Pneumatic muscle actuators within robotic and mechatronic systems

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Abstract

Pneumatic artificial muscles (PAMs) as soft, lightweight and compliant actuators have great potential in applications for the actuations of new types of robots and manipulators. The favourable characteristics of fluidic muscles, such as high power-to-weight ratio and safe interaction with humans are also very suitable during the process of musculoskeletally rehabilitating patients and are often used in making artificial orthoses. This technology, despite the problems of control relatng to nonlinear phenomena, may also have wide future applications within industrial and mechatronic systems. This paper presents several experimental systems actuated by PAMs, which have been designed as test models within the fields of mobile robots, mechatronics, fluid power systems and the feedback control education of mechanical engineering students. This paper first presents the design and construction of a four legged walking robot actuated by pneumatic muscles. The robot has a fully autonomous system with a wireless application platform and can be controlled using a cell phone. Then the paper describes the design and construction of the prototype of an actively-powered ankle foot orthosis. This orthosis device actuated by a single PAM is able to provide the appropriate functions required during the rehabilitations of patients and the loss of mobility. Then the paper focuses on the design and control of a ball and beam system with an antagonistic muscle pair for generating the necessary torque for beam rotation. This mechatronic balancing mechanism falls into the category of unstable, under-actuated, multivariable systems with highly nonlinear dynamics. The final section of the article presents the design and control of a single-joint manipulator arm with pneumatic muscle actuators that enable some new features for the controlled systems.

1. Introduction

Technological improvements and innovations within modern pneumatic components as well as in control methods have made possible some new modalities in traditional pneumatic system applications. One of the research directions relates to the area of pneumatic artificial muscle (PAM) actuators using biological principles for system design and control as an attempt to replicate natural human movement. Due to their adaptive compliance, elasticity, flexibility and lightweight, pneumatic muscles are suitable for use in bionic systems, i.e. biologically inspired designs of technical systems, where the applications of biological methods and processes found in nature are used to improve engineering systems and modern technological products [1]. Scientific and technical works in the past have shown that overall system performance can improve when some biological principles are incorporated within the designing of engineering solutions. Some new applications are also identified, particularly in the areas of bio-robotics and human-friendly orthopedic aid devices for the rehabilitations of polio patients. PAMs are progressively researched and used in modern human-like robotic systems, offering in many cases natural compliance properties. Fluidic muscles also have great potential within industrial applications for the actuation of new devices and manipulators. Their properties such as compactness, high strength, high power-to-weight ratio, inherent safety and simplicity are worthy features in advanced manipulating systems. Unfortunately, due to their highly nonlinear and time-varying nature pneumatic muscles are difficult to regulate regarding motion or force. Therefore, various control methodologies have been applied to control different robotic systems, manipulators and orthopedic devices driven by artificial muscles [2-4].

This paper presents several experimental systems actuated by PAMs, which have been designed as test models within the fields of walking robots, orthopedic devices, mechatronics, fluid power systems and feedback control education.

2. Overview of pneumatic artificial muscles

A pneumatic muscle is a contractile and flexible pulling actuator operated by gas pressure. Since being first conceived (in the early 1930s) a considerable number of concepts of fluidic muscle actuators have been developed and some examples are given in Figure 1. There exist various types of fluidic muscles that are based on the use of rubber or some similar elastic materials which have been studied in scientific literature, such as the McKibben artificial muscle [5-7], the rubbertuator made by the Bridgestone company [8-9], the air muscle made by the Shadow Robot Company [10], fluidic muscle made by the Festo company [11-12], the pleated PAM developed by the Vrije University of Brussels [13], ROMAC (RObotic Muscle ACtuator), Yarlott and Kukolj PAM [14] and some others. In most cases the structure of fluidic muscle is composed of an airtight inner polymer tube placed within a flexible piece of hollow braided construction and appropriate metal end-fitting pieces for external attachment and pressurisation. When the internal membrane is inflated with compressed air, the pressurised gas pushes against its external shell, tending to increase its volume. The muscle radius increases and together with radial expansion the muscle contracts axially and exerts a pulling force.

