Exploring Soft Robotics: Principles and Insights

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***Abstract*—Soft robotics, an emerging field at the intersection of engineering, materials science, and biology, has witnessed remarkable progress with the development of key components such as Pneumatic Artificial Muscles (PAM) and Soft Fluidic Actuators (SFA). This paper provides a comprehensive exploration of the principles and Labs within the context of soft robotics. The introductory section briefly outlines the concept of soft robotics and its diverse applications. The primary objective of this paper is summary and mastery of learning knowledge in soft robotics courses. Through structured experimental sections, the study offering progress in soft robotics practical project design related to these innovative technologies. The subsequent sections summary the reflection based on the experience of participating in this course.**

Keywords—Soft Robotics, Pneumatic Artificial Muscles, Soft Fluidic Actuators, Biomimicry, Flexible Materials, Experimental Analysis, Robotics Applications.

I. Introduction

A. Background

Soft robotics, an interdisciplinary field at the intersection of engineering, materials science, and biology, has witnessed significant advancements in recent 13 years, offering novel solutions for a wide array of applications. Soft robots could interact safely with people or the environment, which can provide with compliance and flexibility. Their structure s mimic the characteristics of animals in nature, such as octopus and elephant trunk, completely changed the design methodology of robots. For broad definition, soft robotics is the subject to study how to develop the basic sub-systems of a robot (i.e., sensor, actuator, body, and controller) with a controlled degree of compliance to its environment that could be humans or physical-ecological entitiesAmong the key components driving innovation in soft robotics are Pneumatic Artificial Muscles (PAM) and Soft Fluidic Actuators (SFA)[1].

B. Proposal

This paper focuses on these pivotal elements, delving into their principles and applications within the realm of soft robotics. As technology continues to evolve, the versatility and adaptability of soft robots have garnered attention in fields ranging from healthcare to search and rescue missions. The purpose of this paper is to comprehensively explore and analyze the roles of PAM and SFA in soft robotic systems, collaborating with the sensing and control component, elucidating their significance and potential impact. Additionally, we would make an overall assessment based on course content to reflect ideas while practicing theoretical knowledge in labs.

C. Content of Sections

Through a structured examination of experimental sections, this paper aims to contribute to the growing body of knowledge in soft robotics, fostering a deeper understanding of these innovative technologies. The subsequent sections of this paper, detailed in the following chapters, will provide an in-depth exploration of the discussed topics, offering insights into the principles, applications, and lab experimental findings related to Pneumatic Artificial Muscles and Soft Fluidic Actuators. At last part, we make a summary of reflections on Soft Robotics course design, combining with teaching content, learning experience and suggestion, etc.

II. Course Knowledge Summery

A. Theoretical Basis

The theoretical knowledge taught in Soft Robotics could be mainly divided into four parts: Actuation(especially the PAM, SFAs), Sensing, Control and application of soft robot.

PAM, as known as pneumatic artificial muscle, is a kind of actuator developed similar with the human muscle. As shown in figure, PAMs are simple mechanical actuators that consist of an elastomeric bladder within a braided mesh sleeve with two end-fittings to seal both the ends of the muscle. Upon pressurization of the bladder by air, the actuator deform (contract/extension/bending) due to the orientation of the braided sleeve fibers. A PAM has a power-to-weight ratio as high as 400:1, vastly outperforming both pneumatic cylinders and DC motors that can attain a ratio of only about 16:1. In addition, the main components of the PAMs are inner tube (elastic material with large strain, e.g. silicone rubber) and braiding pattern materials (flexible and relatively inelastic materials, such as nylon wires, textile fabric, etc.)[2]. The properties of PAM show that the equilibrium length of a PAM at static conditions will be determined by the pressure level, the external load and the volume-to-length change of that particular muscle. The PAMs has various advantages compared with the traditional actuators, because of the direct connection, installation and replacement of a defective PAM is very easily and rapidly done. Aside of that, because of its intrinsically and adjustable compliance it can be made to have a soft touch and is consequently well suited for safe man-machine interaction. To some extent, their structure and materials also bring out some limitations, such as single direction actuation and low efficiency (caused by pressure loss, air compressibility, constant air supply even when not moving), etc. The characteristics of PAMs allow it to be used in a wide range of application. Bioinspired robot, rehabilitation robot and compliant systems are in favor of PAMs as a kind of great performed actuator. But the problem of limited contraction length and tethered to complex pneumatic systems are still under consideration in industry application.

