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DESIGN AND OPTIMIZATION OF SOFT SILICONE PNEUMATIC ACTUATORS USING FINITE ELEMENT ANALYSIS

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ABSTRACT

The necessity of the soft gripper devices is increasing day-by-day in manyapplication especially when safe, gentle motions and soft touch are necessary. In this project, used to the selection of soft silicone pneumatic actuators using finite element analysis has been designed and fabricated to construct a soft gripper. The model of soft silicon pneumatic actuator is designed using solid works and its bending motion is simulated in ANSYS software for optimization and compared with experimental results. Actuator fabrication and experimental tests were presented, and agreements between the Finite Element simulations and test results were achieved. After finalizingthe Finite element simulations were performed to validate this concept and the designed structure. The actuator is fabricated usinginjection molding process that includes the molds. The gripper base was fabricated to have three configurations and three openings. That could be adapted to objects of different sizes and shapes. Experiments conducted show the bending motion characteristics of the actuator at different pressures. The actuator shows excellent bending performance and the eccentricity in its design supports increased bending motion up to a certain extent compared to normal Rubber without eccentricity. Its also measured the full-off force of gripping objects with different stiffness. The effects of profile shape on the actuator performance are analyzed and the results are presented. The possibilities of this gripper can be demonstrated on future industrial gripping. In this soft gripper that can be easily attached to existing robots.

KEYWORDS: *Silicone Rubber, Pneumatic Actuator, Soft Gripper, Soft Materials*

INTRODUCTION

Robots have been traditionally made from hard materials likewise metal and plastics. These robots are more like machines than biological organisms. Soft robotics on the other hand to make robots that are soft, flexible, elastic and Good reachability just like biological organisms. The body of a soft robot is soft like natural tissue. It has several promising features such as Lightweight, inexpensive, easily fabricated and simply to control. Recently, design, fabrication, and actuation of soft robots have shown many promising applications such as medical, biological, chemistry, Robots and mechanical engineering etc., Soft grippers fit the needed criteria because through their inherent compliancy and a variety of other behaviors, they can accomplish feats that would be difficult for hard grippers to achieve. In this blog post, we hope to give you a solid understanding of the state of soft gripper technology through some of the notable grippers and developments made in the field. This will not be an exhaustive list; however, it will cover many well-known grippers as well as some lesser-known ones. soft robots allow for increased flexibility and adaptability for accomplishing tasks, as well as improved safety when working around humans. In recent years, many pneumatically actuated soft actuators and grippers were proposed such as two, three and more fingers. The robot soft hand will not harm objects during the manipulation. It is more suitable for tele operated surgery for handling delicate organs, poultry industries for handling eggs and for handling bottles, rubber tubes, leather products, paper sheets, fragile materials.

In this paper, we focused on the simple form of soft silicone gripper, for a three-fingered pneumatic actuated, the fabrication of abovementioned soft gripper was based on an iterated injection process, poured to the ABS mold. The melting point of silicone rubber is less when compared to ABS material. So, the withstanding capacity of ABS material is high and it is capable of adopting high impact pressure. Injection molding along with extrusion ranks as one of the prime processes for producing plastic articles. The injection process used to create a silicone rubber soft finger.

DESIGN OF MOLD AND FINGER

Design of Mold

The manually focuses primarily on plastic part and mold design, but also includes chapters on the design process, designing for assembly, machining and finishing, and painting, plating, and decorating.

The mold is designed based on the inverse design of soft finger. The hollow section of soft finger converted into a solid section in mold and the gap between two outer parts of soft finger also consider as solid design. Because outer surface soft finger decide the shape of the soft finger when liquid metal is pouring to the mold cavity. The solidsection of soft finger considers as hollow section and it produces required solid finger while pouring silicone rubber into the runner. The mold has been designed using SOLIDWORKS as shown in the figure and isometric view of a soft finger is shown in the figure.