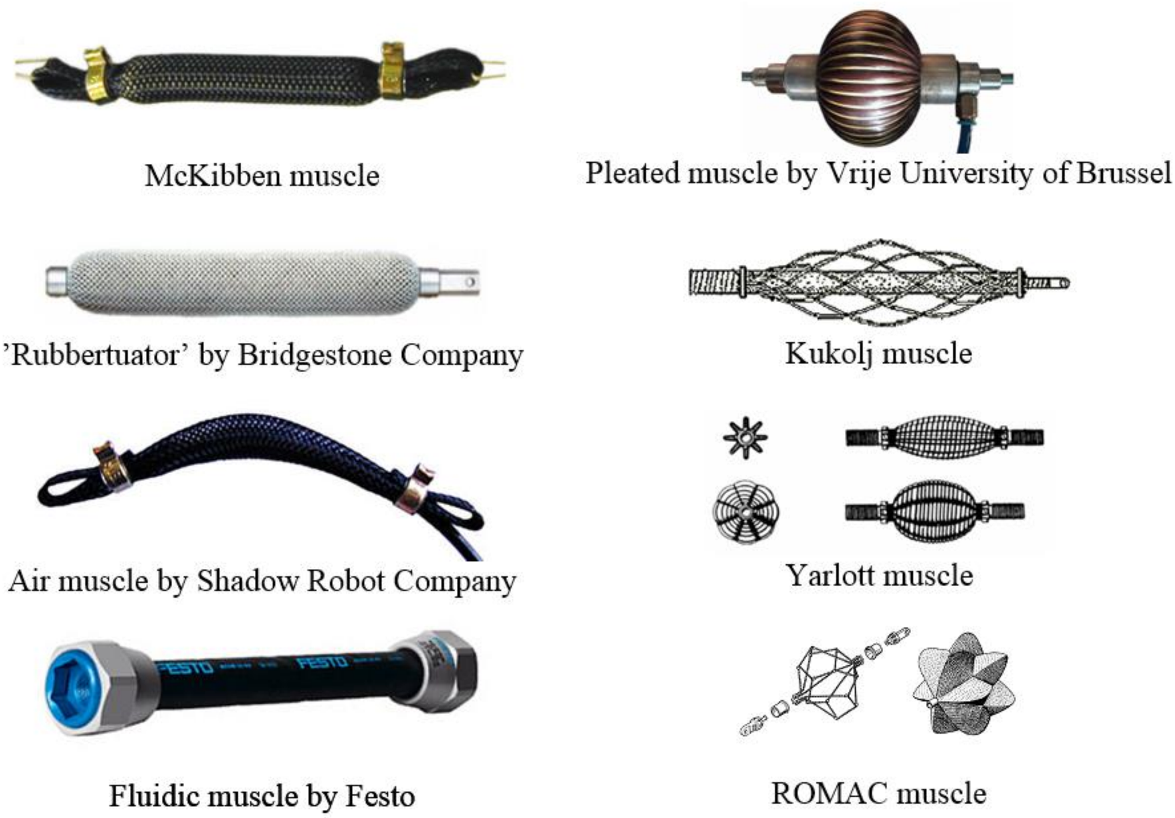


Figure 1: Various types of fluidic muscle actuators

The force of PAM can be described as the function of pressure and length (or contraction ratio) and in most cases the constant-pressure characteristic of fluidic muscle is used. The relationship amongst actuator contraction (pulling) force F, applied air pressure (internal muscle pressure) p and contraction rate ε can be expressed in the folowing form [6]:

$$\begin{cases} F = p\left[a(1-\varepsilon)^2 - b\right] \\ a = \dfrac{3\pi D_0^2}{4\tan^2(\beta_0)} \quad , \; b = \dfrac{\pi D_0^2}{4\sin^2(\beta_0)} \end{cases} \tag{1}$$

where D_0 is the nominal diameter of the PAM when it does not contract and β_0 is the initial angle between the thread and the muscle long axis.

PAM operates by means of overpressure and contract when pressuried, generating a load-carrying capacity at its ends during this contraction. Powered by compressed gas,the artificial muscle actuator contracts lengthwise when radially expanded and converts the radial expansive force into axial contractile force. As can be seen in Figure 2, the force and motion generated by this type of actuator are linear and unidirectional. Typically, maximum contraction of muscle actuators is about 25 % over the nominal length.

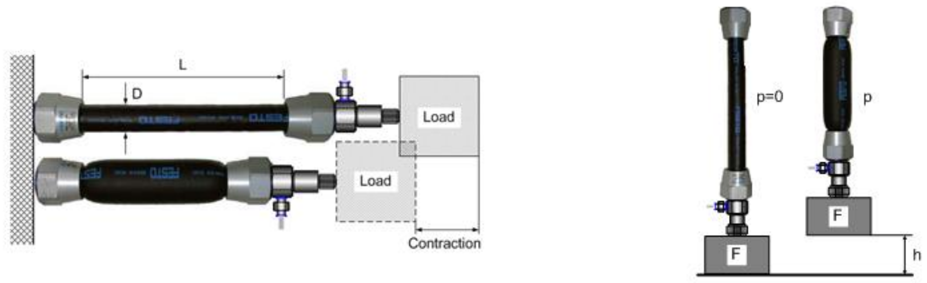


Figure 2: Operating principle of PAM

The pair of PAM actuators put into an antagonism configuration imitate a human biceps-triceps system and emphasise the analogy between this artificial muscle and the human skeletal muscle, Figure 3.

