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A Survey on Applications of Pneumatic Artificial Muscles

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Abstract—The aim of this article is to present a survey on applications of Pneumatic Artificial Muscles (PAMs). PAMs are highly non-linear pneumatic actuators where their elongation is proportional to the interval pressure. During the last decade, there has been a significant increase in the industrial and scientific utilization of PAMs due to their advantages such as high strength and small weight, while various types of PAMs with different technical characteristics have been appeared in the relative scientific literature. This article will summarize the key enabling applications in PAMs that are focusing in the following areas: a) Biorobotic, b) Medical, c) Industrial, and d) Aerospace applications.

I. INTRODUCTION

Pneumatic Muscle Actuator [1], also known as the McKibben Pneumatic Artificial Muscle (PAM) [2], [3], [4], [5], Fluidic Muscle [6] or the Biomimetic Actuator [7], is a tube-like actuator that is characterized by a decrease in the actuating length when pressurized [8], [9], [10], [11], [12]. Best known member of this family is the McKibben–Muscle, which was invented in 1950s by the physician, Joseph L. McKibben and was used as an orthotic appliance for polio patients [2], while the first commercialization of PAMs has been done by the Bridgestone Rubber Company of Japan in the 1980s. PAMs are significantly light actuators that are characterized by smooth, accurate and fast response and also are able to produce a significant force when fully stretched.

Typical manufacturing of a PAM can be found as a long synthetic or natural rubber tube, wrapped inside man–made netting, such as Kevlar, at predetermined angle. Protective rubber coating surrounds the fibber wrapping and appropriate metal fittings are attached at each end. The PAM converts pneumatic power to pulling force and has many advantages over conventional pneumatic cylinders such as high force to weight ratio, variable installation possibilities, no mechanical parts, lower compressed–air consumption and low cost [13]. When compressed air is applied to the interior of the rubber tube, it contracts in length and expands radially. As the air exits the tube, the inner netting acts as a spring that restores the tube in its original form. This actuation reminds the operation of a single acting pneumatic cylinder with a spring return, while this reversible physical deformation during the contraction and expansion of the muscle results in linear motion.

It should be noted that the most significant advantage of utilizing PAM in control applications, is that for their position control, as only one analog variable needs to be controlled, while for the same operation with a pneumatic cylinder, two analog variables need to be controlled (one for each chamber). As a result in the case of a pneumatic cylinder, it is more difficult to find an equilibrium between the two gauge pressures in the chambers, that it is for the case of PAMs. Typical types of PAMs and the corresponding naming, are depicted in Figure 1.

Fig. 1. Various types of PAMs: (a) McKibben Muscle/Braided Muscle, (b) Pleated Muscle, (c) Yarlott Netted Muscle, (d) ROMAC Muscle and (e) Paynter Hyperboloid Muscle.

The aim of this article is to provide a detailed survey on the applications of the PAMs that could be utilized as a basic reference design. The applications will highlight the most successful utilization of the PAMs in the fields of: a) Biorobotics, b) Medical, c) Industrial, and d) Aerospace applications. Due to the limited application of this most promising technology, such a survey will push all the future developments in this area and will provide references in the most important publications in the field.

The rest of the article is structured as it follows. In Section II the fundamental modeling approach for the PAM will be presented. In Section III the most significant applications of PAMs will be presented, categorized in specific scientific fields, while in the last Section IV the conclusions will be drawn.

II. FUNDAMENTAL PAM MODELING

Various modeling approaches have been presented in the scientific field of modeling PAMs. These modeling approaches although incorporate basic and more detailed analysis of PAMs, in the area of PAM applications, most of
the models are based on the geometry of the PAM, mainly
due to the model’s simplicity and great relativity to the
experimental behavior. Among these models, the Chou and
Hannaford model [1] and the Tondu and Lopez model [15]
have been widely utilized in most of the applications that are
going to be presented in Section III.

The Chou and Hannaford model, is the most simple
geometrical model for a static performance of a PAM. The
proposed model is valid under the following assumptions: a) the actuator is cylindrical in shape, b) the threads in the
sheath are inextensible and always in contact with the outside
diameter of the latex bladder, c) frictional forces between the
tubing and the sheath and between the fibers of the sheath
are negligible, and d) latex tubing forces are negligible.

