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DESIGN OF MECHATRONIC ACTUATION SYSTEMS BASED ON FLUIDIC ARTIFICIAL MUSCLES

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Abstract: *The actuators based on pneumatic artificial muscles are unconventional actuation systems which use the properties of special materials. The main advantages of the fluidic artificial muscles are: high actuation force, small weight and volume, flexible, small amount of wear, direct connection with the system, easy to replace, can operate in harsh conditions (sand, water, corrosive agents). For those reasons they may be used in many applications like robotics, industrial systems, rehabilitation engineering and others. A robotic artificial arm actuated by two fluidic artificial muscles in antagonist configuration was designed and developed as an application in the field of rehabilitation engineering, used for testing actuation systems based on pneumatic artificial muscles. Different types of structural schemes and consecrated pneumatic diagrams for controlling actuation systems based on artificial muscles were also studied.*
Keywords: *actuators, fluidic muscle, mechatronics, artificial arm, rehabilitation.*

1. INTRODUCTION

The synergetic union of the mechatronic systems creates major interdependencies among the involved engineering disciplines, which are proved in many ways, for example the mechanical properties which can be combined with the control system characteristics which in their turn are coupled with software properties.

Actuators are execution elements compatible with mechatronic technology, which transform some sort of energy in mechanical energy. Their development completes successfully the conventional execution elements (various types of electrical, pneumatic, hydraulic motors). The development of the actuators is the result of evolution in technological evolving and penetration in some fields of technology where it was hard to believe that it will ever reach. The structure of the actuators can be decomposed in substructures only with the risk of losing the motion generation capacity. A simple, elementary motion, generated by an actuator may be used directly for a certain purpose or may be transmitted, transformed and amplified, or correlated with the motion obtained from other actuators [1].

The specific problems regarding mechatronic system design of actuators must be seen in an integrated vision, seeing the whole, the system in which they act.

The pneumatic actuations are widely used in practice. The actuators based on pneumatic artificial muscles are unconventional actuation systems which use the properties of special materials. The main advantages are: high actuation force, small weight and volume, flexible, small amount of wear, direct connection with the system, easy to replace, can operate in harsh conditions (sand, water, corrosive agents). For those reasons they may be used in many applications like robotics, industrial systems, rehabilitation engineering and others.

2. PNEUMATIC ARTIFICIAL MUSCLE

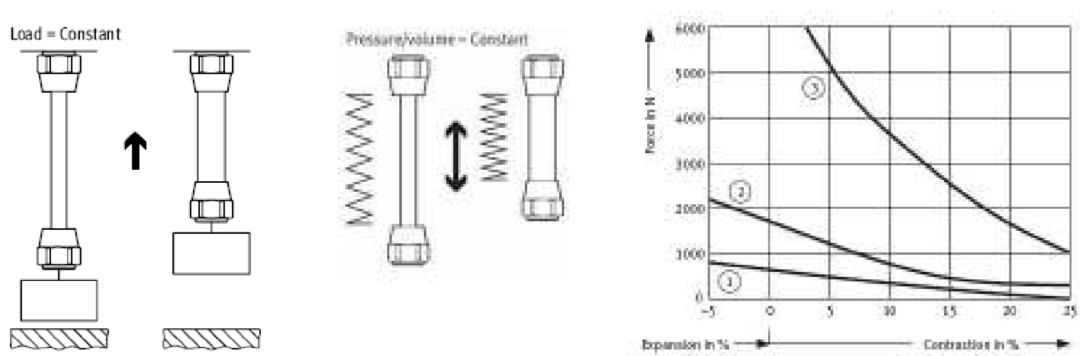
The working principle of artificial muscles is the contraction and relaxation of a membrane, the same as the human muscle. In principle, an artificial muscle is a combination of a flexible tubing, made of chloroprene, a material from the category of elastomers, and an integrated covering consisting of non-flexible fibers in a rhomboidal pattern (fiber structure) creating a three-dimensional grid structure (Fig. 1). When the compressed air is being introduced in the system, the grid structure is deformed. A pushing force is generated in axial direction, the result is a shortening of the muscle according with the internal pressure increase [4].

