FAST AND ACCURATE PRESSURE CONTROL USING ON-OFF VALVES

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Abstract

Pneumatic cylinders and pneumatic muscles are lightweight, clean and multifunctional actuators, requiring pressure-regulating valves for positioning. To use them in mobile applications commercial pressure-regulating valves are quite heavy and rather slow. Therefore an intelligent controlled array of fast switching on-off valves is presented as an alternative. The speed of the on-off valves determines the performance of the pressure-regulating valve. To reduce the opening time of the valves, a higher voltage is applied on the coil for a short time. The influence of this method on the heating of the valve will be discussed. A diode, which drains away the electromagnetic power from the coil, reduces the closing time. When working with pneumatic muscles, it is in some cases justified to remove the internal spring to enhance the opening time. A modified bang-bang controller, with more than one level and a dead zone is presented. Experimental results on a fixed volume are discussed. A special designed collector combines 6 on-off valves into a lightweight pressure control valve island, which is perfectly suited for walking robots such as the pneumatic actuated biped Lucy.

Keywords: pressure control, pneumatic muscles, bang-bang controller

1 Introduction

During the last decades several research groups working on walking robots have increasingly focused on developing dynamically balanced robots in order to achieve higher speed and smoother motion. For these robots, all parts, including the actuators, need to be lightweight in order to limit inertia and motion power. Since electric motors are quite heavy, some research groups (Albiez et al, 2003) and companies (Shadow Robot Company, 2005) started to work with other actuators.

The multibody mechanics research group of the mechanical department of the ‘Vrije Universiteit Brussel’, a member of the European thematic network on Climbing and Walking Robots (CLAWAR) has developed the Pleated Pneumatic Artificial Muscle (PPAM) (Daerden et al, 2001). Currently, a dynamically controlled biped robot, named Lucy, with PPAMs is being built (Ham et al, 2003). Lucy is designed to walk dynamically, which requires a lightweight design. Therefore the frame of the robot is made of a high-grade aluminium alloy and is actuated with PPAMs, which a very high power to weight ratio and an inherent and adjustable compliance. To power a bi-directional joint, two muscles have to be antagonistically coupled, since PPAMs are one-way acting. By only choosing the points where the PPAMs are attached in a specific way, the angle of the joint depends on a weighted difference of both muscle gauge pressures, while its compliance is determined by a weighted sum of the pressures. This means both angle and compliance of a joint can be adjusted independently, which can be very useful for walking robots and is not the case with most other actuators.

As for all pneumatic muscle 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. This solution is used more and more recently in pneumatics (Heon-Sul et al, 2002) as in hydraulics (Varseveld et al, 1997), since putting the valves together yourselves, gives full control over the servo-valve control system, 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, thereby saving valuable energy, it must

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be able to close the muscles completely which cannot be done by all commercial proportional valves.

Controlling the on-off valves can be done by using various algorithms, such as a PWM controller or a bang bang controller. Of importance for each algorithm is the response time of the valves, which is also a function of the pressure over the valve. As a first step the opening and closing times of the valves were measured in a comparable way. Then several approaches to decrease opening time and closing time were studied.

Since the flow rate of the on/off valves was too small to reach adequate speed for the dynamic biped, the pressure control is done by a number of on-off valves placed in parallel.

This pressure control, however designed for a walking robot application, can be used in the much broader field of pneumatics, since not only the weight is an advantage, but also the speed and the price of the designed valve system.

2 Pleated Pneumatic Artificial Muscles

A pneumatic artificial muscle is, in essence, a membrane that will expand radially and contract axially when inflated, while generating high pulling forces along the longitudinal axis. Different designs have been developed. The best known is the so-called McKibben muscle (Schulte, 1961). This muscle contains a rubber tube, which will expand when inflated, while a surrounding netting transfers tension. Hysteresis, due to dry friction between the netting and the rubber tube, makes control of such a device rather complicated. Typical for this type of muscles is the existence of a threshold level of pressure before any action can take place. The main goal of the new design was to avoid both friction and hysteresis, thus making control easier, while avoiding the threshold. This was achieved by arranging the membrane into radially laid out folds that can unfurl free of radial stress when inflated. Stiff longitudinal fibres, which are positioned at the bottom of each crease, transfer the tension. A photograph of the inflated and deflated state of the Pleated Pneumatic Artificial Muscle is given in Fig. 1.

