# Pressure Control with On-Off Valves of Pleated Pneumatic Artificial Muscles in a Modular One-Dimensional Rotational Joint.

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**Abstract.** The power to weight ratio of the actuators is an important design factor for running robots. In this regard pleated pneumatic artificial muscles are excellent actuators. Another advantage is that they can actuate a joint directly, avoiding the additional weight of a gearbox. 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 intelligently controlled array of fast switching on-off valves was tested as an alternative. Ways to decrease the opening and closing times of these valves are discussed in this paper. Simulations and experimental results will be compared. The design of a modular rotational joint with an antagonistic set-up of two pleated pneumatic artificial muscles will be presented.

## 1 Introduction

During the last decades 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 [1] and companies [2] started to work with other actuators.

In the research lab of the mechanical department of the Vrije Universiteit Brussel, a member of the European thematic network on Climbing and Walking Robots (CLAWAR) [3] the Pleated Pneumatic Artificial Muscle (PPAM) has been developed [4]. Currently a dynamically controlled biped robot, named Lucy, with PPAMs is being built. [5]. Lucy is designed to run dynamically, which requires a lightweight design. The frame of the robot is made of a high-grade aluminium alloy. PPAMs—the actuators of the robot—have a very high power to weight ratio and an inherent and adjustable compliance which is important for energy recuperation in faster gaits. To power a bi-directional joint, two muscles have to be antagonistically coupled, since PPAMs are one-way acting. By 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.

As is the case 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. 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, thereby saving valuable energy, it must be able to close the muscles completely which cannot be done by all commercial valves.

The design of the biped is based on modularity and flexibility, in order to decrease design efforts and costs, and to be able to make minor modifications during the building process. Due to the flexible design of the biped, it can be configured easily for other experiments—e.g. using different points of attachment to achieve other force-angle characteristics and other joint angle limits.

As a first step in the design the pressure control was developed and tested on a constant volume. Since the volume of a pneumatic muscle is function of the contraction, further experiments were done with a preliminary joint actuated by two pneumatic muscles, of which the pressure control is done by a number of on-off valves in parallel.

From the experience with a preliminary setup, a final modular 2 dimensional joint was designed. Angle and pressure sensors were evaluated and where necessary replaced by more suitable devices. In the biped the concept of modularity will not only be implemented in mechanical design and on pneumatics, but also on the electronics and low-level control.

## 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 [6]. 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 of this type of muscles is a threshold level of pressure before any action can take place. The main goal of our new design [7] 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. Tension is transferred by stiff longitudinal fibres that are positioned at the bottom of each crease. A photograph of the inflated and deflated state of the Pleated Pneumatic Artificial Muscle is given in figures 1 and 2.

Fig. 1: Photograph of deflated PPAM

Fig. 2: Photograph of inflated PPAM

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

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

where $p$ is the applied gauge pressure, $l$ the muscle's maximum length, $R$ it's unloaded radius and $\epsilon$ the contraction. The dimensionless function $f_t$, which depends only on contraction and geometry, is given for different values of broadness $R/l$ on the graph in figure 3.

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 figure 4 gives the generated force for different pressures of a muscle with initial length $l = 100mm$ and unloaded diameter $R = 25mm$. Forces up to $3000N$ can be generated with gauge pressure of only $3bar$ while the device weighs about $100g$.

The graphs shown are derived from a mathematical model which match experimental results with deviations of less than a few percent. 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 $4bar$, to prevent rupture of the membrane, length becomes the major design factor. Expression (1) shows that the generated

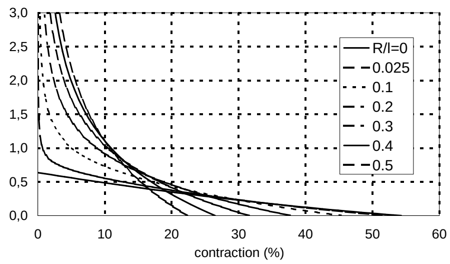


Fig. 3: Dimensionless function $f_t$

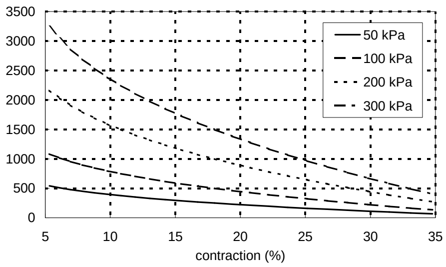


Fig. 4: Generated forces (N)

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

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 [8] weights only $25g$. With their reported opening times of about $1ms$ and flow rate of $180Nl/min$, they are about the fastest switching valves currently available. In figure 5 a picture of the valve is shown.


