LUCY, a Bipedal Walking Robot with Pneumatic Artificial Muscles

B. Vanderborght, B. Verrelst, R. Van Ham, J. Naudet, J.Vermeulen, D. Lefeber & F. Daerden

Vrije Universiteit Brussel
Department of Mechanical Engineering
Pleinlaan 2, B-1050 Brussels, Belgium
bram.vanderborght@vub.ac.be
http://lucy.vub.ac.be

Abstract— **This paper describes the biped Lucy and it's control architecture that will be used. Lucy is actuated by Pleated Pneumatic Artificial Muscles, which have a very high power to weight ratio and an inherent adaptable compliance. These characteristics will be used to make Lucy walk in a dynamically stable manner while exploiting the adaptable passive behavior of these muscles. The paper will focus briefly on the concept of the pleated pneumatic artificial muscle and antagonistic setup. The design and implementation of the pressure control unit will be discussed. A quasi-static global control has been implemented while using adapted PID techniques for the local feedback joint control. These initial control techniques resulted in the first movements of Lucy. This paper will discuss a future control architecture of Lucy to induce faster and smoother motion. The proposed control scheme is a combination of a global trajectory planner and a local low-level joint controller.**

I. INTRODUCTION

Most of the legged robots nowadays use electrical drives. The most well know robots are Asimo[1], Qrio[2], Johnnie[3] and HRP-2P[4]. Because the torquedensity of the drives is too low to actuate legs, gearboxes are used to deliver the required torque at low rotation speeds, thereby making the joint stiff and losing joint compliance. While the compliance characteristics actually can be beneficial for legged locomotion to reduce shocks and decrease energy consumption by exploiting the natural dynamics of the system.

Natural dynamics or passive dynamics is the unforced response of a system under a set of initial conditions. In most of the existing legged robots, these natural dynamics are not or only partially exploited. Examples of exploitation of the natural dynamics are the swing-leg movement freely without hip actuation or the body and stance-leg pivoting as an inverted pendulum around an unactuated ankle. Legged systems that walk completely without actuation are the so called "Passive Walkers". These machines are only powered by gravity and they are mechanically tuned in order to walk down a sloped surface. These "Passive Walkers" could be pointed out as very energy efficient but unfortunately they are of little practical use. A minimum actuation should be provided to walk on level ground to overcome friction and impact losses. Anyway it is important to exploit the natural dynamics by trying to incorporate the unforced motion of a system instead of ignoring or avoiding them. Doing so could positively affect energy consumption and control efforts.

One of the first to incorporate passive dynamics for legged locomotion was Matsuoko (1980)[5], and later Raibert (1986)[6]. Pratt developed the "Series Elastic Actuators"[7] with inherent compliance, used for the two legged "Spring Flamingo" (1998) and consist of a motor drive in series with a spring. The disadvantage of such a setup is that the stiffness can't be changed. Takanishi developed the two-legged walker WL-14 (1998)[8], where a complex non-linear spring mechanism makes predefined changes in stiffness possible. A more elegant way to implement a variable compliance is to use pneumatic artificial muscles, where the applied pressures determine stiffness[9]. Research on this topic was done by Van der Linde (1998)[10], Wisse (2001)[11], Caldwell (2001)[12] and the Shadow Robot Company [13] by implementation of Mc Kibben muscles.

Our research group Multibody Mechanics of the Vrije Universiteit Brussel has built the planar walking biped Lucy. This biped model is actuated by pleated pneumatic artificial muscles (PPAM). These actuators gives an alternative to the McKibben type muscle by trying to overcome some of the latter's shortcomings such as a high threshold of pressure and dry friction. The goal of the biped project is to achieve a lightweight bipedal robot able to walk in a dynamically stable way while exploiting the passive behavior of the pleated pneumatic artificial muscles in order to reduce energy consumption and control efforts.

This paper discusses a control architecture for Lucy.

II. BIPEDAL WALKING ROBOT LUCY

Presently Lucy has been assembled and tested. A picture of the complete set-up is given in figure 1. The movement of Lucy is restricted to the sagittal plane by a sliding mechanism. The structure is made of a high-grade aluminium alloy, AlSiMg1, and is composed of two legs and an upper body. The robot, all included, weighs about $30kg$ and is $150cm$ tall. The robot has 12 pneumatic actuators for 6 DOF's.