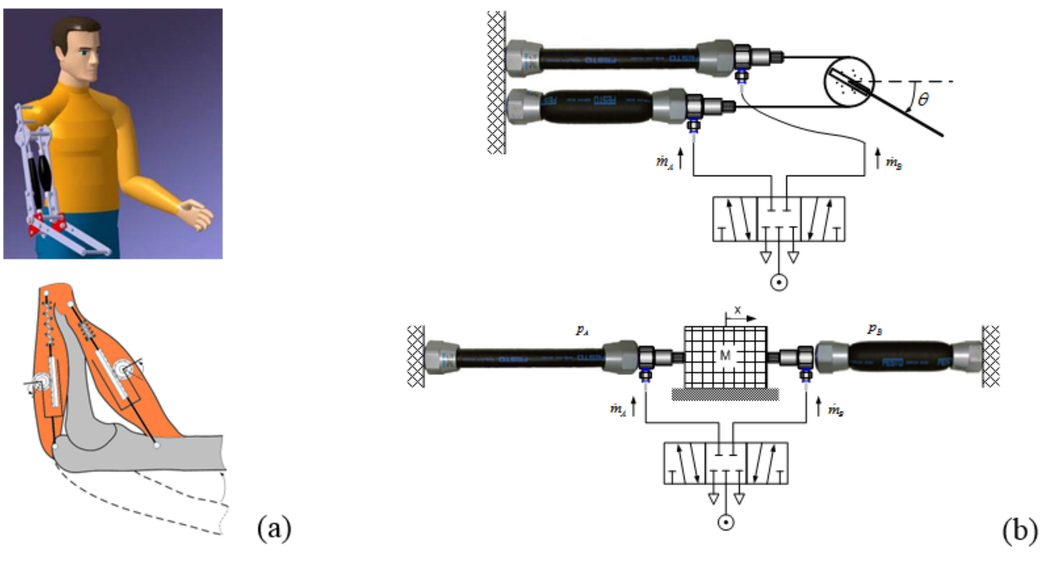


Figure 3: Similarity of the working principle, a) human arm: rotating the forearm around the elbow, b) rotational and translational system driven by a pair of PAMs

When the input pressure at one muscle (biceps) increases, then the input pressure at other muscle (triceps) decreases and vice versa, achieving the torque on the revolute joint. Typical configuration either rotates a pulley or moves a load linearly.

3. Robotic and mechatronic systems actuated by PAMs

3.1 Four legged walking robot actuated by PAMs

Mobile robotics as a fast evolving engineering discipline is one of the more complex and most interesting research areas. People seem to have a fascination with human-looking robots and machines that mimicking existing biological systems. The field of robotics, and especially mobile robotics, is a multidisciplinary research domain which includes mechanical, electronic and software engineering. Legged robots over standard wheeled or tracked robots offer the potential to navigate highly challenging terrain. Walking robots can operate successfully within a complex, dynamic environment and recently the robotics community has attributed great potential to legged robots for acting within unstructured outdoor environments. Researchers inspired by the biomechanics of humans and animals (dogs, horses, insects, etc.) have developed a number of mono-pedal, bipedal, quadrupedal and hexapod robots driven by pneumatic muscles in an attempt to create improved robotic systems [15-18]. Pneumatic muscles have performance characteristics very close to human muscles and due to similarities with biological muscles pneumatic actuation is a quite often used approach for actuating walking robots.

Inspired by this trend and boosted by the initiative of the Croatian Robotic Association we launched a project for developing a horse-inspired four-legged Walking Robot Actuated by Pneumatic Artificial Muscles (WRAPAM). This quadruped robot was designed with two degrees of freedom within each leg actuated by eight Festo air muscles and controlled by a modular valve terminal system which includes eight solenoid coils. Two Festo air muscles per leg, model DMSP-20-150N-AM-CM, are mounted for actuating the robotic joints. Each leg consists of two movable rotational segments and additionally incorporates a torsional spring which supports faster movement of the leg joint. The robot contains a small custom electronics module. The microcontroller ATmega2560 in a hardware interface Arduino Mega is used for controlling the movement of the robot. This microcontroller was chosen because of its accessibility, low cost and the large number of inputs/outputs that will be required in the future to upgrade the robot. In order to activate eight pneumatic valves the integrated chip ULN2803A is used which contains Darlington transistor drives for amplifying the electrical signals sent from the microcontroller to the level required by the valve block. The electronic circuit board includes a Bluetooth module which enables wireless communication between the controller and operator.

