Design of a Biped Actuated by Pleated Pneumatic Artificial Muscles

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ABSTRACT

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 frame of the robot is made out of a high-grade aluminium alloy. The weight of the machine, all included, is about 30 kg and its height 150 cm. 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. All microcontrollers are linked to the PC through a dual ported ram unit that acts as a buffer and data transfer agent on a 16 bit parallel asynchronous bus. 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.

Keywords: Biped, Pneumatic Artificial Muscle, flexible design

1 INTRODUCTION

The last decades the field of robotics encounters new directions in which new applications are gaining more and more commercial interests. The mobility of robots has not been an issue for long since research was 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 became more and more important in our society 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 and P2 focusing on the field of domotics [13].

In the leisure industry the Sony company already made one commercially available four legged robot, Aibo [8], and a humanoid robot DSR-4X [7] will become available soon. But also for industrial use legged robots are gaining more and more interest for example in 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 part of the technological evolution. But in spite of the magnificent models already created this evolution is just started. A dextrous, intelligent, fast and fully autonomous humaniod robot is still far-off.

A lot of research has to be done in many different fields ranging from artificial intelligence to mechanical design. 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. The compliance characteristics can be used to reduce chocks and decrease energy consumption exploiting the natural dynamics of the system.

Extreme models are the so called Passive Walkers (Garcia, Ruina et al. [5]) 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 [11] and M2 [10] 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. To increase flexibility, by means of being able to change this frequency, one has to implement passive elements of which compliance is variable. 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 determines stiffness. Research on this topic is done by Van der Linde [14], Caldwell [4] and the Shadow Robot Company [6] 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

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 [12]. 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] 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. The membrane's stiff longitudinal fibres transfer tension. The inflated and deflated state of the Pleated Pneumatic Artificial Muscle are illustrated in figure 1.

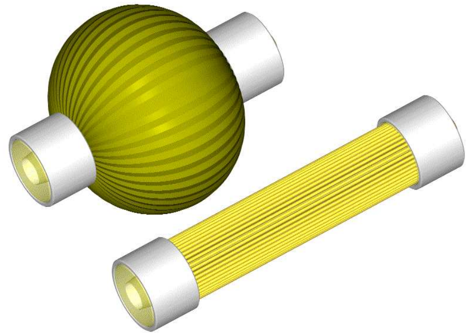

Figure 1: **Pleated Pneumatic Artificial Muscle**

The generated force is highly 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.

2.2 Revolute joint, Passive behaviour

Pneumatic artificial muscles only generate force when they shorten. To have a bi-directional working joint one has to couple two muscles antagonistically. At each joint the muscles are attached in a leverage mechanism by pulling rods. The points of attachment are essential in the design since they determine torque characteristics.

In an antagonistic setup, position will be determined by the ratio of pressures in both muscles. In previous work [3] a revolute joint was build for rotations between $-30°$ and $30°$. A step response from $0°$ to $10°$ was achieved with end error within $0.1°$ and overshoot less than $1°$ making use of proportional valves to control both pressures.

The artificial muscle is inherently compliant due to gas compressibility and the dropping force-contraction curve. In an antagonistic setup compliance is determined by the sum of the pressures in both muscles, therefore both position and stiffness can be controlled. To investigate this, a hopping mechanism [16] composed of a lower leg, upper leg, hip and body sliding along a guide shaft was built. Only the knee is actuated by a pair of artificial muscles. During experiments the leg was dropped from a fixed height while both muscles were kept closed. During stance, the leg will bend and stretch the extensor muscle. In this muscle, pressure and forces will increase as it extends, which implies that the extensor muscle stores motion energy that will be released as soon as the leg starts straightening. During these tests energy recuperation of up to 30% is registered.

3 MECHANICAL DESIGN

Following the rotative drive and the one-dimensional hopping robot a two-dimensional bipedal walking robot has been designed. During the design phase several criteria have been taken into account. First of all the machine's structure had to be lightweight and easy to assemble, eliminating complex gearing and connecting mechanisms. A second criterion was to have a test bed which should allow to make changes during the experimental period and this especially regarding the muscle connections since these determine torque characteristics.

Figure 2 shows the complete setup. The bipedal robot, all included, weighs about 30kg and is 150cm tall.