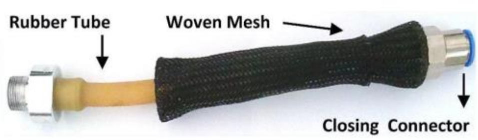

Fig. 1. Example of Pneumatic artificial muscles (PAMs)

SFAs, known as soft fluidic actuators, are inspired from mollusk. A hydrostatic skeleton, or hydroskeleton, is a flexible skeleton supported by fluid pressure. Hydrostatic skeletons are common among simple invertebrate organisms. Soft pneumatic actuators are composed of compliant material body with pneumatic chambers and constraint structures. Constraint structures may be the same material of the actuator body, or a different material. The pneumatic chambers are used to actuate the soft pneumatic actuator with deformation that are controlled by the constraint structure. By injecting air/gas, the pneumatic chambers produces anisotropic deformation on the actuator body. Motion transmission is accomplished through the compliant body. One typical examples of SFAs is pneu-net, has connected design sPN and discrete design fPN, primary structure of pneu-net is shown in Figure 3. While the pressure get into the chamber the actuator decline due to the different deformation of two side of pneu-net. The other type of SFAs is fiber-reinforced actuator. The basic design consists of an elastomer bladder wrapped with inextensible reinforcements. Hemicircle chamber design is easier to bend. It is the most common chamber design for soft bending actuator. Longer actuator needs less air pressure for the same bending angle, which is applied in soft intelligent gloves.

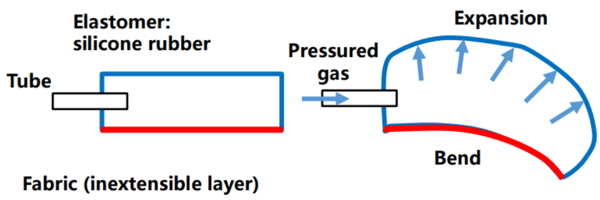

Fig. 2. Example of Soft fluidic actuators (SFAs)

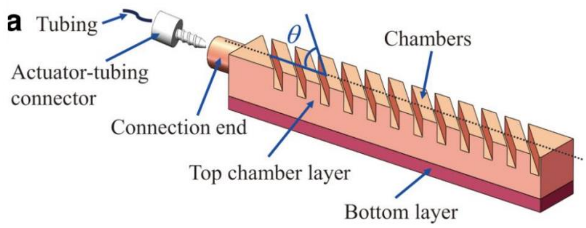

Fig. 3. Example of Soft fluidic actuators (SFAs)

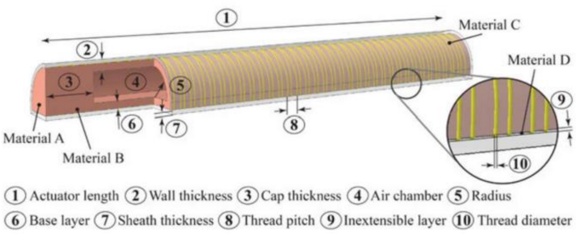

Fig. 4. Example of fiber-reinforced actuator

Dielectric elastomers actuators (DEA) are a class of electroactive polymers which work based on inducing of deformation with an electric field A common design of DEAs is to sandwich a soft insulating elastomer membrane between two compliant electrodes. When a voltage is applied between the electrodes, the arising electric field causes a decrease in thickness and increase in area of the membrane. The dielectric elastomer actuators consist of a soft, pre-stretched, dielectric membrane that is attached to a rigid circular frame. The actuation performance is strongly influenced by the properties of the material. Materials with low stiffness and large fracture stretch often show larger actuation strains than stiff materials. Theoretically every soft, stretchable, insulating elastomer membrane can be used in dielectric elastomer actuators. The main failures with DEAs are mechanical failure, electric breakdown electromechanical instability and loss of tension. In addition, there are various of application for DEAs, especially the underwater robot, such as soft robotic fish, etc.

The sensing mechanism is derived from the structural deformation of the robot, which can realize sensing in the soft materials of the robot body, reduce stress concentration, and achieve structure sensory integration. Resistive sensors measure changes in resistance caused by changes in the geometry or resistivity of a conductive material. It can be divided into three categories according to the materials and principles used:

1) Sensing functions are achieved by utilizing the flow characteristics of conductive liquids embedded in elastomers or the highly stretchable characteristics of conductive polymers and hydrogels. Conductive liquids include low melting point metals and metal alloys (such as mercury (Hg), eutectic gallium-indium alloy (EGaIn), gallium-indium-tin alloy (Galinstan), etc.) and various ionic liquids (such as sodium chloride solution);

2) Utilize the highly stretchable properties of conductive polymers and hydrogels to achieve sensing functions;

3) Made of elastic composites filled with conductive nanofillers, the resistivity and geometry will change when strain or pressure is applied changes occur.