Because of the relationship between the output force and the shortening of the fluidic muscle, it is difficult to be compared with the classical pneumatic cylinders. The fluidic muscles have an important advantage, their whole weight being approximately eight times lower than the weight of the pneumatic cylinders with the same diameter, though the force is ten times stronger. Very slow movements are possible because the fluidic muscles do not present the stick-slip effect, and the dynamic performances are better.

Figure 1: The fiber structure of a fluidic muscle

The positioning tasks are made through pressure regulation, but an independent system of guidance is necessary, as well as force absorption devices at the ends. In contrast with the pneumatic cylinders, the maximum stroke of the fluidic muscles is 25% of total length, and the initial force is highest at the beginning of the stroke descending to 0 when it reaches 25% of total length (Fig. 2).

The Festo Company developed a series of artificial muscles that has some important characteristics: high actuation forces, very good dynamics, resistant to vibrations, flexibility, various methods of installation, suitable for clean or contaminated environments, no need to use lubricants, consumes less air, noiseless, easy to transport, etc. They have an initial force of 600 daN and the acceleration reaches 50 m/s^2, being suited for applications where high accelerations and high force are required, like sorting, speed cutting, manipulation process systems. They are hermetically sealed and don't have any movement components which generate friction forces so they work smooth, and allow uniform movements even at low speeds [7].



a) b)

Figure 2: a) Festo artificial muscle working at constant load and at constant pressure/volume.
b) Force characteristics versus contraction for 1) 10 mm, 2) 20 mm, 3) 40 mm diameter of fluidic muscles

The bionic principle that is at the basis of this product is the contraction of the human muscle, a simple and fascinating process at the same time. The human muscle is capable of strong contractions or slow relaxations, though the technical implementation of this natural system implies a series of challenges. Festo managed to implement this natural principle until the limit of series production, developing fluidic artificial muscles with diameters of 10 mm, 20 mm and 40 mm, various types of connectors, any actuators length being easy to produce (Fig. 3) [7].

Figure 3: Festo artificial muscles

4. STRUCTURAL SCHEMES OF MECHATRONIC ACTUATION SYSTEM BASED ON FLUIDIC MUSCLES

The main disadvantage of this type of artificial muscles is that they can generate movement only in one direction. So, in order to generate motion in both directions the actuation system must be in antagonic configuration.

Another inconvenient of the fluidic muscle is the short stroke. This might be improved by using external devices like a loose roller, although, in this case, the fluidic muscle has to be able to generate twice the initial force (Fig. 4).

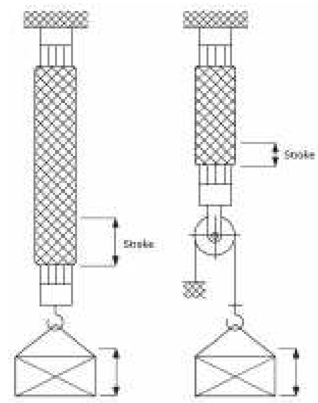


Fig. 4. Solution for improvement of the stroke using a loose roller

The artificial muscles have major advantages in lifting operations due to their high force capabilities and the lack of the stick-slip effect. The parallel connection of the muscles multiplies the initial force. The serial connection allows the achievement of bigger strokes, proportional with the number of fluidic muscles connected serially. The force F for the parallel connections and also the stroke S for serial connections are cumulative properties, which make the fluidic muscle a alternative for pneumatic actuations.

If cables, ropes, chains, belts or other tensile elements are used for the transmission of the tensile forces, there is no motion guidance, and this has to be created additionally. All guides require additional components, which increase labor and costs. A number of options for motion guidance are illustrated in Fig. 5 [4].

