Concept of Combining Adaptable Passive Behaviour with an Active Control Structure Using Pleated Pneumatic Artificial Muscles for the Bipedal Robot LUCY

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Abstract. This paper reports on the concept of combining passive behaviour with an active control strategy using Pleated Pneumatic Artificial Muscles. These actuators have a very high power to weight ratio and an inherent adaptable compliance which makes them extremely suitable for legged machines. Lucy, our Bipedal robot, is equipped with these muscles in order to walk in a dynamically stable way while the adaptable compliance will be used to alter the natural dynamics of the system.
The paper presents the concept of the Pleated Pneumatic Artificial Muscle and its characteristics. It shows the implementation of these muscles to actuate a rotative joint and discusses briefly the low-level controller designed to settle the pressures in each muscle. For the high-level controller the philosophy of combining passive behaviour with an active control strategy will be considered while explaining in detail the adaptability of the compliance.
The different concepts of our design for Lucy will be discussed. Special attention will be given to the flexibility of the mechanical construction and the elaborate control hardware hereby focussing on the modularity for both mechanical and electronic design.

1 Introduction

During the last decades the field of robotics encounters new directions in which novel applications are gaining more and more commercial interests. The mobility of robots, however, has not been an issue for long since research focused on the development of robots to be used in factory plants in order to enhance and automate the production process. Mobile robots and especially legged robots were exclusive research topics for the academic and military world. But as domotics and certain areas in the leisure industry are becoming more and more important in our society, as such the idea of mobile robots is also inspiring commercial companies. One example is the Honda Motor Corporation, that developed the

Honda Human Robot followed by its successors P1, P2 and recently ASIMO focusing on the field of domotics [15]. In the leisure industry the Sony company already made one commercially available four legged robot, AIBO [9], and a humanoid robot SDR-4X [8] will become available soon. But also legged robots for industrial use are increasingly gaining interest. For instance the maritime industry with climbing robots developed in Spain [1]. At European level exists the European Thematic Network on Climbing and Walking Robots CLAWAR which tries to cluster the different research efforts in Europe.

These examples show that legged robots are no longer only futuristic elements for science fiction movies but that they will become fully-fledged part of technological evolution. In spite of the magnificent models already created this evolution has however just began. A dextrous, intelligent, fast and fully autonomous humaniod robot is still far-off.

A lot of research in many different fields ranging from artificial intelligence to mechanical design is needed. One of the topics is the implementation of novel actuators replacing the widely spread electrical drives in order to make lightweight structures and compliant joints. Compliance characteristics can be used to reduce shocks and decrease energy consumption exploiting the natural dynamics of the system.

Extreme models are the so called Passive Walkers (Garcia, Ruina et al. [6]) which have no active control at all, since only gravity leads them down a sloped surface. In order to walk on a horizontal plane, minimum actuation should be provided to compensate energy loss due to collision and friction. This concept gets more and more attention. Recent examples are the two legged Flamingo Spring [13] and M2 [12] developed in the Leg Laboratory at MIT. This model uses standard passive elements for which the eigenfrequency of the system is determined by the mechanical construction. Analogue investigations on simple quadruped models as SCOUT I and II are carried out at Mc Gill University by Buehler e.a. [5]. Flexibility, with the ability to change this frequency, is increased by implementing passive elements with variable compliance. In this context the group of Takanishi developed the two legged walker WL-14 [10], where a complex non-linear spring mechanism makes changes in stiffness possible. A more elegant way to implement variable compliance is to use pneumatic artificial muscles, where the applied pressures determine stiffness. Research on this topic is done by Van der Linde and Wisse [16], Caldwell [4] and the Shadow Robot Company [7] by implementation of Mc Kibben muscles.

Our research group Multi-body Mechanics of the Vrije Universiteit Brussel, a member of CLAWAR, is focusing on developing a biped actuated by pleated pneumatic artificial muscles. The goal is to achieve a lightweight bipedal robot able to walk in a dynamically stable way exploiting the passive behaviour of the pleated pneumatic artificial muscles.

2 Pleated Pneumatic Artificial Muscles

2.1 Concept and Characteristics

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 [14]. 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 muscle is a threshold level of pressure before any action can take place. The main goal of the new design [2, 3] 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 figure 1.

