Control of a Six-legged Robot using Fluidic Muscles

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Abstract

The use of fluidic muscles as actuator for walking machines offer several advantages due to their performance weight relation or to the passive compliance of this type of actuators. Passive compliance is an important component for the control of locomotion in rough terrain. Because of an incomplete description of the environment feet often hid unforeseen obstacles. This paper presents the mechatronics of a six-legged insect-like robot Airbug with fluidic muscles as actuators. Main focus lies on the control concept of the antagonistic actuators.

1. Introduction

In the last 6 years several small walking machines like the six-legged machine LAURON [7], the mammal-like machine BISAM [6] or the simple biped TORQUEL are developed in our group(for more information about the robots in our groups see URL: http://www.fzi.de/ids/) . All these machine use electrical motors combined with special gears simple damper mechanisms. During locomotion of these machines unforeseen ground or obstacle contact of a foot could lead to a strong disturbance of the movement or damage parts of the mechanics.

Even if control concepts with active compliance are implemented it is very hard to cover these impact problems, especially in cases of fast movements. A second motivation for the use of other kind of actuators for walking machines is the possibility to redesign the locomotion apparatus of animals. In both cases soft actuators like artificial muscles seem to solve the actuator problem. In literature there are three types of artificial muscles electrochemical, fluidic [8], and mechanical ones [10]. To build up a lightweight machine, fluidic muscles are more powerful compared to the two other classes. Fluidic muscles have the advantage of high forces according to the size and the weight of the actuator, relatively high velocity for the contraction and a high-energy efficiency [4], [9]. In the following the mechatronic system and the control concept of the insect-like robot Airbug are presented, which uses fluidic muscles as actuators.

2. The fluidic actuator

The idea of using a rubber hose as a technical replacement of muscles was first discuss in 1872 by Prof. Reuleaux study "Kinematik im Thierreich". At the end of the 60th Prof. Morecki and his colleagues were one of the first who develop a robot arm actuated by air muscles. This so-called biomanipulator was control by myopotentials of the muscles of a human operator. which was actuated by air muscles [11],[12]. Since this days several research groups worldwide use fluidic actuators to build up robots. In most case these muscles are self-made consisting of an inner rubber liner, an outer containment layer of braided nylon and end caps that seal the open ends of the muscles (see [3] and URL: http://www.shadow.org.uk/). All air muscles have in common that their length and diameter can be easily adapted to the mechanical requirements, that they can contract similar than natural muscles (up to 30 %), and that they can be used in liquid or explosive environments.

As actuators of Airbug machine the artificial fluidic muscles MAS-20 produced by FESTO are selected (for more information see URL:http://www.festo.com/ and http://www.festo.com/pneumatic/deu/muskel/index.htm).

These membrane-contraction-systems contract under the pressure of 6bar. Combining a fluidic tight, high load bearing flexible tube and a strong fabric builds a three-dimensional compound structure. Embedding the fibres completely in the tube minimizes friction (fig. 1).

Filling in fluidic media (here: compressed air) forces the compound structure to deform in radial direction. At the same time the actuator contracts in axial direction and the needed tensile force arises. Without weight the actuator can reach a stroke of 25 % of his maximum length.

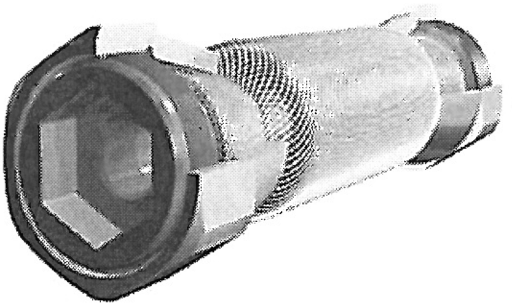

Figure 1: Design of the MAS-20 fluidic muscle

The tensile force depends on the actuator‘s contraction. The force of the MAS-20 decreases almost linear from its maximum of about 1700 N at its maximum length to zero when the neutral angle is reached. The actuator‘s maximum force is only available under static conditions (0 mm/s), and decreases with increasing velocity. In our case the average velocity is ~300 mm/s giving us a waste of less than 9 % of the actuator‘s force.