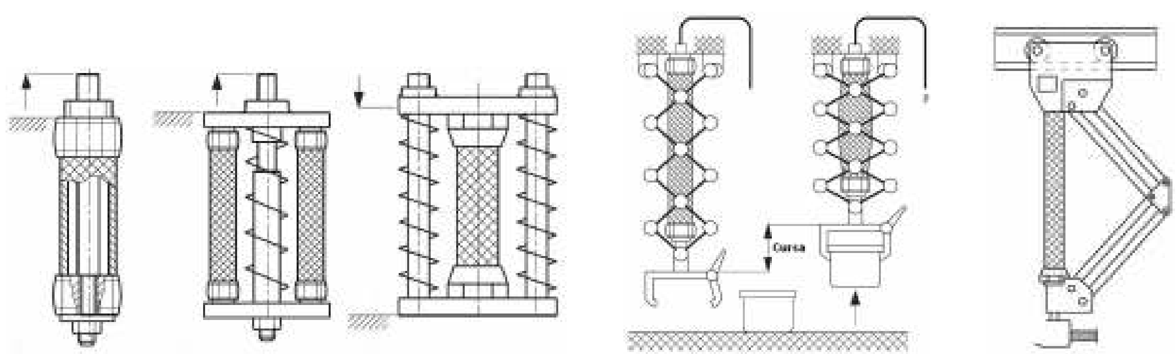


Fig. 5. Motion guidance examples used for actuation systems based on pneumatic muscle

The actuation system based on fluidic muscles might be included in the field of mechatronics, particularly in the field of pneutronics. Functionally, the structural scheme of a pneutronic system is determined by the type and complexity of the industrial application of the system, by constrains imposed to the controlled energetic flux. The controller confers the system a high functional flexibility for a specific hardware configuration. In particular, the pneumatic actuation system has a specific configuration depending on the controlled parameters like pressure or debit, types of actuators, precision, energy consumption, circuit level of protection, environment influences, etc.

The industry has consecrated specific controlling circuits for actuations by means of fluidic muscles in specific task. The proposed pneumatic circuits for actuations of the fluidic muscles are showed in Fig. 6, in which: 1- fluidic muscle type MAS-…MC, 2- fluidic muscle type MAS-…MO, 3- 3/2-way valve, 4- non-return valve, 5- rapid exhaust valve, 6- flow control valve, 7- 5/2-way double-pilot valve. The valves must be mounted as closer as possible to the pneumatic muscle, and the connections and the tubing must have large diameters [4].

The force generated by the pneumatic muscle depends directly on the pressure applied to the muscle; therefore the force may be controlled by means of pressure regulations.

A pneumatic circuit for high-precision, wide range of pressure regulation used for actuation of a pneumatic muscle is showed in Fig. 7. The active device is a proportional pressure regulator type VPPE-3-1/8-6-010 made by Festo Corp. [8].

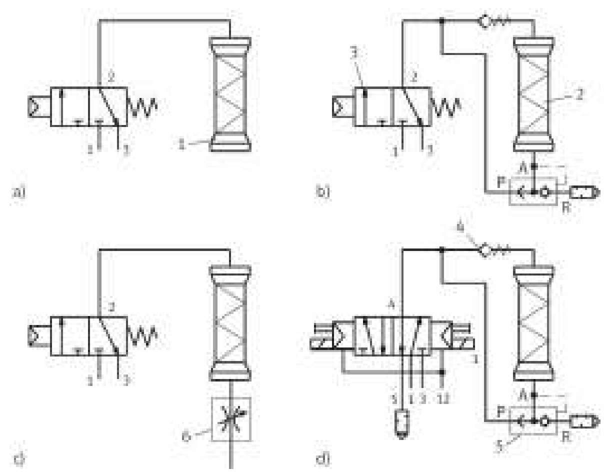


Fig. 6. Pneumatic circuit diagrams for the connection of a pneumatic muscle
a) for frequencies up to 0,5 Hz; b)-d) for frequencies more than 0,5 Hz

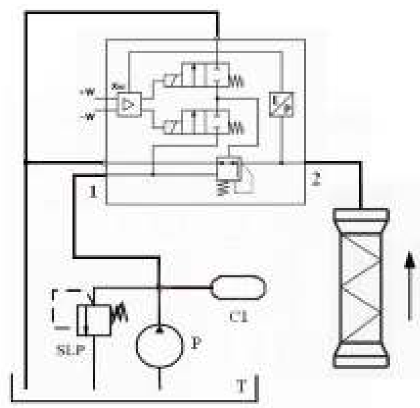


Fig. 7. Pneumatic circuit diagram using a proportional pressure regulator type VPPE-3-1/8-6-010

In this circuit the pressure limiting valve adjusts the pressure to 8 bars, which is applied to port 1 of the pressure regulator valve (input). The port 2 of the pressure regulator is the output port which is connected directly to the muscle. The proportional pressure regulator delivers a pressure of 0 to 6 bars depending on the analog voltage applied on W+ and W- pins (0...10V).