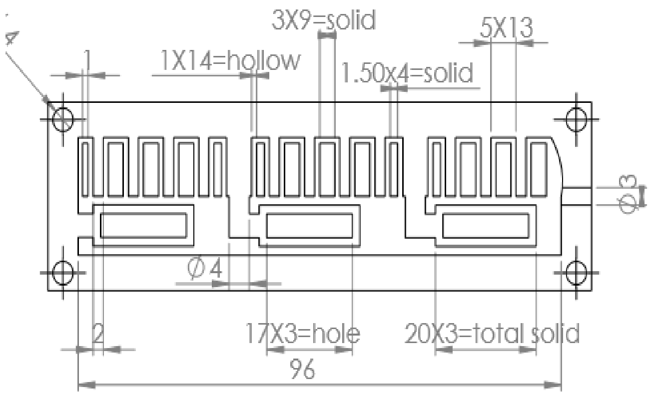

Figure 1: Front View of 3D Mold

The runner dimension and linear contraction passage design are selected from standard pressure requirement and standard dimension. The mold design of inner void sections is made of a solid part. Because the real finger design of void sections are hollow based on the reverse design of the void section.

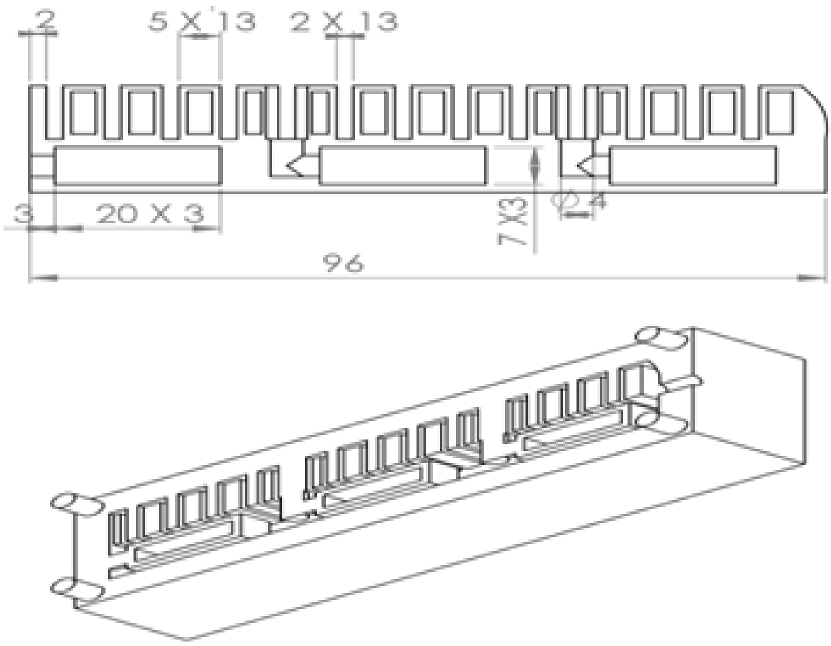

Figure 2: Isometric View of Mold

The runner dimension 3 mm is selected as per the injection molding of metal injector dimension. The bottom layer consists of 5 mm cylindrical extrusion. It is used to connect two parts in the mold. The inner shape of the mold is a totally opposite structure of the soft mold.

Design of Finger

The soft finger contains various layer and design of various parts are created using SOLIDWORKS. The design parts are assembled to obtain the soft finger. The finger is made of silicone rubber which consists of two layers and is a solid structure. The self-weight of the lower layer is larger when compared to the upper layer. The full structure of soft finger is shown in the figure.

The design consists of an upper and lower part. The upper part contains square shaped elevating pattern and its dimension is selected from the literature. Hollow section of the finger is created using extrudes cut option and the same pattern are copied using linear pattern option. The material to be selected based on Young's modulus and Poisson ratio. This design mimics the normal human finger. The average person's finger length is 9.5 to 9.7 cm. The soft finger length in this project is 9.6 cm. The center dimension of each void section hose is 4 mm diameter and extra 1 mm provided for fixing the pneumatic hose line inside the soft finger. The gap between each square section contains 2 mm gap and it prevents extra pressure building inside the void section. The hollow section in the upper part controls the heat dissipation inside the chambers.