With this approach the PAM actuator can be modeled as a
cylinder, depicted in Figure 2, with a length \(L\), thread length
\(b\), diameter \(D\), and number of thread turns \(n\). The angle \(\theta\)
is defined as the angle of the threads with the longitudinal axis
[16].

\[
L = b \cos \theta, \quad D = b \sin \theta/(n\pi) \tag{1}
\]

where the thread length can be calculated as:

\[
b = (L^2 + D^2 n^2 \pi^2)^{1/2} \tag{2}
\]

Equation (2) is referred in the literature as the geometric
relationship for the PAM, while its volume is provided by:

\[
V = b^3 \sin^2 \theta \cos \theta/(4 \pi n^2) \tag{3}
\]

Utilizing the energy conservation principle, the PAM
simple geometric force \(F_g\) can be calculated as the gauge
relative pressure \(P'\) multiplied by the change in volume with
respect to length (this model can also be found in [17]):

\[
F_g = P'b^2 (3 \cos^2 \theta - 1)/(4 \pi n^2) \tag{4}
\]

Another simple and widely utilized geometrical model of
PAM is that of Tondu and Lopez [15]. Based on this
approach and by: a) utilizing similar geometric description of
the muscle with [14], b) assuming inextensibility of the mesh
material, and c) angle changes during the alteration of the
PAM’s length, the following mathematical modeling
approach can be derived, based on the theorem of virtual
work [13]:

\[
F(e, P) = \pi r_0^2 \cdot P \left[ a(1-e)^2 - b \right] \tag{5}
\]

where:

\[
e = (l_0 - l)/l_0, \quad 0 \leq e \leq e_{\text{max}}, \quad a = 3/\tan^2 \theta_0, \quad b = 1/\sin^2 \theta_0
\]

In equations (5) and (6), \(r_0\) is the nominal inner radius, \(l_0\)
the length of the muscle, \(l_0\) the initial nominal length, \(P\) the
pressure and \(\theta_0\) is the initial angle between the membrane
fibres and the muscle axis, while this model can also be
found in [18].

A disadvantage of the model is that its design is based on
the hypothesis of a continuously cylindrical–shaped muscle,
whereas it takes a conic shape at both ends when it contracts.
Consequently, the more the muscle contracts, the more its
active part decreases. This phenomenon results in the actual
maximum contraction theoretically being smaller than that
expected from (5) [18]. For improving equation (5), an
empirical factor \(k\) has been added [15] to account for end
deforation of the PAM:

\[
F(e, P) = \pi r_0^2 \cdot P \left[ a(k-e)^2 - b \right] \tag{7}
\]

where again \(0 \leq e \leq e_{\text{max}}\) and \(e_{\text{max}}\) is provided from:

\[
e_{\text{max}} = (1/k)(1-\sqrt{b/a}) \tag{8}
\]

inserted in this way within the considered static model, the
insertion of the parameter \(k\) does not modify the value of the
maximum force given at zero contraction. This is in
concordance with the conducted experiment since the PAM
has a cylindrical shape only when its contraction ratio is
zero.

III. APPLICATIONS OF PAMS

A. Biorobotic Applications

Until now PAMs have been applied mostly in the area of
biorobotic applications or in biomimetic robots. As these
actuators resemble the characteristics of actual skeletal
muscles, researchers have tried to emulate the “soft”
compliant structure of organic muscle, bone, tendons and
skin by PAMs. This approach has led to the development of
biologically inspired robots that mimic the morphology and
physiology of humans and animals. Several biorobotic
applications of PAMs are presented in Figure 3.
A pioneering PAM–actuated robot has been the Shadow Biped Walker (Figure 3.1) by Shadow Robot Co., a life-size humanoid robot that has been in development since 1988. Twenty–eight PAMs (fourteen on each leg) were acting across the eight joints of the robot, enabling a total of twelve Degrees of Freedom (DOF). In [20], the humanoid robot Intelligent Soft Arm Control or ISAC (Figure 3.2), was consisted by two six–DOF arms and multiple PAMs that antagonistically actuated each joint of the arms. The construction of a six–legged, insect–like robot, called “Airbug” (Figure 3.3), with fluidic muscles as actuators and the control concept of antagonistic actuators, has been presented in [21].

In [22], a hopping robot (Figure 3.4) has been built, composed of a lower and upper leg, hip and body that slide along a guide shaft with the use of pleated PAMs for the knee joint movement. In [23], the authors developed the four–legged prototype Pneumatically Actuated dyNamically sTable quadrupEd Robot (PANTER)(Figure 3.5). Every leg of the PANTER had four active degrees of freedom and was PAM–actuated. In [24] the “Ajax” robot (Figure 3.6) has been introduced. Ajax was a cockroach inspired robot with legs that were controlled via several PAMs. The biped robot “Lucy” (Figure 3.7) has been constructed in [25], a two dimensional walking robot with two articulated legs and a body that utilized 12 PAMs for 6 DOFs. The autonomous
PAM–actuated bipedal robot “Stumpy” (Figure 3.8) appeared in [26]. In [27], the authors designed a pneumatic air muscle actuated robotic hand (Figure 3.9), incorporating basic human finger, thumb, forearm and elbow movements. In [28], a pneumatic muscle bicycle experimental apparatus (Figure 3.10) has been constructed, which consists of one-DOF scale model of human lower limbs actuated by PAMs and mounted on a stationary bicycle. A three–legged robot (Figure 3.11) with antagonistic pairs of PAMs controlled by a nonlinear oscillator network has been developed in [29]. In [30], a pneumatically actuated bipedal jumping and landing robot called “Mowgli” (Figure 3.12) has been presented. Mowgli’s artificial musculoskeletal system was consisted of six PAMs.

