Experimental Results on the First Movements of the Pneumatic Biped “Lucy”

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Abstract

This paper presents the biped Lucy and the first experimental results of this robot. 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 dynamic stable way while exploiting the adaptable passive behaviour of these muscles.
The paper will describe briefly the concept of the pleated pneumatic artificial muscle and the creation of the revolute joint used for the biped. The design and implementation of the pressure control unit will be discussed followed by an overview of the complete robot.
During the assembly and debugging phase of the robot 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, which will be shown and discussed.

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 [5]. In the leisure industry the Sony Company already made one commercially available four-legged robot, AIBO [7], and a humanoid robot SDR-4X [6] 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].

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 humanoid 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. [4]) 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. A recent example is the two- legged Spring Flamingo [8] 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. 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 [9], 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 [10] and Caldwell [3] by implementation of Mc Kibben muscles.

Our research group Multi-body Mechanics of the Vrije Universiteit Brussel 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 MUSCLE

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. 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] 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 deflated and inflated state of the Pleated Pneumatic Artificial Muscle is given in figure (1).

Fig 1 Photograph of the deflated and inflated state of the PPAM

The generated force is non-linear and proportional to the applied gauge pressure in the muscle and square of the initial length while slenderness of the muscle determines the force characteristic. At a pressure of 3 bar the force can be as high as 4000N for a device with initial length of 10cm, weighing only 100g.

2.2 Revolute joint

Pneumatic artificial muscles only generate force when they bulge. To have a bi-directional 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 (2) shows the straightforward connecting principle.

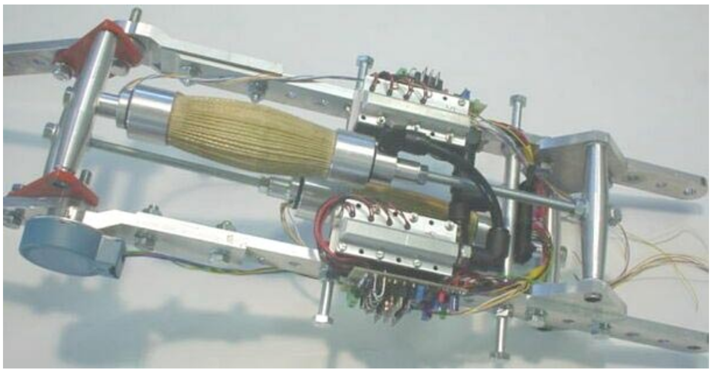


Fig. 2 Photograph of antagonistic set-up

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

In such an antagonistic set-up position will be determined by pressure differences in both muscles while stiffness is set by the sum of pressures. Position of the joint can be maintained while for example increasing the stiffness can be realised by increasing the sum of pressures.

3 PRESSURE CONTOL OF A CONSTANT VOLUME

The previous paragraph showed that pressure control is a key element and lowest level in the control hierarchy. In order to realize a fast, accurate and lightweight pressure control, fast on-off valves are used. The pneumatic solenoid valve 821 2/2 NC made by Matrix weights only 25g. With their reported opening times of about 1 ms and flow rate of 180 Nl/min, they are about the fastest switching valves currently available.

In the 821 valves a flapper forced by an internal spring to close the outlet interrupts the airflow. The electromagnetic force of the coil opens the valve. 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 were 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. To ensure proper closing of the valve, the spring cannot be removed if the pressure difference across the valve is less than 2 bar.

Ways to enhance opening and closing times of the valve were studied. Opening and closing times were defined as the time between the moment the corresponding signal is given and the moment the outlet pressure reach 10% of it's final level, in case of opening, or a 10% drop in the outlet pressure, in case of closing. To decrease the opening time the manufacturer proposes a speed up in tension circuitry using 24V during 2.5ms and 5V afterwards. Raising the level of the opening voltage up to 36V resulted in a shorter opening time of the valve. If the voltage is dropped to 5V when the valve is open, the energy when using 36V is lower than when using 24V during the proposed 2.5ms. This opening energy is a measure for the produced heat, which is of major influence on the valve's service life.

