumatic solenoid valve 821 2/2 NC made by Matrix [3] weights only 25 g. With their reported opening times of about 1 ms and flow rate of 180 Nl/min, they are about the fastest switching valves currently available.

Since experiments resulted in switching times of more than 1 ms for most of the permitted values of pressure difference across the valve, ways to speed up the valve were studied. In the 821 valves the airflow is interrupted by a flapper forced by an internal spring to close the outlet. The electromagnetic force of the coil opens of the valve. To decrease the opening time the manufacturer proposes a speed up in tension circuitry using 24 V during 2.5 ms and 5 V afterwards. The flapper is thus mainly subjected to 3 forces: the spring, the electromagnetic force and the resultant force caused by the difference in pressure. The influence of each of these forces on opening and closing times will be studied. The magnetic force was varied by the level of the initial opening voltage. Running tests with and without spring revealed the influence of the spring. It was found that to ensure proper closing of the valve, the spring cannot be removed if the pressure difference across the valve is less than 2 bar.

Distinct and easy determinable opening and closing times have to be defined to compare test results. The moment the valve is fully opened can be determined from the electrical current pattern [4]. However the airflow through the valve starts before the valve is fully opened and closing times cannot be defined consistently by the current pattern, the outlet pressure pattern was studied. Opening the valve resulted in a step like increase of outlet pressure, closing in a step like decrease. The moments of opening and closing are defined as the time 10 % of the full step size was measured.

The influence of the level of opening voltage is diagrammed in figure 1. Increasing this voltage reduces opening time, so it needs not to be applied for 2.5 ms. Figure 2 shows the consumed electric power—a measure for the produced heat—if the voltage is dropped to 5 V as soon as the valve is open. These results show that increasing the voltage to 35 V followed by an immediate drop to 5 V when the valve is open, will reduce opening times without increasing the produced heat, which is of major influence on the valve's service life. Figure 3 shows enhanced opening times as function of the difference across the valve.

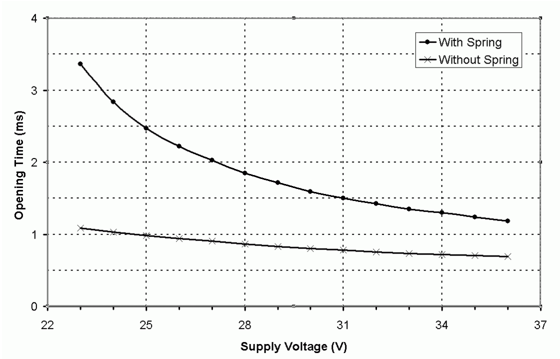


figure 1 : Influence of supply voltage on the opening time of the valves, Δp=4,6 bar

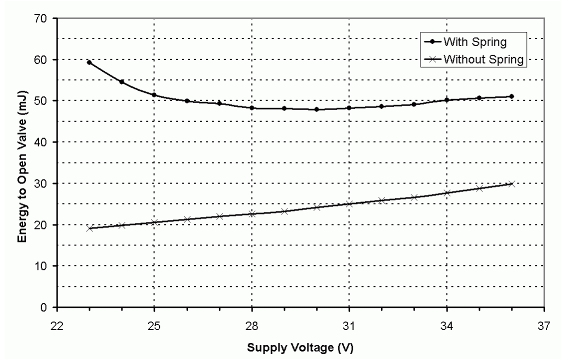


figure 2: Influence of supply voltage on energy to open valve, Δp=4,6 bar

To improve the closing times, a resistor was added to the coil's discharge circuit. This will dissipate the electromagnetic energy but, at the same time, impose a reverse voltage on the coil. Too high a resistance will thus destroy the coil. Too low a resistance will slow down the energy dissipation. Experiments showed a resistor of 200 Ohms to be a good compromise. The reverse voltage will be kept beneath 50 V and the demagnetisation time remains less than about 200 ms. This results in shorter closing times, as can be seen in figure 4.