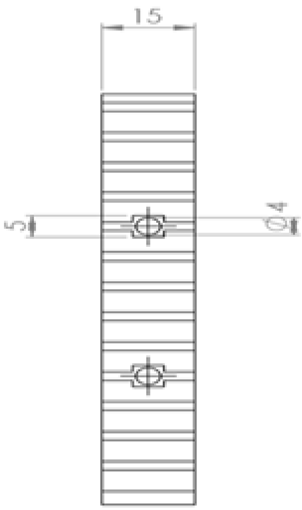

Figure 3: Top View of Soft Finger

Figure 4: Isometric View of Soft Finger

FABRICATION OF SOFT FINGER

The silicone soft finger is made with the help of a 3D printed mold. The mold material must withstand high pressure, high velocity of flow and high-temperature impact. The mold material used in 3D printing is Acrylonitrile Butadiene Styrene (ABS). The mold material properties are listed in the Table. The ABS material is compact for various temperatures rate and suitable for high-pressure ranges. The soft finger completely made of silicone rubber. The 3D printer produces ABS mold layer by layer. The inner parts of the mold created using supporting material

Table 1: Mold Material Selection

Property	ABS Plastic	Polystyrene
Density	900 kg/cm^3 – 1530 kg/cm^3	1600–6400 kg/cm^3
Young's Modulus	2275–2900 MPa	3000–3600 MPa
Refractive Index	2.6	1.6
Specific Heat	1.675 KJ/(kg.K)	1.3 KJ/(kg.K)
Tensile Strength	41-67 MPa	46–60 MPa

The mold design considers about mechanical properties of ABS plastic and polystyrene. In the cost basis polystyrene is less when compared with ABS plastic. The ABS plastic must withstand high pressure and high density. The mold fabrication produced using a 3D printer. The quip pro software determines the amount of material used to produce mold. The 3D printer consists of 3 types of ABS material. The supporting material prevents sudden fall of the void section. The sidewall material used to attach and detach3D material from supporting pad. The mold velocity property determined from Refractive Index value of the material. The ratio between the velocity of flowing fluid and velocity of the standard fluid is called a refractive index. The compactness of ABS material determines from the density of particular material.

The silicone rubber porosity predicts the settling time and shape of the soft finger. The silicone rubber costs high when compared to natural rubber. The silicone rubber contains low cohesive strength and it prevents the environmental effect. The material selection is shown in Table.

Table 2: Soft Finger Material Selection

Property	Silicone Rubber	Natural Rubber
Elongation	800 %	700 %
Temperature range	–100° F and +450° F	–55° F and +210° F
Modulus of rapture	2.4 MPa	1.1 MPa
Young’s modulus	0.05 GPa	0.005 GPa
Density	1250kg/m^3	930kg/m^3

The silicone rubber has 800 % of elongation and it possesses compact mechanical properties. The ratio between the change in length and the original length is called elongation. The elongation can also be determined from the double integration method and moment area method. The prestress concept implemented in a soft finger and this concept produces maximum elongation. Silicone is a synthetic rubber. It is synthesized by modifying silicon. Silicone consists of a backbone of silicon atoms with alternating oxygen atoms. As silicone has high energy silicon-oxygen bonds, it is more resistant to heat than other rubbers or elastomers. Unlike in other elastomers, the inorganic backbone of silicone makes its resistance to fungus and chemicals higher. In addition, silicone rubber is resistant to ozone and UV attacks because the silicon-oxygen bond is less susceptible to these attacks than the carbon bond of the backbone in other elastomers. Silicone has a lower tensile strength and lower tear strength than the organic rubbers. However, at high temperatures, it shows excellent tensile and tears properties. This is because the variation of properties in silicone is less at high temperatures. Silicone is more durable than other elastomers. These are a few of the beneficial properties of silicone. Regardless, the fatigue life of silicone rubbers is shorter than the organic rubbers. It is one of the disadvantages of silicone rubber. In addition, its viscosity is high; therefore, it causes manufacturing problems due to poor flow properties. Rubber is used for many applications like cookware, electronics, automotive applications, because of their elastic behavior. As they are waterproof materials, they are used as sealants, gloves etc. Rubbers or elastomers are excellent materials for insulating purposes. From all the rubbers, silicone is much better for thermal insulation due to its heat resistance. Silicone rubber offers special properties, which organic rubbers do not possess. The Young's modulus and density of silicone rubber determine the elastic limit and breaking point of silicone rubber. The elastic limit is determined from the strain and stress curve of silicone rubber. The thermal conductivity of silicone rubber is minimum compared to natural rubber. The crosslink molecule in silicone rubber is complex than other rubber material and it produces compact porosity. Both rubber and silicone are elastomers. They are polymeric materials that exhibit the viscous elastic behavior, which is generally called elasticity. Silicone can be distinguished from rubbers by the atomic structure. In addition, silicones have more special properties than normal rubbers. Rubbers are naturally occurring, or they can be synthesized. Based on this, silicone can be differentiated from rubber.