A. Pleated Pneumatic Artificial Muscle

The Pleated Pneumatic Artificial Muscle (PPAM) [9] is essentially a membrane that will expand radially and contract axially when inflated, while generating high pulling
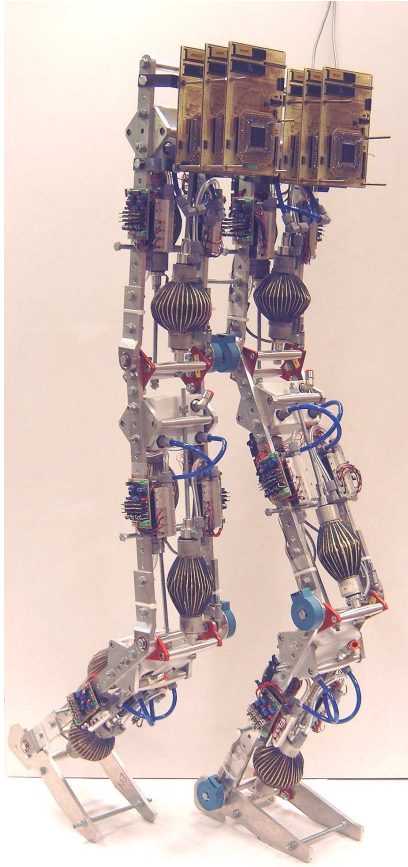
Fig. 1. Photograph of Lucy

Fig. 2. Photograph of deflated and inflated state of the PPAM

forces along the longitudinal axis. To avoid friction the membrane is arranged 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 (PPAM) is given in figure 2. If we omit the influence of elasticity of the high tensile strength material used for the fibres, the characteristic for the generated force is given by:

$$F = pl^2 f(\varepsilon, \frac{l}{R}) \qquad (1)$$

where p is the applied gauge pressure, l the muscle's full length, R its unloaded radius and ε the contraction. The dimensionless non-linear function f depends only on contraction and geometry. 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 $R/l = 0$.

B. Antagonistic Setup

Pneumatic artificial muscles can only pull. In order to have a bidirectionally working revolute joint one has to couple two muscles antagonistically. A rod transmission was chosen because of its inherent asymmetrical operation about its central position, which can compensate the non-linear muscle characteristic. Depending whether the joint

is a knee, ankle or hip the dimensions of the connection 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.

Taking into account equation (1) and if r_1 and r_2 define the leverage arm of the extensor and flexor muscle respectively, the joint torque T is given by following expression:

$$\begin{aligned} T = T_1 - T_2 &= p_1 l_1^2 r_1 f_1 - p_2 l_2^2 r_2 f_2 \\ &= p_1 t_1(\theta) - p_2 t_2(\theta) \end{aligned} \qquad (2)$$

with p_1 and p_2 the applied gauge pressures in extensor and flexor muscle respectively which have lengths l_1 and l_2. The dimensionless force functions of both muscles are given by f_1 and f_2. The functions t_1 and t_2, in equation (2), are determined by the choices made during the design phase and depend on the joint angle θ. Thus joint position is influenced by weighted differences in gauge pressures of both muscles.

The PPAM has two sources of compliance: gas compressibility and the dropping force to contraction characteristic. 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):

$$\begin{aligned} K &= \frac{dT}{d\theta} = \frac{dT_1}{d\theta} - \frac{dT_2}{d\theta} \\ &= \frac{dp_1}{d\theta} t_1 + p_1 \frac{dt_1}{d\theta} - \frac{dp_2}{d\theta} t_2 - p_2 \frac{dt_2}{d\theta} \end{aligned} \qquad (3)$$

The terms $dp_i/d\theta$ 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 polytropic compression/expansion the pressure changes inside the muscle will be a function of volume changes:

$$P_i V_i^n = P_{i_o} V_{i_o}^n \qquad (4)$$

with:

$$P_i = P_{atm} + p_i \qquad (5)$$

leading to:

$$\frac{dp_i}{d\theta} = -n\left(P_{atm} + p_{i_o}\right)\frac{V_{i_o}^n}{V_i^{n+1}}\frac{dV_i}{d\theta} \qquad (6)$$