Fig. 5: Photograph of Matrix 821 2/2 $NC$ Valve

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. 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 $24V$ during $2.5ms$ and $5V$ 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 $2bar$.

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 [9]. 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.

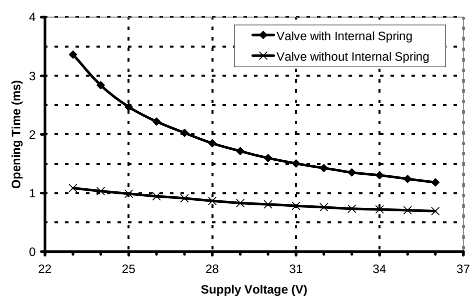


Fig. 6: Influence of supply voltage on the opening time of the valves, $\Delta p = 4.6bar$

The influence of the level of opening voltage is diagrammed in figure 6. Increasing this voltage reduces opening time, so it needs not to be applied for $2.5ms$.

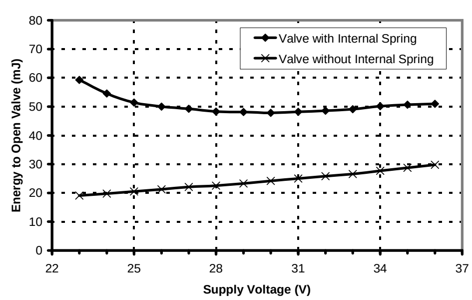


Fig. 7: Influence of supply voltage on energy to open valve, $\Delta p = 4.6bar$

Figure 7 shows the consumed electric power—a measure for the produced heat—if the voltage is dropped to $5V$ as soon as the valve is open. These results show that increasing the voltage to $35V$ followed by an immediate drop to $5V$ when the valve is open, will reduce opening times without increasing the produced heat, which is of major influence on the valves service life. Figure 8 shows enhanced opening times as function of the difference across the valve.

To improve the closing times, a resistor was added to the coils 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 $200\Omega$ to be a good compromise. The reverse voltage will be kept beneath $50V$ and the demagnetization time remains less than about $200ms$. This results in shorter closing times, as can be seen in figure 9.

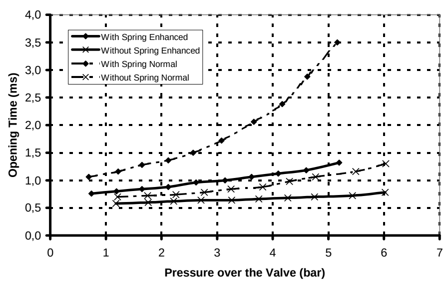


Fig. 8: Opening times of valves

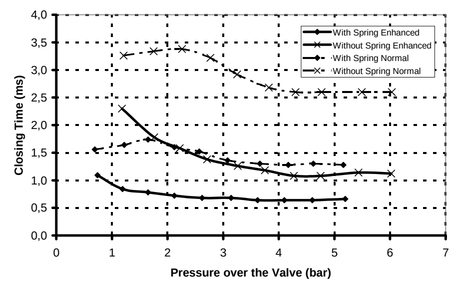


Fig. 9: Closing times of valves

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 3 bar and the differential pressure across outlet valves is always lower than $3bar$. This justify the use of the valve with internal spring as outlet valve and a valve without spring as inlet valve.

Figure 10 points out that removing the spring from the inlet valves justifies the $35V$ to be applied only for $1ms$, since all opening times are within this time. Figure 11 shows that in these cases closing times are always less than $1.5ms$, in case of using the valves in combination with PPAMs, working between $0bar$ and $3bar$.