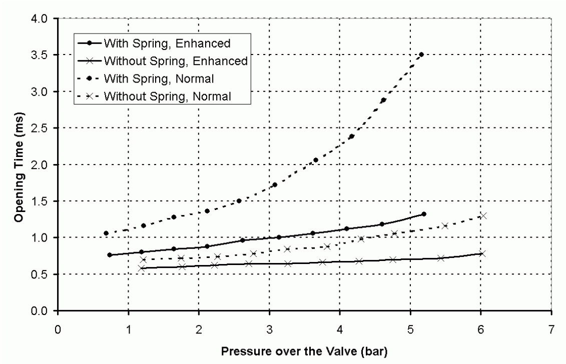


figure 3: Opening times of valve

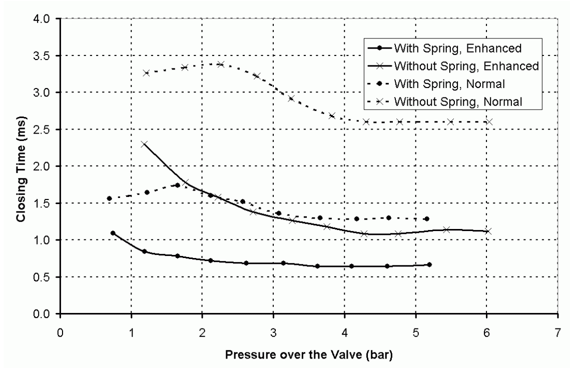


figure 4: Closing times of valve

Due to the enhancements to the speed up in tension circuit and the resistor to dissipate the energy of the coil, opening times and closing times are reduces significantly. In the targeted system – pressure control of a PPAM - the differential pressure across the inlet valves is at all times higher than 4 bar and the differential pressure across outlet valves is always lower than 3 bar. Figure 3 points out that removing the spring from the inlet valves justifies the 35 V to be applied only for 1 ms, since all opening times are within this time.

3 PRESSURE CONTOL OF A CONSTANT VOLUME

When using on-off valves instead of a proportional valve, a controller is needed to generate the command signals for the valves. A Motorola 68HC916Y3 microcontroller will be used because of the experience with this type of controller, the processing power, the internal memory and the valuable features [5]. In order to control the pressure with 2/2 valves a minimum of 1 inlet and 1 outlet valve is required. Obviously the more valves used in parallel, the faster a volume can be pressurised or depressurised, but power consumption, price and weight of the pressure control will increase.

A model of the valves and volume was made in Matlab - Simulink [6] and tuned with experimental results to ease the simulation of different control algorithms. In the simulations a volume of 300 cc was used, since this is comparable to the volume of the PPAMs used in the biped robot.

To optimise the number of valves, the ability to pressurise and depressurise the volume in approximately the same amount of time is used as criterion. As is well known from fluid mechanics, the mass flow is proportional to the supply pressure. This results for the 821 valves and 300 cc volume in a twice as fast increase compared to decrease of pressure. Therefore the number of outlet valves should be twice the number of the inlet valves. Secondly, the use of the pressure control for a PPAM in a dynamical biped requires the ability to change the pressure in the volume faster than in case of 1 inlet and 2 outlet valves. Therefore the number of valves was doubled, resulting in a set-up with 2 inlet valves and 4 outlet valves. From the satisfactory results of the simulations as shown in figure 5, the decision was taken not to increase the number of valves any further.

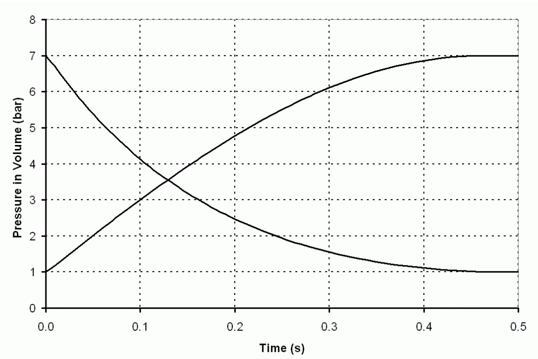
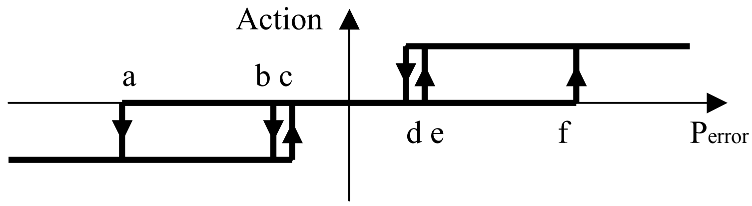


figure 5: Comparison 2 Inlet and 4 Outlet valves on 300 cc volume

One should realise the pressure limit of the PPAM—being 4 bar—introduces an even more unbalanced situation: since the pressure difference across the inlet valve is minimum 4 bar and across the outlet valves it is maximum 3 bar, the inlet mass flow—when not choked—will be larger than the outlet mass flow, even through the double number of valves.