B. Practical Applications

The lab practical application of Soft Robotics could be summarized as following:

1) Sketch of bent fPN/ fiber-reinforced actuator bodies and moulds;

2) Design parts and assemblies for soft grippers. Crawl performance pre-assessment analysis.

3) Make different lengths of PAM to compare their maximum shrinkage at different air pressures and to compare their shrinkage at different loads. rate under different loads;

4) Make two types of bending actuators and the bending angles under different air pressures are measured to compare the effects of different cutting gaps on the bending angles.

5) Collect the printed parts and moulds and complete the model casting for the final project.

6) Test sPN, fPN, fibre-reinforced soft actuator, analyse its characteristics (from bending angle, bending force, bending speed).

For final soft robot, we mainly developed two components:

1.Pneumatic Gripper

The pneumatic soft gripper was developed to demonstrate the grasping capabilities of soft robots. It involved the design of a multi-chambered structure that expands and bends in response to pneumatic pressure, allowing the gripper to conform to objects of various shapes and sizes, i.e. pneu-net (PN) architecture. The gripper's performance in terms of grasping different objects was evaluated, taking into consideration factors such as shapes, size, and weight. The gripper comprises a hollow cube featuring four fluidic pneumatic networks (fPNs) strategically arranged along its perimeter, as illustrated in Figure 5. Inflation of the fPNs, facilitated through channels connected to the cube's top, is anticipated to induce bending motions, thereby enhancing the gripping capabilities for a diverse range of objects. Comprising two essential parts, namely the actuating layer and the strain-limiting layer, the fPNs exhibit a distinctive mechanism. Through meticulous adjustment of the air pressure within the fPNs, the gripper can attain specified bending angles and directions. This adaptability empowers the gripper to effectively grasp objects with varying shapes, sizes, and weights, showcasing its capacity for adaptive gripping.

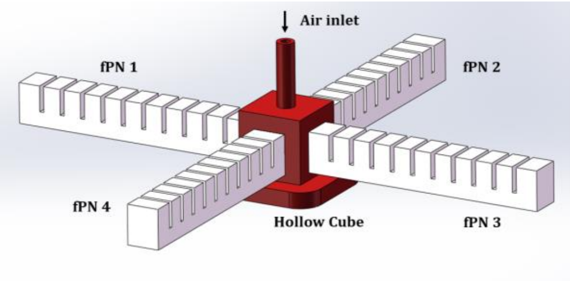

Fig. 5. Schematic representation of the soft pneumatic gripper

2. Soft Crawling Robot

The soft crawling robot, on the other hand, aimed to replicate the locomotion of quadrupedal animals using soft and deformable materials. By incorporating pneumatic networks and motion planning techniques, the robot was able to achieve crawling motions and exhibit different gaits. The effectiveness of the crawling mechanism and the robot's ability to traverse various terrains were assessed through experimental testing. By integrating PNs into the actuating layer, these chambers behave akin to balloons, expanding when pressurized. To ensure precise control over the bending of the robot's limbs, we have opted for poly as the strain-limiting layer, characterized by its relatively low extensibility under the stresses generated during the pressurization of the PNs. The disparity in strain between the actuating top layer and the strain-limiting bottom layer facilitates controlled bending of the robot's limbs upon pressurization.

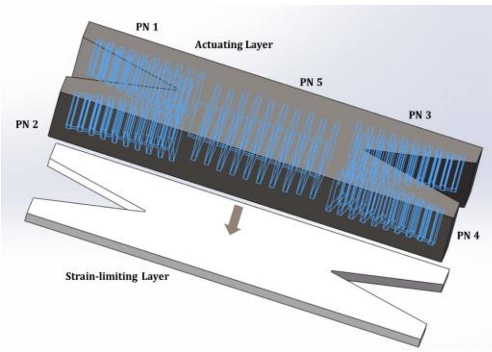

Fig. 6. Schematic representation of the soft crawling robot

Segmented by the regions where PNs are situated, the soft robot can be categorized into five primary air chambers, each equipped with an air channel for external connection via flexible tubes. This design enables the soft robot to execute a variety of walking motions. Figure 7 illustrates the configuration of the five independent air chambers and the corresponding air channels, highlighting the modular and flexible nature of the soft robot's locomotion mechanism.

