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DESIGN AND FABRICATION OF A SOFT PNEUMATIC ACTUATOR WITH HEXAGONAL SHAPED PNEUMATIC CHANNELS

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Abstract- *A soft pneumatic actuator consists of a network of channels and subchannels and divided into chambers made inside a body of flexible and soft material. These channels expand when pressurized air is supplied, and thus create motion. In this paper, a new model for this particular type of soft actuator was demonstrated and evaluated. A soft pneumatic actuator having nine separate chambers connected internally by a hexagonal-shaped pneumatic channel was designed and a commercialized version of liquid silicon rubber having a modulus of 86 psi named Dragon Skin™ 30 was used as the soft material to fabricate the designed actuator. The chosen soft material was cast in the 3D printed mold. Then, some empirical test was carried out on the fabricated actuator to evaluate its performance. The actuator was inflated using 9.8 kPa pressure increments till the maximum displacement was obtained. The trajectory of the tip of the actuator was found to curl and give bending motion. The maximum angular displacement obtained was 180˚ at ΔP=245 kPa while the average actuation speed was found to be 0.18 rad/sec. Different shaped objects such as rectangle, cylinder, and oval were used to determine the grasping ability of the actuator.*

Keywords: Soft robotics, actuators, soft pneumatic actuator.

1. INTRODUCTION

Soft robotics is an emerging field of science and technology of the last decade. Soft robotics is inspired by the biological system whose verisimilitude elements have been incorporated in the robotic system to facilitate particular functions and advantages over conventional robotic technology. Soft robots are those robots that are primarily composed of flexible and soft materials, active structures and components. They are engineered in such a way that they would be capable of safely interacting with its surrounding environment and adapt accordingly while executing its' predetermined function. Here, the word 'soft robotic' is used as a broad term. It includes soft pneumatic networks, actuator, stretchable sensors, artificial muscle, and energy harvesting soft sensors, electro active polymers and soft electronics [1]. In the past decades, the focus on human-centered technology has increased substantially which has subsequently fueled a paramount number of researches in soft technologies.

Mechanical machines and conventional robots have limited ability to deform elastically since they are typically made of hard materials. Furthermore, they have difficulty in adapting their shape to external obstacles and constraints. Although these rigid robots execute their tasks with superior precision, these robots tend to be conspicuously limited in their functions. They rarely demonstrate the multi-functionality nature of the job performed. The soft robots are considered as the next generation of robots since they are elastic in nature and capable of safe cooperation in regards to human safety and capable of navigating through constrained environments.

Pneumatically powered elastomeric actuators are of special interest in soft robotics because they can be inexpensive, light-weight, simple fabrication processes and are capable of providing non-linear motion without any complicated inputs. Soft pneumatic actuators (SPAs) are devices made from soft material that can be actuated simply by the means of air pressure. SPAs are particularly convenient in the research field because of their pertinent gait abilities, simple fabrication methods and most importantly, the nature of compliance.

SPAs can realize different types of motion by implementing different geometric structures and designs, such as a linear soft body having parallel channels, networks of sub-chambers, a fiber-reinforced monolithic chamber. [2]

Several investigations have been conducted on different sizes and shapes of the soft pneumatic actuators which have been employed for different applications. Among them, the work of Polygerinos et al. [3] is noteworthy. They designed, developed and evaluated a preliminary design of a hand rehabilitation glove that was fabricated with the help of a soft pneumatic actuator. They geometrically analyzed this soft pneumatic actuator embedded with repeated rectangular chambers and rectangular-shaped pneumatic channels inside them which gave bending motions that mimicked the human finger motion. While Ge et al. [2] presented a paper in which the account of fabricating a soft pneumatic actuator with a number of oblique chambers was given in detail. The oblique chambers of the soft robotic actuator rendered the actuator to move in three-dimensional (3D) space. They showed that this particular design of oblique chambers enabled the actuators twisting capabilities and to form coupled bending. Also, Abd et al. [4] in their work presented a study on the effect of implementing various taper angles (θ) on the performance of the soft pneumatic actuator. The width of the SPA was continually decreased toward the tip region with a trapezoidal chamber.