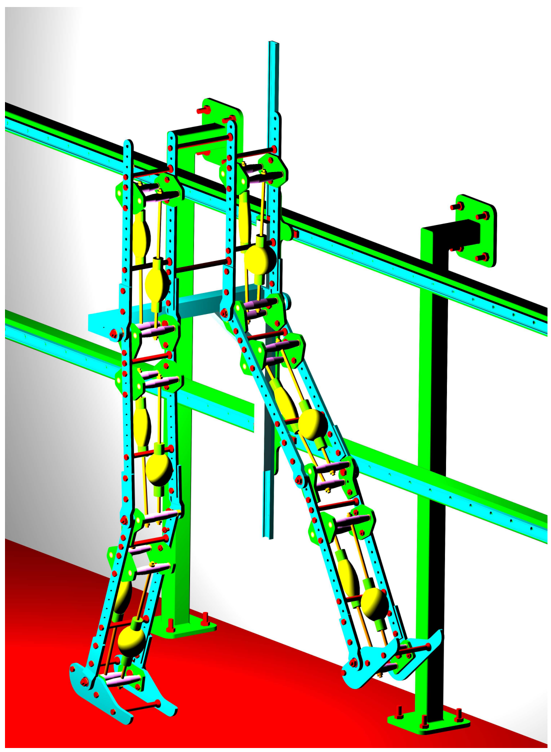

Figure 2: **Mechanical construction of the biped**

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.

One of the key ideas during the design was modularity which resulted in nearly the same configuration for each structural element, except for the foot, as shown in figure 3. This picture shows the straightforward connecting principle of the muscles to achieve rotative motion. As was mentioned before, the points of attachment together with muscle dimensions determine torque characteristics and also the range in which the joint can rotate since the muscles have limited contraction. The attachments can be chosen in such a way that the non-linear force characteristics transform to linear angle/torque relations and the required range and maximum torques are assured. The design allows an easy replacement of all parts in order to meet the requirements that several experimental tests may impose on the actuation system.

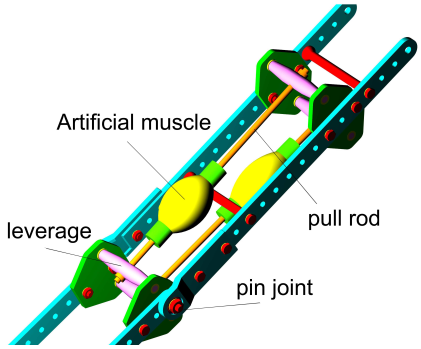

Figure 3: Modular part of the robot

4 ELECTRONIC DESIGN

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 produces the trajectories of the different joints from the dynamical model of the robot and runs on a PC. The low level controller has input and output tasks consisting of reading both position and pressure sensors and regulating the pressures in both muscles in order to follow the desired trajectories. This low level controller is implemented on a 16-bit microcontroller MC68HC916Y3 manufactured by Motorola.

Position measurements are done by incremental encoders HEDM6540 made by Sasco which have 2000 pulses per revolution and pressures are captured by miniature absolute silicon pressure sensors CPC100AFC from Honeywell. To have reliable and noise free pressure measurements these sensors, together with their DA converter (12 bit SPI output) are mounted inside the muscle. Both encoder and digital pressure signals are linked to a separate processor on the microcontroller, TPU, in order not to load the CPU whilst reading their values.

Lightweight pneumatic on/off valves, OX.821.104.C2KK, manufactured by Matrix are used to regulate pressure in the muscles. Each valve weighs 50gr and 6 valves are used per muscle: two inlet and four outlet valves. The valves are equipped with enhanced speed-up circuitry resulting in opening and closing times of about 1ms. More information on this topic can be found in [15].

Additional information such as contact with the ground and absolute position of the body are observed by a seventh microcontroller. 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 microcontroller. This controller is also responsible for communication between PC and all seven microcontrollers. A serial CAN bus system is often used for data transfer, but due to its serial character this system becomes slow when large amounts of data have to be transferred in relatively short times, as is the case for a dynamically controlled biped. Therefore a unique communication hardware and protocol was designed. Figure 4 gives a schematic overview of the complete electronic circuitry.