Figure 4: Construction process of WRAPAM and its final form

All components are mounted on the robot's frame in such a way that maintains the robot's centre of gravity. The robot frame is made using aluminum L-profiles or square tubing and all components are hand-made. The power source for the compressed air supply and the control unit are housed on-the board. This pneumatically actuated quadrupedal robot, as shown in Figure 4, is a fully autonomous system, equipped with Bluetooth technology and USB connection for communication with a computer. It is controlled by a cell-phone or tablet computer. The robot's design includes an energy system that is used for supplying compressed air, executive components of the system which allow the movements of the robot's joints, and the controlling and electronic parts of the system with sensors.

3.2 Active ankle-foot orthotic device actuated by PAM

Pneumatic muscles are widely used during the processes of musculoskeletal rehabilitations of elderly or injured people as actuators for actively powered orthoses. Ankle-foot orthoses can be roughly categorised as passive or active orthoses. Passive foot orthoses generally use various spring mechanisms made of different materials for supporting the patient's gait. Unlike conventional passive orthoses, active orthoses contain powered mechanisms that achieve the required force to lift the foot into a position that is necessary for normal gait [19-20]. The second test system presents an active, pneumatically powered ankle-foot orthosis as a technical device that could help people who have difficulty lifting their feet independently when they walk (so-called 'foot drop'). This device can prevent foot drop and provide the necessary force to return the patient's foot to its neutral position to maintain a better walking ability. Our attempt to create an efficient and light-weight foot orthosis powered by an air muscle is shown in Figure 5. The orthosis as a powered mechanism uses an air muscle (Festo DMSP-20-150N-AM-CM) driven by a solenoid valve (Festo MHE2-MS1H-3/2G-QS-4-K).

During the process of making the proposed orthosis we made a 3D prototype using SolidWorks design software and then print it in PLA plastic using a 3D printer. In order to reduce the weight of the orthosis, the plastic parts are made with hollow interiors. The connecting pieces are made of aluminum or steel materials. The device is designed to be worn fixed to the patient's lower leg and tied with strap belts.

The controller is implemented by using a TmegA 328 microcontroller. On the bottom side of the orthosis two switches are built-in, in the areas under the heel and toes. The microcontroller receives a signal from the first micro-switch located on the heel, then activates the timer and waits for a signal from the second micro-switch. After receiving the second signal, the microcontroller stops the timer and activates the valve over the same period of time that has elapsed between the two signals. This principle allows the patient to control the walking speed, which helps to keep his/her stability and faster adaptation to the device. For activation of the solenoid valve, a signal voltage of 24 V is required. Therefore, a voltage regulator was developed which uses the ULN2803A Darlington driver. By controlling the pressure within the muscle, the contraction force of the muscle is also controlled and thereby the foot is lifted into position for a new movement of the leg.

