INVESTIGATION OF THE UTILIZATION OF SOFT GRIPPERS IN LOADING AND UNLOADING APPLICATIONS

By:

Hazem Gamal El-Bana

Supervisor

Dr. Ayman Abbas

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The British University in Egypt, (BUE)

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DEVELOPMENT OF A SOFT ROBOTIC GRIPPER FOR CARPET HANDLING

Thesis Approved:

Thesis Advisors Name	Signature / Date
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Internal Committee Member	Signature / Date
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Internal Committee Member	Signature / Date
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Internal Committee Member	Signature / Date
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External Committee member	Signature / Date
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External Committee member	Signature / Date
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Head of Mechanical Department

Faculty of Engineering. The British University in Egypt

Name: ___________________________________

Signature: _______________________________ Date: _________________

Attestation

I hereby declare that this work titled “Investigation of the Utilization of Soft Grippers in Loading and Unloading Applications” submitted to the mechanical engineering department of the British University in Egypt is an original piece of work and has not been published or showcased anywhere else in the past. This work was carried out under the supervision of Assoc. Prof. Dr. Ayman Abbas. All other excerpts are mentioned in the references section.

Name: Hazem Gamal El-Bana

Signature / Date: ________________________________

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Abstract

In this research paper we will discuss the investigation of soft robotic in loading and unloading application. Soft robotic gripper is a new technology that will replace the traditional hard grippers which used as an attachment for the robotic arm in the factory. The basic concept to use soft robotic is that for gripping soft, sensitive objects, fragile parts as the old grippers may damage it. In addition to that soft grippers is easy to control since it does not need any per setup to the part being gripped as it inflate untie it grip the object ant any position.

There are many types of soft robotic design, while in this paper we will study the half rounded cross-section design. As it fulfil the requirement of our point of interest.

We have done experimental test to test different configuration of the actuator, also to get the optimum casting technique for the used material which is Dragon Skin 20 that is a special type of platinum base silicon rubber. At the end of this experimental work we conclude a specific technique to deal with this materiel for different mold design, also we list some recommendation to follow in order to get your cast air bubbles free from the first time.

We are successfully incorporated a flex sensor inside the soft gripper actuator to can easily control the gripper to avoid slipping, and over squeezing the gripped part. According to that we have implement a fully control system that control each actuator in the gripper separately to reach the optimum gripping control. Our developed gripper is made out from three actuator that simulate the human hand finger while grasping objects.

At the end of this research we investigate a soft robotic gripper that is made out three half rounded cross-section actuator that can carry different object with different morphology. The total weight it can carry it one kilogram object. As an future development, the actuator is to be attached to new control system that is basically implementing neural networking techniques in order to enhance the controlling speed and avoid slipping using high speed camera, also the camera will used to detect the object size to prepare the gripper quickly in order to minimize the grasping time which will be cost effective for the industrial application.

Keywords: Soft robotic grippers, loading/unloading application,, PneuNet actuators, half-rounded chambers

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Chapter 1 Introduction

1.1 Background

As the nature of humanity, hands are the most necessary parts in whole body while interaction with environment is needed. Quite the same, human hands give the brain a huge amount of sense to process in order to grasp many types of objects in different shape, size and weight; robots also need a tool acts like human hands for material handing process since the whole world is heading to automation nowadays, the tools responsible for this task is called grippes; which can be defined as a functional device that has a grasping and manipulation function, as Jun Shintake stated "grasping can be simply defend as the ability of the robot to pick-up and hold object (work piece) in an external contradiction of disturbance, and manipulation is the ability of the robot to exert forces on the work piece that cause it to interact with the gripper in both rotational and displacement motion in the reference frame of the manipulator " (Shintake, Cacucciolo, Floreano, & Shea, Soft Robotic Grippers, 2018)The working principal of robotic grippers is load –controlled friction technique which can be defined as "friction force between the gripper and work piece surface, which happen due to normal force between those surfaces" as (Hawkes, 2018) stated. According to that concept the grasping feature increased with increasing the normal force applied, this squeezing process highly affect the work piece specially those made out from soft and sensitive material. Also, these types of traditional grippers have limited flexibility to grasp different work pieces with different shapes as they are rigid manipulators that is because the squeezing force must be normal to the work piece and the gripper itself have to be tangent to the work piece.

Figure 2 Soft robotic gripper (Hao, et al., 2017)

Figure 1 Normal gripper (Ghiet, DAKHIL, & DAYAB, 2016)

1.2 Research stimulus

As known robotics in industry are found without end effector (grippers), because there are variety types of grippers depending on the task assigned to it. We can assume that degrees of freedom of the normal rigid grippers is not important, that is because the industrial robotics arm compensate that by its own degrees of freedom (e.g. 3 axis robotic arm, 4, 5, 6 axes robotic arm).

In order to solve the problems related to the normal rigged gripper such as force sensing grasping sensitive objects and flexibility orientation grasping, we must implement new grasping technology.

The weaknesses of operation of normal rigid grippers attached to the existing industrial and commercial robots can be eliminated by emulating the cleverness of human hand by softly grasping and sensing the objects. Also, the gripper must be programmed to determine the required grasping force in order to achieve the most comfortable grasping condition. The most important reason of normal gripper weakness is that no feedback of gripping force exerting on the object which particularly affect the soft and sensitive objects.

1.3 Problem Statement

The core purpose of this research is to implement convenient gripper that can carry different object with seniority feedback system.

1.4 Aim

The aim of this research is to develop, design and manufacture a pneumatic soft gripper with complete control including sensor`s feedback system to get the required performance.

1.5 Objective

In order to achieve the aim of this research the following objectives is required:

It must be able to grip different objects with different shapes and various weight without slipping under the influence of external and internal disturbance. Also, it should be able to grip fragile objects without damaging them.

In addition to that, the attached sensors must provide a rapid repose to grasping force applied on the object and to detect object slipping. Also, it should have perception about the object being lifted

As known the gripper control system define the dexterity of mechanical system skills that can be achieved. Accordingly, the gripper will be enquired with a full control system in order to achieve the desired goal. In addition, the gripper design must be validated by using computer simulation and finite element analyses (FEA) to give complete imagination of the system.

Chapter 2 Literature review

2.1 Introduction

As mentioned in the previous section this research is to design soft gripper to do various tasks. Therefore, the following survey has been concluded in four areas as below,

1. Soft pneumatic gripper (SPG), the different types and its grasping machinery.
2. Software modelling and simulation, gripper simulation results.
3. Grasping force, how to determine the grasping force while the SPG is in action.
4. Soft robotic sensors, the type of sensor to be attached to the gripper.

2.2 Soft material gripper

According to what stated above we must establish a new grippers material that can safely deals with sensitive soft and irregular shapes work pieces. (Katzschmann & Rus)stated that "using soft material for robotic gripper make it have large number of degrees of freedom, furthermore, it can carry large deformation in the normal operation conditions in order to grip the object with fully enclosure as much as it can, additionally it is safe to operate and can work with structured and non-structured objects. Also, soft material reduces the harm that occurs by using the robotic system". Soft robotic efficiency and functionality mainly depends on the "material and actuation method" as (Hughes J, 2016) concluded, which must be matching each other. There are two common material used for soft gripper, silicon rubber and nylon. The silicon rubber is preferable due to its simplicity in fabrication rather than nylon which require an advanced manufacturing technique (3D printing). In other hand, there are variety actuation methods for a soft robotics, for instance pneumatic actuator which can be defined as (Katzschmann & Rus) stated "air is pressurised into the actuator champers to fill the cavity and causes deformation, usually the power source of pneumatic is compressor and the overall gripper efficiency depends on the valves efficiency" in other hand, cable driven actuation is the lowest actuation methods have degree of freedom because it requires a hinged joint to cause deformation. Shape memory alloy actuators can be defined as (Katzschmann & Rus) concluded "is a material that can be deformed and can return to its initial shape when heated". Each material, material fabrication and actuation method have its advantage and limitation depends on its service condition.