In [31], a hybrid actuation concept was validated on a two–DOF arm (Figure 3.13) that employed inherently safe PAMs augmented with small electrical actuators, human–bone–inspired robotic links, and newly designed distributed compact pressure regulators. In [32], a bipedal robot (Figure 3.14) with an Artificial Musculoskeletal System based on PAMs has been presented. In [33], the authors constructed and controlled a quadruped robot (Figure 3.15) with PAMs in antagonistic pairs to drive the musculo–skeletal system. A fully PAM–actuated humanoid muscle robot torso called “Zwei–Arm–Roboter” (Figure 3.16), in human-like proportions and functionality, has been developed in [34]. In [35], a Pneumatic Athlete Robot (Figure 3.17) has been presented, with musculoskeletal system driven by PAMs and applied human muscle activation patterns for dynamic bipedal running.

The development and control of a vertical climbing robot (Figure 3.18), actuated via four PAMs, has been described in [36]. Festo AG & Co. constructed the “Airic’s” robotic arm (Figure 3.19), which is depicted with artificial bones and muscles. In this robot the bone structure was moved via 30 PAMs with the use of very small valves based on piezo technology.

Additionally, Festo AG & Co. introduced the “Aqua Ray” robot (Figure 3.20), a remotely controlled fish using six PAMs in three antagonistic pairs that move the two wings and the tail with the help of artificial tendons. Shadow Robot Co. presented the Shadow Robot–Leg (Figure 3.21), a human size PAM–actuated robotic leg developed for investigation of myoelectric control of powered prosthetic legs. A prototype robotic eye (Figure 3.22) with an artificial oculomotor system that was driven by PAMs is currently
been developed in Bristol Robotics Laboratory. In [37], the authors control a robot with two degrees of freedom driven by four artificial pneumatic muscle actuators.

B. Medical Applications

Among the several advantages of the PAM actuator, is the ability to provide high power outputs, with relatively light weights and possesses inherent compliance, thus, meeting the need for safety, simplicity and lightness that human–robot interaction requires. Those characteristics, combined with the fact that PAM possesses similar properties with those of the human muscle, make it a promising actuator choice for therapeutic devices, which are designed for rehabilitation therapy of patients suffering from degenerative muscle diseases, extremity impairment or neurological injuries that affect their kinetic abilities. In this subsection, PAMS that are focused in medical applications will be presented. Most of these applications are depicted in Figure 4.

In [38], the performance of a PAM used in a prototype wheelchair–mounted robot arm has been reported. The design and control of a Human Muscle Enhancer (HME) system was described in [39]. The system augmented the muscle capabilities of subjects requiring partial lower–limb weight–bearing gait support.

The bipedal motion system design utilized PAMs in order to provide the pneumatic power required to operate a motion–support robotic orthosis. In [40], the authors studied the utilization of compliance regulated and controlled pairs of antagonistic PAMs in the construction of dexterous prosthetic hands and the construction of a power assist device that could be used to augment the strength of those suffering from degenerative muscle wasting diseases. A PAM–actuated prosthetic forearm (Figure 4.1) with flexor and extensor groups of muscles, has been presented in [41], [42].

The development of an armor–type muscle suit (Figure 4.2) that provided muscular support to paralyzed patients has been reported in [43]. The muscle suit was a garment without a metal frame and utilized PAMs driven by compressed air. In [44], a powered ankle–foot orthosis (Figure 4.3) for leg rehabilitation has been constructed. PAMs were used to provide single–joint support to the plantar flexion in different phases of gait. A therapeutic device, called the "RUPERT" (Figure 4.4), which had five DOFs and was powered via four PAMs, has been described in [45], [46]. This device was able to provide a supplementing therapy in addition to the clinic treatment of patients suffering from upper extremity impairment.

An exoskeleton (Figure 4.5), consisted of a hip orthosis equipped with PAMs, has been developed in [47] to assist the lower limb movements when a physical deficiency was installed. In [48], [49], [50], the authors developed a powered ankle–foot orthosis (Figure 4.6) that utilized PAMs for assisting patients during gait rehabilitation after injury. The design of a five–DOF PAM–actuated haptic arm exoskeleton (Figure 4.7) for training and rehabilitation in virtual environments has been presented in [51]. In [52], [53], [54], the authors developed compliant PAM–actuated exoskeletons that permit the execution of upper (Figure 4.8–4.9) and lower limb (Figure 4.10) physiotherapy.

