Lucy : a Walking Biped

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Abstract— **During the last decade research groups working on walking robots have increasingly focused on developing dynamically balanced robots in order to enhance speed and flexibility. Dynamic control takes inertia into account as opposed to static balance control mechanisms where these effects are avoided by implementing slower motion. Using dynamical control algorithms lightweight robot parts are desirable so as to be able to deliver the necessary power. Furthermore, the evolution of faster robots implies improving computation ability of the control unit. Therefore, adequate hardware and software design for control purposes has to be made.**

This paper presents the design of a biped actuated by Pleated Pneumatic Artificial Muscles. These actuators have a very high power to weight ratio and an inherent adaptable compliance. The mechanical design of the bipedal robot is modular, making parts easy to change and replace. The applied control has two levels: a high level controller for the complete system and a low level controller for each joint, locally implementing the high level decisions. The high level controller runs on a PC and each low level controller is implemented on a 16-bit microcontroller and operates a set of fast switching pneumatic on-off valves that set the muscle pressures in order to follow required trajectories. The paper discusses in detail the different concepts of our design. Special attention is given to the flexibility of the mechanical construction and the elaborate control hardware because through these an adaptable and broad experimental platform is ensured.

I. 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 DSR-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].

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 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.

II. Pleated Pneumatic Artificial Muscles

A. 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 muscles 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 figure1.

Fig. 1. Deflated and inflated state of the PPAM

If we omit the influence of elasticity of the high tensile strength longitudinal fibres, 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. Thus generated force is highly

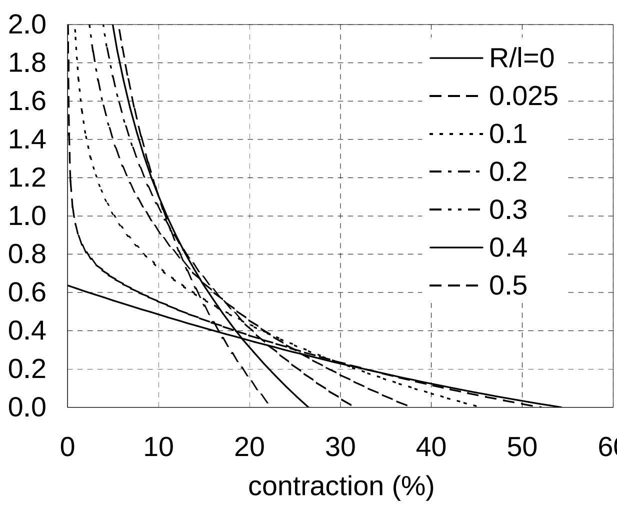

Fig. 2. Dimensionless force function

non-linear and proportional to the applied gauge pressure in the muscle. At a pressure of 300 kPa the force can be as high as 4000N for a device with initial length of 10cm, weighing only 100g.

B. Creating a Revolute Joint

B.1 Design and Characteristics.

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 3 shows the straightforward connecting principle.

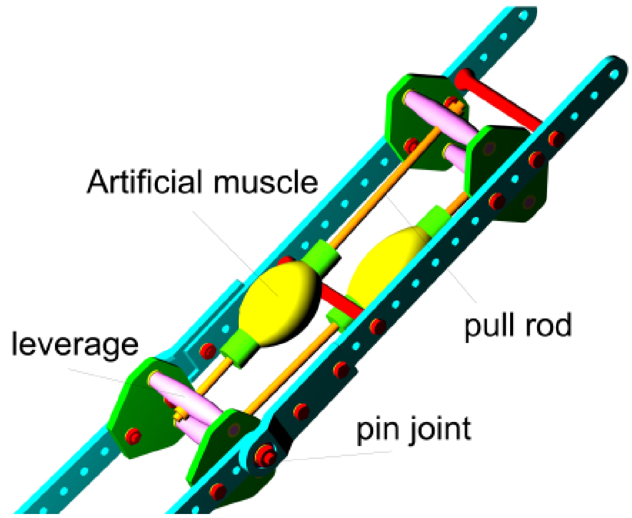

Fig. 3. Antagonistic working joint

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 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 4 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.

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

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

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

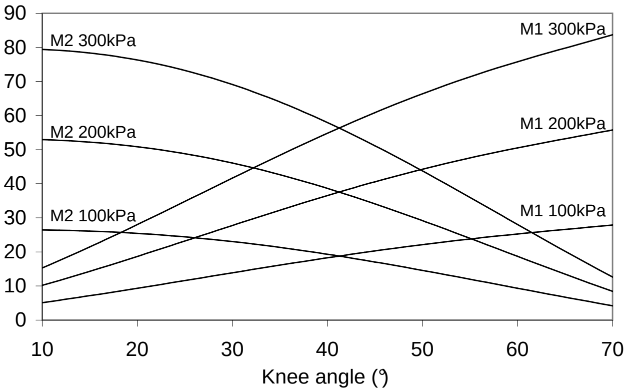

Fig. 4. Torques in the knee (Nm)

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.

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):

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

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. With closed muscles and the joint rotating, pressure variations in both muscles will have opposite signs. The same counts for both $dm_i/d\alpha$ because of the different slopes for m_1 and m_2 as can be seen in picture 4. Due to these sign differences, stiffness will be dependent on a weighted sum of both gauge pressures. This means that stiffness can be controlled independently from angular position since the latter is determined by pressure differences.

B.2 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 5 a drawing of the collector with 6 control valves is depicted.

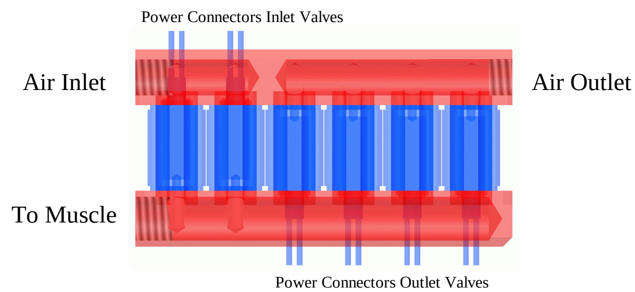

Fig. 5. Pressure control unit with six valves

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 6. To enhance the

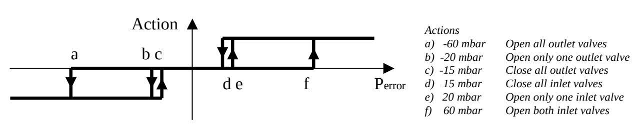

Fig. 6. Multi-level bang-bang control scheme

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.

III. 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