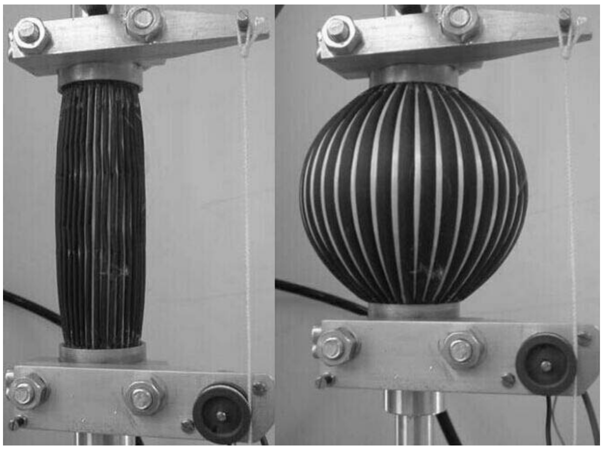


Fig. 1: *Deflated and inflated PPAM*

If we neglect the influence of the elasticity of the high tensile strength material used for the membrane, the characteristic for the generated force is given by:

$$F_t = pl^2 f_t\left(\varepsilon, \frac{l}{R}\right) \tag{1}$$

where p is the applied gauge pressure, l the muscle's maximum length, R it's unloaded radius and ε the contraction. The dimensionless function f_t depends only on contraction and geometry. The higher R, the less it contracts and the higher the force it generates. Contraction can reach up to 54% in a theoretical case with $R/l = 0$, which is bounded in practice because of minimum space needed to fold the membrane. Forces at low contraction are extremely high, causing excessive material loading, and generated forces drop very low for large contraction, thus restricting the useful contraction range to about 5 to 35%, depending on R/l. The graph in Fig. 2 gives the generated force for different pressures of a muscle with initial length l=100 mm and unloaded diameter R=25 mm. Forces up to 3000 N can be generated with gauge pressure of only 3 bar while the device weighs about 100 g.

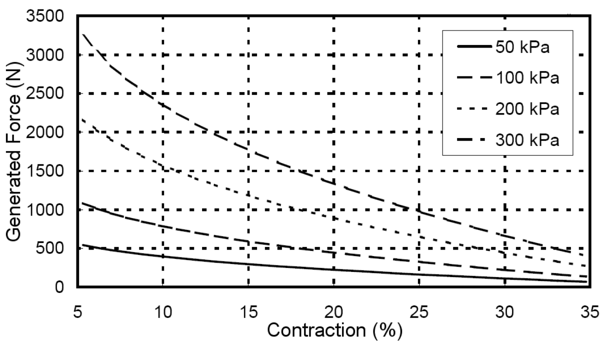


Fig 2: *Generated forces PPAM (N)*

The graphs shown are derived from a mathematical model, which match experimental results with deviations of less than a few percent (Daerden et al, 2001). This mathematical model will be of great importance for the design process of the different joints. Low values of the broadness R/l result in the highest possible contractions. However space limitations impose a lower limit on R/l. Once the broadness is chosen and the pressure limits are set at 3 to maximum 4 bar, to prevent rupture of the membrane, length becomes the major design factor. Equation 1 shows that the generated force is proportional to l^2. Once the PPAM is made with a certain length and radius, the pressure is the only way to control the PPAM.

3 The Valves and Speedup Circuitry

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. In (Raparelli et al, 2001) a solution with small on-off valves is described to build a robotic arm with pneumatic muscles. Figure 3 shows the pneumatic solenoid valve 821 2/2 NC made by Matrix (Matrix, 1998), which weights only 25 g. With their reported opening times of about 1ms and flow rate of 180 Nl/min, they are about the fastest switching valves currently available.

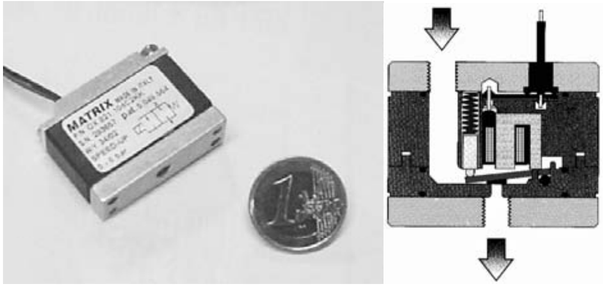


Fig. 3: *Picture of the Matric 821 2/2 NC Valve and sliced view (Matrix, 1998)*

Since experiments resulted in switching times of more than 1ms for most of the permitted values of pressure difference across the valve, ways to speed up the valve were studied. The airflow through these valves is interrupted by a flapper, which is forced by the pressure difference over the valve and additionally by an internal spring to ensure proper closing of the valve. The electromagnetic force of the coil working on this flapper 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 pressure difference over the valve. The influence of each of these forces on opening and closing times was studied. The initial magnetic force was varied by the level of the initial voltage to open the valve. Since opening the valve requires more force than keeping the valve open, the voltage over the coil will be reduced to 5 V once the valve is opened. Running tests with and without spring revealed the influence of the spring. The force of the spring acts in the same direction as the pressure over the valve. It was found that to ensure proper closing of the valve, one of these forces is required, so the spring cannot be removed if the pressure difference across the valve is less than 2 bar.