## 4 Pressure Control 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 [10] will be used because of the experience with this type of controller,

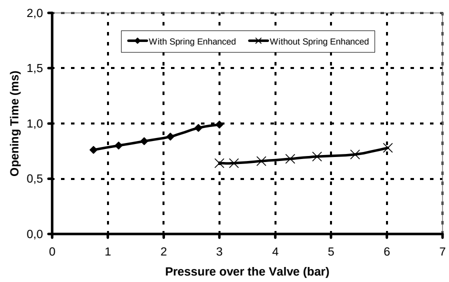


Fig. 10: Opening times of valves, in pressure range for PPAMs

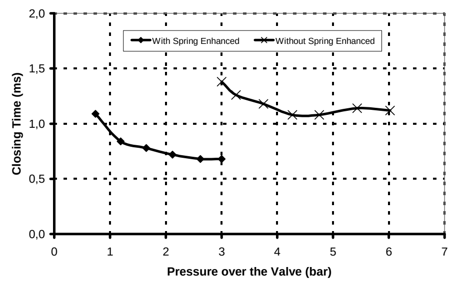


Fig. 11: Closing times of valves, in pressure range for PPAMs

the processing power, the internal memory and certain valuable features—e.g. analog to digital convertor, incremental encoder readout. 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 was made in Matlab - Simulink [11] and tuned with experimental results to ease the simulation of different control algorithms. In the simulations a volume of $300cc$ was used, since this is comparable to the volume of the PPAMs used in the biped robot.

To optimize the number of valves, the ability to pressurize and depressurize 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 $300cc$ 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 12, the decision was taken not to increase the number of valves any further.

One should realize the pressure limit of the PPAM—being $4bar$—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

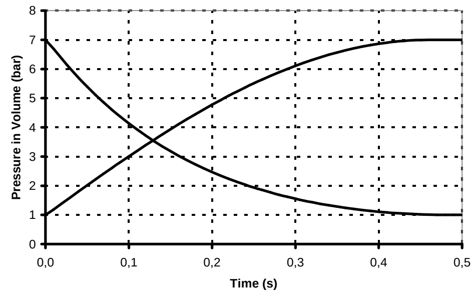


Fig. 12: Comparison 2 Inlet and 4 Outlet valves on $300cc$ volume

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 13 visualizes the actions of the modified bang-bang controller.

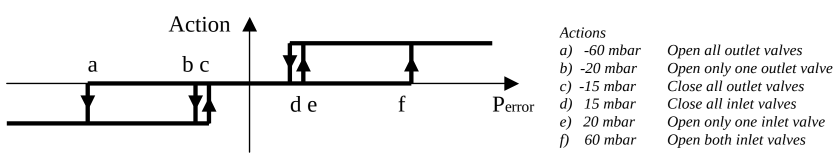


Fig. 13: Visualization of the actions of the bang-bang controller

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 $723\mu s$, because figure 10 shows this the shortest opening time. Figure 14 shows the experimental results of an increase of pressure from 1 bar to 1.5, 2, 3 and 4 bar, while figure 15 shows the results for a decrease from 4 bar to 3, 2, 1.5 and 1 bar in the volume.

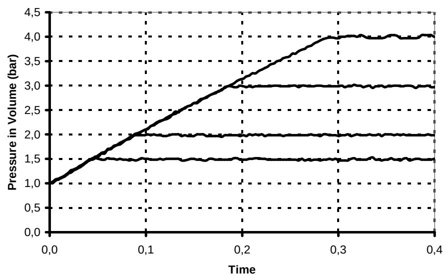


Fig. 14: Pressure Control
(Increasing Pressure)

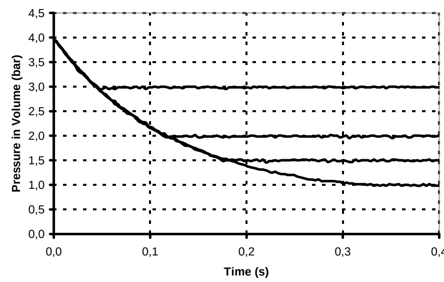


Fig. 15: Pressure Control
(Decreasing Pressure)

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 optimize the controller in case of higher or lower requested pressures.