To improve the closing times, a resistor was added to the coil's discharge circuit. This will dissipate the electromagnetic energy faster 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 200Ω to be a good compromise. The reverse voltage will be kept beneath 50V and the demagnetisation time remains less than about 200ms. This results in shorter closing times, as can be seen in figure (4).

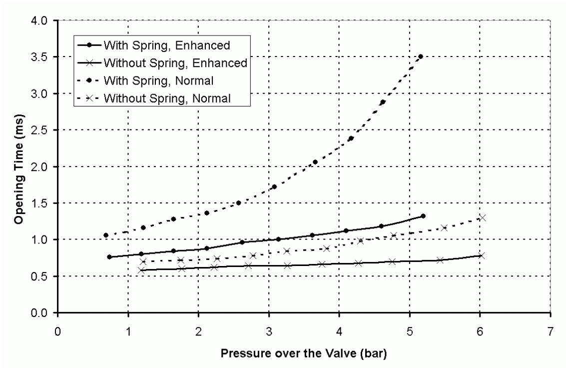


Fig. 3 Opening times of valve

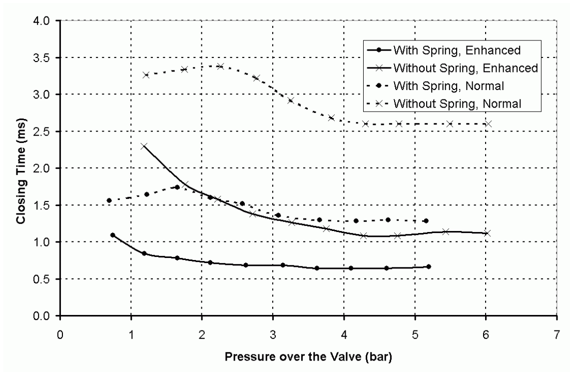
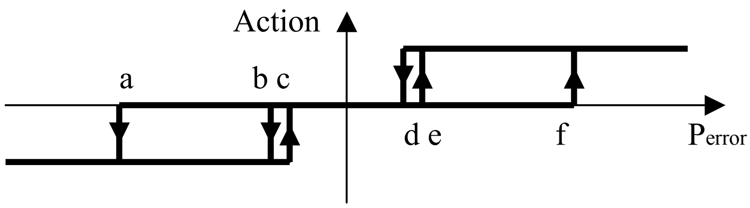


Fig. 4 Closing times of valve

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

In order to control the pressure with 2/2 valves a minimum of 1 inlet and 1 outlet valve is required. Obviously the more valves used in parallel, the faster a volume can be pressurised or depressurised, but power consumption, price and weight of the pressure control will increase. In simulation the valves and a volume of 300cc, since this is comparable to the volume of the PPAMs used in the biped robot, were studied. Out of the simulations we could conclude that the use of 2 input valves and 4 output valves was a good compromise between weight, price and speed.

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. To make the pressure control more accurate the inlet valves and outlet valves were divided in two levels: for the inlet 1 or 2 valves, for the outlet 1 or 4 valves. Figure (5) visualizes the actions of the modified bang-bang controller.



Actions

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

Fig. 5 Visualisation of the actions of the bang-bang controller

Figure (6) shows the experimental results of an increase of pressure from 1 bar to 1.5, 2, 3 and 4 bar, while figure (7) shows the results for a decrease from 4 bar to 3, 2, 1.5 and 1 bar in the volume.

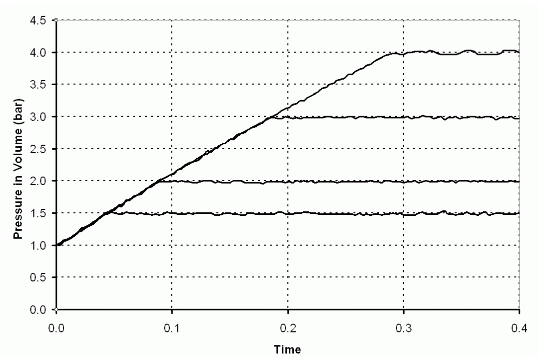


Fig. 6 Pressure Control (increasing pressure)