Two control algorithms will we simulated and the better will used for experiments. The use of Pulse Width Modulation requires modification of the algorithm, since a standard PWM controller generates only one output signal of which the duty cycle is function of the error between the requested value and measured value. For the discussed pressure control a positive error—pressure too low—requests an action of the inlet valves. A negative error triggers the outlet valves. Therefore, the absolute value of the error is used to generate the PWM signal and its sign determines which valves are used. Simulations showed improvement in accuracy when different inlet and outlet valves were controlled separately. Therefore the duty cycle was calculated as if there was only one inlet and one outlet valve. In case of a duty cycle higher than 100 % more valves are used and the duty cycle is divided by the number of valves.

Secondly a bang-bang controller, which normally takes only the sign of the error between the requested value and measured value in consideration, was studied. The output signal was split to control inlet and outlet valves and a dead zone was introduced to eliminate oscillations about the requested pressure. As was the case for the PWM, the separate control of the 2 inlet or 4 outlet valves showed improvement in accuracy. Therefore, in case of the outlet valves, the value of the error was compared to 4 levels, each controlling 1 outlet valve. Since no significant improvement was seen compared to 2 levels—1 valve or 4 valves—the outlet valves were controlled in 2 levels, as was done with the inlet valves. Figure 6 visualizes the actions of the modified bang-bang controller.



Actions

a)	*-60 mbar*	*Open all outlet valves*
b)	*-20 mbar*	*Open only one outlet valve*
c)	*-15 mbar*	*Close all outlet valves*
d)	*15 mbar*	*Close all inlet valves*
e)	*20 mbar*	*Open only one inlet valve*
f)	*60 mbar*	*Open both inlet valves*

figure 6: Visualisation of the actions of the bang-bang controller

The simulations of PWM and bang-bang control gave comparable results, but the bang-bang algorithm requires less processor time, which is important when incorporated in a higher-level controller. To structuralize the program, the bang-bang controller is programmed as a real time interrupt with a period of 723 μs, because figure 3 shows this the shortest opening time. Figure 7 shows the experimental results of an increase of pressure from 1 bar to 1.5, 2, 3 and 4 bar, while figure 8 shows the results for a decrease from 4 bar to 3, 2, 1.5 and 1 bar in the volume.

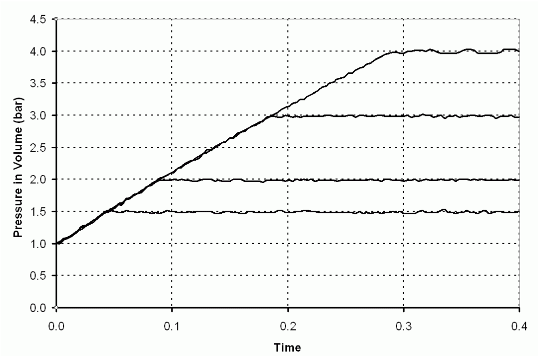


figure 7 : Pressure Control (increasing pressure)

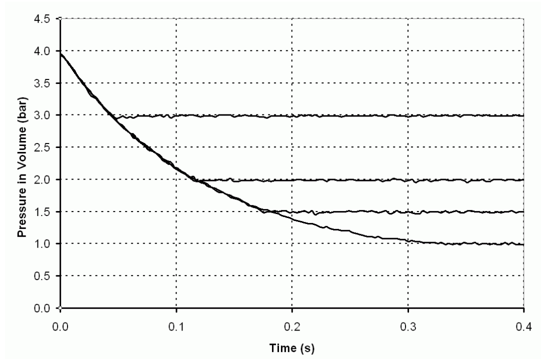


figure 8 : Pressure Control (decreasing pressure)

As can be seen from previous figures, this pressure control is fast and accurate. Experiments showed the different levels of the bang-bang controller can be adapted to optimise the controller in case of higher or lower requested pressures.