Mold Fabrication

The mold fabricated using quip pro software in a 3D printer. The filament used for creating this mold is ABS Acrylonitrile butadiene styrene. ABS is a terpolymer made by polymerizing styrene and acrylonitrile in the presence of polybutadiene. The proportions can vary from 15 to 35% acrylonitrile, 5 to 30% butadiene and 40 to 60% styrene. The result is a long chain of polybutadiene crisscrossed with shorter chains of polystyrene-co-acrylonitrile. The nitrile groups from neighboring chains, being polar, attract each other and bind the chains together, making ABS stronger than pure polystyrene. The styrene gives the plastic a shiny, impervious surface. The various parts of the mold are shown in the figure.

Figure 5: Upper Layer of Mold

The mold is fabricated using Acrylonitrile Butadiene Styrene (ABS) plastic material. It contains reduced volume which produces highly solidify pressure into the material. The mold design initially converted into ". stl" format for calculating the amount of required material. The soft finger mold produces layer by layer technique. The hollow space of soft finger is produced with the help of support material. The soft finger is developed by pouring the silicone rubber into the mold through the runner.

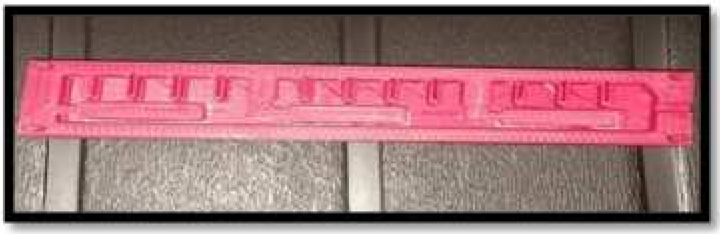

Figure 6: Lower Layer of Mold

The prototype of soft finger produced using a 3D printer. The ABS material is used for creating the prototype of a soft finger. The void section inside the soft finger is provided with the help of support material. The design created in solid works converted into ".stl" format. This format used to determine the material requirement. The soft finger prototype is shown in Figure

Figure Soft Finger Prototype

The design is completed using Solid works software and fabrication produced using FDM technology.

RESULTS AND DISCUSSIONS

Soft robots development involves soft materials, modeling, fabrication, control, and experimental tests. Soft materials are essential for creating soft robot bodies. Using 3D printing technology, multiple materials (soft to hard) can be simultaneously printed and the fabrication process can be significantly simplified. Due to the high printing resolution, the homogeneity and repeatability of the fabricated robot can be better guaranteed. Additionally, the mechanical properties of the printable soft materials are well defined. Using the parameters in the datasheet, the behavior of the soft actuator can be predicted. The 3D printable soft materials also have disadvantages. The softest printable material is harder than Ecoflex but similar to Dragon Skin 30. The stretchability is less than Ecoflex or Dragon Skin. The maximum elongation of the softest material is approximately cent percentage.