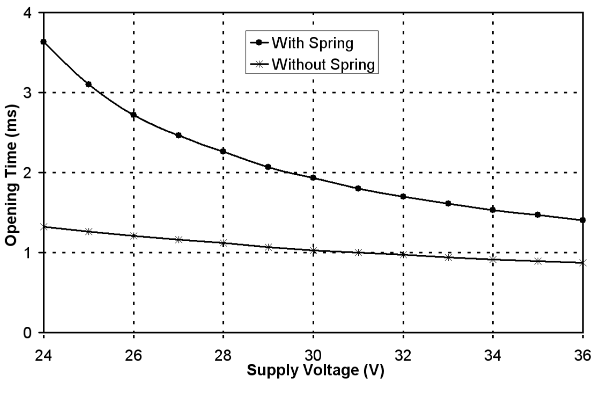


Fig. 4: *Influence of supply voltage on the opening time of the valves, Δp=4.6 bar*

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 (Eschmann, 1994). However the airflow through the valve starts before the valve is fully opened, also closing times cannot be defined consistently by the current pattern. Therefore the outlet pressure pattern was studied. Opening the valve resulted in a steplike increase of outlet pressure, while closing resulted in a step like decrease. The moments of opening and closing are defined as the time at which 10% of the full step size in outlet pressure was measured.

The influence of the opening voltage level, for a pressure over the valve of 4.6 bar, is diagrammed in Fig. 3. Increasing this voltage reduces opening time, so the higher voltage doesn’t need to be applied for 2.5 ms.

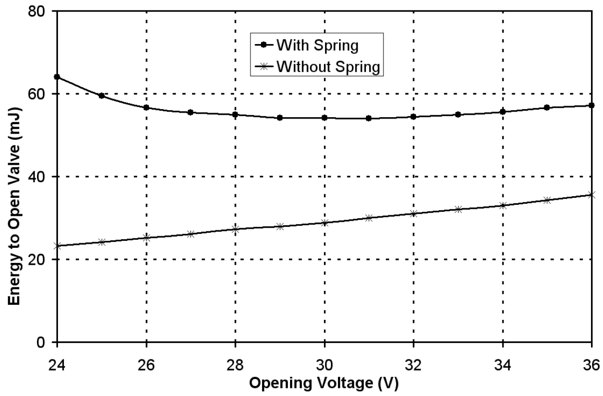


Fig. 5: *Influence of supply voltage on energy to open valve, Δp=4.6 bar*

Figure 5 shows the consumed electric power to open the valve, which is a measure for the produced heat. These results show that increasing the voltage to 35 V followed by an immediate drop to 5 V, when the valve has opened, will reduce opening times without increasing the produced heat, which is of major influence on the valve’s service life. Figure 6a shows enhanced opening times as function of the pressure difference across the valve. A significant improvement can be seen in case of larger pressure differences over the valve.

To improve the closing times, a diode between the negative contact of the coil is connected to the 35 V, so the demagnetization time drops to about 200 ms. Obviously, this results in much shorter closing times, as can be seen in Fig. 6b.

Due to the enhancements to the speed up in tension circuit and the placement of the diode, opening times and closing times are reduced significantly, in some cases to less than 50%.

In the targeted system - the pressure control of a PPAM working between 0 and 3 bar, with a supply pressure of 6 bar - the differential pressure across the inlet valves is at all times higher than 3 bar and the differential pressure across outlet valves is always less than 3 bar. In Fig. 7, showing partly the same data as Fig. 6, the enhanced opening and closing times of the outlet valve with spring and the inlet valve without spring are plotted. Figure 7 shows that the use of the valve with internal spring as outlet valve and a valve without spring as inlet valve is justified.