3. Mechanics and sensor system

Based on a prototype leg construction [2], which was used to optimise the leg geometry and to develop first control concepts, the insect-like machine Airbug was designed (see fig. 3). The leg of Airbug with a weight of 2.5kg is divided in three segments (coxa 94mm, femur 470mm, tibia 600mm) similar to the leg of a stick-insect (fig.2).

The single legs are fixed on the body in an angle of 30°. For the drive of the leg altogether eight FESTO MAS20 fluidic-muscles are used, thereof 2 for the control of the α-joint, 4 for the β-joint and two for the γ-joint.

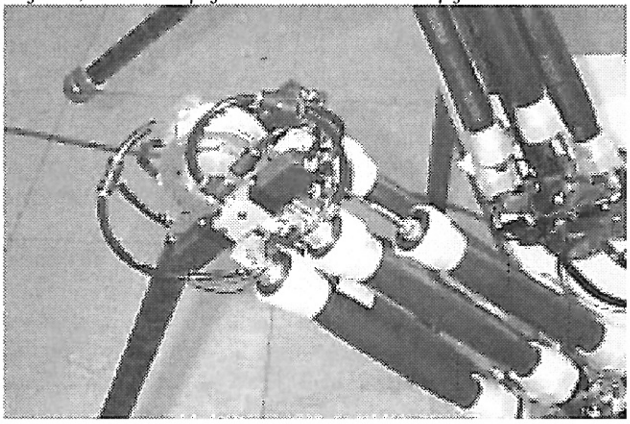

Figure 2: Leg construction of Airbug

Unlike an electric motor fluidic muscles do not generate a rotary motion but a linear contraction. When operating legs it is necessary to transfer the linear contraction in rotary motion. Therefore, the muscles are connected to sheaves being mounted on the particular joints. The range of each joint depends on the maximum contraction of the muscle and the radius of the sheave. The limit of the range depend on the length of the “tendon” respectively its joint on the circumference of the sheave. The ankle range of α-joint, is 78°, of the β-joint 94° and of γ-joint 78°. The maximum torque of α-joint and γ-joint is 59.5Nm and that of the β-joint 98,6Nm. At the begin of the contraction torque is only available. It goes nearly linear to zero till the max. contraction.

The body is about 650mm in length, 600mm in width and 250mm in height. The final machine has a total weight of about 25 kg including the valves for the muscles and the embedded PC, which is located in the central body of the machine (see fig. 4).

To measure the joint angles special shaft encoders based on photo reflectors have been developed. They are able to measure the absolute position of each joint. For the closed loop control of the air muscles the pressure inside the muscle is measured. Also a force sensor, was developed, whose measurement principle is based on strain gages. This sensor can measure the forces on the tendons. Up to now this sensor was only used inside the test leg, because the information of the pressure sensor seems to be sufficient for close loop control.

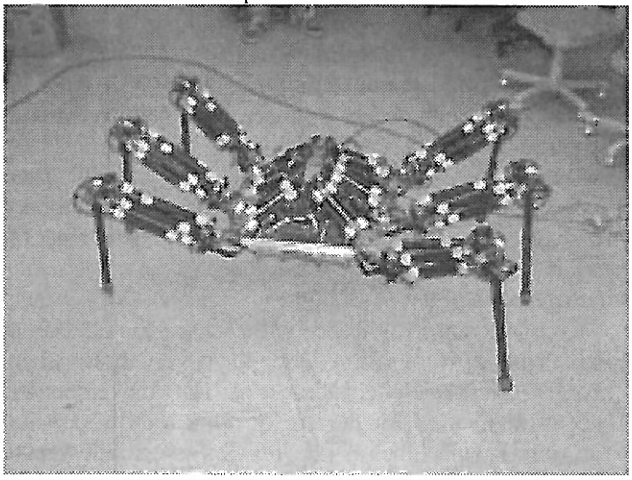

Figure 3: Airbug the stick insect like robot

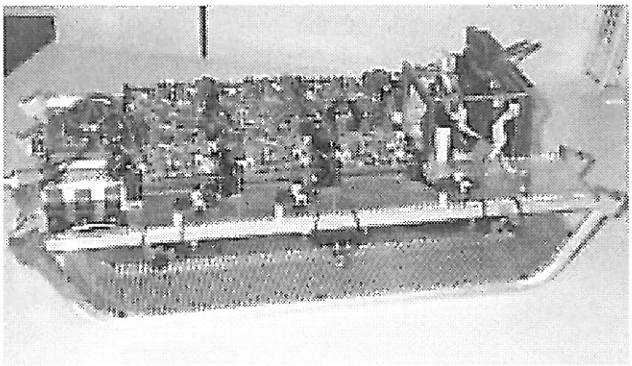

Figure 4: Central body of Airbug including controller cards for the muscles and a PC/104 system.