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

Combining equation (3), (4) and (6) gives:

$$K = k_1 p_{1_o} + k_2 p_{2_o} + k_{atm} P_{atm} \qquad (7)$$

with:

$$k_1 = t_1 n \frac{V_{1_o}^n}{V_1^{n+1}}\left|\frac{dV_1}{d\theta}\right| + \frac{V_{1_o}^n}{V_1^n}\left|\frac{dt_1}{d\theta}\right| \quad > 0$$

$$k_2 = t_2 n \frac{V_{2_o}^n}{V_2^{n+1}}\left|\frac{dV_2}{d\theta}\right| + \frac{V_{2_o}^n}{V_2^n}\left|\frac{dt_2}{d\theta}\right| \quad > 0$$

$$k_{atm} = k_1 + k_2 - \left|\frac{dt_1}{d\theta}\right| - \left|\frac{dt_2}{d\theta}\right|$$

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 (7) the conclusion is drawn that a passive spring element is created with an adaptable stiffness controlled by the weighted sum of both initial gauge pressures when closing the muscle.

Since stiffness is depending on a sum of gauge pressures while position is determined by differences in gauge pressure, the angular position can be controlled while setting stiffness.

C. Pressure Control

Torque and stiffness of the joints are determined by pressures, thus a fast and accurate pressure control is needed. Because proportional valves are too heavy we use a set of fast switching on-off valves (821 2/2 NC made by Matrix). The opening time is about 1 ms and it has a flow rate of 180 Std.l/ min.

Simulations showed that a combination of 2 inlet valves and 4 outlet valves is a good compromise between total mass and needed flow rate. There are twice as much outlet valves than inlet valves because 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.

The pressure control in a volume is achieved with a bang-bang controller with various reaction levels depending on the pressure error (see figure 3). 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.

D. Control Hardware

Key elements in the design phase are modularity and flexibility regarding the ability to make changes to the

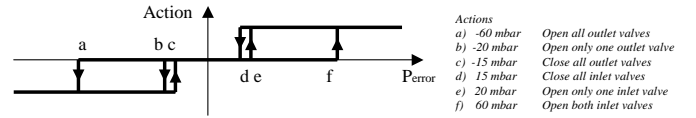| Actions	
a) -60 mbar	Open all outlet valves
b) -20 mbar	Open only one outlet valve
c) -15 mbar	Close all outlet valves
d) 15 mbar	Close all inlet valves
e) 20 mbar	Open only one inlet valve
f) 60 mbar	Open both inlet valves

Fig. 3. Multi-level bang-bang control scheme

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. The modularity is also incorporated in the control hardware. Every joint has its own 16-bit micro-controller (MC68HC916Y3 made by Motorola). They incorporate the bang-bang controller and collection of the sensor information. The sensors are the HEDM6540 encoder for reading the joint position information and 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. An additional micro-controller is used to detect ground contact, absolute position of the body and compressed air consumption.

The high-level control will be implemented on a PC which is connected to the different low-level micro-controllers by a USB2.0 interface.

III. Control Architecture

The last months Lucy has been assembled and debugged, here basic control strategies were implemented. With basic PID techniques already satisfactory behavior was attained[14]. The following step will be the implementation of a dynamic control scheme to induce faster and smoother motion. An overview of this control architecture is given in the next paragraphs. In order to evaluate the proposed control structure a hybrid simulator was created. This means that both the pneumatics and mechanics are put together in a dynamic simulation. To have real-time simulations of the mechanics the method studied by Naudet [15] is used. This efficient formulation uses canonical momenta to obtain the equations of motion in a Hamiltonian formalism. The pressure building inside the muscle is represented by first order differential equations deduced from the first law of thermodynamics for an open system while assuming a perfect gas for the compressed air. The orifice valve flows are derived from the model presented by ISO635[16]. The integration of these first order differential equations coupled with the mechanical differential equations gives the torques.

The considered controller is given in the schematic overview of figure 4 and is a combination of a global trajectory planner and a local low-level joint controller.