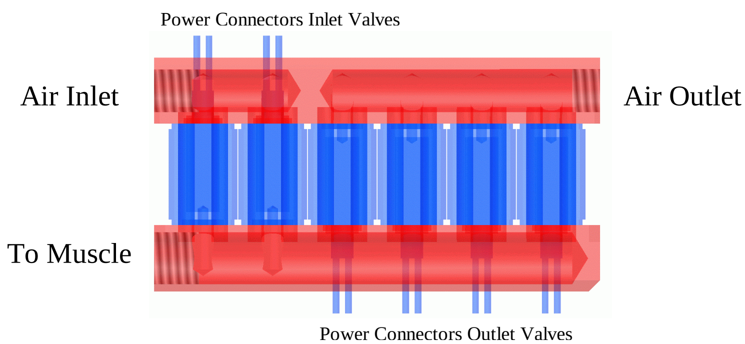


Fig. 16: Pressure control block with 2 inlet and 4 outlet valve

To connect the 6 valves into one compact pressure regulating valve two special collectors were designed. This 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. In figure 16 a section this pressure valve is shown.

Worked until now on a constant volume, one should realize the volume of PPAM increases when contracting, resulting in a less accurate pressure control.

## 5 Preliminary Rotational Joint with PPAMs

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 17 the system under test, see also [4], 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 $+30°$.

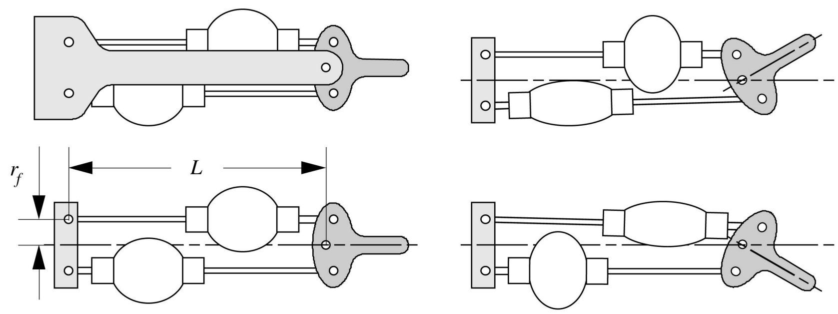


Fig. 17: Rotative joint actuated by 2 antagonistic PPAMs

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, 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 18.

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

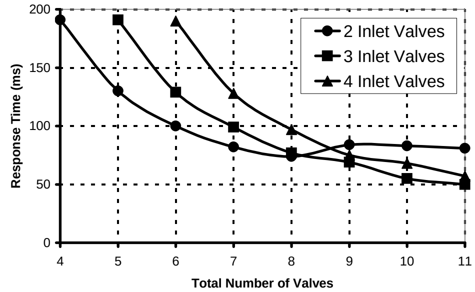


Fig. 18: The open loop step response time with different number of valves.

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 disabled temporarily.

In figure 19 the simulated response of steps of 0° to 10°, 20° and 30° with an average pressure of $2.5bar$ are plotted. Figure 20 shows the corresponding experimental results. Figure 20 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 to stabilize the joint when fully contracted [4].

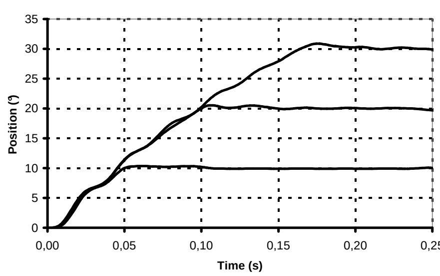


Fig. 19: Simulated step response without load

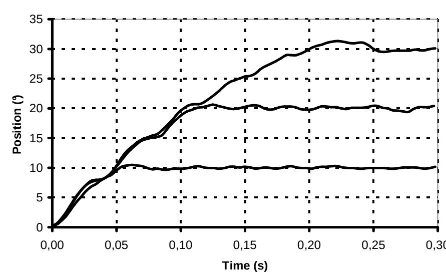


Fig. 20: Experimental step response without load

When an arm with a length of $195mm$ is charged with a load of $1kg$, 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 21) shows the joint can be controlled without oscillations, this cannot be achieved in the experimental set-up (figure 22). Modification of the D-gain cannot eliminate the oscillations, since the noise on the pressure measurements is blown up in the differentiator.