In order to choose the most suitable material and actuation technique for the soft gripper, the gripper morphology must be firstly studied. Morphology is the gripper shape or structure which determine the gripper degrees of freedom. As discussed earlier, the main goal of the soft gripper is to carry objects of various sizes, shapes and weights, particle jamming technique which is a morphology method must be taken into consideration while designing the soft gripper. According to () particle jamming technique is "evacuating internal channels in the actuator to cause stiffening of the material in order to reach the desired morphology".

2.3 Soft pneumatic gripper (SPG)

Soft grippes have been developed to solve the problems caused by normal grippers while grasping objects. There are many researches and experiments done in the universities in all over the world while few of them see the light to the industries. Accordingly, there are several types of soft grippers are published by the academicians and scientist in the last few years; as we are studying the pneumatic actuation type of soft gripper, we will focus on soft pneumatic gripper only in this study. Soft pneumatic gripper or as (Whitesides Research Group, n.d.) Defended as "pneumatic network bending actuator". SPG consist of a series of air channels champers which expand when pressure is applied. The soft pneumatic gripper mainly controlled by changing the inlet pressure which inflate the chamber to cause deformation. In addition to that, it is better to combine different materials to get better control capability of the gripper behaviour. The reason behind that is the use the elastic behaviour to facilitate the gripper control, as (Whitesides Research Group, n.d.) Stated "the actuator is combined from two types of material stretchy and rigid material, the stretchy material will inflate more when pressure is applied. Accordingly, the rigid material knows as (strain limiting layer) ".

To summarize the previous the academicians and scientist work the following table shows the most important published studies in pneumatic actuation soft gripper

Table 1 Summary of published studies in pneumatic actuation soft gripper

#	Published paper	Material	Cavity shape	Sensor type	Operating pressure	Year
1	Design, fabrication and control of soft robots	Different materials (mainly silicon rubber)	Many	Many	-	2015
2	Soft Manipulators and Grippers	Silicone rubber, other elastomeric polymers	-	Strain gage	-	2016
3	Modelling and experiments of a soft robotic gripper	Dragon skin 30	Trapezoidal with different angles	Non	Up to 35 Kpa	2017
4	Size recognition and adaptive…	Silicon rubber	Rectangle	Bending sensor	from 175 to 184 Kpa	2018
5	A Structural Optimisation Method for a Soft Pneumatic Actuator	Silicon rubber	Rectangle, half round and round	Non	from 5 to 35 Kpa	2018
6	Sleeved Bending Actuators for Soft Grippers	Silicon elastomer	Full cavity with strain limiting layers	Non	from 275 to 310 Kpa	2018
7	Bending angle prediction and control of soft pneumatic actuators	EcoFlex-50	Rectangle	Flex sensor	Up to 10 psi	2018

By comparing the data shown in the table 2.1 to get full over view about what the scientist reaches in soft robotic griper until now, the following observations were found,

- Most of soft pneumatic grippers consisting of three fingers to have better grasping action.
- The application that the gripper will be served in determines the desired design, the design is intentional with it the inner channel, because it is the main responsible for the gripper final shape and grasping force.
- Increasing number of fingers will increase the total degrees of freedom which will increase the universe of the gripper.

- The gripper fabrication technique affects the system stiffness, deformation shape and degrees of freedom. (E.g. combining different stiffness material will make the gripper follow the required path, rotate in desired direction while actuation or prevent large deformation in cross section area).
- Most soft grippers were fabricated using shape deposition manufacturing method.
- The design morphology affects the gripper strength, response time and power consumption.
- Silicon rubber is the most common material used for soft pneumatic actuation due to its good stiffness when pressurised.

The department of mechanical engineering at (Beihang University) study different shapes of soft pneumatic actuator to find its effect on the bending radius and pressure consumption, the actuators are as shown in Figure 2. The study concludes that using trapezoidal inner chamber morphology with an angle of 15 degree gives the best bending radius and enclosure pressure as well as the operation in vacuumed pressure.   Also, they found that the width of this actuator morphology affects its efficiency according to them the smaller width gives low pressure consumption and more bending radius. (Hao, et al., 2017)

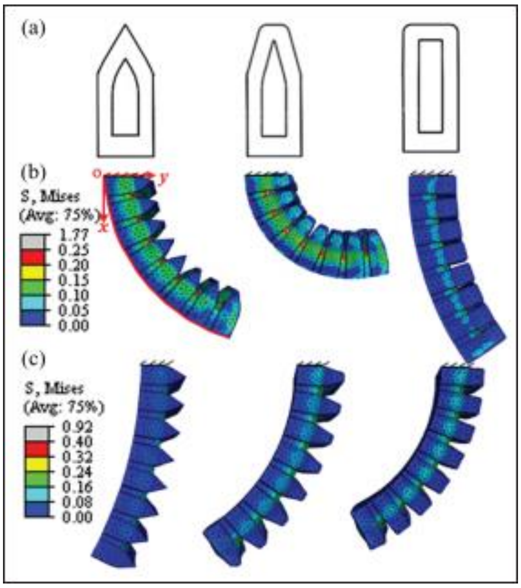


Figure 4 trapezoidal shape with angle 15 degree width study (Hao, et al., 2017)

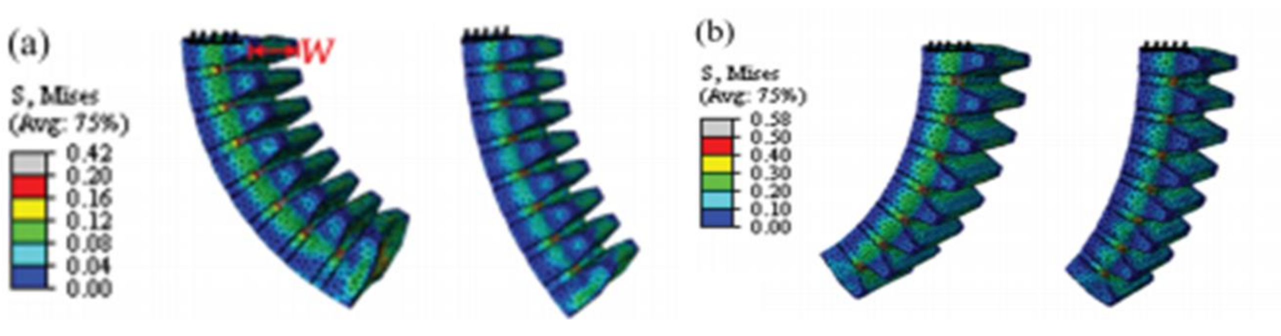


Figure 3 different width of trapezoidal shape actuator (Hao, et al., 2017)