Fig. 1. photograph of deflated and inflated state of the PPAM

If we omit 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 full length, R its unloaded radius and ϵ 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 2.

The thicker the muscle, the less it contracts and the higher the forces it generates. Contraction can reach up to 54% in a theoretical case with $R/l = 0$, which is bounded in practise because of minimum space needed to fold the membrane.

Low contraction forces are extremely high causing excessive material loading, and the generated forces drop too low for large contraction. Thus contraction will be bounded between two limits, 5 and 35%, in practise. The graph in figure 3 gives the generated force for different pressures of a muscle with initial length $10cm$ and unloaded diameter $2.5cm$. Forces up to $3000N$ can be generated with gauge pressure of only $300kPa$ while the device weighs about $100g$. The graphs

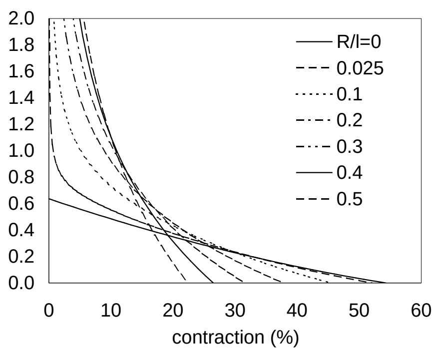

Fig. 2. Dimensionless force function

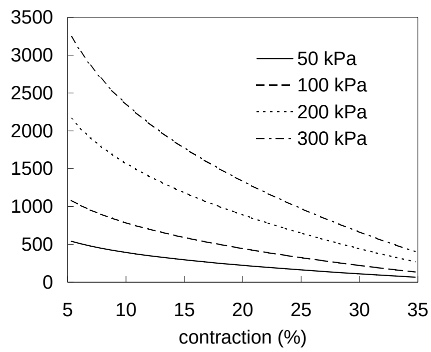

Fig. 3. Generated forces (N)

shown are derived from a mathematical model which fits experimental results with deviations less than a few percent. This mathematical model will be of great importance for the design process of the different joints. Once the slenderness is chosen and the pressure limits are set at $300kPa$ to $400kPa$, in order to protect the membrane, an important design factor will be the length of the muscle. Expression (1) shows that the generated force is proportional to l squared.

2.2 Creating a Revolute Joint with its low-level pressure control

Design. Pneumatic artificial muscles only generate force when they bulge. To have a bidirectional working revolute joint one has to couple two muscles antagonistically while generating revolute motion. A rod transmission was chosen because of its inherent asymmetrical operation about its central position which can compensate the high non-linear muscle characteristic. Large differences for the forces between low and high contractions can be flattened at torque level by choosing appropriate muscle connection points in the leverage mechanism. Figure 4 shows the straightforward connecting principle.

Thus the dimensions of both muscles, being slenderness R/l and its initial length, together with the positions of the points of attachment determine torque

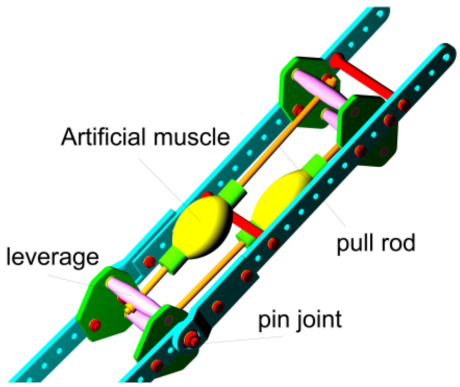

Fig. 4. Antagonistic working joint

characteristics for each joint. Depending whether the joint is a knee, ankle or hip these dimensions can be chosen in order to meet the needs of the specified joint function, not only in torque levels but also in range of motion which is completely different for an ankle and a knee. The graph in figure 5 gives the knee torque characteristics which presently have been chosen for LUCY. Here M_1 is the extensor muscle torque and M_2 the torque generated by the flexor muscle. Both torques are given for different pressure values. If the knee is stretched the knee angle has value zero.