A. Trajectory Planning

The trajectory planner generates motion patterns based on two specific concepts, being the use of objective locomotion parameters, and exploiting the natural upper body dynamics by manipulating the angular momentum equation [17]. The trajectories of the leg links, represented by 6th or-
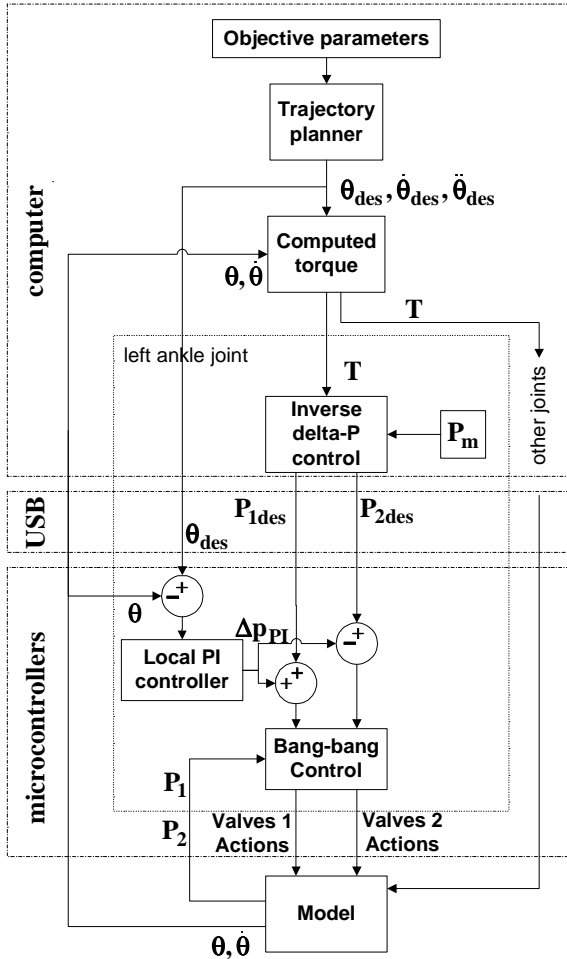
Fig. 4. The applied low-level control scheme

der polynomials, are planned in such a way that the upper body motion is naturally steered. One of the most interesting aspects of this method is that they are based on fast converging iteration loops, requiring only a limited number of elementary calculations. The computation time needed for generating feasible trajectories is low, which makes this strategy useful for real-time applications.

B. Complete Low-level Joint Controller

The low-level controller can be divided in four parts: the computed torque module, the inverse delta-p unit, the local PI controller and the bang-bang controller.

B.1 Computed Torque

Using the Lagrange equations of the dynamic model the equations of motion can be summarized in the following matrix form (during single support):

$$M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + G(\theta) = T$$

Where M is the inertia matrix, which is symmetric and positive definite, C is the centrifugal matrix which contains the centrifugal torques (involving $\dot{\theta}_i^2$) and the coriolis torques (involving $\dot{\theta}_i\dot{\theta}_j$ for $i \neq j$), G is the gravitational torque vector. This is the feedforward calculation which

is added with a proportional and derivative feedback part for which the gains are tuned in order for the mechanical system to behave as critically damped.

Immediately after the impact of the swing leg, three geometrical constraints are enforced on the motion of the system. They include the stepheight, steplength and angular position of the foot. Due to these constraints, the robot's number of DOF is reduced to three.

The equations of motion are then written as

$$M(\theta)\ddot{\theta} + C(\theta, \dot{\theta})\dot{\theta} + G(\theta) = T + J^T\Lambda$$

where J is the Jacobian matrix and Λ is a column vector of Lagrange multipliers representing the generalized constraint forces.

This problem can be solved by dividing the 6 coordinates into a group of independent $(Z_1 = (\theta_1, \theta_2, \theta_3)^T)$ and dependent $(Z_1 = (\theta_4, \theta_5, \theta_6)^T)$ coordinates. Using the matrix pseudoinverse as described in [18], the torque vector can than be calculated. This feedforward term is added with a feedback part which gives the computed torque.

B.2 Inverse Δp Control

For each joint a computed torque is available. The computed torque is then feeded into the inverse delta-p control unit, one for each joint, which calculates the required pressure values to be set in the muscles. These two gauge pressures are generated from a mean pressure value p_m while adding and subtracting a Δp value:

$$p_1 = p_m + \Delta p \tag{8}$$
$$p_2 = p_m - \Delta p \tag{9}$$

Feeding back the joint angle θ and using expression (2), Δp can be determined by:

$$\Delta p = \frac{T + p_m\left((t_2(\theta) - t_1(\theta))\right)}{t_2(\theta) + t_1(\theta)} \tag{10}$$

The delta-p unit is actually a feed-forward calculation from torque level to pressure level using the kinematic model of the muscle actuation system. The calculated Δp affects the torque needed to follow the desired trajectory while p_m is introduced to determine the sum of pressures which influences the stiffness of the joint as was discussed in section II-B. Increasing p_m will lower the compliance of the joint. Note that this control law does not decouple stiffness control from position control since the weights k_1 and k_2 (see section II-B) are not taken into account. Until now p_m has a fixed value, in the future we will adapt this parameter to reduce energy consumption and control efforts.