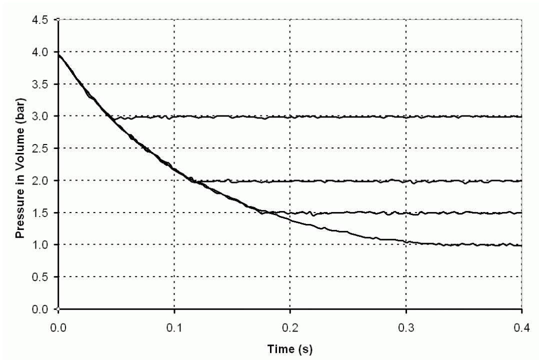


Fig. 7 Pressure Control (decreasing pressure)

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

4 GENERAL DESCRIPTION OF LUCY

Presently Lucy has been assembled and tested. A picture of the complete set-up is given in figure (8). 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 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 (2).

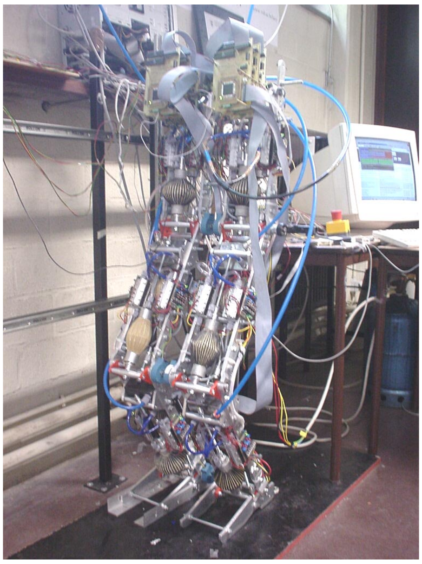


Fig. 8 Photograph of Lucy

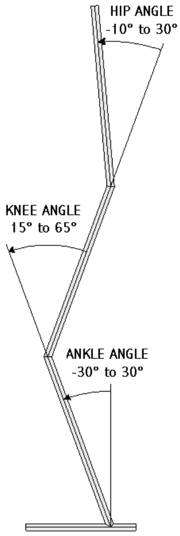


Fig. 9 Range of motion for the joints

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 (2). These connection plates and muscles can be replaced easily ensuring the required flexibility of the set-up. Figure (2) 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 from HEDM6540 encoders with 2000 pulses per revolution and the serial data originating from the pressure sensors inside the muscles. Both these encoder and pressure signals are captured by a separate processor, TPU, on the micro-controller in order not to load the CPU whilst reading their values. 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 FIRST STEPS OF LUCY

The last months Lucy has been assembled and debugged, therefore basic control strategies were implemented. On high level a quasi-static trajectory generation was used to balance the robot and to make it's first steps. On joint level an adapted feedback PI controller was implemented to settle position. The output of this controller is a delta-p signal, which will be added by and subtracted from a chosen mean pressure resulting in two new pressure values for both muscles of a joint. These new values are the set points for the bang-bang pressure controllers.

In order to avoid overshoots the integral term was made adaptive. When pressure differences are too high, the pressure controller won't be able to settle the pressure and thus the integral term will be lowered. In addition different sets for P and I values were used depending whether a leg is support leg or swing leg.

The graphs below show results of the first movements of Lucy. Here Lucy stands up from its rest position with both feet on the ground, lifts up and positions the left leg 0.1m further than the ankle of the stance leg. The same action is than performed by the right leg and next the left leg lifts again and places the feet back together after which the robot finally goes to its rest position.