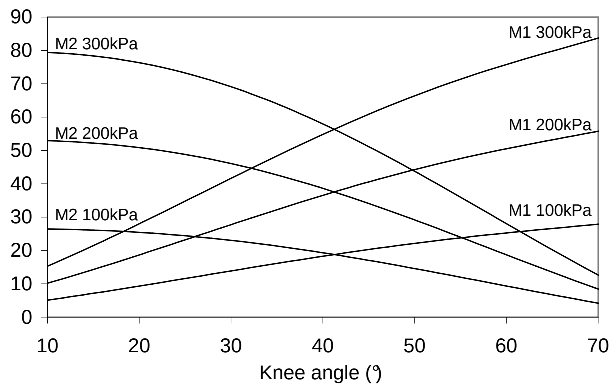

Fig. 5. Torques in the knee (Nm)

If r_1 and r_2 define the leverage arm of the extensor and flexor muscle respectively, the joint momentum is given by following expression

$$M = M_2 - M_1 = p_2 l_2^2 r_2 f_{t_2} - p_1 l_1^2 r_1 f_{t_1} = p_2 m_2 (\alpha) - p_1 m_1 (\alpha) \qquad (2)$$

p_1 and p_2 are the applied gauge pressures in extensor and flexor muscles respectively which have lengths l_1 and l_2. The dimensionless force functions of both muscles are given by f_{t_1} and f_{t_2}. The functions m_1 and m_2, in equation (2), are determined by the choices made during the design phase and depend on the knee angle α. Thus the generated joint torque, and consequently joint position, is proportional to weighted differences in gauge pressures of both muscles.

Pressure control [17]. In the previous section it was shown that torque and position depends on pressure differences between extensor and flexor muscle in an antagonistic setup. Therefor the lowest level in the control hierachy is pressure control which has to be realized with pneumatic valves. This can be done by proportional valves or by on-off operated valves. The former were found far too heavy and would undo the advantages of using lightweight pneumatic artificial muscles.Therefor on-off operated valves were chosen. More precisely Matrix $OX821.104C2KK$ solenoid valves were used because they weigh only $25gr$ each and their closing and opening times can be less than $1msec$. In order to reach these small operating times special speedup circuitry has been designed with the following strategies. A first one is based on the speed-up in tension for which the opening of the valve is realized by temporally increased voltage over the solenoid. The level and the time course of increased voltage were optimized during experimental tests. To enhance closing times a resistor is placed to dissipate the remaining energy in the solenoid.

Since these fast switching Matrix valves have small orifice sections, a number of valves have to be placed in parallel in order to increase the flow rate. An asymmetrical situation between inflating and deflating the muscle exists since the pressure difference over the valves for these two situations are different. The pressure difference for the outlet valves is maximum 3 to 4 bar while for the inlet valves this difference can reach up to 8 bar,being the pressure level of the supply. Taking into account that equal flow conditions for inlet and outlet are desired for control reasons and that the total mass of all valves together should be limited, simulation results showed that two inlet and four outlet valves was a good compromise. In figure 6 a drawing of the collector with 6 control valves is depicted.

The pressure control in a closed volume was achieved with a bang-bang controller with various reaction levels depending on the pressure error. If this error is large the two inlet or the four outlet valves, depending on the sign of the error, are switched together. If this error is smaller only one valve will be switched and when the error is within reasonable limits no action will be taken. The principle of this control scheme is depicted in figure (7). To enhance the dynamic response for this control loop pressure is measured with a micro silicon pressure sensor inside the muscle where the analog pressure signal is immediately converted to a 12-bit digital SPI-signal in order to avoid noise generation as much as possible.