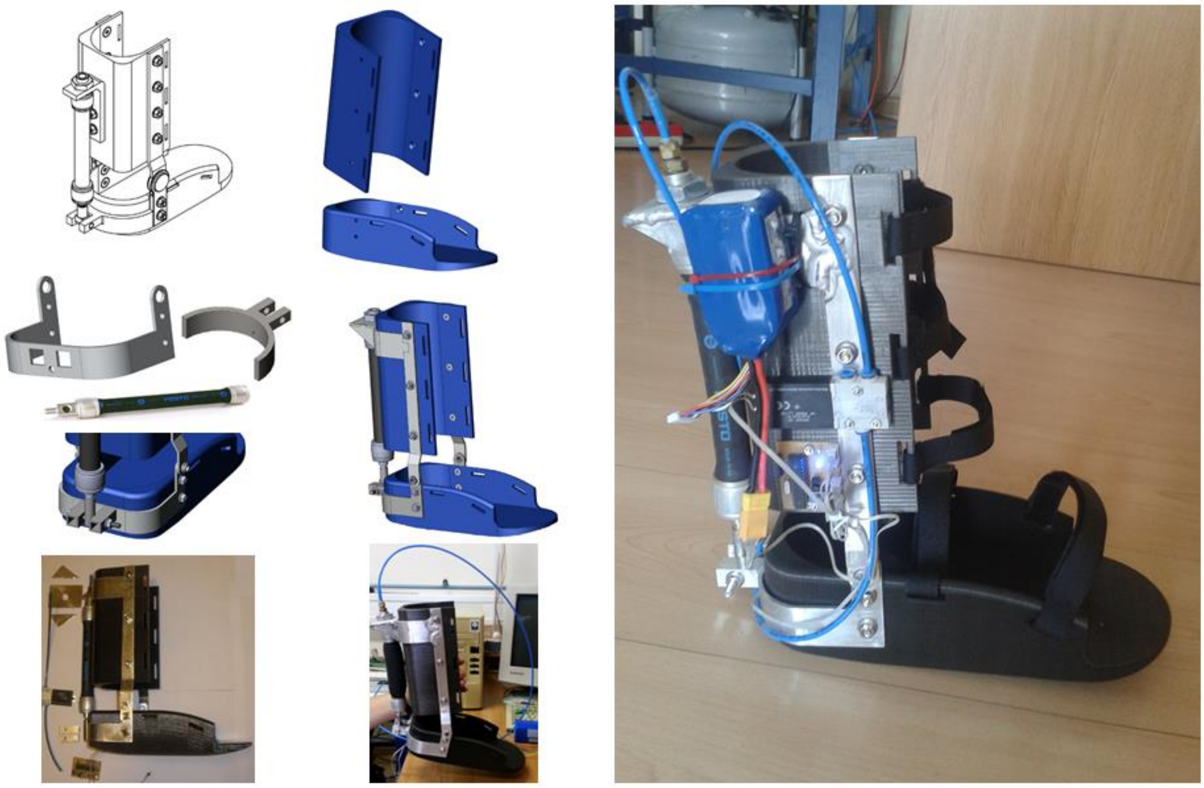


Figure 5: Construction process of ankle foot orthosis and its final form

In order to make the device portable, the system should only be equipped with an external compressed gas source (for example CO_2 tank with regulator), which the user should carry on his/her back.

3.3 Ball and beam balancing mechanism actuated by PAMs

One of the more common and popular laboratory systems is the ball and beam balancing mechanism [21-23]. This system represents a class of under-actuated, high-order nonlinear and non-minimum phase systems, which are characterised by an open-loop unstable equilibrium point. The physics of these balancing mechanisms is intuitively clear and their motion is very attractive as well, which emphasises the synergistic effect of theoretical considerations and practical demonstrations of problem solutions.

The complex nature of the ball and beam system presents many challenges in control design and application and this is the reason for its frequent use as a benchmark example for some advanced control methods. As with inverted pendulums or inverted wedge systems, the ball and beam system can also be used to illustrate many of the ideas emerging within the field of nonlinear control such as feedback stabilisation, variable structure control, passivity-based control, back-stepping and forwarding, nonlinear observers, friction compensation and many others [24]. The proposed solutions concerning the ball and beam system can lead to the solving of many control engineering problems that require the stabilisations of inherently unstable systems. Balancing the ball and beam system requires control forces in the forms of actuators which in this case is realised by a pair of PAMs. The compressibility of the air and nonlinear force/contraction characteristic of a PAM makes this system even more difficult to control.

The experimental set-up can be divided into two parts: the mechanical part that includes the ball and beam balancing mechanism with pneumatic valve and measuring components, and the control part that includes the control computer and data acquisition system. A photo of the ball and beam balancing mechanism actuated with PAMs is given in Figure 6.

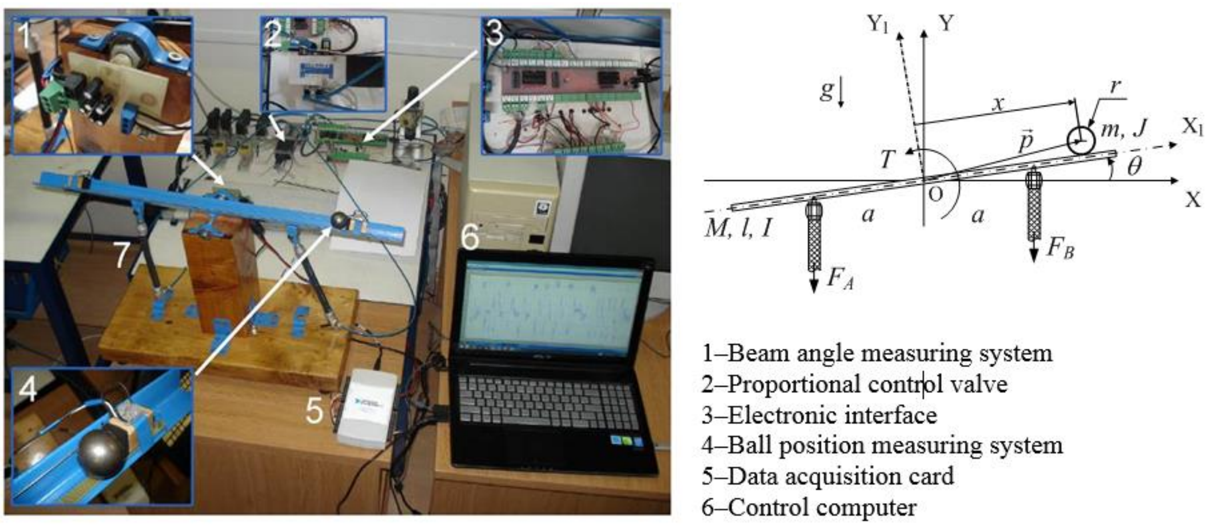
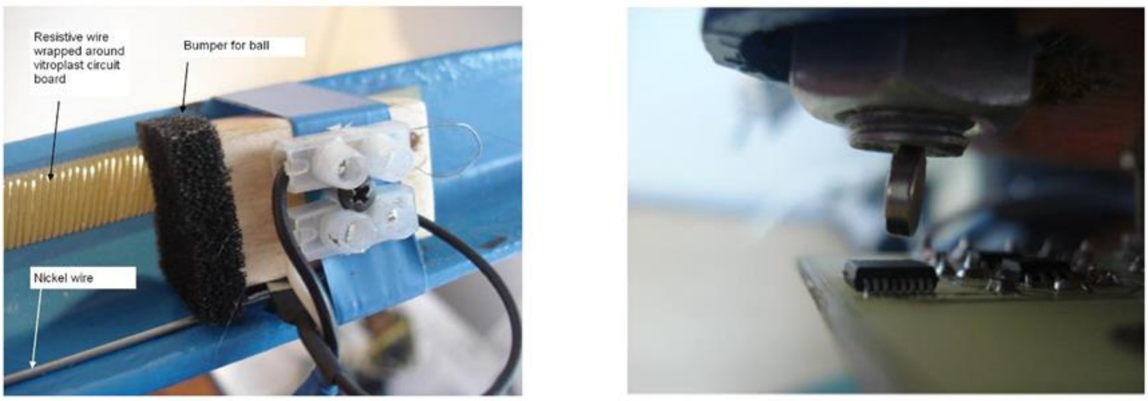