Another research from (Hu, Mutlu, Li, & Alici, 2018), they use the finite element analysis to find the optimum modelling structure for soft pneumatic gripper actuator for silicon rubber material, by using ANOVA analysis to find the significant actuator variables that affect the total deformation. The factors tested was actuator operating pressure, actuator channel cross-sectional shape, strain limiting layer thickness, the gap thickness between sequential actuator chambers. The tests result as concluded below:

- Effect of strain limiting layer thickness: the test was performed on thickness from 3 to 8.5 mm, for higher bending angle the layer thickness should lie between 4.5 mm, while increasing and decreasing the thickness will affect the bending angle negatively. On the other hand, the layer thickness should be studied since it does not affect the actuator strength.
- Effect of gap thickness between sequential actuator chambers: the smaller gab gives more bending angle, while the smaller gap makes the channels to touch each other which will cause interaction forces on the actuator that will damage the channels while operating. Therefore, the larger gap is preferred form stress analyses overview while smaller gap is preferred to have laager bending angle.
- Effect of actuator channel cross-sectional shape as shown in Figure III, the round .3 cross section gives the lowest bending radius comparing with the other cross section types while actuating with the same pressure. On the other hand, using rectangle,

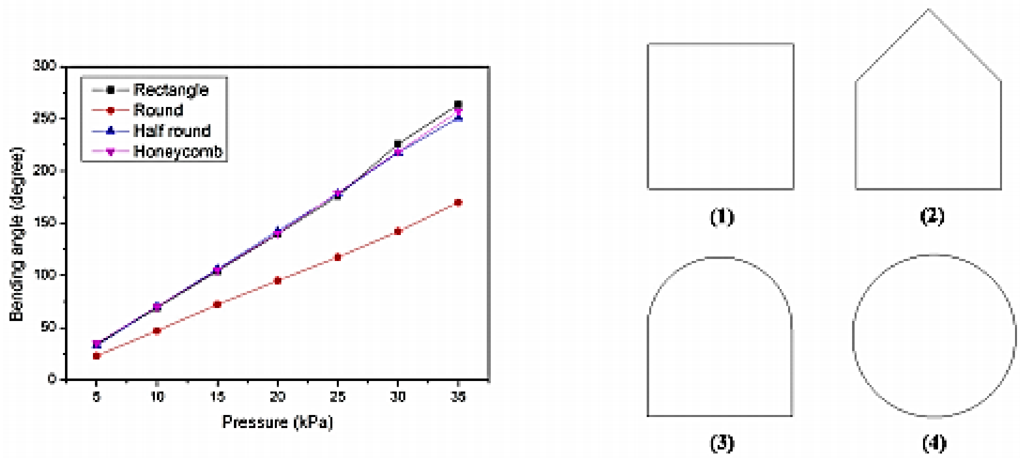


Figure 5 Effect of actuator channel cross-sectional shape. (1) Rectangular cross section; (2) honeycomb cross section; (3) half-round cross section and (4) round cross section.

honeycomb or half round can be assumed to have the same bending radius while actuating at the same pressure conditions.

2.4 Sensor used in soft pneumatic grippers

In addition to that, choosing the gripper actuation and material fabrication method will drive us to choose a suitable sensor in order to get the most suitable gripper for the desired application. These sensors which can be called “soft sensors “according to (Hughes J, 2016) helps to increase the gripper control system functionality and contribution with obtaining required sensing information from the gripped objects.

In order to choose soft sensor, the following parameters should be taken into consideration to achieve the desired goal of their use,

- High sensitivity: according to (zadeh, 2013)“sensitivity is the gradual change in sensor output to the gradual change of measurement in input”, sensitivity can be considered as the slope of sensor data. In soft gripper sensor sensitivity is critical parameter since the sensor will be attached to soft base, the problem is that if the sensitivity is low the soft material will deform before the sensor sense the applied force.
- Low relaxation and hysteresis: (zadeh, 2013) define hysteresis as “the difference between the output reading in the same measurement”. Hysteresis can drive the gripper control to take undesired action that may result in slipping the object being measured
- Short settling time
- Small normalized signal variation

Based on the previous sensors properties there are many types of sensors can be attached to SPG, sensors have an advantages and limitations therefor, the sensor should be chosen while designing the actuator because the sensor location, fixation and connection determine its functionality with the gripper. The following are common soft sensors used in soft gripper actuators.

Implementing resistive Ionic sensor was done by (Devaraj, Giffney, Petit, Assadian, & Aw, 2018), in this paper they used carbon based which is a fixable stain sensor made from ionic and liquid metals impeded while manufacturing the actuator, this type of sensors work based on the change in its resistance when stain is applied. The strain in this case is the deformation caused by pressure applied to the actuator. The problem in this sensor that it requires a carful design, preparation and implementation of the liquid to get the required stretch. On other hand, this type gives high conductivity and low hysteresis properties. Also using this material of the sensor can measure high strain up to 200% by make multiple layers of carbon-based ionic elastomer using printing techniques as shown in Figure .I below.4

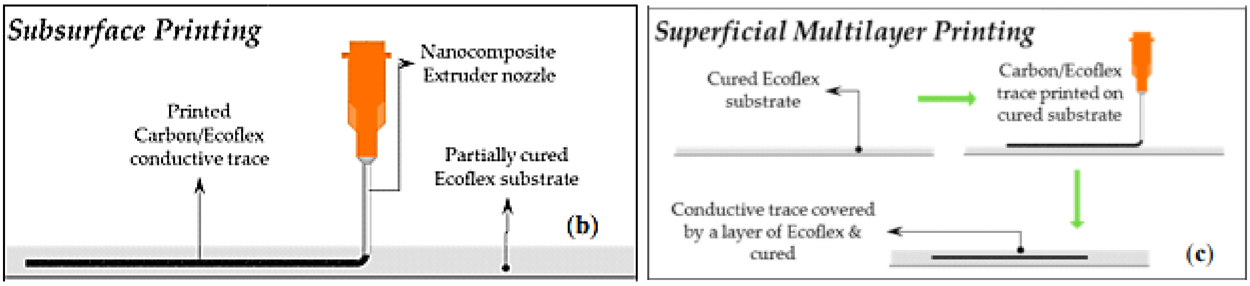


Figure 6 Printing the Carbon based resistive Ionic sensor (Xu, et al., 2018)

One of sensors used in soft robotic gripper is causative stain sensor which is implemented by (Yuen, Kramer-Bottiglio, & Paik, 2018), they stated that using capacitive strain sensors can provide an accurate strain measurements as well as hysteresis free merriments under the static and dynamic actuation conditions. On other hand implementing capacitive strain sensors in soft gripper is very hard and limit the actuator flexibility. The schematic of capacitive strain sensors shown in Figure II, as .4 shown the fabrication techniques is a long process using multiple layer films from silicon elastomer based conductive material. Mainly the layers are “conductive electrode, dielectric layer and conductive electrode”. The problem is that the sensors layers must be shielded to avoid electromagnetic noise comes from external influences.