This paper presents an innovative design of soft pneumatic actuator with regular-shaped chambers, connected internally by honeycomb-shaped (hexagonal) pneumatic channels. Later it evaluates its performance capability through several empirical tests such as the speed of actuation and bending angle. Finally, the grasping ability of the fabricated actuator was tested by grasping different shaped objects.

Honeycomb shape was particularly chosen as the pneumatic channel as this shaped polygon is the most naturally recurring shape in the world of natural structure. Hexagonal cells can create an immaculately strong and lightweight structure that’s up to the weight of 95% air while hexagonal cells can also naturally absorb mechanical impacts whilst still maintaining its original shape [5]. Since soft pneumatic actuator is inspired by nature itself and is supposed to mimic human finger approximately[6], it was decided to incorporate this geometric shape in the actuator along with it's lightweight, strong and impact absorption properties.

2. METHODOLOGY

A soft pneumatic channel expands the most in the most compliant region i.e. in the least rigid region when it is provided with compressed air. Therefore, when the soft pneumatic actuator is entirely composed of a single soft material or elastomer (elastic polymer) homogenously, then the expansion occurs the most at the thinnest part of the actuator geometry.

Again, when a soft pneumatic channel or actuator consists of one or more layers of materials with different elasticity, the material with more elasticity will expand more than the material with lesser elasticity when it is pressurized. The difference in the elastic behavior of the constituent materials in the actuator creates a differential strain.

The material with more rigid elastic behavior, typically used in the soft pneumatic actuator for this kind of configuration is called the "strain limiting layer", as it exerts restriction on the amount of strain that can develop. This differential strain effect can be manipulated into obtaining useful motions such as twisting and bending.

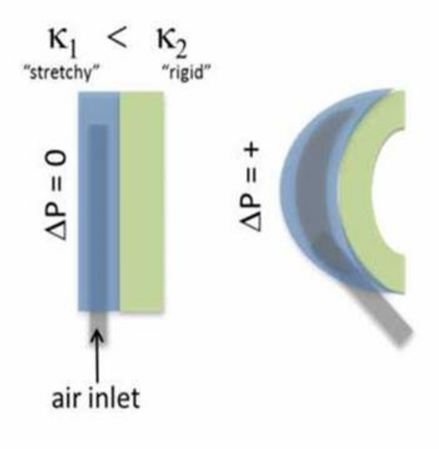

Fig. 1: The differential strain effect of the soft pneumatic actuator [7].

2.1 Equipment and Materials

The list of the equipment and materials used for the purpose of the fabrication of the actuator are given below:

1. Liquid silicon rubber RTV-2 (Polysiloxanes or polydimethylsiloxanes),
2. a restraining material (Paper),
3. lab oven,
4. digital mass scales,
5. mixing cups,
6. pneumatic tubes,
7. m-seal.

The soft material chosen should be able to withstand large strains >300% [3], material stiffness of the soft material should be in the range of modulus of 10^4 to 10^9 Pa, comparable to the biological modulus of human skin or muscle [8]. Several flexible materials have been conventionally used such as elastomer, polymer, granules, hydrogels [1]. Silicon rubber is a popular choice for its compliant mechanical properties. It is also called an elastomer. The property of this material renders the soft robotics its unique characteristic.

A commercialized version of the silicon rubber RTV - 2 named Dragon skin™ 30 (Smooth-On, Inc.) was chosen for fabricating our actuator whose material properties align with the required properties of the soft robotic actuator. It has a shore hardness of 30 A, 86 psi modulus (6×10^5 pa) and elongation at break of 364%. It has platinum cure liquid silicone compounds.

2.2 Design of the Actuator

The soft actuator was designed using SolidWorks software. It was composed of two main parts: the main body and the base. The main body of the actuator contained hexagonal cut pneumatic channels and so when pressurized air was supplied to the chamber of the actuator and it passed through this connected hexagonal-cut pneumatic channel, hence inflated the actuator.