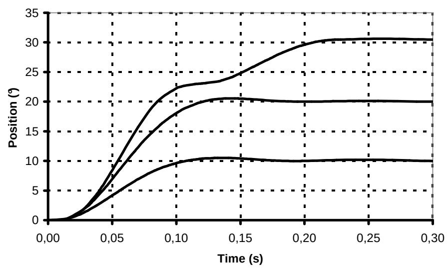


Fig. 21: Simulated step response with load

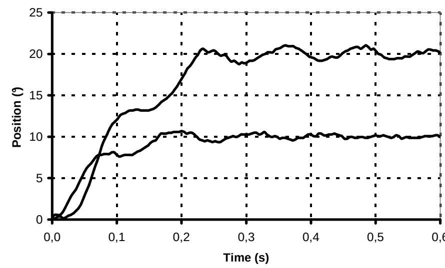


Fig. 22: Experimental step response with load

The analogue pressure sensor, placed outside the muscle, is linked to the internal AD converter of the microcontroller by relatively long wires, which are subject to noise from power circuits of the valves and the microcontroller clock. 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. The digital pressure sensor will be incorporated in the muscle, to improve the quality of the pressure signal.

## 6 Modular 2-Dimensional Rotative Joint with PPAMs

Modularity is gaining importance in robot design to reduce cost [12]. In order to be able to build our 2-dimensional robot Lucy with modular parts, the joints have all been chosen to be rotational. Since the lower-leg, upper-leg and torso have approximately the same length, one leg can be built with 3 quasi-identical modules. However, the modules should be configurable for a specific range of motion and specific force characteristics. Both are determined by the length, diameter and points of attachment of the PPAMs.

A photograph of such a modular element is given in figure 23. Figure 24 shows a more detailed view of the joint. The two darker plates—which determine the points where the PPAMs are attached—can easily be replaced to configure the range of motion and force characteristics of the joint in order to configure the module to be a hip, knee or ankle joint.

In the preliminary design a potentiometer was used to measure the angle. The analog signal was digitized in the microcontroller by an internal 10 bit AD

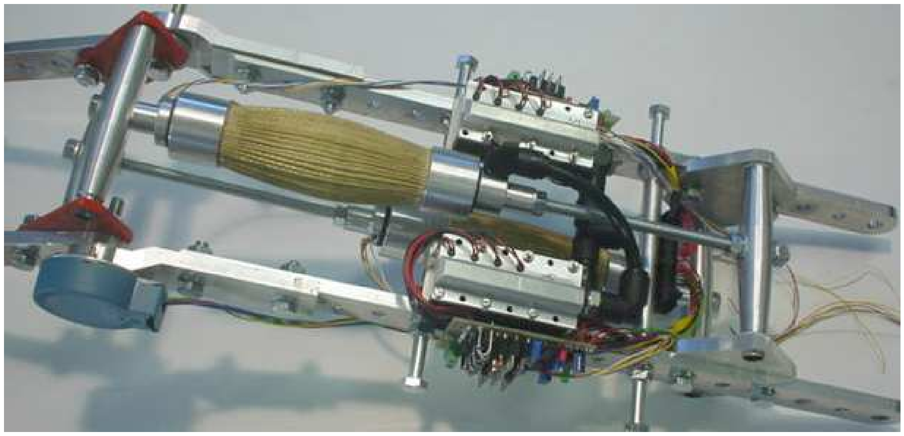

Fig. 23: Modular part, configured as knee joint

convertor. The noise on the analog signal, induced in the long wires by the electromagnetic field of the speed up circuitry of the valves, disturbed the angle measurement and therefore determination of the angular velocity. Therefore an optical incremental encoder was preferred. The microcontroller has a special submodule, which can be configured to read out an incremental encoder and convert it to a absolute position, without taking any resources from the main processor. In figure 24 the encoder, which has a resolution on 0.044°, is shown.