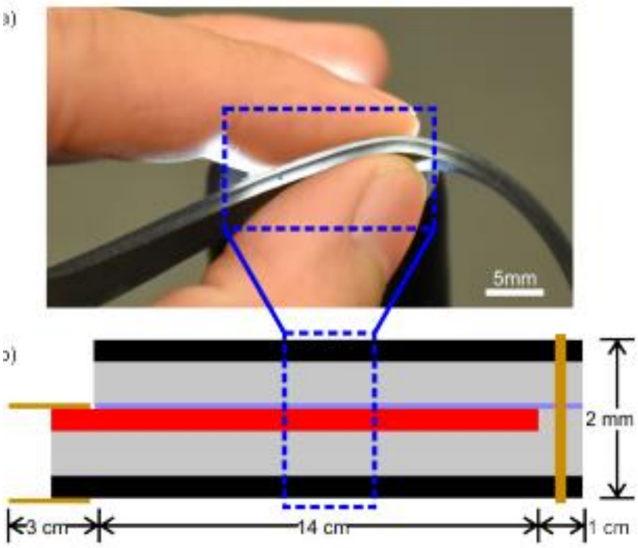


Figure 7 capacitive strain sensors schematic (Yuen, Kramer-Bottiglio, & Paik, 2018)

Using high speed camera is one of the method used to control soft pneumatic gripper where (Shintake, Cacucciolo, Floreano, & Shea, Soft Robotic Grippers, 2018), state that using camera to detect the deformation of the actuator fingertip allow to have high accuracy and sensitivity sensing. While using this technique still very expensive and not applicable to be used in large scale deformations yet. In addition to that, it is necessary while using optical sensing sensor rigid workspace to give accurate results.

2.5 Soft gripper fabrication

There are many researches in soft gripper fabrication techniques which can be concluded to used shape deposition manufacturing technique, mainly it is 3D printing method due to its high intensity and applicable tolerance inflation pressure.

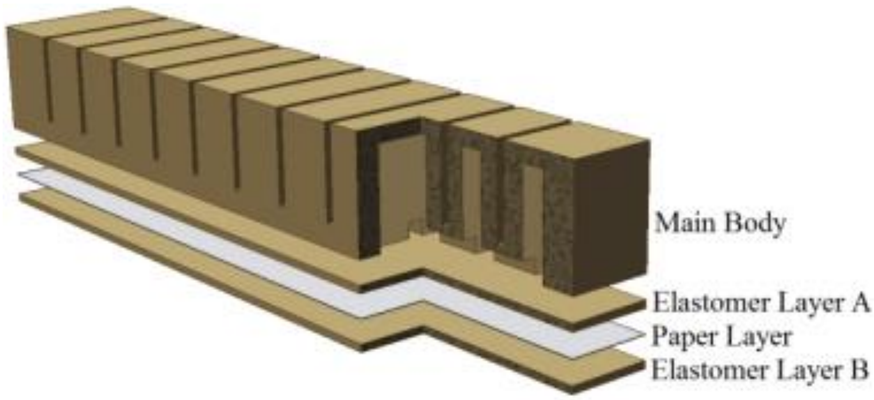
2.6 Soft gripper kinematics

As the soft grippers has a large number of degrees of freedom, the final shape of the actuator is hard to be predicted, while it is only can be defined by a continuous function using continuous mathematics. This method called “Bernoulli–Euler beam mechanics” which used to predict the actuator deformation. On the other hand, this approach has some limitation to solve inverse kinematics for linear soft bodies, due to variation of kinematic of single actuator since there is special kinematics for the whole body and the actuator end effector.

Chapter 3 Experimental work

3.1 Introduction

After researching and studying what has been done in the past years, it is time for practical implementation to gain experience and monitor all the possibilities in the implementation of the soft gripper, also it helps to identify elements that may cause difficulties in the final design. For this experiment we choose an existing design from (Whitesides Research Group, n.d.). The design has rectangular cross-sectional area as shown in Figure below.



3.2 Actuator design

3.2.1 Bill of materials

1. 3D printed Mold
2. Elastomer material: Smooth-On Dragon skin 20
3. Release agent 200
4. Mixing cup
5. Steering element

<u>3D printed Mold:</u> As the design is very complicated and the actuator must be fabricated with this tiny detail the mold is having to be fabricated using advanced manufacturing technique.

The mold consist from three parts as follow, main body consist of two parts the bottom one is to make the pneumatic channels and champers details, while the top one to create the wall thickness. The third part is to fabricate the actuator base and the strain limiting layer. The 3D printed mold shown in the figure 10.

Figure 8 3d- printed mold

Elastomer material: Smooth-On Dragon skin 20 is a high-performance liquid silicon having high flexibility. This material is the stretchy material of the actuator. It is preferable because it is very easy to use since it have mixing ratio of 1:1 by weight or volume, also it can cure at room temperature as well as using furnace. In addition to that, it has a negligible shrinkage. The properties of Dragon skin 20 material listed in Table 3: Ibellow. Also the material photo is shown in Figure 11 bellow

Table 2 properties of Dragon skin 20

Properties	Value	Properties	Value
Specific Gravity	1.08 g/cc	**Mix Ratio by Volume**	1A:1B
Specific Volume	25.6 cu. in./lb.	**Mix Ratio by Weight**	1A:1B
Pot Life	25 minutes	**Colour**	Translucent
Cure Time	4 hours	**Useful Temperature (min)**	-65 °F
Shore Hardness	20 A	**Useful Temperature (max)**	450 °F
Tensile Strength	550 psi	**Mixed Viscosity**	20,000 cps
100% Modulus	49 psi	**Die B Tear Strength**	120 pli
Elongation @ Break	620 %	**Shrinkage**	<.001 in. / in.

Figure 9 Release Agent 200

<u>Release agent 200:</u> releasing agent is important wile fabricating soft gripper to make the demanding process easier. (Ease Release™ 200) is special releasing agent for silicon rubber mold.

As shown in figure 11 below

Figure 10Dragon Skin 20 BOX

3.2.2 Tools needed

- Scale: to mix the elastomer martial at the correct ratio
- Centrifugal mixer: to make sure that the liquid rubber part A and B is well mixed. Figure 15
- Vacuum chamber: to make degassing for the mixed elastomer in order to remove all air bubbles created inside the material while mixing process in the centrifugal mixer. Figure 14

- Electrical oven: in order to accelerate the material curing. It is electrical to ensure that the oven is operating at the required temperature figure 13

Figure 12 centrifugal mixer

Figure 13 vacuum chamber

Figure 11 electric oven

3.3 Fabrication

As discussed before the actuator is made out from two main parts, the top and bottom mold will be moulded separately and then glued together even with the same elastomer material or by using the silicon rubber adhesive.

After preparing all required material and tools stated before the following steps are conducted

5.3.2 Preparing the material.

The silicon rubber is mixed in a ratio of 1:1 by weight from parts A and B. we pure 50g from part A with 50g from part B in the centrifugal mixer cub.

5.3.2 Mixing

According to the material requirement, the purred material have to be mixed at the centrifugal mixer for 3 minutes at 2000 RPM. The mixing process is done in the centrifugal mixer cub after balancing the mixer by adjusting the mixer wheel balance to match the elastomer and cub assembly weigh.

5.3.2 Pouring the mixture

The mixture after mixing require carful handing and must be poured as slow as possible to not let large air bubbles to be established. While the pouring process the mixture has to fill the half of mold then complete it until all chambers are evenly spread out.

5.3.2 Degassing

The degassing process should be varied out for 10 to 15 min until there is no new big air bubbles are created. It may need to supply the mold with mixture due to leeks and over flow of the mold while the degassing process is conducted.

5.3.2 Curing

Based on the martial properties the curing is taking place at room temperature for at least 4 hours. On other hand, if you need to accelerate the curing process the electrical oven is to be used with temperature of about 60 degree for 15 minutes.