4 ROTATIVE JOINT WITH TO PPAM'S

Since the PPAM is a unidirectional actuator, two antagonistic coupled PPAMs are needed to actuate a rotative joint. The joint controller will consist of two pressure controllers, one for each muscle, and a higher-level position controller. In figure 9 the system under test, see also [1], is sketched. The points of attachment of the PPAMs together with muscle dimensions determine the torque characteristics and also the range in which the joint can rotate, since the muscles have limited contraction ratios. These points are chosen such that the highly non-linear force characteristics of the PPAMs transform to a linear angle/torque and the rotation of the lever arm is ranging from –30° to 30°.

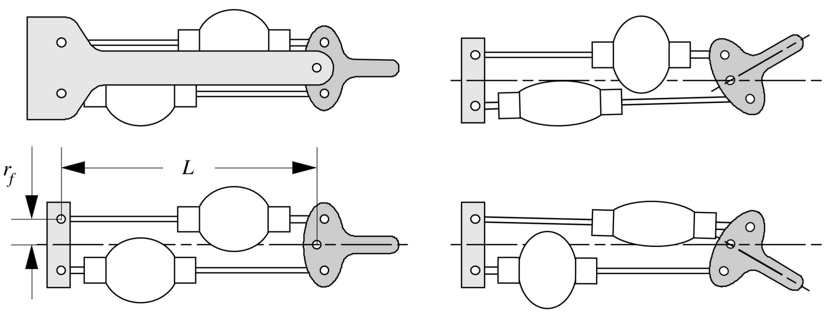


figure 9: Rotative joint actuated by 2 antagonistic PPAM's

Since the optimal number of valves was determined for a constant volume, a new criterion is needed for this set-up, involving the controllability of the angle. To reduce oscillations when moving the lever arm at constant compliance [1], the pressure in one muscle should decrease as fast as the pressure in the other muscle increases. The joint angle controller was simulated with different number of inlet and outlet valves for an average pressure of 2.5 bar. The response times for a variation of 0.8 bar, which results in a rotation from 0° to 21°, are plotted figure in 10.

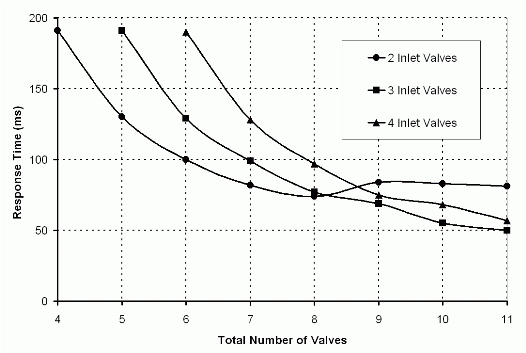


figure 10: The open loop step response time with different number of valves.

The curves start at the same level due to the fact that all three set-ups initially make use of 2 outlet valves, which determine the speed. The curve with 2 inlet valves rises when used in combination with 7 outlet valves because the difference between inlet and outlet speed creates strong oscillations, which decrease the average speed. Two inlet valves will be used, since response times are satisfactory on a comparable constant volume with 2 inlet valves. Although when two inlet valves are used speed still can be increased slightly, 4 outlet valves are a preferred compromise on price, electric power consumption and weight.

The complete system is highly non linear since it has two bang-bang controllers with a dead zone and two levels, twelve on-off valves and 2 PPAMs. Standard linear techniques are not able to create a robust angle controller for this system. A PID controller will be studied by simulating the different actions separately on a system without external load.

Since elimination of the final error requires an I-action, first a purely I-controller was tested. Too high an I-gain will create an overshoot. Too low an I-gain slows down the system response. Since the optimal gain depends strongly on the average pressure and on the angle variation, an adaptive controller is required. The oscillations appearing in the step response can be eliminated almost completely by introducing a D-action with a small gain, independent of the pressure. To complete the PID controller a P-action was added, but since no significant improvement was seen on the system without load, the P-action will be removed temporarily.

In figure 11 the simulated response of steps of 0° to 10°, 20° and 30° with an average pressure of 2.5 bar are plotted. Figure 12 shows the corresponding experimental results. Figure 12 shows the system without load and with an adaptive ID-controller is fast and accurate, except in the extreme limits. A small overshoot can be seen for angles around 30°, probably because the PPAMs cannot deliver enough force when fully contracted [1].