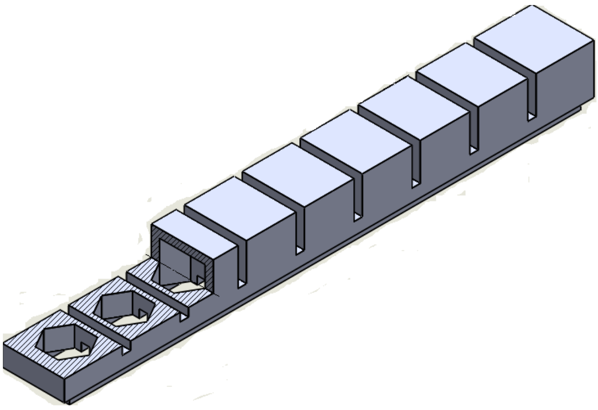

Fig. 2: Cross-section of the main body of the soft pneumatic network actuator.

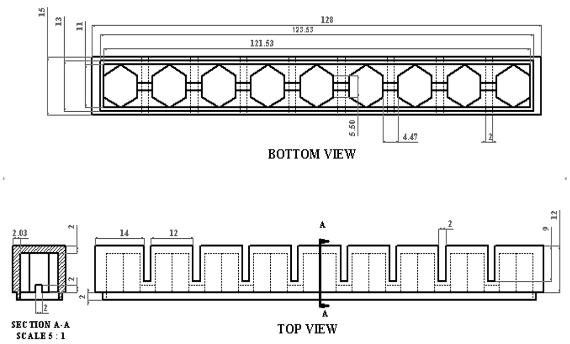

Fig. 3: Geometrical dimensions of the CAD model of the main body of the actuator (Top and bottom view).

The base part which contained the rigid layer (in this case: paper) was bonded with silicone rubber to the main body resisted this expansion of the above soft material. This baselayer was again divided into three consecutive parts: the top silicon rubber layer A, the encased and submerged paper layer and the silicon rubber layer B as shown in figure 3.

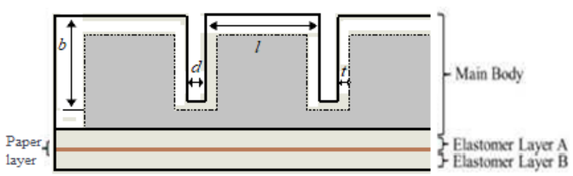

Fig. 4: Schematic diagram of the assembled soft pneumatic network actuator.

2.3 Fabrication of the Mold Using 3d Printing Technology

The CAD model of the mold in which the liquid silicon rubber was poured to fabricate the actuator was designed in SolidWorks.

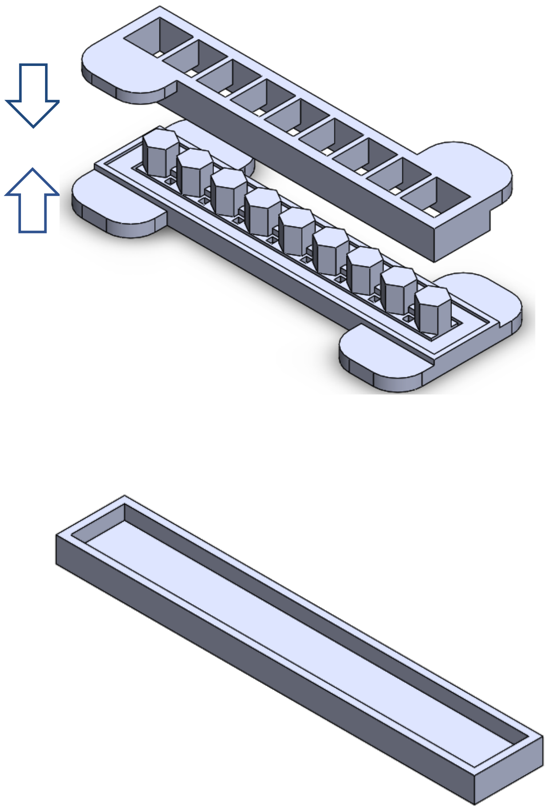

Fig. 5: 3D model of the main body and base of the mold.

The 3D printer Ultimaker3 was used, courtesy of the 3d printing system of Fab Lab, Chittagong University of Engineering and Technology (CUET). The raw material ABS having a 2.85 mm diameter was used as the ink material of the 3D printer.