5.3.2 Strain limiting layer

The strain limiting layer implementation is very tricky because it is very hard to get it submerged. The best way is to put some elastomer material in the base then put the strain limiting layer after that put another layer from elastomer.

5.3.2 Two parts assembly

After the two parts are fully cure the assembly process is done by mixing new material and use it as a glue for the top and bottom parts. Or using the adhesive to bond the two parts.

5.3.2 Observation from fabrication process

After the fabrication process the following observation were recorded:

- Degassing process must take place before the pouring process.
- The pouring should take place in each chamber cavity until it until all chambers are evenly filled out.
- While pouring process the mold needs to set on shaking table in order to fill all minute cavity in the mold.
- The mold design have to be modified by adding additional part work as a reservoir to supply the main cavity with material in degassing process.
- Air supply connection must be implemented in the mold design to prevent the connection from leaking
- before mixing process the material have to be cold eater by working in cold area or put the container in refrigerator

3.4 Actuator simulation

In this section we will describe how to solve fluid structure interaction problem which is basely a very complicated inverse kinematic problem since the actuator deforms according to the supplied air pressure and affected by gravity and the live load it carry. Accordingly the best method to solve this type of problems is to make finite element analysis of the pneumatic actuator using computer software, the software could be either Ansys or Abaqus. As we use both for simulation Ansys software is easy to handle and easy to deal with, while its results is not correct all the time because the simulation process stops because it needs a high processor computer. On the other hand, Abaqus software have a complex setup for the analysis, but it gives a good results and shows the analysis from different point of view, like stress, strain, strain limiting layer behaviour and bending radius.

Using finite element analysis methods make us able to test the actuator behaviour while changing the design parameters of the actuator, without refabricating the actuator and test it at every change of its design parameters.

To make the simulation process easy we will list the simulation parameters we will use at all the following simulation process as follow:-

3.4.1 Material properties of material used

a- silicon rubber (dragon skin 20) have the following properties:

Table 3 Dragon Skin material configuration Abaqus

Property	Value	notes
Yeoh stain	C10 = 0.11 , C20 = 0.02	---
Density	1130 kg/m^3	Assuming density is isentropic

Yeoh strain is a phenomenological characteristic describe the deformation of the incompressible non-linear material

b- Strain limiting layer. We will use two different types of strain limiting layer as follow

1- Woven ribbon, which have the following properties

Table 4Fabric paper configuration Abaqus

Property	Value
Density	1130 kg/m^3
Young's Modulus	6.5 GPa
Poisson's ratio	0.2

2- The sensor martial share the same characteristic of dragon skin material

The simulation steps could be concluded in the following steps:-

1. import the designed models from solid works
2. assign surface for the strain limiting layer in the actuator base
3. add material and assign it to the imported parts
4. assemble the actuator as it require to be
5. create the inner cavity of the actuator chambers
6. add loads to the actuator assembly
7. set the boundary conditions and fixation surfaces
8. define the interactions that should be done in the real actuator
9. create the mesh and assign it to all parts

Accordingly the following are the detailed explanation of the most critical steps in order to make a complete actuator simulation.

3.4.2 Importing the designed models

To import the fire that the Abaqus can deal with it is required to be with (.STEP) extension.

Accordingly we have to save the 3 modelled parts for the actuator which are the main actuator body and the base that consist of two parts the base bottom and the base top separated by the strain limiting layer as STEP files.

The importing process is simply done by right click on the parts in the model tree and browse for each part. At the end of this process we will have 3 imported parts in the model tree.

<u>Choose the strain limiting layer location</u>

in order to define the strain limiting layer in the simulation process firstly its location must be defined in the imported parts.to define it, return back to the imported file section and choose the top part of the base, in the surface option the model tree choose import surface and crate surface for it

3.4.3 Actuator assembly

After the modelled parts were imported and the strain limiting layer is defined it is now the time to the actuator to get its shape, therefor we will assemble all the imported parts together. The assembly section in located in the model tree where we choose (instance) and select our three parts of the actuator and choose the instance type to be dependant. By choosing "Auto-offset from other instances" the imported parts will located far away from each other without any overlaps, this option

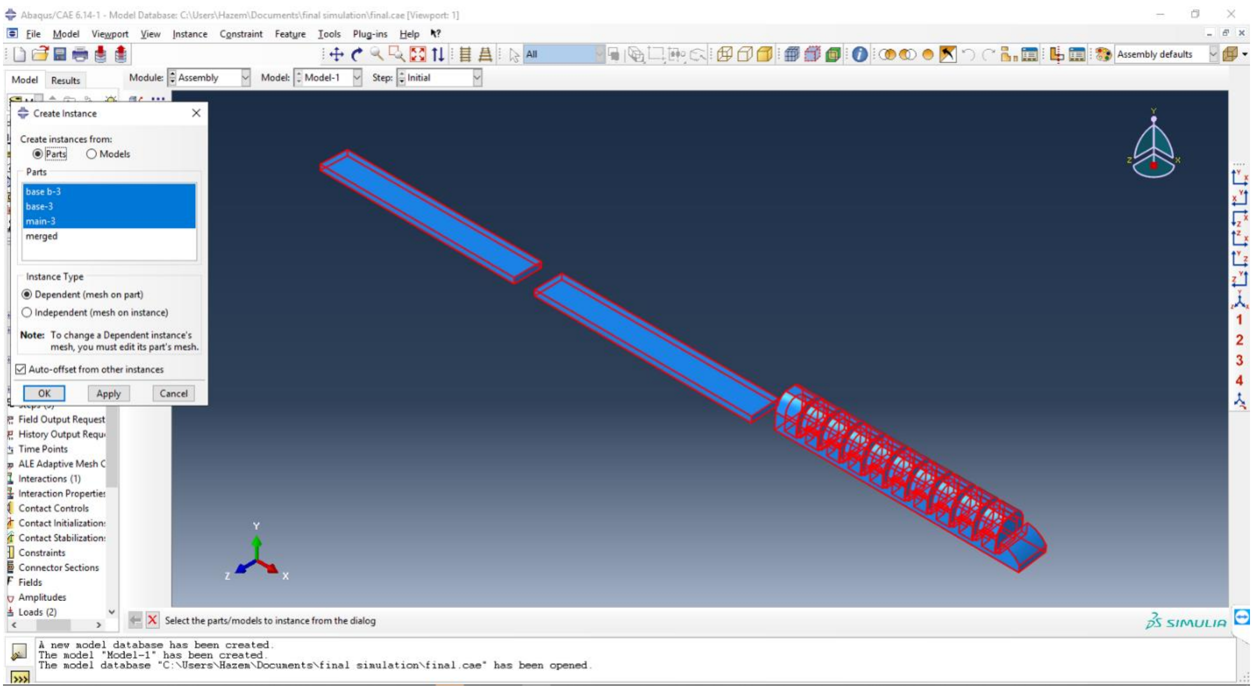


Figure 14 actuator assembly process Abaqus will simplify the assembly process easy to choose the surface need to be merged.as shown in figure 16

After that we have to define the positions of the parts relative to each other, in the as simply section we will choose the “face-to-face” option to mate the parts together.

Accordingly we have to define six constrains, that because we will consider the bottom base is our fixed part and make three translation degree of freedom mate to the other two parts relative to the bottom base.

This mating option require to take into consideration the face selection sequence as you have to start with the movable part then followed by the fixed part. Otherwise, while you reach the final step which is running the simulation you will get an error and you have to repeat the assembly process gain.