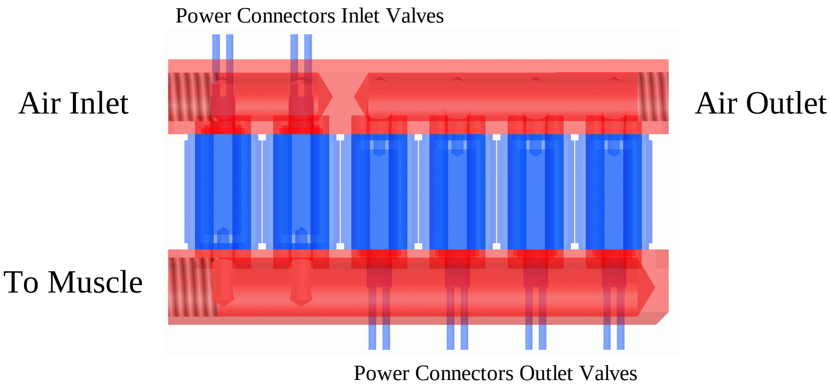

Fig. 6. Collector with six valves to control muscle pressure

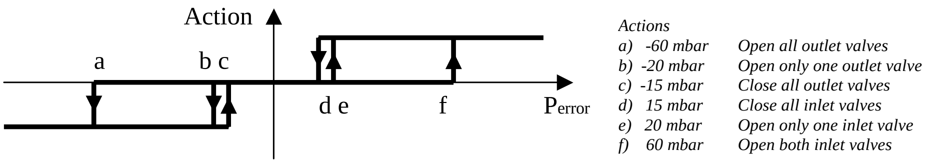

Fig. 7. Multi-level bang-bang control scheme

3 High Level Control Philosophy

3.1 Concept

As was mentioned in the introduction one can state that the search for a dextrous, intelligent, fast and fully autonomous humaniod robot is far from complete. The four keywords in this sentence keep many researchers busy each in their specific field and each of them trying their own point of view for solving a very complex problem. One part of this problem is the complex mechanical system of walking for which many models have already been studied starting from statically balanced robots, which generally move slowly, to dynamically balanced robots to make faster and smoother movements. An important control strategy for these models is trajectory tracking because of its ability to create desired motion with reference trajectories for each joint, calculated by a high-level control unit and tracked by a controller at low-level. An important example in this field is the dynamic walking biped JOHNNIE [11] which at this moment is able to walk smoothly at various moderate speeds. In our department research on this topic is done by Vermeulen e.a. [18, 19] where the scope is to translate objective parameters as step length, step height and walking speed into realtime calculated trajectories for the different joints by means of polynomials. The ability to change the objective parameters from one step to another is an important tool towards a dextrous walking machine but not always energy efficient.

Regarding the autonomous character it is important to search for control principles which consume little energy. One extreme is a Passive Walker which need no external energy input at all because it is mechanically tuned to walk completely within the natural dynamics of the system. One can state in fact that trajectories for each joint are generated and followed by the mechanical system itself. But these trajectories are fixed and ensure no online flexibility of such machines towards changing objective parameters.

The control philosophy proposed in this paper is to combine trajectory control based on objective parameters with the natural dynamics of the system. More precisely, the natural dynamics of the system will be adapted to reach the desired values of the objective parameters approximately in a pure passive way. Then, correcting trajectories will be added to attain the desired values exactly. This implies that a tool is needed to change the natural frequency of the system online while an actuator should be able to track the corrections. The Pleated Pneumatic Artificial Muscle is an actuator able to track trajectories while its adaptable passive behaviour can be adjusted in order to change the natural dynamics by means of compliance variations in the different joints.

3.2 Adaptable Passive Behaviour of the PPAM

The PPAM has two sources of compliance: gas compressibility and the dropping force to contraction characteristic. The latter effect is typical for pneumatic artificial muscles while the first is similar to standard pneumatic cylinders. Joint stiffness, the inverse of compliance, for the considered revolute joint can be obtained by the angular derivative of the torque characteristic in equation (2):

$$K = \frac{dM}{d\alpha} = \frac{dM_2}{d\alpha} - \frac{dM_1}{d\alpha} = \frac{dp_2}{d\alpha} m_2 + p_2 \frac{dm_2}{d\alpha} - \frac{dp_1}{d\alpha} m_1 - p_1 \frac{dm_1}{d\alpha} \qquad (3)$$

The terms $dp_i/d\alpha$ represent the share in stiffness of changing pressure with contraction, which is determined by the action of the valves controlling the joint and by the thermodynamic processes taking place. If the valves are closed and if we assume isentropic compression/expansion the pressure changes inside the muscle will be a function of volume changes:

$$\begin{aligned} & P_i V_i^\gamma = P_{i_o} V_{i_o}^\gamma \qquad \text{with} \quad P_k = P_{atm} + p_k \\ \Longrightarrow \qquad & \frac{dp_i}{d\alpha} = -\gamma \left(P_{atm} + p_{i_o}\right) \frac{V_{i_o}^\gamma}{V_i^{\gamma+1}} \frac{dV_i}{d\alpha} \end{aligned} \qquad (4)$$

With P_i, V_i the absolute pressure and volume of muscle i, P_{i_o}, V_{i_o} the absolute initial pressure and initial volume when muscle i was closed, p_i, p_{i_o} the gauge pressure and initial gauge pressure. γ is the isentropic coefficient and P_{atm} the atmospheric pressure.