Figure 6: Ball and beam system actuated with PAMs

The beam, which has a V-shaped steel profile, is attached to a wooden 'pillar' with bearings and can rotate over a perpendicular plane to the axis of the supporting shaft. A pair of pneumatic muscles (Festo DMSP-10-150N-RM-CM) is mounted antagonistically to actuate a revolute joint. The rotating torque is achieved by the pressure difference between the antagonistic muscles causing beam rotation over a vertical plane. A directly actuated proportional 5/3 control valve (Festo MPYE-5 1/8 HF-010B) is attached to the muscles. The PAM is inflated by supplying control voltage to the proportional valve (0-10 V) that controls the flow of pressurised gas into the cylindrical rubber tube. When inflated, the PAM shortens and exerts a pulling force. For the input voltage of 5V, all control edges are closed and the air flow equals zero. The stabilisation of the ball is possible by using a digital controller realised on the control computer. The measured signals from the process are fed back to the control computer equipped with a data acquisition card (NI USB-6212 with 16-bit A/D and 16-bit D/A converter). The control software is implemented within the Matlab/Simulink environment using the Real-Time Workshop (RTW) program for generating ANSI C code from the block diagram edited in Simulink.

The ball position measuring system is designed like a sliding potentiometer where the sliding part is a balancing metal ball. The ‘sliding resistor’ is made of kanthal resistive wire and is wrapped around the vitroplast board. When the angle of the beam is changed, the influence of the gravity field causes the ball to roll freely along the beam. The rolling ball provides the contact between the resistive wires, thus closing the electrical circuit. The beam angle is measured with a 12-bit contactless magnetic rotary position sensor (Ams AS5045). It is a system-on-chip, combining integrated Hall elements, analog front end and digital signal processing in a single device. In order to measure the angle, a neodymium magnet is placed on a beam shaft and centred above the magnetic encoder. The ball position and the beam angle measuring system are shown in Figure 7.



(a) (b)