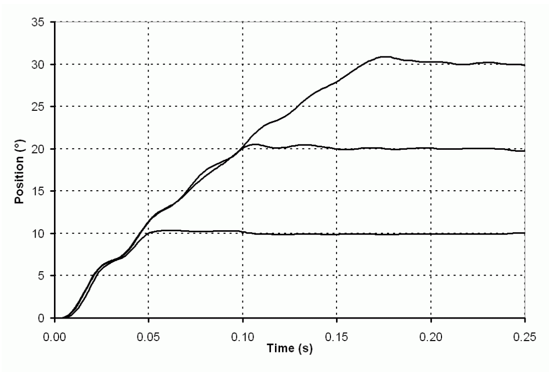


figure 11: Simulated step response without load

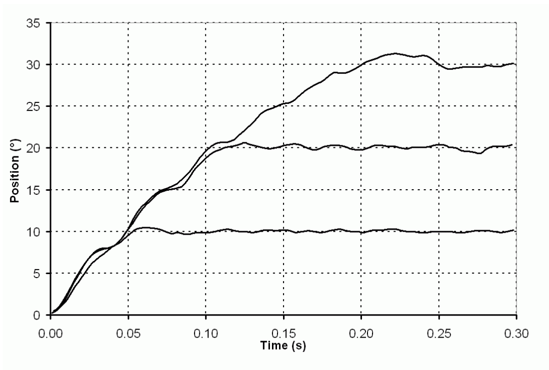


figure 12: Experimental step response without load

When an arm with a length of 195 mm is charged with a load of 1 kg, the P-action of the controller becomes more useful to decrease the response time. The gains of the PID controller have to be tuned again as a function of angle variation and average pressure. Although the simulation (figure 13) shows the joint can be controlled without oscillations, this cannot be achieved in the experimental set-up (figure 14). Modification of the D-gain cannot eliminate the oscillations, since the noise on the pressure measurements is blown up in the differentiator.

The analogue pressure sensor, placed outside the muscle, is linked to the internal AD converter of the microcontoller by relatively long wires, which are subject to noise from the microcontoller clock and power circuits of the valves. Preliminary tests with a digital pressure sensor increased the resolution of the pressure measurement by a factor 4, which will allow the D-action to lower the oscillations.

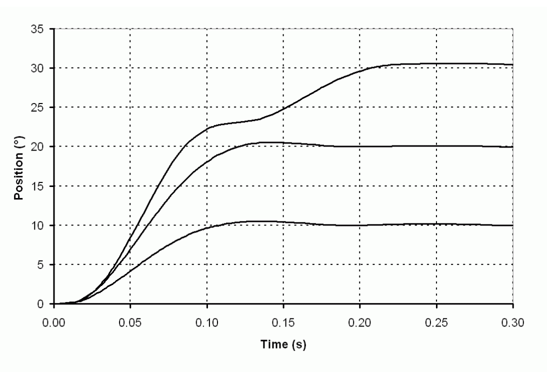


figure 13: Simulated step response with load

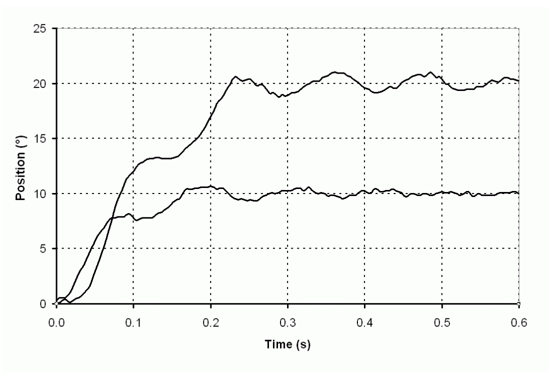


figure 14: Experimental step response with load

CONCLUSION

A lightweight on-off valve with enhanced speed up circuitry and in some cases removal of the internal spring, showed significantly reduced opening and closing times. These enhanced valves can be used to build a fast and accurate pressure control system, which is lighter and cheaper than existing proportional valves. The bang-bang controller with dead zone is an optimal pressure controller, which is easy to program, needs little computing power and results in good performance. A rotative joint actuated by two pneumatic muscles and controlled by an adaptive PID angle controller combined with two bang-bang pressure controllers, gives satisfactory results.

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