In figure 8 the calculated volumes of the two muscles in the knee are given as a function of the knee angle. This graph and the one shown on figure 5

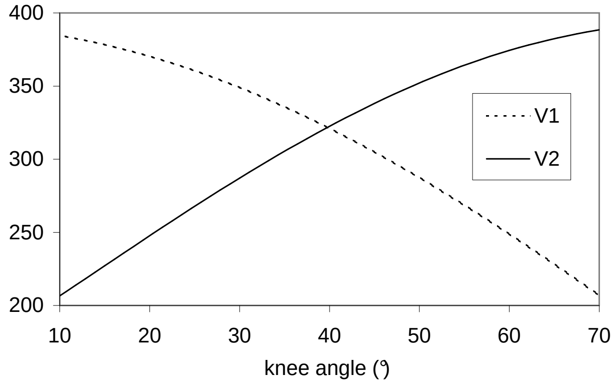

Fig. 8. Calculated volumes (ml) to angle for both muscles in the knee

give information about the sign of both $dm_i/d\alpha$ and $dV_i/d\alpha$. This information combined with equation (3), (4) gives:

$$K = (k_1 p_{1_o} + k_2 p_{2_o} + k_{atm} P_{atm}) \tag{5}$$

$$\text{with} \quad \begin{cases} k_1 = m_1 \gamma \frac{V_{1_o}^{\gamma}}{V_1^{\gamma+1}} \left|\frac{dV_1}{d\alpha}\right| + \frac{V_{1_o}^{\alpha}}{V_1^{\gamma}} \left|\frac{dm_1}{d\alpha}\right| & > 0 \\ k_2 = m_2 \gamma \frac{V_{2_o}^{\gamma}}{V_2^{\gamma+1}} \left|\frac{dV_2}{d\alpha}\right| + \frac{V_{2_o}^{\alpha}}{V_2^{\gamma}} \left|\frac{dm_2}{d\alpha}\right| & > 0 \\ k_{atm} = k_1 + k_2 \end{cases}$$

The coefficients k_1, k_2, k_{atm} are a function of the angle and are determined by the geometry parameters of the joint and muscles. From equation (5) the conclusion is drawn that a passive spring element is created with an adaptable stiffness controlled by the weighted sum of both initial pressures when closing the muscle. Even if one does not consider isentropic expansion/compression the same conclusion can be draw except that the coefficients in equation (5) will be changed.

Since stiffness depends on a sum of pressures and position is determined by differences in pressure, the angular position can be controlled while settling stiffness independently. This concept validates the proposed idea of adapting natural dynamics in combination with trajectory control.

4 General Description of LUCY

Presently LUCY is in its construction and test phase. Piecewise all components are being assembled and tested. The control software implemented during this phase is based on pure kinematic control of the different parts. The movement of LUCY is restricted to the sagittal plane and therefor attached to a sliding mechanism which makes it easier to gradually implement and test hardware and respective control software. Figure 9 shows a photograph of LUCY.

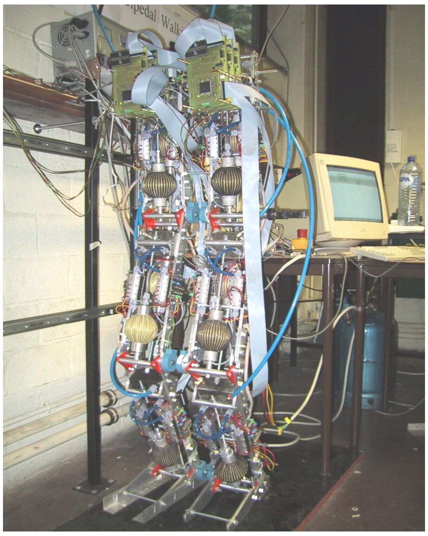

Fig. 9. Photograph of LUCY

The structure is made of a high grade aluminium alloy, AlSiMg1, and is composed of two legs and an upper body. The legs are identical, each having a foot, a lower leg and an upper leg. All parts are connected by one-dimensional pin joints creating the ankle, knee and hip. The hip is connected to a horizontal and vertical sliding mechanism by means of a seventh pin joint to avoid turning over in the frontal plane. The robot, all included, weighs about $30kg$ and is $150cm$ tall.