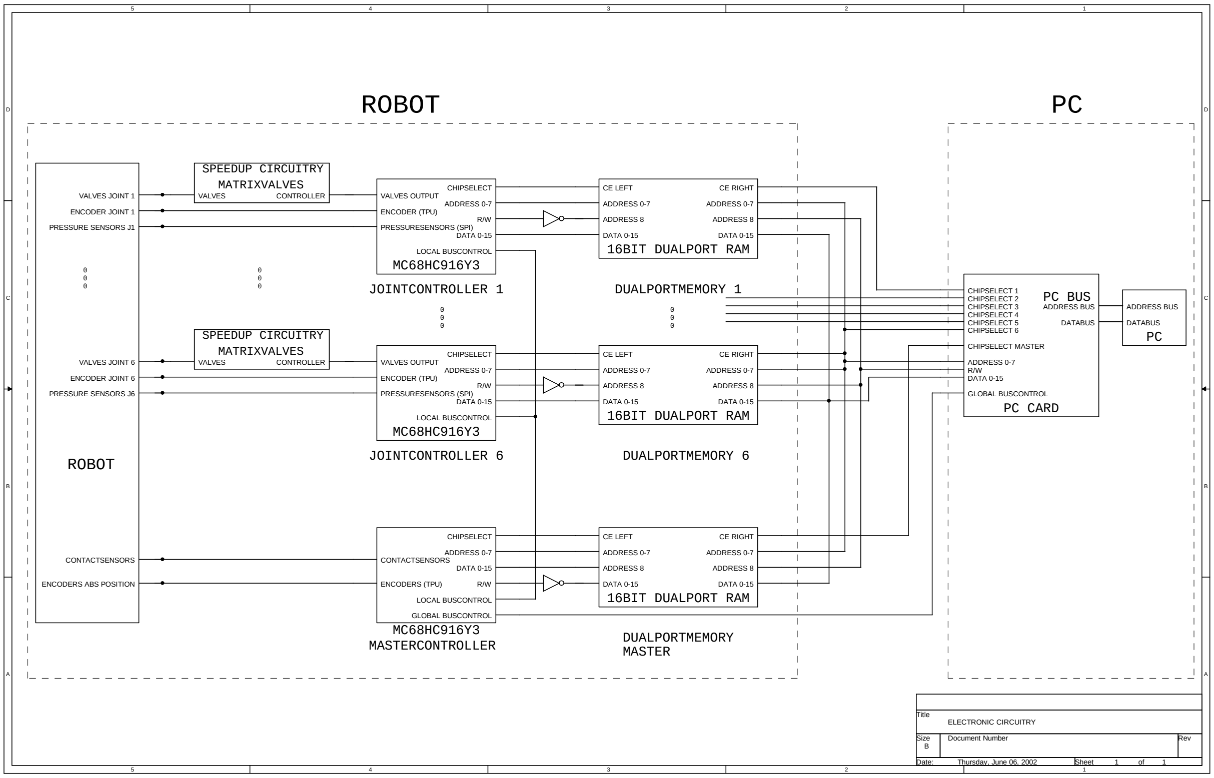

Figure 4: **Schematic description of the electronic design**

The key element for communication is the use of 16 bit dual ported RAM units which are the transfer and buffer agents between the PC and each microcontroller. In total there are seven such units. Each unit has an address and data bus for the microcontroller on one side and an address and data bus for the PC on the other. This allows 16 bit parallel data transfer. Two strategies were developed to enhance data transfer rates. Firstly, the memory space was divided into two parts. One part reads for the microcontroller and writes for the PC and the other part does the opposite. This allows simultaneous data transfer of microcontroller and PC to the dual ported RAM unit. To achieve this separation the R/W signals are connected on the highest address pin of the RAM unit but with a negation at the controller side. Secondly, a PC card was designed which enables the PC to validate only once an output address in order to scan all seven RAM units over the several data per unit. This is achieved with the use of counters both for incrementing the RAM unit number and the addresses within each unit. The seventh microcontroller or master controls the whole data transfer by handling bus control bits.

5 CONCLUSION

In this paper we presented the design of a bipedal robot actuated by pleated pneumatic artificial muscles which are implemented to create a lightweight structure with adaptable compliance characteristics. Both the mechanical and the electronic design were discussed in detail showing the machine's modularity, straightforward actuator connections and elaborate hardware. This design results in a flexible experimental platform which allows easy changes in the actuator characteristics. Presently the robot is being constructed and its electronic circuitry tested.

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