B.3 Local PI Controller

Because the communication between PC and the microcontrollers is slower dan $1ms$, instabilities occur when the proportional and derivative feedback part of the computed torque are too high. To track the desired trajectory a local PI controller was needed to regulate the error introduced by lowering the feedback gains.

B.4 Bang-bang Controller

In the last control block the desired gauge pressures are compared with the measured gauge pressure values after which appropriate valve actions are taken by the bang-bang pressure controller.

C. Results

The following values for the objective parameters characterize the walking pattern:

$$\nu = 0.4\frac{m}{s} = 1.44\frac{km}{h} \qquad \text{walking speed} \qquad (11)$$

$$\lambda = 0.3m \qquad \text{steplength} \qquad (12)$$

$$\delta = 0m \qquad \text{stepheight} \qquad (13)$$

$$\gamma = 0.02m \qquad \text{footlift} \qquad (14)$$

So the duration of one step becomes $0.375s$.

A 5% deviation on the modelparameters mass and COG and 10% on the inertia were used. The walking motion is considered to be a steady walking pattern, consisting of successive single support phases separated by an instantaneous double support phase. Also a zero touch-down velocity of the foot was chosen.

The simulations also takes the time delay of $1ms$ for the closing and opening of the valves into account. The sampling time for the calculation of the desired pressures is $2ms$, which is restricted due to the communication between PC and micro-controller. The local PI controller and bang-bang controller, both implemented in the micro-controllers, work with a refresh rate of $0.5ms$.

To get a clear view on how the robot moves, a stick diagram is given in figure 5. The successive robot positions are shown at equal time intervals.
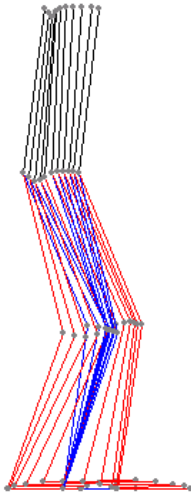

Fig. 5. Stick diagram

Figures 8 and 9, representing respectively the pressures and valve actions of the front and back muscle of the ankle of the supporing leg, clearly shows the control strategy of keeping the mean pressure constant, which in this case is set at a value of $2bar$. Also the valve action due to the

bang-bang controller is shown. Note that in these figure a closed muscle is represented by a horizontal line depicted at the same level of the initial pressure while a peak upwards represents one or more opened inlet valves, a peak downwards one or more opened exhaust valve. The selection of an appropriate mean pressure value is important regarding energy consumption and control activity. Future work will be the incorporation of this mean pressure value determination in a higher-level control strategy. To protect the membrane the maximum pressure is limited to $4bar$, this phenomena can be seen at $0.15s$. Also the limited flow rate when for example all the outlet valves are opened, can be seen around $0.12s$.