Figure 7: a) Ball position measuring system, b) Beam angle measuring system

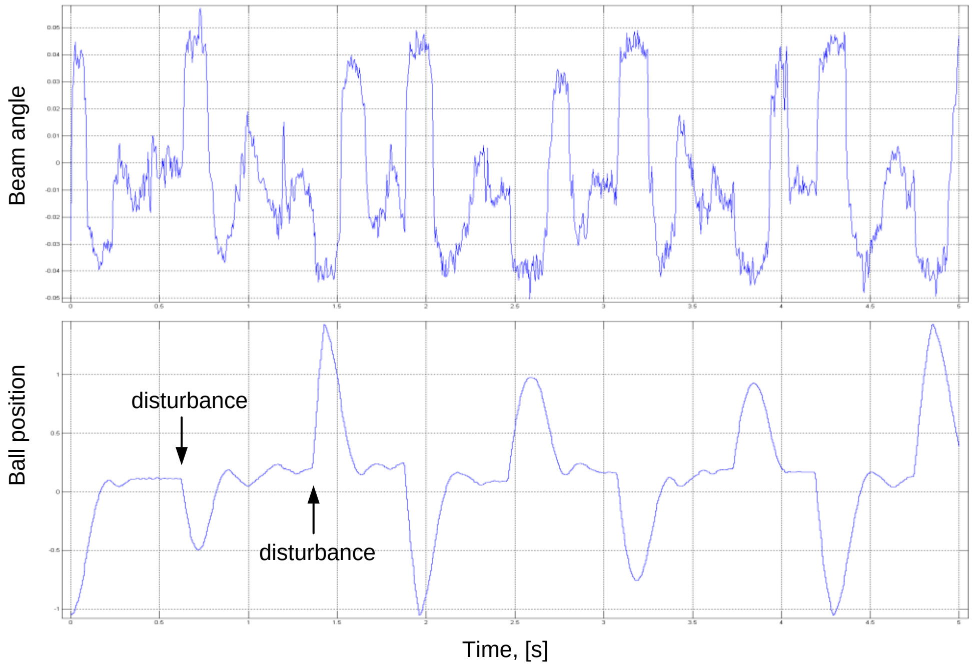
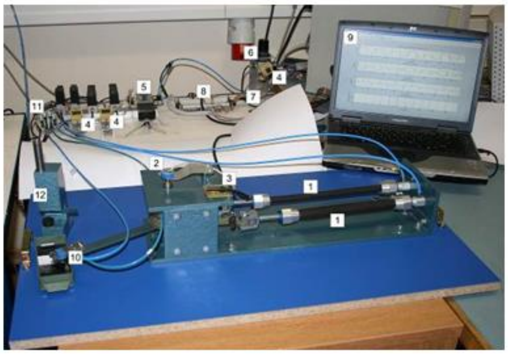


Figure 8: Experimental results for ball and beam system

The experimental results from stabilising the control system using the state feedback controller are shown in Figure 8. The disturbances to the system were made by flicking the ball with fingertips so that the ball was displaced from the equilibrium position by approximately 10-20 centimetres.

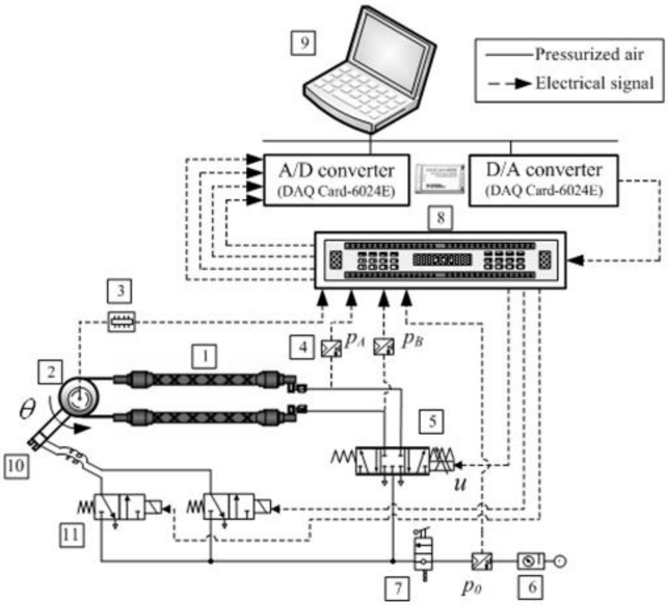
3.4 Manipulator arm actuated by PAMs

PAMs also have great potential for the actuations of new types of driving mechanisms and manipulators within industrial applications, which have traditionally been dominated by pneumatic cylinders or motors.



a)

1–Pneumatic muscles; 2–Rotary potentiometer; 3–Voltage reference card; 4–Pressure sensors; 5–Proportional control valve; 6–Filter-regulator unit; 7–Manually operated valve; 8–Electronic interface; 9–Control computer with DAC card; 10–Gripper; 11–High-speed on/off solenoid valve; 12–Feeder



b)

Figure 9: Manipulator arm actuated by pneumatic artificial muscles

A single-joint manipulator arm driven by PAMs in an antagonistic coupling is illustrated in Figure 9. The pneumatic part includes PAM manipulator with pneumatic valve and measuring components, and the control part includes a control computer and data acquisition system. The pneumatic part is composed of an air supply with a filter/regulator unit, a directly actuated proportional control valve, and two pneumatic rubber muscles (Festo, MAS-10-220N-AA-MC-K), which are mounted antagonistically to actuate a revolute joint. The rotating torque is achieved by the pressure difference between the antagonistic muscles and the lever with a pneumatic gripper (Festo, HGP-06-A) is rotated as a result. For activation of the gripper a high-speed on/off valve (Matrix 758 series, 8 channel, 2-way) is used. Precision industrial single-turn potentiometer (made by Vishay Spectrol), which is attached to the revolute joint is used for measuring its angle θ. The measured signals from the process are fed back to the control computer equipped with a data acquisition card (NI DAQCard 6024E for PCMCIA with a 12-bit A/D and 12-bit D/A converter). The control software is implemented within the Matlab/Simulink environment using the Real-Time Workshop (RTW) program [25]. The experimental results for the angular displacement control of the manipulator arm are shown in Figure 10. The experimental results point out that the stable and well-damped response of the control system was obtained for both directions of the manipulator arm motion.