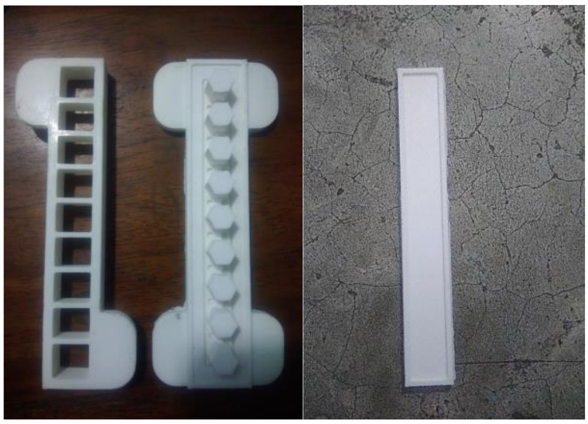

Fig. 6: The 3d printed mold parts,
(a) The 2-part main body mold & (b) the base mold.

2.3 Fabrication of the Actuator

The fabrication process of the actuator involves preparing the liquid silicon rubber and pouring it into the main body mold and base mold, demolding it after its curing and later assembling the main body part and base part bonded by the same silicon rubber.

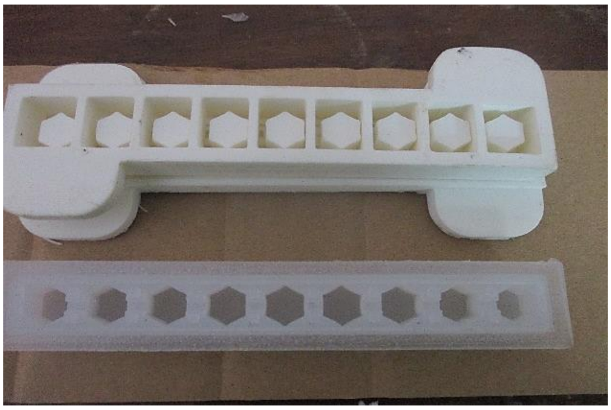

Fig. 7: The fabricated main body of the actuator (bottom view) and its mold.

Fig. 8: The assembled fabricated soft pneumatic actuator.

3. EXPERIMENTAL SETUP

In the system, an air compressor of 2 horsepower, courtesy of Compressible Fluid Mechanics and Renewable Energy Laboratory, Department of Mechanical Engineering, CUET was employed to activate the actuator motion through a series of pneumatic pipes. The air pressure from the compressor was controlled primarily through a gate valve in-built on the compressor and mainly with the aid of a pressure regulator. A single actuator was mounted on a clamp in a vertical position. A single digital camera was used to capture the actuator's trajectory of motion placed normal to its direction.

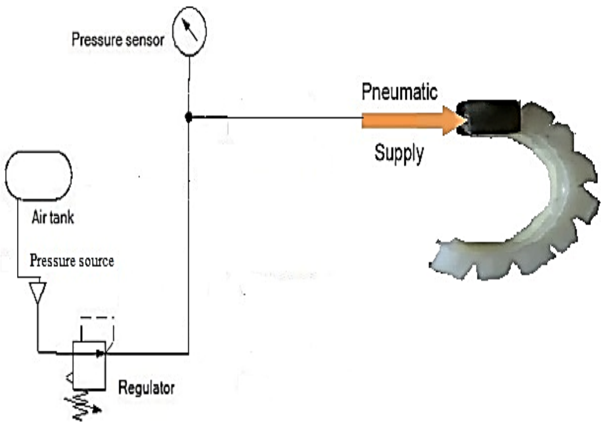

Fig. 9: The schematic diagram of the soft pneumatic actuator system.

4. DATA ACQUISITION AND ANALYSIS

The project's final goal is to evaluate the performance profile of the actuator designed and fabricated. So, the parameter defining its performance profile has primarily been determined through continuous testing of the actuator.

The angular displacement of the actuator is defined by its bending motion. When the pressurized air is supplied to the actuator, the actuator bends. By measuring this bending angle, the required angular displacement profile has been obtained. The bending angle has been defined as the angle between the body line along the actuator's length in its unactuated original position and the body line in its actuated state measured in degrees. The pressure has been calculated from 0 to 1.4 Kgf/cm^2 (0 to 137.3 kPa) with an incremental step of 9.8 kPa or 0.1 Kgf/ cm^2.