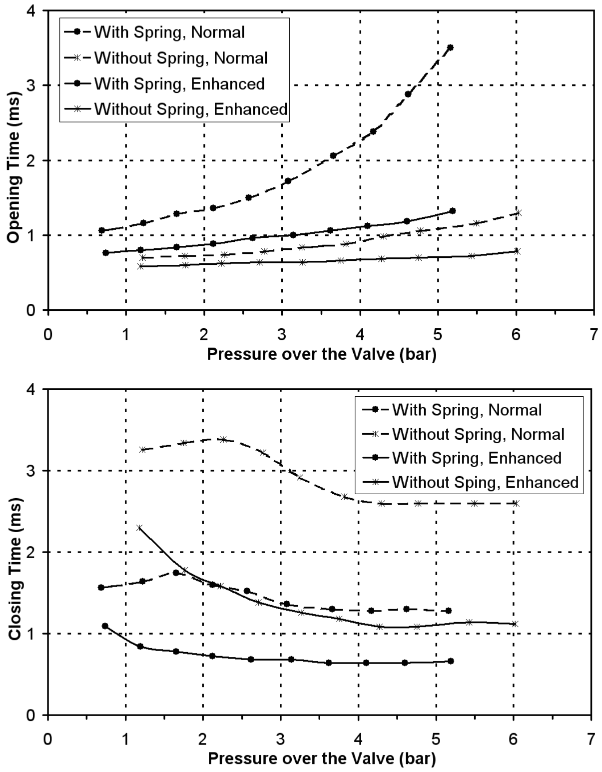


Fig. 6: *(a) Opening times and (b) closing times of valves*

Figure 7 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. In our setup we'll use a fixed time of 1ms, since detecting the actual opening of the valve would require an extra pressure sensor placed nearby the outlet of the valve. This was avoided to reduce costs. On the other hand when several valves will be placed in parallel, it's difficult to detect the exact opening moment of each valve by looking at the pressure.

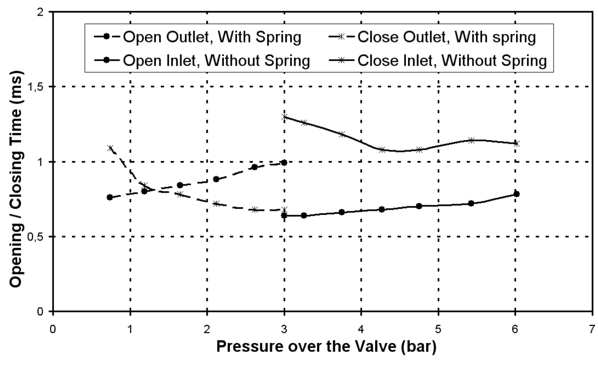


Fig. 7: *Opening times and closing times of valves – when using PPAM between 0 and 3 bar*

Figure 7 also shows that closing times are always less than 1.5 ms when using the valves in combination with PPAMs, working between 0 bar and 3 bar and with a supply pressure of 6 bar.

4 Pressure Control of a Constant Volume

When building a pressure control with on-off valves, a controller is needed to generate the command signals for the valves. A Motorola 68HC916Y3 microcontroller (Freescale Semiconductor, 2004) is used because of the experience with this type of controller, the processing power, the internal memory and certain valuable features: e.g. analogue to digital converter, incremental encoder counter. 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 pressurized or depressurized, but power consumption, price and weight of the pressure control will increase.

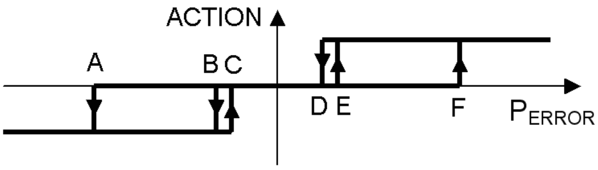
A model of the valves and volume is made in Simulink^{TM} and tuned with experimental results to ease the simulation of different control algorithms. In the simulations a volume of 300 cc is used, since this is comparable to the volume of the PPAMs in the biped robot Lucy (Ham et al, 2003).

To optimize the number of valves, the ability to pressurize and depressurize the volume in approximately the same amount of time is used as a first criterion. As is well known from fluid mechanics, the mass flow is proportional to the supply pressure. This results for the 821 valves with a supply pressure of 6 bar 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 is feasible with 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.

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

Two control algorithms were simulated and the better was used for experiments. First a Pulse Width Modulation (PWM) was studied. The use of a PWM 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 - meaning that the pressure is 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. Since controlling the inlet valves separately improves the accuracy, the PWM algorithm was modified. The calculated duty cycle was divided over the valves, e.g. when the duty cycle for the two inlet valves is 60%, one valve will be opened continuously (duty cycle equals 100%) and the other with a duty cycle of 20%.

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 around 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 8 visualizes the actions of the modified bang-bang controller.