4. Control architecture

The control architecture is similar to that of our walking machines LAURON III and BISAM [1]. Instead of the power electronic card, for the electrical motors a special card for controlling the valves is developed. The close-loop control as well as the interpretation of the sensor measurement of each leg is done on a micro-controller 80C167. This micro-controller is installed in an industrial controller board (Phytec, miniMODUL-167). This controller board is plugged on a circuit board containing circuitry for the control of 1 proportional and 8 digital valve. The proportional valve is suited from one PWM output channel of the 80C167 with a switching frequency of 20-80kHz at a resolution of 10bit. Additional circuitry was implemented, i.e. for signal conditioning of the joint encoders or configuration and display purposes. The micro-controller boards are connected via CAN-Bus to the higher control level system, a PC/104 system. The use of different hardware and operating system units results in a three level system: C167, RT-Linux and Linux. In order to achieve a clear arrangement of those levels modular controller software architecture is used [13]. This software architecture allows the programming of all levels in the same way.

The C++-class library hides the communication between the levels. Hence, the system developers can focus on the development of methods while the communication is done automatically. Every method of the controller architecture is realised in a C++-class module. The modular architecture allows the manipulation of each parameter of every module via LAN while the system is running. This possibility results in small and fast development cycles. The manipulation tools run on the Linux part of the system so that critical parts that are assigned to the real-time part are not directly influenced by the manipulation itself.

The detachment of the user interface from the controlling PC disburdens the on board PC/104. For example, the user interface can include high-end graphic animations without straining the controlling mechanism too much. Linux is also used as development platform. All parts of the software architecture are compiled with GNU-C++-(cross-) compilers. The C167-programs are downloaded via CAN-bus during the initialisation of the system.

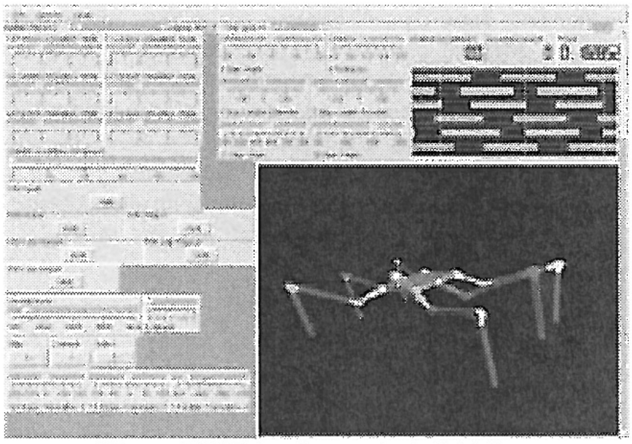

Figure 5 GUI for the control of Airbug

5. Close loop control

In the first experiments on the knee joint of the prototype leg two 3/2 valves with pneumatic springs for zero position return were used. One valve served as air inlet and the other as air outlet. Although this valve type is very fast (14/18 ms switch time) it needs at least 2,5 bar pressure at the inlet to keep the pneumatic spring working. This cannot be guaranteed for the muscle outlet valve, since it must be possible to empty the muscle completely. Right now one 5/3 valve with a mechanical spring is used to fill and empty the muscle. This valve is a bit slower (12/30 ms) but it weights less (50g opposed two 80g) since only one has to be used and first experiments have shown that the open/close time is sufficient.