4. ARTIFICIAL ARM ACTUATED BY FLUIDIC MUSCLE

The loss of motion capacities of a human arm or forearm as a result of a trauma, disease, paraplegia, congenital anomaly requires procedures which promote the motion as the basic element of a rehabilitation treatment. Rehabilitation using orthesis is recommended in several cases like central nervous system lesions, after long immobilizations, congenital malformations etc. [6].

By studying the anatomy and physiology of the elbow is aimed the development of a model which may be applied in orthesis actuation systems, being close enough to the real model. The pneumatic artificial muscles may be used for actuation of orthesis systems, with the goal of locomotion rehabilitation for the handicapped persons. The artificial muscle has found applicability in rehabilitation engineering because of the similarity with the skeletal muscle. Like the skeletal muscle, the artificial muscle has only the ability of pulling; this is the reason why two artificial muscles in antagonist configuration are used for bidirectional motions (flexion/extension).

The use of pneumatic energy in the case of artificial muscles for orthesis actuation systems, for the lower or upper limb, is the latest trend that can still be improved. Finding new solutions for patient independence and lowering metabolic costs is a challenge for all the specialists involved in this field of rehabilitation.

An artificial arm with application for human upper limb rehabilitation was designed. This artificial arm can be attached to the human arm with two fastening elements as can be seen in Fig. 9 and Fig. 10, and assist the flexion/extension using two rigid elements and a revolute joint. This assures the correct motion of the forearm and amplifies the muscle forces at patients who are not capable of normal biological functions of the skeletal muscles after lesion at the level of the nervous system, or muscular atrophy due to long term immobilization. In the artificial arm two pneumatic muscle type DMSP-10-145N-AM-CM made by Festo Corp were used in antagonist configuration.

We chose a model which only revolves about the y-axis, by means of flexion and extension, because this type of motion is generated by the biggest muscles in the human upper limb, biceps and triceps, which will be rehabilitated. After the first step in the design according to the task of rehabilitation the actuation system from Fig. 8 was chosen, in which: 1,2 – pneumatic artificial muscles, 3,4 – clamp elements, 5,6 – traction steel wires, 7 – roller with ball bearing, 8 – rigid element (forearm).

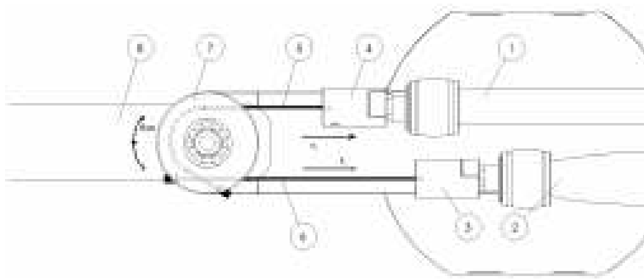


Fig. 8. The design elements for the artificial arm

The designed and developed artificial arm with applications in rehabilitation engineering, used for testing actuation system based on pneumatic artificial muscle, is showed in Fig. 9, where it performs the flexion of the forearm on the arm, and in Fig. 10 where it performs the extension of the forearm on the arm.