This has an implication on the level of the torque (figure 7) where the desired torque can't be delivered due to the limitations of the pressure control. Nevertheless the simulations showed already promising results. The difference between desired and real angle (for example figure 6, giving the angle results for the ankle of the supporting leg) never exceeds the $0.1°$. For biped locomotion this tracking error is not a problem if the overall stability of the robot is not threatened. Walking with a zero touch-down velocity of the foot and an instantaneous double support phase asks also very high and fast changing torques. A more general trajectory generation strategy for walking patterns with an impact and a non-instantaneous double support phase is presently under construction.
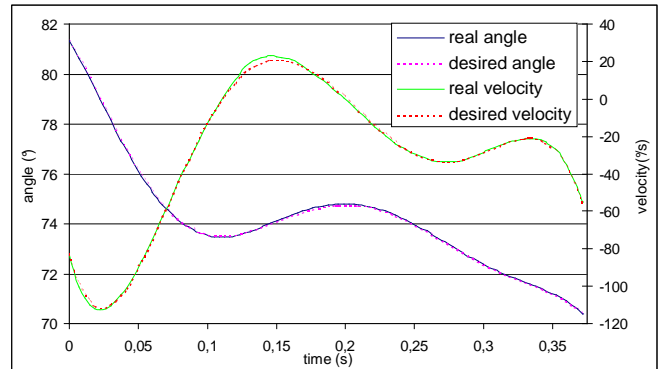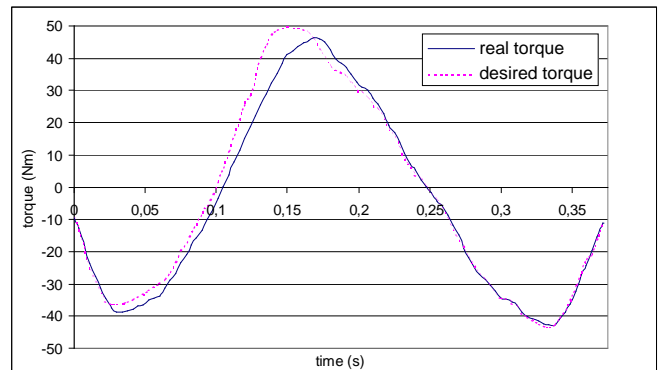

Fig. 6. ankle angle of supporting leg
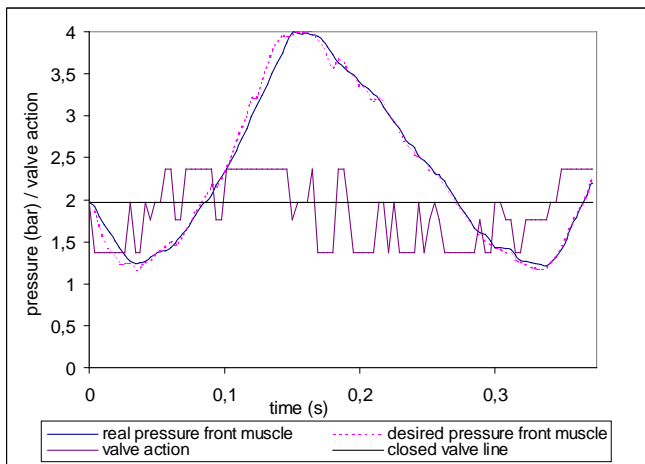

Fig. 7. ankle torque of supporting leg

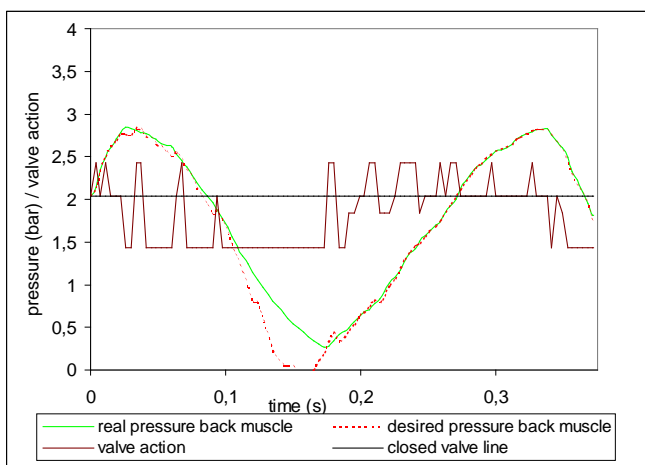Fig. 8. pressure and valve action of front ankle muscle of supporting leg

Fig. 9. pressure and valve action of back ankle muscle of supporting leg

IV. Conclusion

The Pleated Pneumatic Artificial Muscle has interesting characteristics, which make it very suitable to power a smooth walking bipedal robot. This actuator has a high power to weight ratio and an inherent adaptable passive behavior. 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. The biped Lucy is a robot actuated with these muscles. For debugging reasons, basic control techniques were implemented which allowed Lucy to make her first steps. These first experiments showed already promising results.

The future control architecture, based on a global and local control, was discussed and tested in simulation for the single support phase. The global control is the trajectory planner for dynamically balanced bipeds, the local control can be divided in four parts: the computed torque module, the inverse delta-p unit, the local PI controller and the bang-bang controller.

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