The parts mating steps will be as follow:-

1. <u>Main body is the movable part and the base top is the fixed part</u>
    1. Mate bottom faces of the main body and the base top
    2. Mate side faces of the main body and the base top
    3. Mate the front faces of the main body and the base top
2. <u>The assembled parte will be considered as the movable parts and the base bottom is the fixed particularly</u>
    1. Mate bottom faces of the assembled parts and the base bottom
    2. Mate side faces of the assembled parts and the base bottom
    3. Mate the front faces of the assembled parts and the base bottom

While mating process it is highly important to take into consideration the mating direction which is represented by arrows, if the parts is not in the same direction simply choose flip and the arrows will be pointing to the same direction. The final assumedly step is that we have to save the assembly as an

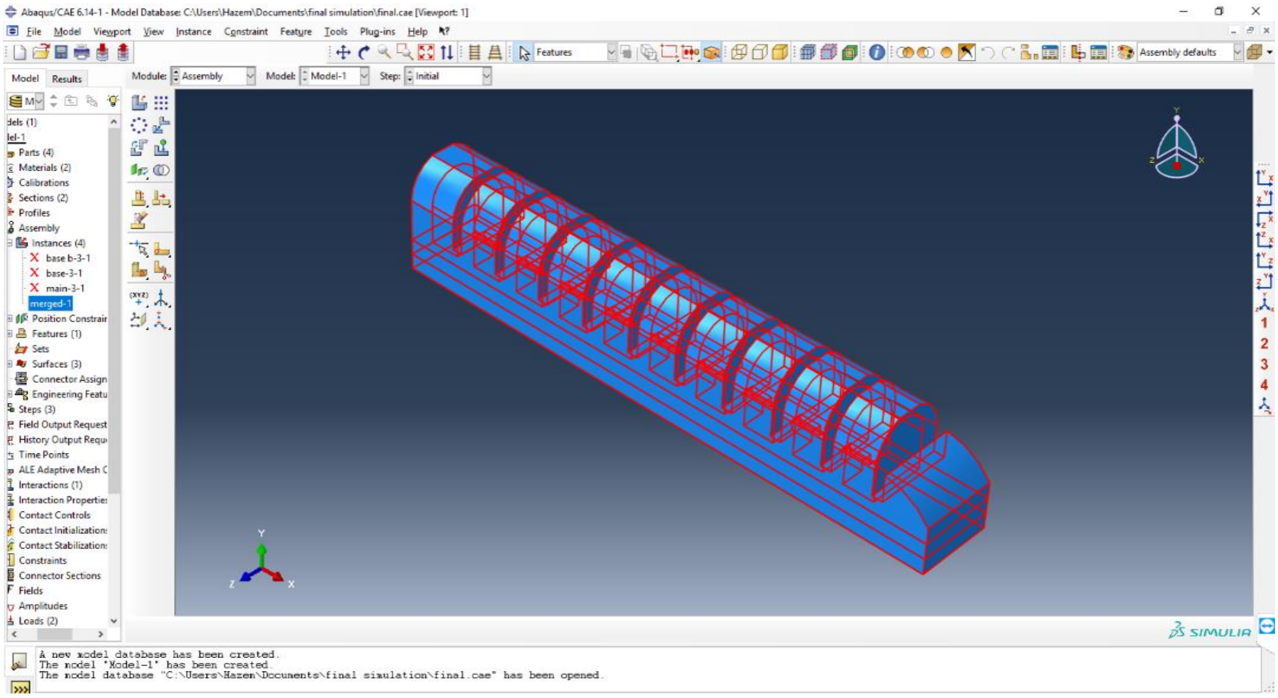


Figure 15 assembly merged part Abaqus

individual part. By choosing the “Merge” option and select the assembly it will be saved as a part. In the merge setting you have to choose the merge type as “Raiten” to keep the interaction boundary.

3.4.4 Create strain limiting layer in the new assembly

We have to re-define the strain limiting layer with respect to the assembly in order to assign it to specific section of material this is done with the following steps :-

- Isolate the skin made the previous steps by going to “tools” then open manager in the display group.
- In the display manager choose create
- Select surface and choose replace to isolate the stain limiting layer from all parts in the display.

After that you have to assign section material to the strain limiting layer in the assembly, this is done by navigating again to the merged part in the model tree and select “section assignment” and choose the top layer f base bottom which is the previously created strain limiting layer skin, then in the section manager choose the section type to be “shell and homogeneous”

3.4.5 Add load to the actuator

The first step before adding load to the actuator is that we have to define the actuator chambers where the pressure will be action on. We will use cut view to make the selection process easy, the cut view can be used to section view the actuator from all sides and with different distance and variety and cutting angles. This option can be reached by choosing “TOOLS > VIEW CUT > MANAGER”. You have to reposition the cutting location until the all chambers wall including air channels is selected. The final shape of the inner cavity is shown in the figure

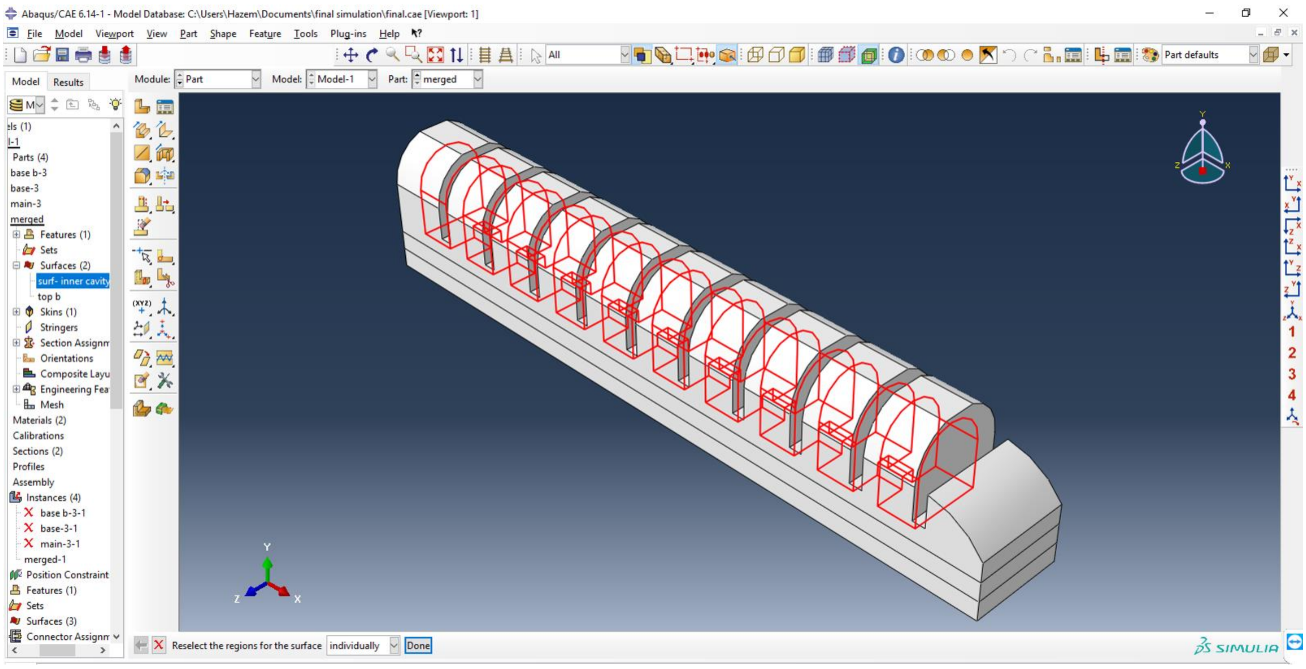


Figure 16 actuator inner cavity

3.4.6 Gravity step

Next, the gravity step needs to be created. All other steps will propagate from this. Once the step is created then we can go on to create the load for gravity which is set as a force in the correct direction depending on the model created on Abaqus. In this case, the gravity is acting the y direction. This is set

Once the gravity step is created and the load is added, we can go on to define the boundary conditions for the gravitational force. Because the actuator is going to be fixed in one place, we pick the fixed end, encase option to emulate the fixed end.