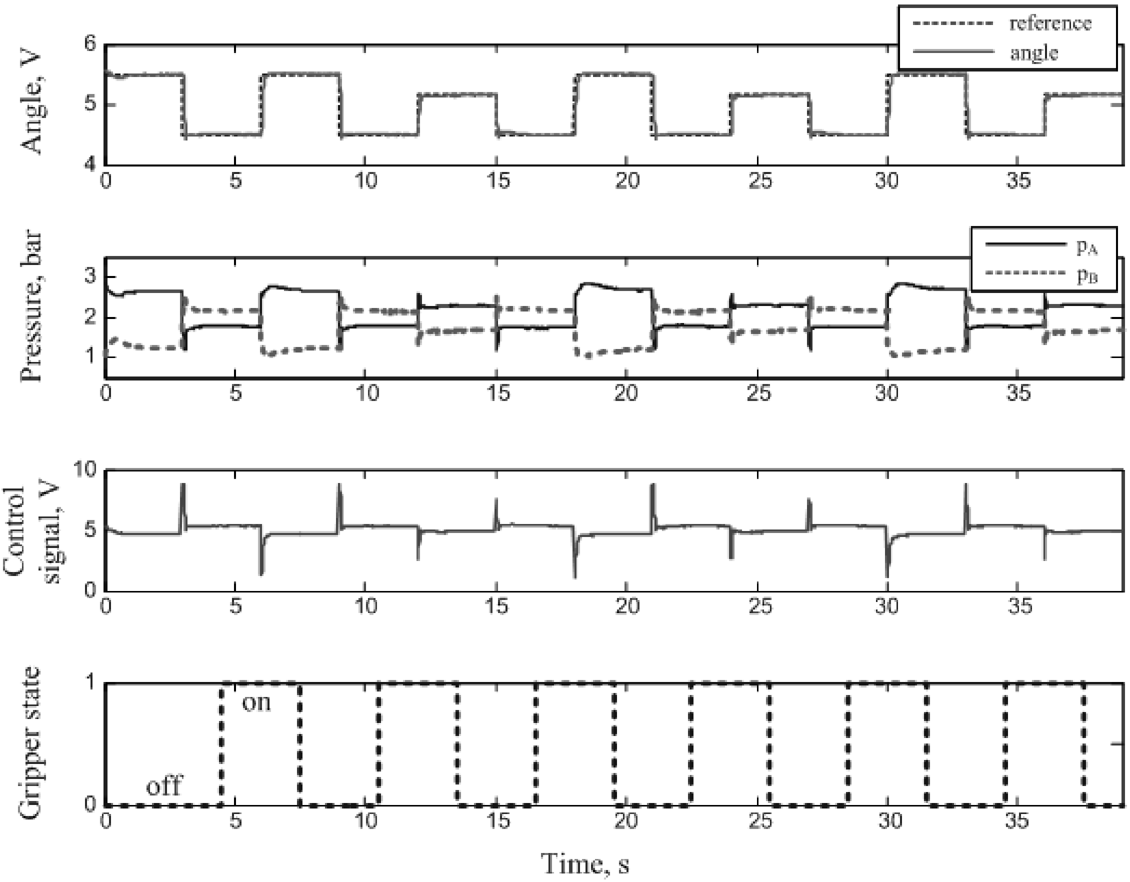


Figure 10: Experimental results for the angular displacement control of the manipulator arm driven by PAMs

4. Conclusion

This paper has presented several experimental systems powered by pneumatic artificial muscles. They have been designed as test models within the field of pneumatic systems and the feedback control education of mechanical engineering students. PAMs are undoubtedly very suitable actuators for new types of industrial and walking robots, mechatronic systems and devices that mimic human functions. By using these pneumatically-based experimental models, which have intuitively clear and attractive operating principles, through both theoretical and practical parts, students have the opportunity to learn about mechanical system construction, mathematical descriptions of practical systems, parameter identifications of real processes, simulations of nonlinear and linearised models of the system, consideration of different control techniques and their experimental verifications. The complete educational experience involving classical and modern control theory as well as practical applications and comparative analyses of different control techniques are recognised by educators in universities and control laboratories around the world. Applying the controller design process to a real physical system, therefore, helps the students to better understand the theory of automatic control. Student feedbacks have pointed out that laboratory-oriented teaching activities allow them an opportunity for practical realisations of control systems, experience with different electric and pneumatic components, a physical insight into the mathematical model of the system and also perception of the imperfect nature of real systems in their operation versus theoretically ideal, which is mostly used during system simulations.

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