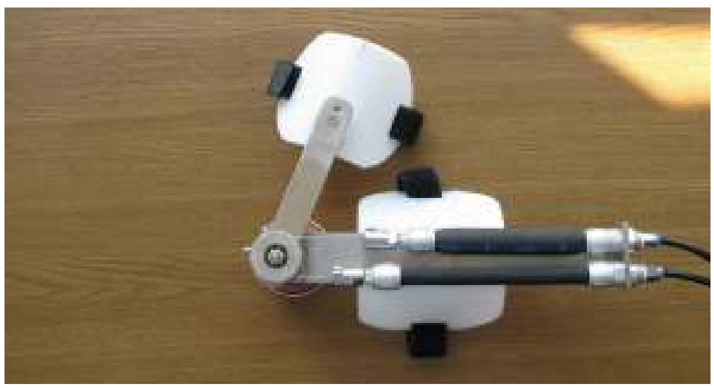


Fig. 9. The flexion of the forearm on the arm

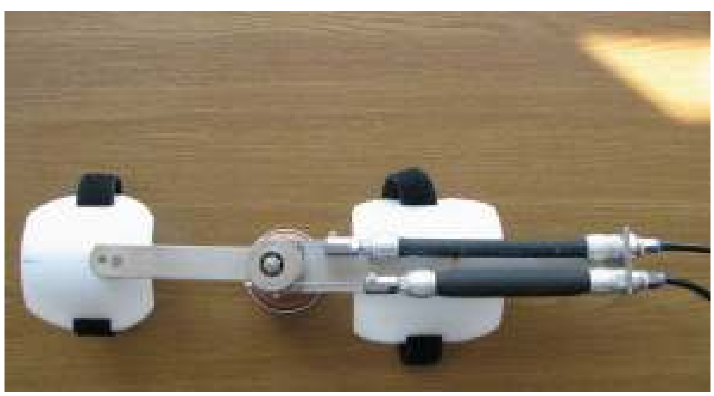


Fig. 10. The extension of the forearm on the arm

For controlling the artificial arm in this application, it is necessary to adjust the force which assists the human arm or which resists to the partially working human arm, based on the exercise proposed by rehabilitation specialists. The control of the generated force is made directly by means of pressure regulation. The solution presented in chapter 2 was chosen, using a proportional pressure regulator type VPPE-3-1/8-6-010 (Fig. 7)

The control system for the artificial arm is showed in Fig. 11, based on Cerebot development board, from Digilent Inc. The main controller is an ATMega64L microcontroller from Atmel Corp. On pins PE 4, 5, 6 and 7 is connected a PMod-Switch with 4 switches, which sets the exercise, and two analog potentiometers connected on ADC1 and ADC2 are used for adjusting the speed of the artificial muscles according to the rehabilitation program.

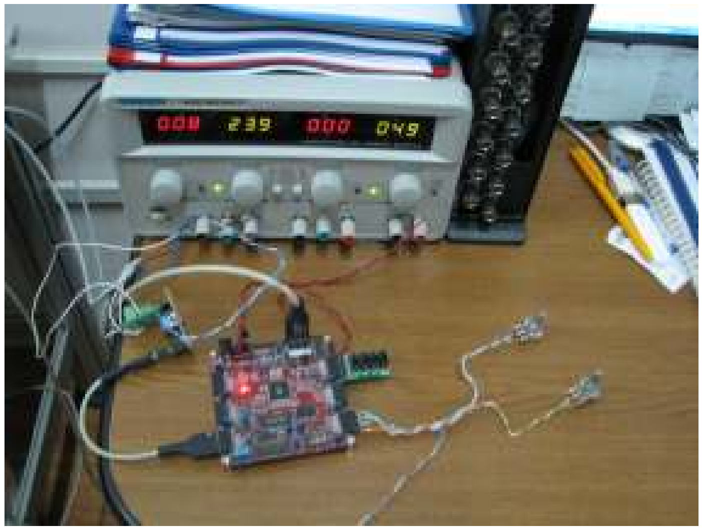


Fig. 11. The control system for the artificial arm

On PD4, PD6 ports and PB5, PB6 ports is connected a module Pmod-DA (digital-to-analog convertor) which is used for setting the value for proportional pressure regulators. After the DA converter is the circuit made with the operational amplifier LM324D with a gain of 2, and the connections for the two proportional pressure regulators. The control system is powered from a laboratory power supply with 24V for regulators and 5V for the Cerebot board.

The applications of this artificial arm might be also used in the field of robotics, where it can be attached to a wheel-chair and used as prosthesis or by attaching to a partially functional human arm where may be used for regaining the full muscle force of the arm.

5. CONCLUSIONS

The actuators based on pneumatic artificial muscles are unconventional actuation systems which use the properties of special materials. The working principle of artificial muscles is the contraction and relaxation of a membrane, the same as the human muscle.

This paper analyzed different structural schemes for actuation systems based on artificial muscle, as well as serial or parallel connection properties and has presented the consecrated pneumatic diagrams for controlling the artificial muscle actuation by means of pressure regulation.

An artificial arm based on the real model was designed and developed, with applications in rehabilitation engineering, used for testing actuation systems based on pneumatic artificial muscles. It has two pneumatic muscles in antagonist configuration used for rehabilitation of the biceps and triceps. The control system for this application which controls the force of flexion and extension actions according to several rehabilitation programs was also developed.

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