3.4.7 Pressure step

We then go on to create the pressure step this will propagate from the gravity step. What this means is that when the simulation is run, Abaqus starts with the gravitational force. This is as at this point, no pressure will have been applied at time 0. Once the pressure is applied and the force is then bigger than the gravitational force, the program then goes on to simulate the pressure addition.

We then select the surfaces on which the pressure is going to be acting on. This surface was created in the previous steps so we simply select the surface on which the force will be acting and we define the magnitude of the force.

3.4.8 Contact interaction

Finally, before we do the mesh, we need to consider that the chambers of the actuators are going be coming into contact with one another. This requires us to add a contact interaction. If we do not do this, during the simulation, the chamber walls will go into one another and will not simulate the correct movement of the chambers coming into contact and pushing on one another to create more bending.
This is added as self-contact in the Abaqus option select tangential behavior

Chapter 4 Actuator design iteration

5.1 Design 1

Based on the information and data collected from literature review and experimental work done we have to implement new deign to achieve the required research objectives.

4.1.1 Concept design

This design idea was taken because it is the only actuator shape which is supported by some inverse kinematics calculations like calculating bending angle, stress and strain. The impact of equation is that it will reduce the iteration process of simulation steps, as we will calculate the bending radius of the actuator by direct substitute in the equation with our design parameters and get the required data to check that the actuator will fitful the requirement of bending. After that we got a safe design parameters we will do the simulation step once to check the bending radius and to know wither the actuator will withstand the applied pressure or not.

4.1.2 Design details

The drawing sheet provided with all dimensions of the actuator is shown in the figure 19 and 20

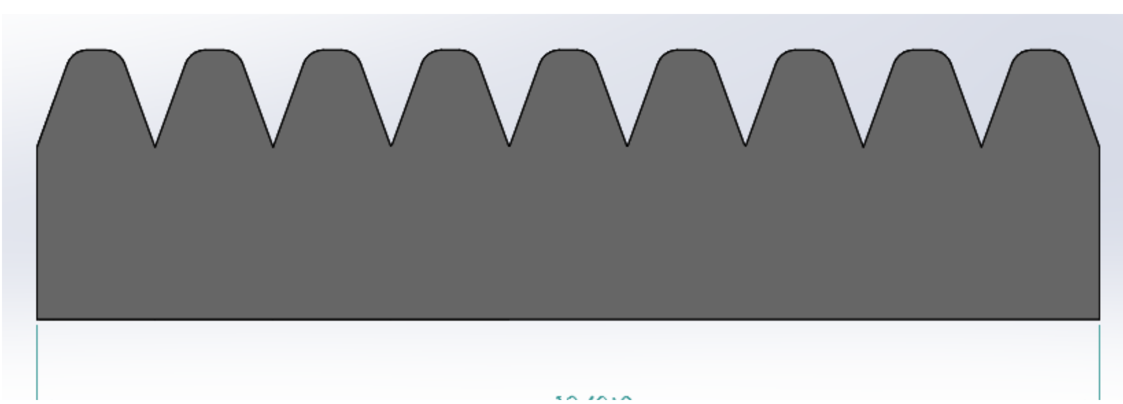


Figure 17 trapezoidal actuator

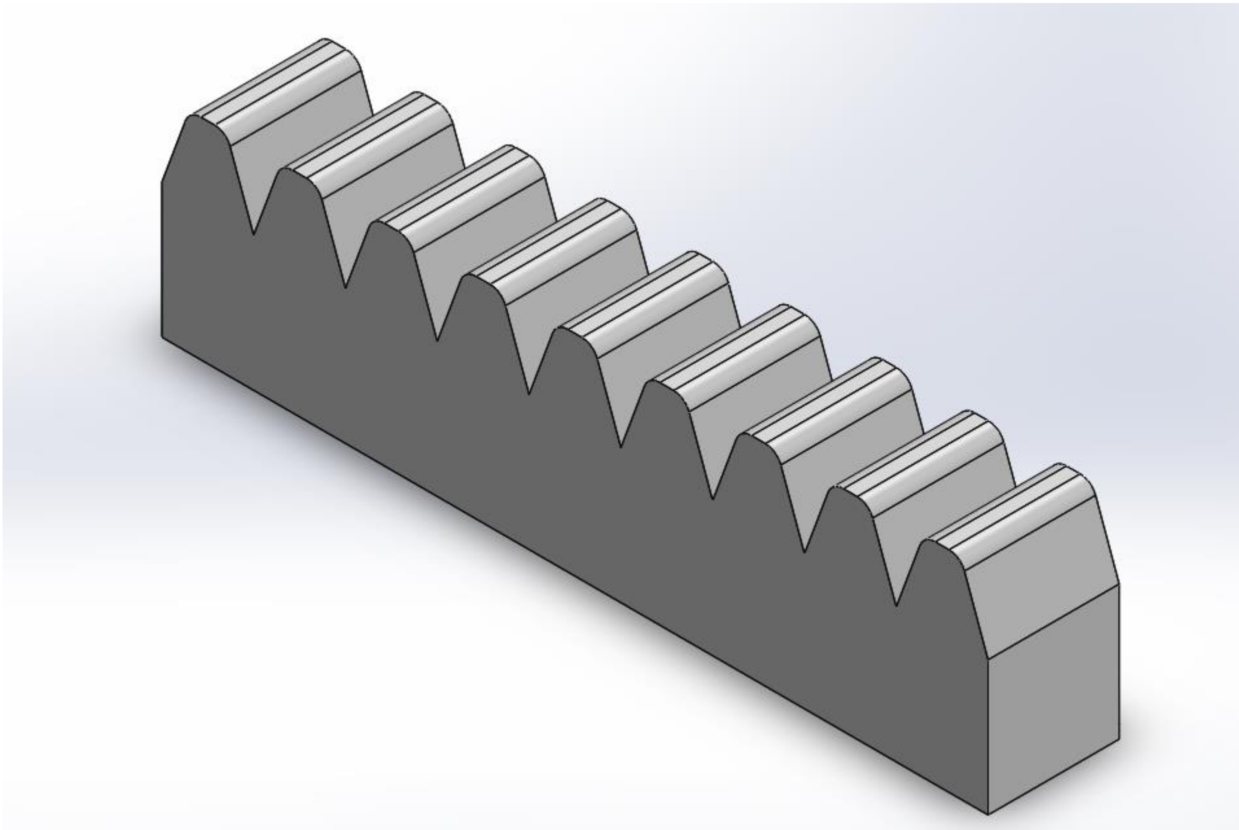


Figure 18 trapezoidal actuator isometric view

4.1.3 Calculations

The chosen shape is trapezoidal cross section and special tip design. The main calculation parameters were taken from (Hao, et al., 2017) to predict the bending radius and its invers kinematics. As shown in Table 3