Key elements in the design phase are modularity and flexibility regarding the ability to make changes to the robot configuration during the experimental process. This resulted in nearly the same configuration for each structural element such as lower-leg, upper-leg and body. A photograph of such an element is given in figure 10. The only difference between the elements used for the various functions such as hip, knee and ankle are muscle dimensions and the connection plates of the leverage mechanism. The latter can be seen at the left side of figure 10. These connection plates and muscles can be replaced easily ensuring the required flexibility of the setup.

Figure 10 shows the two pressure control units with its electronic circuitry aside. The low-level control of these two units is for each joint implemented on separate 16-bit MC68HC916Y3 micro-controller unit. These controllers are responsible for reading the joint position information from HEDM6540 encoders with 2000 pulses per revolution and the SPI signals originating from the pressure sensors inside the muscles. Both these encoder and pressure signals are registered with a separate processor, TPU, on the micro-controller in order not to load the CPU whilst reading their values.

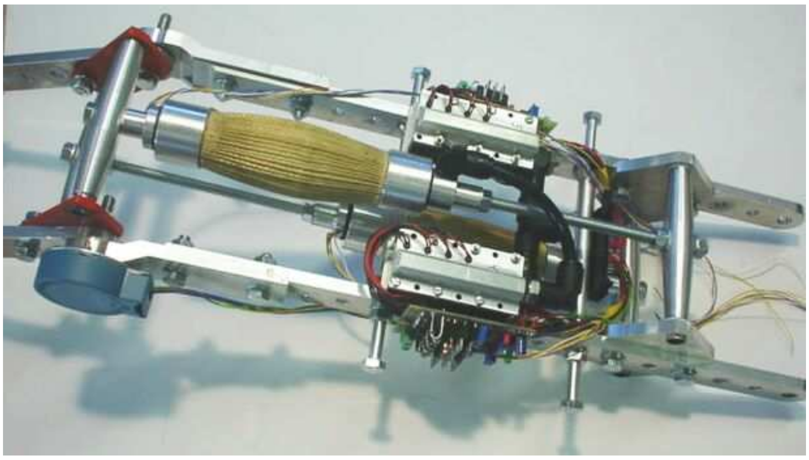

Fig. 10. Modular part of Lucy

The high-level control will be implemented on a PC which is connected to the different low-level micro-controllers by a 16 bit parallel data bus with in between dual ported RAM units. For each joint, six in total, one such unit is used for transfer and buffer agent between PC and micro-controller. Additional information such as contact with the ground and absolute position of the body are observed by a seventh micro-controller. The absolute position includes absolute rotation and vertical and horizontal displacement of the body. The latter two, being redundant information to evaluate the movement of the robot, are measured along the sliding mechanism. All three position signals are captured by the same type of incremental encoders via the TPU of the seventh micro-controller which also masters the 16-bit communication bus by handling bus control bits.

The modularity for the different structural elements in the mechanical design is also present in the electronic design which makes it possible to change the configuration of the set-up. This aspect can be used to perform experiments on different mechanical set-ups such as for instance a one-legged hopping robot.

5 Conclusion

The Pleated Pneumatic Artificial Muscle has some interesting characteristics which make it very suitable to power a bipedal walking robot. This actuator has a high power to weight ratio and an inherent adaptable passive behaviour. Two antagonistically coupled muscles can be implemented in a straightforward manner to power a rotative joint. The angular position of such a rotative joint depends on the difference in gauge pressures of both muscles and the stiffness of the joint is determined by the sum of pressures. Thus stiffness can be controlled while changing angular position. Within this framework the concept of combining passive behaviour with an active control was introduced by combining both trajectory generation with adaptable natural dynamics of the system.

Both mechanical and electronic design of the biped LUCY were discussed in detail showing the machine's modularity and elaborate hardware leading to a flexible experimental platform.

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