4.1 Motion Tracking

The tip of the actuator was monitored as it bent to track the trajectory of the actuator's motion. The cumulative time of the total bending displacement was measured using a stopwatch to determine the actuation speed. A digital camera was placed normal to the actuator clamped and was used to record the motion. The actuator was placed vertically on the clamp for convenient tracking of the motion. In figure 10, it is seen the actuator curls with the increase of gradual pressure.

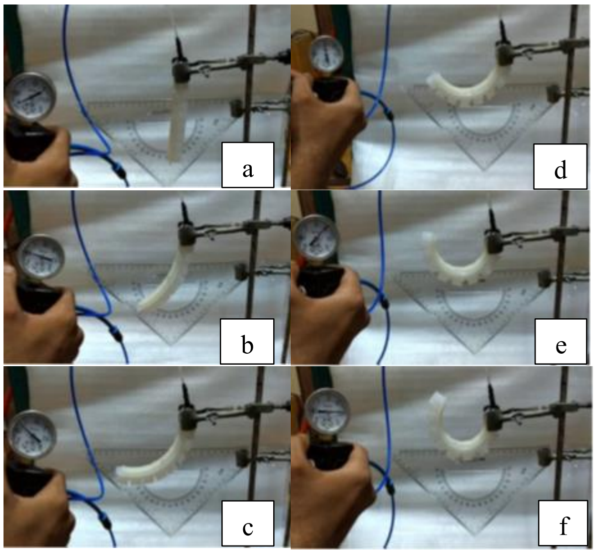

Fig. 10: Performance testing of the fabricated actuator. (a) This photo shows the position of the actuator in rest position at $\Delta P=0$ Kgf/cm^2, (b) the actuator at $\theta=60^\circ$ & $\Delta P=.6$ Kgf/cm^2, (c) the actuator at $\theta=90^\circ$ & $\Delta P=.8$ Kgf/cm^2, (d) the actuator at $\theta=130^\circ$ & $\Delta P=1.4$ Kgf/cm^2, (e) the actuator at $\theta=160^\circ$ & $\Delta P=2$ Kgf/cm^2, (f) the actuator at $\theta=180^\circ$ & $\Delta P=2.5$ Kgf/cm^2.

4.2 Grasping Test

Alongside with the measure of angular displacement and time of actuation of the actuator, the grasping test is also a good indicator of the performance evaluation test. In addition to functioning as an actuator, the fabricated soft pneumatic device was able to grasp different objects of different shapes and sizes. It was also capable of holding a fragile object without destroying it.

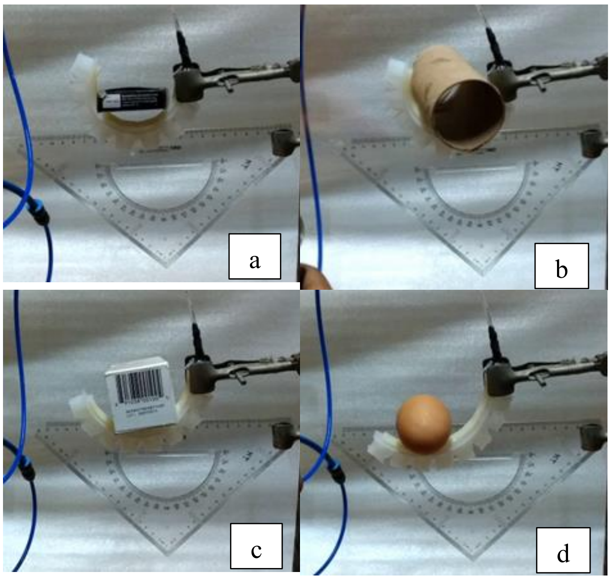

Fig. 11: Performing the grasping test of the actuator with different shaped objects. (a) Gripping a 7×5 cm solid rectangle box, (b) gripping a hollow cardboard cylinder, (c) holding a 10×4 cm hollow rectangular box, (d) holding an oval-shaped egg.