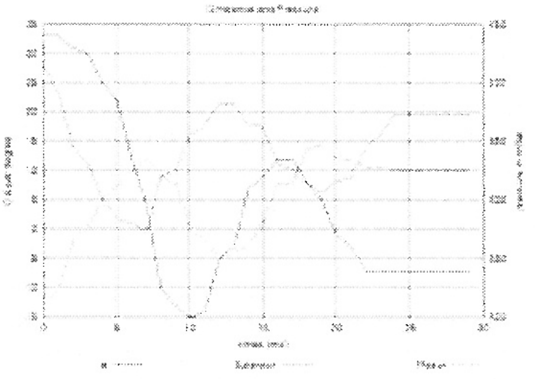

Figure 6 Curve of the Bang-Bang Control

The task to control one muscle-joint consists of the five sub tasks of controlling the pressure and force of the flexor and the extensor activator and the joint angle position, which is controlled by the coupled actuator extension. Since the only variables of the control loop are the airflow into and out of the muscle in a trinary form (three valve states: in-close-out) the first step is to generate a basic control scheme. As testing environment for the different control schemes the position control of the knee joint was used. Since the muscle-actuators can only generate a force in one direction a complete joint with protagonist and antagonist has to be used. The first test was just to open and close the valves and try to control with the following Bang-Bang controller scheme:

$$u_{ext} = \begin{cases} 1 : e > 0 \\ -1 : e < 0 \\ 0 \end{cases} \qquad \text{Eq.4}$$

$$u_{fex} = \begin{cases} -1 : e > 0 \\ 1 : e < 0 \\ 0 \end{cases} \qquad \text{Eq.5}$$

where e=0 means the valve is closed, e=1 the valve lets air into the muscle, e=-1 the valve lets air out of the muscle. The result of this can be seen in fig.6. It shows the control deviation e and the pressures of the extensor and the flexor activator. The unit of e is 0.4 degree (which is the encoder distant). Although this control scheme is very fast, it tends to oscillate around a control deviation of zero. To stop this behaviour a pulsing-valve approach like the one introduced in [5] was used. To have a better control of the airflow in and out of the muscle-activator the valve is only allowed to "pulse", meaning to open for a very short time and close again afterwards. u is now interpreted as the pulse-frequency (a negative frequency means letting air out of the activator) and is controlled by a classical P-Controller:

$$u_{ext} = T_r * e \qquad \text{Eq.6}$$

$$u_{fex} = -T_r * e \qquad \text{Eq.7}$$

Fig. 7 shows this for a T_r of 0.32Hz and a pulse length 40ms and a maximum frequency of 18Hz. Note here as in the previous example, that the manipulation variable of the flexor is always the opposite of the extensor variable thus showing the antagonistic principle of the actuator pair.

As it is quite obvious the time to drive over the complete working area of the joint is very long (80 ms) opposed to the first Bang-Bang controller (30 ms). To speed up a PD controller approach was used. The P part is the one stated above, the D part is implemented by changing the length of the pulses depending on the derivation of e. The result of this is shown in fig. 8. It is quite good visible that the PD-Controller combines the good elements of the P and the Bang-Bang controller, as it is expected to do.