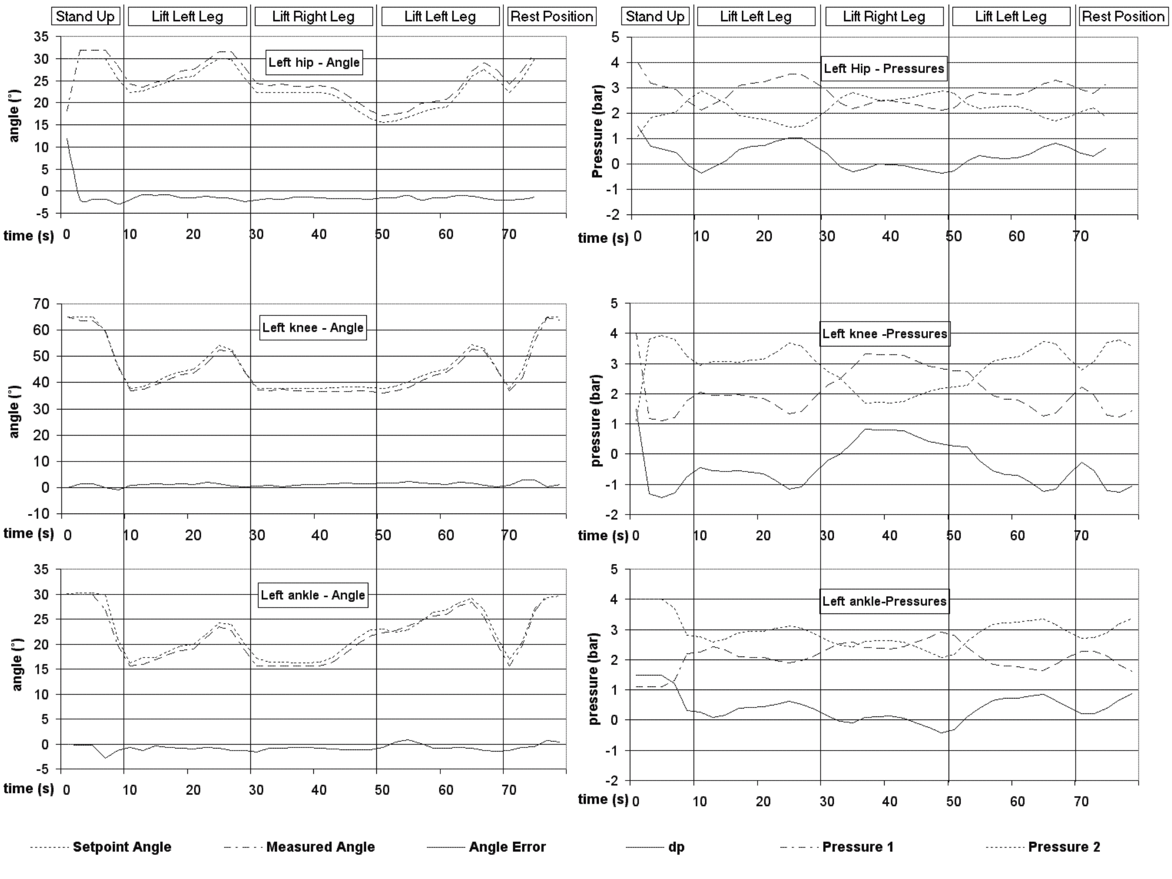


Fig. 10 First experimental steps: angle and pressure values for the left leg

At the left side of figure (10) angle, desired angle and the difference between them is given for the hip, knee and ankle of the left leg. At the right the pressures in both muscles of each corresponding joint and the control value delta-p is depicted. The definition of the angles can be found in figure (9).

The graphs show clearly the control strategy of keeping the mean pressure constant, which in this case is set at a value of 2.5 bar. One can have an understanding of the antagonistic working principle of the muscles when looking at the pressures for the knee between 10 and 50 seconds. During this time period the left leg switches function from swing leg to stance leg. From 10 to 30 seconds pressure 2, in the flexor muscle, must be higher than pressure 1, in the extensor muscle, to lift the weight of the lower left leg while from 30 to 50 seconds the pressure in the extensor muscle must be higher to hold the weight of the robot.
The results of this first control implementation with basic PID techniques show already satisfactory behaviour. Following step will be the implementation of a dynamic control scheme to induce faster and smoother motion for which the local feedback controller has to be redesigned with non-linear control techniques.

6 CONCLUSIONS

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 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. The biped Lucy is a robot actuated with these muscles. Both mechanical and electronic design of the robot was discussed showing the machine's modularity and elaborate hardware leading to a flexible experimental platform. For debugging reasons, basic control techniques were implemented which allowed Lucy to make her first steps. These first experiments showed already promising results.

7 REFERENCES

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