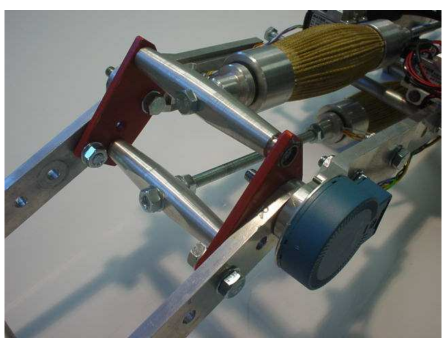

Fig. 24: Detailed view of the attachment points of the muscles

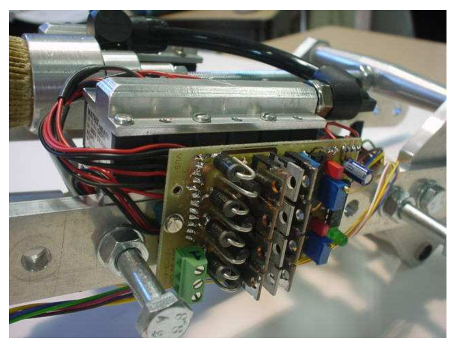

Fig. 25: Detailed view of the valves with speed up circuitry

Although the dimensions of the muscles have their influence, not only on maximum torque, but also on air consumption, all muscles will initially be identical for practical reasons. In later designs the muscle volume can be decreased in order to achieve a better match between provided torque and the torque needed for powering a specific joint. This increases efficiency: the smaller the muscle the less air needed to inflate them.

Figure 25 shows a detailed view of the pressure valves, placed on the modular part. Since the bang-bang controller works with 2 levels for the outlet valves—resulting in 3 valves controlled simultaneously (see figure13)—the speed up circuits of these 3 outlet valves are combined into 1. On the side of the module the electronics of the 4 speed up circuits are combined on one printed circuit board.

One connector, containing all electrical signals to and from the joint, is linked with the 68HC916Y3 controller board. The controller measures the angle of the joint and pressure in both PPAMs, communicates with the high-level controller and generates the control signals for the 12 on-off valves.

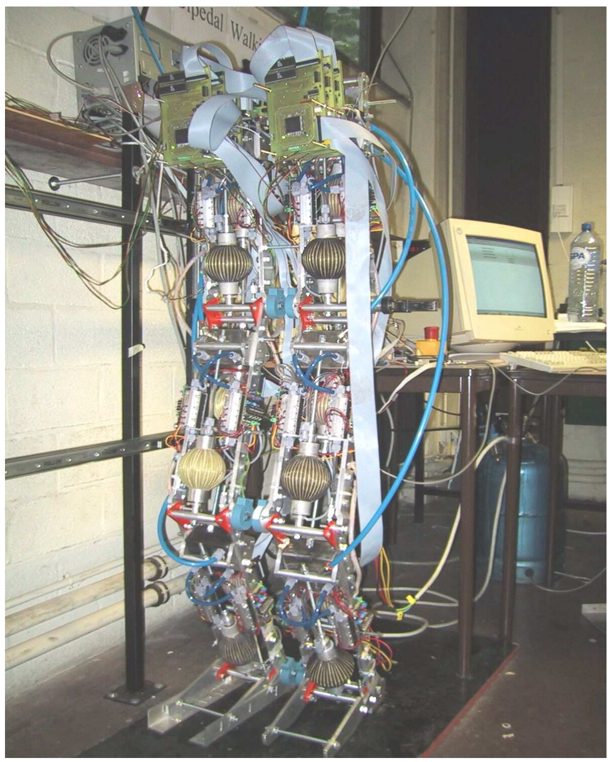

Fig. 26: The Biped Lucy

Figure 26 shows a photograph of the complete assembly of 6 modular parts, resulting in the biped Lucy. The horizontal and vertical sliders reduce the movements into a plane parallel with the sliders.

## 7 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 are used to build a fast and accurate pressure control, which is lighter and cheaper than existing proportional valves. The low-level bang-bang controller with dead zone is shown to be an excellent 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 was designed. Due to the concept of modularity and flexibility, coupling 6 of these modules—each configured as specific joint—results in the 2-dimensional biped Lucy.

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