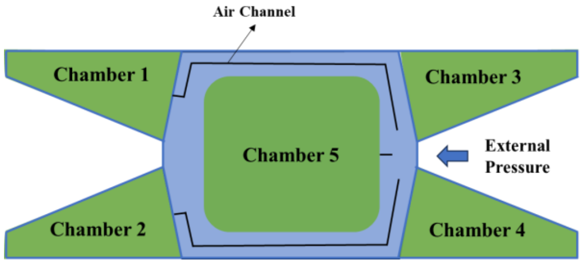

Fig. 7. Green regions represent air chamber (PNs); Blue region represents elastomer; Black lines represent air channel

The pneumatic gripper is divided into two integral parts. The first component, termed the "Gripper Base," is a hollow cube measuring 30mm x 30mm x 30mm, serving as the connection point for the four fast pneumatic networks (fPNs). Its primary function is to link with an external air source, providing pressure to inflate the fPNs. The top of the cube features an inner diameter of 4mm, facilitating connection to an external PU tube. Additionally, the cube exhibits four protruding tubes on its sides, each with a length of 10mm and an outer diameter of 5mm, designed for the insertion and secure fixation of the fPNs (Figure 8.a).

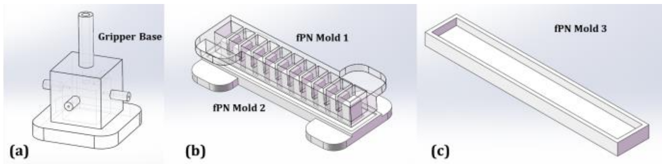

Fig. 8. The figure shows the 3D mold of the pneumatic gripper.

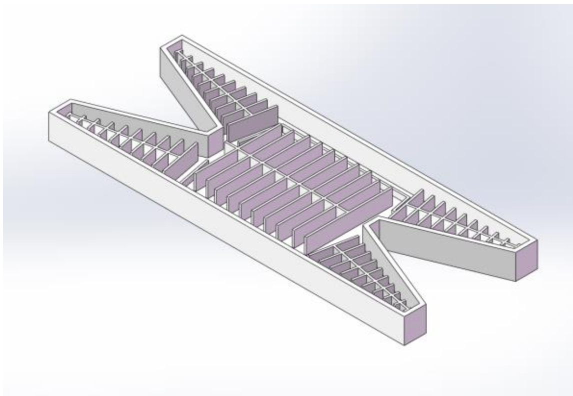

Fig. 9. Actuating Layer Mold.

The four fPNs, resembling rectangular prisms with dimensions of approximately 112mm x 15mm x 15mm, comprise an actuating layer and a strain-limiting layer. The strain-limiting layer takes the form of a simple rectangular plate (fPN Mold 3), while the actuating layer is molded using a two-part mold (fPN Mold 1 & 2). This mold configuration creates air chambers and pneumatic pathways, forming the PneuNet within the fPNs (Figure 8.b, 8.c).

The mold design for the soft crawling robot shares similarities with the slow PneuNet design, but with a distinct focus on the incorporation of pneumatic network architecture in the limbs and central body, mimicking the shape of a quadrupedal animal. Similar to the gripper, the mold for the soft robot includes an actuating layer (Figure 9) and a strain-limiting layer. The actuating layer embeds the pneu net's air chambers, while the strain-limiting layer takes the form of a plate resembling a quadrupedal animal.

C. *Results Showcase*

Following the completion of the mold printing process, the subsequent step involves utilizing elastomer to cast the upper and lower layers of the fast pneumatic networks (fPNs). It is imperative to follow a specific sequence in this process. Initially, the two-part mold, consisting of fPN Mold 1 & 2, is poured, and once this initial layer solidifies, the subsequent step involves pouring fPN Mold 3. To mitigate the deformation of the elastomer, a layer of fiber is added to the bottom layer before placing the solidified upper layer on the fiber, allowing it to solidify further. This process results in the configuration depicted in Figure 10, showcasing a structured and stable formation.

Upon the completion of casting all four fPNs, the next step involves affixing them to the Gripper Base, forming the complete pneumatic gripper, as illustrated in Figure 11. This integration represents the culmination of the manufacturing process, demonstrating the successful implementation of the designed fast pneumatic networks within the gripper structure.

Fig. 10. Prototype of fPN

Fig. 11. Prototype of pneumatic gripper.

The fabrication process of the soft crawling robot mirrors the approach taken for the fast pneumatic networks (fPNs). Initially, elastomer is employed to cast the actuating layer. Once the actuating layer has solidified, a layer of fiber is positioned on the bottom layer of the strain-limiting layer mold. Subsequently, elastomer is poured over the fiber to ensure a strong bond with the solidified actuating layer. After the full solidification of the robot structure, PU tubes can be inserted into the five independent air chambers, enabling inflation and pressurization. The result is the final product depicted in Figure 12, showcasing the successful integration of the actuating and strain-limiting layers in the soft crawling robot and its readiness for pneumatic operation.