In [55], a wearable power assist gloves (Figure 4.11) driven by rubber PAMs has been described. This device was able to assist the bending motion and increase the grasping force of the fingers through the installation of curved rubber PAMs. A PAM–actuated knee rehabilitation device (Figure 4.12) has been developed in [56]. In [57], the authors presented the application of PAMs in a novel motorized orthosis (Figure
for intensive home–based gait training in patients with neurological disorders. Construction of a power–assisted robot arm that utilized rubber PAMs covered with exoskeleton suits to mimic the motion of biarticular muscles, has been appeared in [58]. A PAM–actuated rehabilitation robotic system with biofeedback has been developed in [59]. In [60], the development of a PAM–actuated isokinetic equipment (Figure 4.14), designed for recovery exercises of the hip and knee joints, has been reported, while in [61], the authors present a pneumatic muscle actuated robotized arm for persons with locomotive disabilities.

C. Industrial Applications

The utilization of PAMs in the construction of industrial robots has received significant attention during the last years. PAMs are able to generate high torques at low and moderate speeds, able to be installed easily without gearing and able to work as the actuator of portable machinery due to their lightweight properties. Having, also, a natural compliance and shock resistance, PAMs are a suitable solution for actuation of industrial machinery and particularly industrial robots for safe human–robot interaction. Several industrial applications of PAMs are presented in Figure 5.

In [62], the authors developed a multi–jointed manipulator with three fingers and an opposal thumb powered by 18 braided PAMs. The development of a modular one–DOF pneumatic element and a three–DOF robot arm (Figure 5.1) based on rubber PAMs, has been described in [63].

A rubber PAM–actuated Robot Arm System (Figure 5.2) with six degrees of freedom has been developed in [64] and a two–DOF planar robotic manipulator (Figure 5.3) that assisted in handling of heavy loads and was actuated by Pleated Pneumatic Artificial Muscles, has been appeared in [65], [66]. In [67], the authors propose a prototype design of a teleoperational rig for retrieval of radioactive material that uses a combination of the traditional man-handled manipulation pole combined with PAMs.

The identification of the modal parameters of bridges (Figure 5.4), with the use of PAMs, has been introduced in [68]. In [69] a parallel–kinematic hexapod tool (Figure 5.5), driven by PAMs. The robot consisted of six discrete linear actuators, each of which has been assembled as an antagonistic setup of PAMs with pressure and position sensors. In [70], the authors developed a prototype hybrid robot (Figure 5.6) that included two bellows and one PAM–actuated module for safe human–robot interaction.

In [71], other industrial applications of the PAM actuators have been reported. One of them was the gripping process (Figure 5.7), where the pneumatic artificial muscle was being fitted sufficiently close to the center of rotation of the finger, while this short muscle was being adequate to execute the clamping motion. PAMs can also be utilized in simple positioning systems (Figure 5.8). In this case the work pieces can be raised or lowered as required by pressurizing or exhausting the muscle via a hand lever valve.

D. Aerospace Applications

In [72], the authors developed the “AGAS" system, an autonomously controlled deployable airdrop system that consisted of a round parachute, which was being controlled via four PAMs, while a PAM–activated trailing edge flap for flight control (Figure 6.1) is described in [73]. In [74], PAM applications have been presented for the actuation schemes of a morphing cell for a wing section and trailing edge flaps for wings or rotorcraft blades.

E. Other Applications

In [75], the “FM Motion Seat” (Figure 6.2) has been developed, a driving and flight simulator based on a hexapod structure with 6 spatially oriented PAMs that moved the seat in all the 6 axes and also acted as a passive suspension. Engineered Arts Limited (Penryn, Cornwall, U.K. 2010), developed the “RoboThespian” (Figure 6.3). This robot was a life–sized PAM–actuated humanoid robot that was created to educate, communicate, interact and entertain.

Jake Loniak (Art Center Pasadena, California, 2008) designed the “Deus Ex Machina" project (Figure 6.4), an electric, single passenger, vertically parking, and wearable motorcycle. With seven artificial vertebrae behind the helmet, for supporting the rider’s head, the control of the “Deus Ex Machina" was achieved via 36 pneumatic muscles and 2 linear actuators combined with the rider’s body.

IV. CONCLUSION

In this article a survey on applications of Pneumatic Artificial Muscles has been presented. A brief modeling of the widely utilized geometrical model of PAM has been presented while the attention has been focused in presented the most significant applications in the areas of: a)
Biorobotic, b) Medical, c) Industrial, and d) Aerospace applications. These applications have been accompanied with a sufficient number of references, transforming this article in a fundamental getting started guide in developing applications with PAMs.

REFERENCES