The prestress gripper presented in this study could generate initial openings more than twice as large as the gripper without prestressing and simultaneously it maintains the large contact area while grasping. It improved the adaptability of the gripper. One downside of the gripper is that the extra pressure is required to overcome the prestress. Actuation tests are showed similar bending behavior compared to prestress actuator. However, the pre-curled actuator requires complex design, increases gluing difficulty, and fills more support material into the air chambers. The resulted surface after removing support material affected the gluing quality. The SOLIDWORKS simulation used to determine input pressure loading and bending force relation of soft finger performance.

Simulation Results

Analyses are taken by applying the same pressure at each chamber and the results are recorded as shown in the figures.

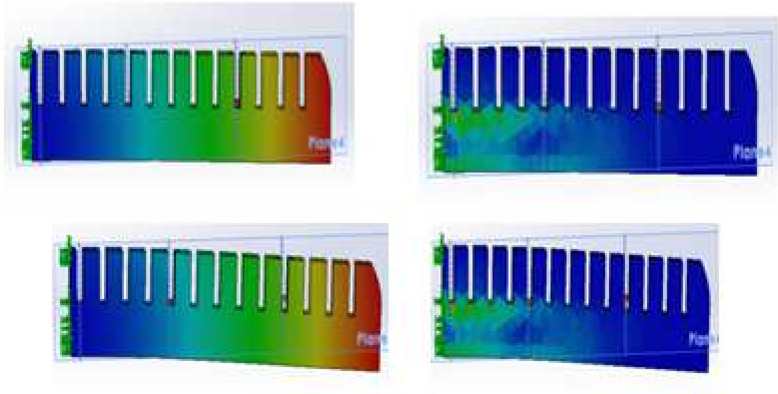

Figure 7: Displacement and Strain of Single Finger at 0.5 Bar

Figure 8: Displacement and Strain of Single Finger at 1 Bar

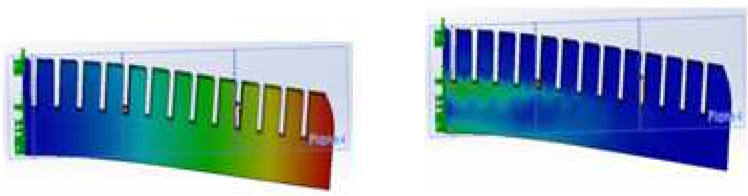

Figure 9: Displacement and Strain of Single Finger at 2 Bar

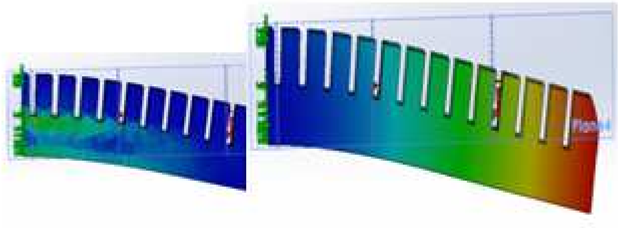

Figure 10: Displacement and Strain of Single Finger at 3 Bar

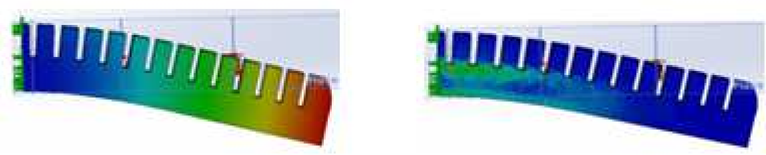

Figure 11: Displacement and Strain of Single Finger at 4 bar

From the figure, the displacement and strain of the gripper are shown clearly for various pressures applied to it. The results reveal that the designed gripper could withstand even for larger pressure values. Even up to 4 bar pressure, the finger doesn't break. Table shows displacement and strain values for different pressures.