Fig. 12. Prototype of soft crawling robot.

The setup of a pneumatic control system includes the following components: Arduino microcontroller, relays, an The Arduino microcontroller is a commonly used control device that allows programming and control of various electromechanical systems. It has digital and analog pins that can be connected to other electronic components. Relays are electronic switches used to control high current or voltage devices. They can be controlled by low current signals, such as to switch the three-way solenoid valves. Three-way solenoid valves are devices used to control the flow of gases or liquids. They typically have three ports, one for the inlet and two for the outlets, which can be opened or closed by controlling the relay switched three-way solenoid valves.

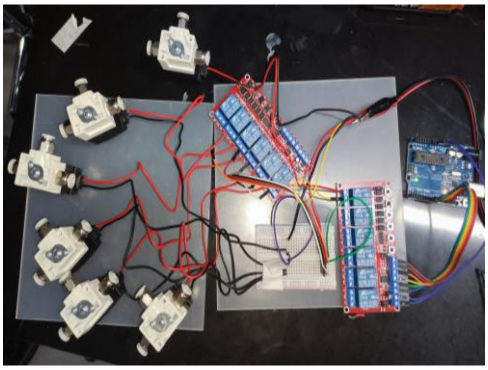

Fig. 13. Circuit diagram of the pneumatic control system.

Upon the successful fabrication of the soft crawling robot prototype, each of the five pneumatic networks (PNs) was pressurized individually using an external source connected to the robot via flexible PU tubing. Subsequently, through the sequential pressurization of the five PNs, the robot was effectively actuated. Upon pressurization, each PN would bend to a specific angle, resulting in a deliberate alteration of the robot's posture. The manipulation of the pressurization sequence among the PNs enabled the demonstration of two distinct gaits: undulation and crawling. The implementation of the undulation gait is vividly depicted in Figure 14. Under this gait, the soft robot exhibits a worm-like motion, moving its entire body forward (with the robot's forward direction indicated towards the white plate in the illustration). Figure 15 portrays the progression from the initial state (Figure 14.1) to the robot approaching the white plate after completing a pressurization cycle (Figure 14.6). This highlights the significant crawling capability of the robot when employing the undulation gait, showcasing its versatility in achieving diverse and purposeful motions.

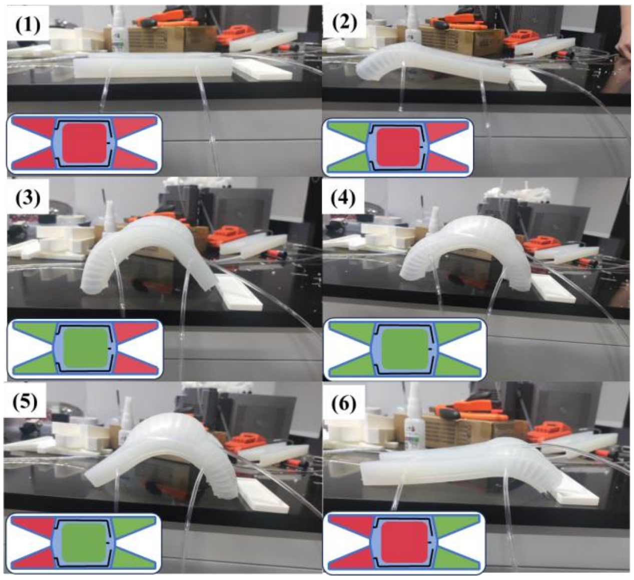

Fig. 14. Cycle of pressurization and depressurization of PNs that results in undulation.

III. CONCLUISIONS

This paper introduces the theoretical basic knowledge of soft robotics, especially two kinds of actuators: PAMs and SFAs. For course project design, we developed a soft crawling robot step by step following the instruction of labs.

Looking ahead, the field of soft robotics holds immense potential for transformative advancements, offering solutions to challenges that rigid robotics face. One promising avenue is the further integration of smart materials and advanced sensing technologies, allowing soft robots to exhibit enhanced adaptability, responsiveness, and interaction with their environment. As artificial intelligence continues to evolve, incorporating AI algorithms into soft robotic systems could lead to more sophisticated and autonomous functionalities. Moreover, the collaboration between soft robotics and other emerging technologies, such as bioengineering and nanotechnology, may open up new frontiers for applications in healthcare, exploration, and industry. The development of biohybrid systems, combining biological components with soft robotics, could revolutionize medical interventions and prosthetics.

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