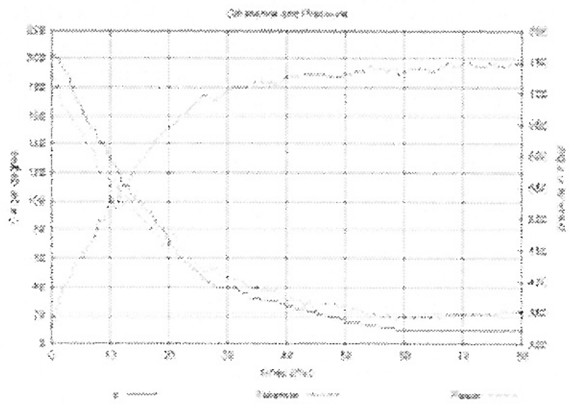

Figure 7: Curve of the P-Control

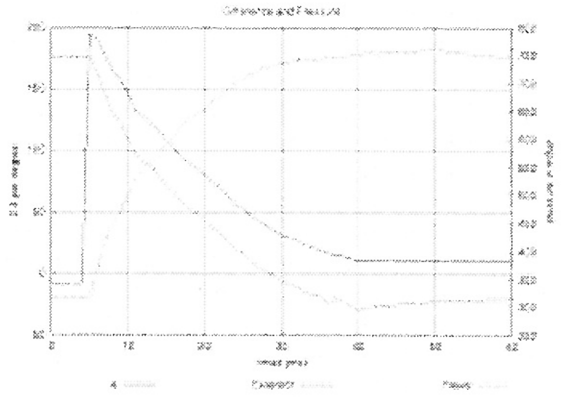

Figure 8: Curve of the PD-Control

6. Experiments with Airbug

The first experiments on the assembled robot have shown the potential of the mechanical construction. With the described close-loop control and the movement generation part of the Lauron III control program it is possible to move the robot in pentapod, tetrapod and tripod gait. The presented control only allows very slow gait-cycle periods, if the robot moves faster the control is not able to compensate the dynamic effects of the moved masses. A further study of the pressure-force relation in conjunction with the used pressure sensor will be done to evaluate the possibility of using a force observer for calculating the leg internal torques and forces. This work is still under development. It is also planned to to include the foot force sensor in control process so that a better adaptation to the ground condition is possible.

Based on the very positive locomotion test (Airbug was presented at the Hannover Fair in April 2001) next it is planed to optimise the mechanics and the control concept of Airbug, so that also fast movements are possible. Concerning the use of air muscles as actuator we have started to build a biological inspired leg which should allow fast movements of a mammal-like machine so that dynamical stable walking will be possible.

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References

[1] K. Berns, W. Ilg, M. Deck, J. Albiez, and R. Dillmann. Mechanical Construction and Computer Architecture of the Four-legged Walking Machine BISAM. *IEEE Transactions on Mechatronics*, 4(1):1--7, march

[2] K. Berns, V. Kepplin, R. Müller, M. Schmalenbach, *Six-legged Robot Actuated by Air Muscles, In Proceedings CLAWAR 2000, 3rd International Conference on Climbing and Walking Robots*, Madrid, 2-4. Oct. 2000.

[3] D.G. Caldwell, G.A. Medrano-Cerda and M. Goodwin. Characteristics and Adaptive Control of a Pneumatic Muscle Actuators for Robot Elbow. *IEEE Robotics and Automation Conf.*, San Diego, USA, May 1994.

[4] C. Chou and B. Hannaford. Measurement and Modelling of McKibben Pneumatic Artificial Muscles. *IEEE Transactions on Robotics and Automation*, 12(1), 1996.

[5] R.W. Colbrunn: Design and Control of a Robotic Leg with Braided Pneumatic Actuators, Masterthesis, Department of Mechanical and Aerospace Engineering, Case Western Reserve University.

[6] W. Ilg, J. Albiez, K. Berns, R. Dillmann. Learning of Posture Control Mechanisms for the Four-legged Walking Machine BISAM. In Proceedings *CLAWAR 2000, 3rd International Conference on Climbing and Walking Robots*, 2-4. Oct. 2000

[7] V. Kepplin, K. Berns, A Concept for Walking Behaviour in Rough Terrain. *CLAWAR'99 2nd International Conference on Climbing and Walking Robots*, p.763-772. University of Portsmouth, U.K., Sep. 1999

[8] G. K. Klute, J.M. Czerniecki, and B. Hannaford. Pneumatic Actuators with Biomechanical Intelligence. In *IEEE/ASME Intern. Conf. on Advanced Intelligent Mechatronics*, Atlanta, GA, USA, Sep. 1999.

[9] G. K. Klute and B. Hannaford. Fatigue Characteristics of McKibben Artificial Muscle Actuators. In *IEEE/RSJ Intern. Conf. on Intelligent Robots and Systems*, Victoria, B.C, Canada, Oct. 1998.

[10] G. Mennitto, P. Gregoire, and M. Buehler. Carl: A Compliant Articulated Robot Leg for Dynamic Locomotion. In *IAS-4, Intelligent Autonomous Systems*, p. 702--707, Karlsruhe, Germany, 1995

[11] A. Morecki, Polish Artificial Pneumatic Muscle. To appear in CLAWAR 2001 *4th International Conference on Climbing and Walking Robots*, Karlsruhe Sep.2001

[12] A. Morecki, J. Ekiel, K. Fidelus. Some Problems of Controlling alive Upper Extremity and Bioerosthesis by Myopotential, External Control of Human Extremities, *ETAN Belgrade* 1967

[13] K.-U. Scholl, V. Kepplin, J. Albiez, R. Dillmann. Developing Robot Prototypes with an Expandable Modular Controller Architecture, Proceedings of the International Conference on Intelligent Autonomous Systems, Venice 2000, pp 67-74.