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

Fig. 8: *Visualisation of the actions of the bang-bang controller*

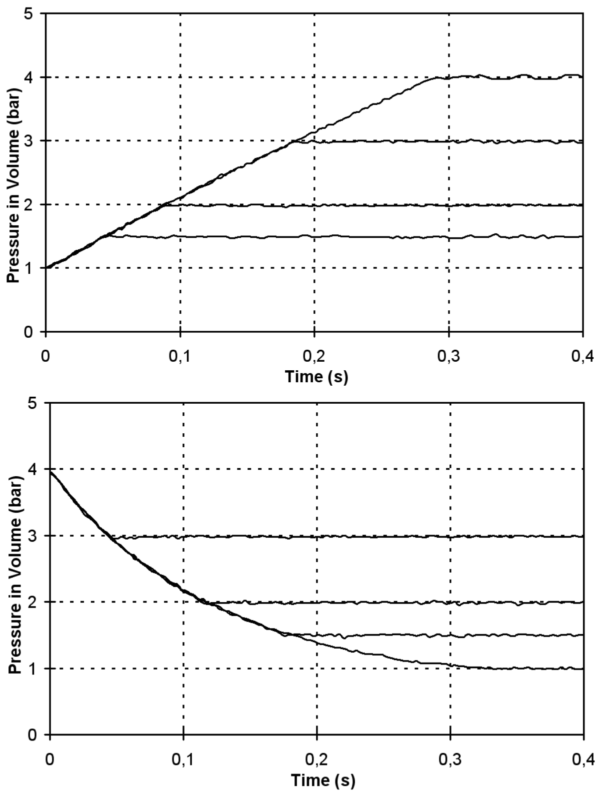


Fig. 9: *Pressure Control (Increasing and decreasing pressure)*

The simulations of PWM and bang-bang control gave comparable results, but the bang-bang algorithm can be adjusted in a more intuitive way; e.g. when the final error is to big, the dead zone can easily be reduced or when small oscillations around the final value occur, they can be reduced by enlarging the dead zone. This is useful when this pressure controller will be 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 microsec, because Fig. 7 shows this the shortest opening time. Figure 9 shows the experimental results for an increase of pressure from 1 bar to 1.5, 2, 3 and 4 bar. Figure 8 shows also the results for a decrease from 4 bar to 3, 2, 1.5 and 1 bar in the volume.

As can be seen from Fig.9, this pressure control is fast and accurate. Additionally, experiments showed that the different levels of the bang-bang controller could be adapted to optimize the controller in case of higher or lower requested pressures.

Since each valve has it's own collector to connect the in and outlet tubes, a lot of useless weight is present. To remove this extra weight and make the valve array as compact as possible, a special collector was designed. The complete pressure-regulating valve, built with 6 single on-off valves and the two special collectors are shown in Fig 10.

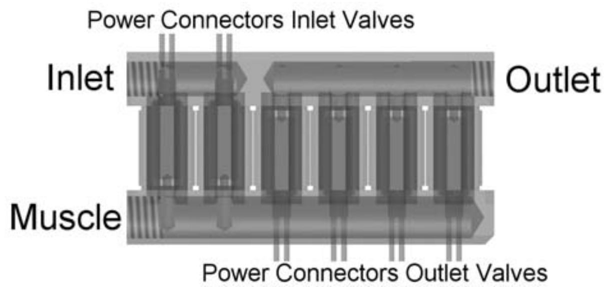


Fig. 10: *Sliced view of the complete pressure control valve island with 2 inlet and 4 outlet valves*

These collectors replace the original aluminium connector plates of the valves, resulting in a weight of the complete pressure valve not more than the weight of 6 single valves.

5 Conclusions

In this paper a fast and lightweight pressure-regulating valve was presented. It was constructed with 6 on-off valves and 2 special designed collectors. The opening times of the on-off valves were enhanced significantly by increasing the initial value of the supply voltage and, depending on the pressure difference over the valve, removing the internal spring. A diode to drain away the electromagnetic power from the coil reduced the closing time to less than 50% in some cases. Since these adaptations do not increase heat production, the life span of the valves is not reduced

A multilevel bang-bang controller was presented. This control strategy allows the user to modify easily the parameters of the controller. The presented pressure-regulating valve allows the volume of a muscle, used in the biped Lucy, to be fully pressurized and fully depressurized in less than 300 ms.

This pressure control, which was designed to be used in walking robots, can however be used in the much broader field of pneumatics, not only due the low weight, but also due to high operation speed and low cost.

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