Table 3: Same Pressure Loading

S. No	Pressure (bar)			Result	
	C1	C2	C3	Displacement (mm)	Strain
1.	0.5	0.5	0.5	$2.330e^{+000}$	$8.06e^{-003}$
2.	1	1	1	$4.672e^{+000}$	$1.061e^{-002}$
3.	2	2	2	$9.384e^{+000}$	$3.209e^{-002}$
4.	3	3	3	$1.412e^{+001}$	$4.795e^{-002}$
5.	4	4	4	$1.887e^{+001}$	$6.364e^{-002}$

Experimental Results

The real-time analysis does not produce as same as predicted result. The manufacturing of soft finger developed from FDM technology with post-processing. The table contain the result of real-time analysis. The soft finger failure occurs at 2.5 bar pressure and it produces 18.51 N force only. The manufacturing process of a finger is mainly concentrated on the temperature cooling method with post-processing. The post-processing method does not suitable for elongation property. Because a density of silicone is too high and changes its linear property with temperature changes So, the process should be carried out in low-temperature changes. The breakage of a soft finger is shown figure.

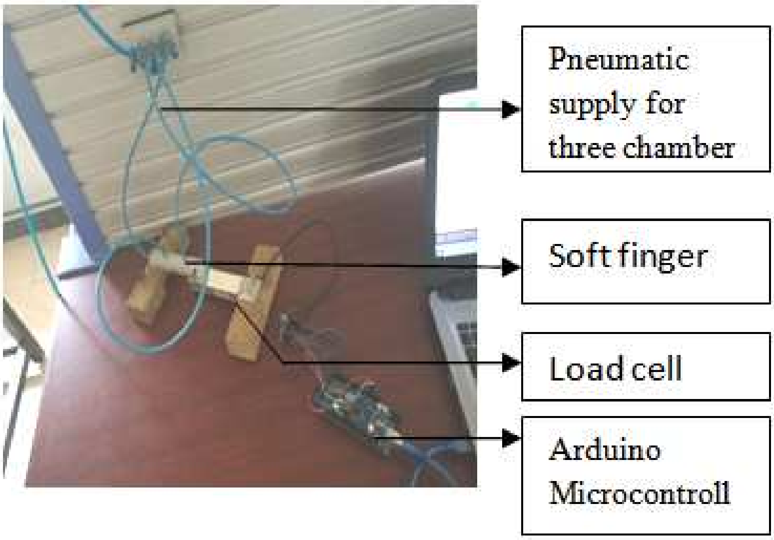

Figure 12: Setup of Real -Time Testing

The figure shows the setup of real-time testing. The testing process consists of three pneumatic pressure hose lines. Each hose line diameter is 4mm. The fabrication process produced pneumatic hose line as per the standard. When applying 2.5 pressures to each void section breakage was occurred. The post-processing manufacturing technique produces breakage in the soft finger. The breakage states that temperature manufacturing post process produce brittle nature to silicone rubber.

Table 4: Real -Time Analysis

S. No	Pressure Loading (Bar)	Bending Force (N)
1	0.4	2.30
2	0.7	5.25
3	1	7.41
4	1.4	9.41
5	1.8	12.30
6	2.1	16.38
7	2.3	18.34
8	2.5	Breaking pressure

Figure 13: Breakage of Soft Finger

The FDM Technology of 3D printing produce crack and failure structure to silicone rubber material. In real time pressure loading each void section subjected to separate pneumatic pressure loading. The same pressure loading produces great impact on the inner void section. The prestress produce breakage to soft finger at the pressure of 2.5 bar.

CONCLUSIONS

The soft finger with a single chamber was designed using SOLIDWORKS 2016 and analyzed in ANSYS software to select the finger stretcher pattern. The stretcher with a rectangular pattern was chosen for designing soft finger with three chambers since it gives better bendingperformance at lower pressure range about 55 kPa. The soft finger with three chambers was designed using SOLIDWORKS to mimic the human finger for material handling. The structural behavior was analyzed by applying different pressures (1 bar to 5 bar). The 3D printed soft finger was fabricated using silicon rubber. The grasping performance of soft finger was analyzed by applying the same and different pressure to void section. The pressure creates sufficient amount prestress to each void section. Due to some post processing manufacturing technique, the density property of silicone rubber was improved. It creates breakage to silicone rubber at minimum amount pressure (250 kPa) and it produces minimum amount force. The manufacturing technique other than FDM technology will produce better grasping performance in a soft finger. The hollow structured supporting upper half will improve the performance of gripper. Construct two material combine structure will improve the grasping performance of gripper.

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