5. RESULTS AND DISCUSSION

The evaluation of the performance of the actuator shows a promising result. The maximum angular displacement obtained is 180 ˚ at ΔP= 2.5 Kgf/cm^2 or approx. 245 kPa. The minimum pressure needed for actuating through an angular displacement of 10 ˚ is 9.8 kPa. The average angular speed through 180 ˚ angle is 0.18 rad/sec obtained using the formula $\omega = d\theta /dt$. The actuator has been able to hold objects of rectangular, cylindrical and oval shapes without any difficulty.

In figure 11, the angular displacement of the actuator changes linearly with the change of pressure, even if there is slight deviance in the middle of the graph. But, the overall trend of the graph shows a linear relationship between pressure and displacement

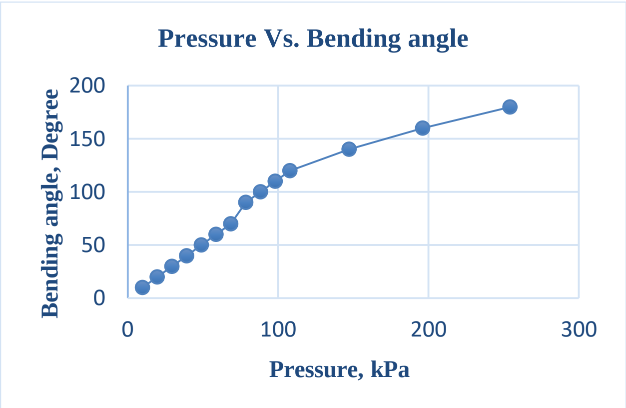

Fig. 12: The angular displacement profile of the designed actuator.

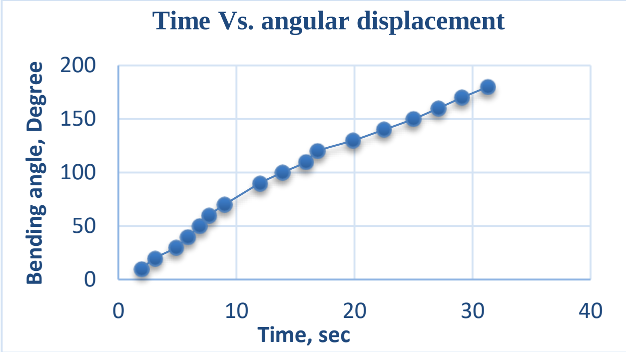

Fig. 13: Actuation speed of the designed actuator.

6. CONCLUSION

In this paper, a soft pneumatic actuator was designed with a honeycomb-cut pneumatic channel and Dragon skin^{TM} 30, a commercialized liquid silicon rubber was used as the soft material. The designed soft pneumatic actuator has given slightly different results than that of existing soft pneumatic actuator design (rectangular pneumatic channel) as found in the previous research paper [3],[8]. It might be owing to its non-uniform thickness around the honeycomb pneumatic channel, as a result the rate of expansion has been non-uniform around the honeycomb edges inside the actuator. The designed actuator followed linear relationship between the pressure increase and its angular displacement throughout its actuation. It gave 10˚ angular bending for each 9.8 kPa increment of pressure. Also, the tested actuator didn't give full circle bending curve like that of existing rectangular chamber pneumatic network actuator [3] since the maximum bending curvature obtained was a little over 180˚. But it is mainly due to the marginal faults occurred in the fabrication process. The performance can be improved if the limitation of the actuator fabrication process can be eliminated. Furthermore, it was able to grasp the rectangle shaped and cylindrical shaped object better than the oval shaped object.

The soft pneumatic actuator designed has a huge potential in the future research field. A series of fabricated actuators can be employed as an industrial gripper for handling fragile things by attaching it as an end effector to a mechanical arm after a thorough refinement of the process. It can also be employed as pneumatic hand gloves for hand rehabilitation purposes. The addition of different sensors and incorporating a feedback system to the actuator can greatly elevate its control and hence performance.

7. ACKNOWLEDGMENT

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9. NOMENCLATURE

Symbol	Meaning	Unit
ΔP	Pressure	(kPa)
K	Modulus of Elasticity	(Pa)
θ	Bending angle	(Degree)
ω	Angular speed	(rad/sec)