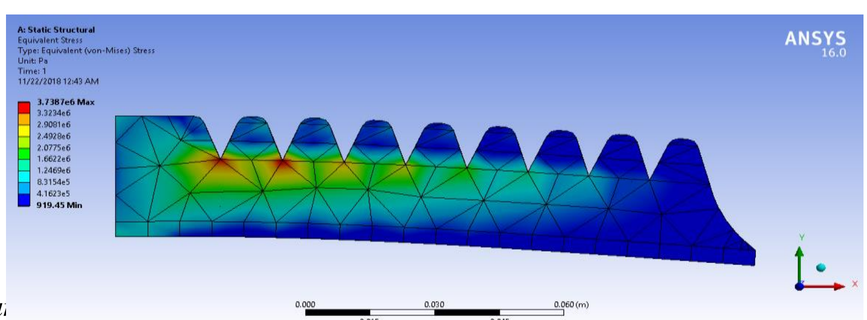
Table 5 actuator calculation

pressure	stress calculation	strain	bending angle of the actuator (degree)	bending radius angle 10	bending radius angle 15	bending radius angle 20	bending radius angle 30
5	14.90504846	0.123248527	24.20564328	289.1887615	42.57825776	43.03328592	44.36681357
10	29.81009691	0.263779199	51.76241109	135.2332678	50.67741821	51.22079339	52.81276136
15	44.71514537	0.404592014	79.28089232	88.29365809	62.74107514	63.41397208	65.38469854
20	59.62019383	0.545686972	106.7116012	65.59736638	82.57918026	83.46062456	86.04083034
25	74.52524228	0.687064075	134.0059952	52.23646888	121.1823522	122.4558828	126.1805666
30	89.43029074	0.828723321	161.1169789	43.44669351	228.7130249	230.9909518	237.6379231
35	104.3353392	0.970664711	187.999369	37.23416753	291.8193786	295.5546076	306.5739845

After checking that the design parameters will fulfil the gripper requirements, the simulation step will determine wither the actuator will withstand with the supplied pressure or not.

4.1.4 Gripper simulation

Using the finite element analyses (FEA) to check the stress on the actuator when the pressure is applied the following results were found



Figu

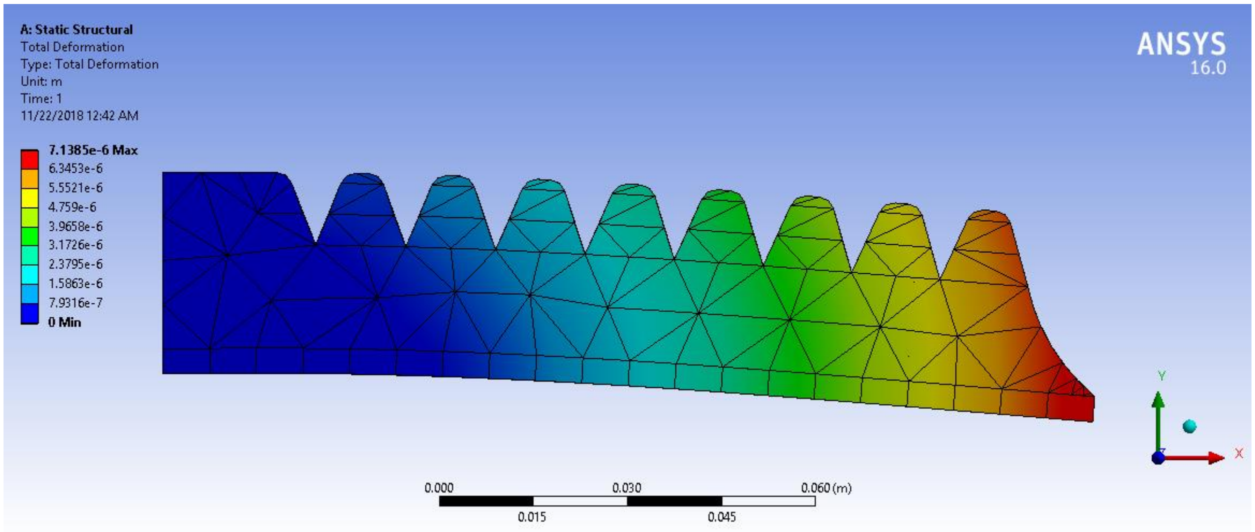


Figure 20 the total deformation of the actuator when pressure of 5 KPa is applied using FEA

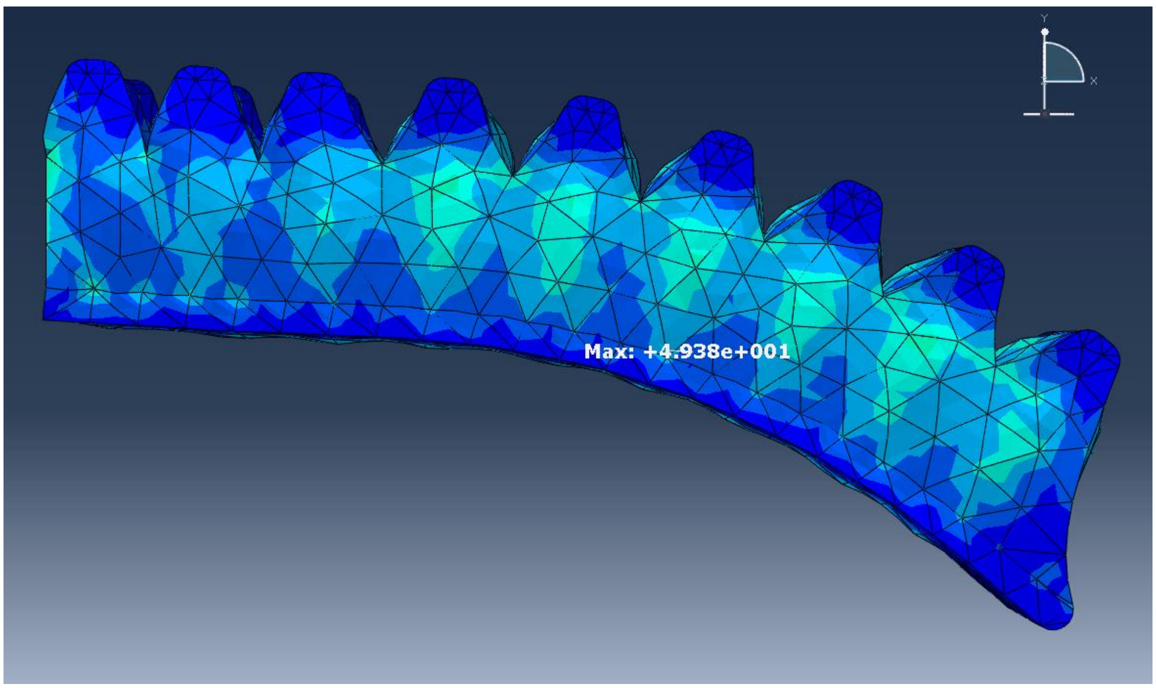


Figure 21 deformation of the actuator when pressure of 35 KPa is applied the simulation results obtained shows that the design is not safe as it exploded form the second chamber due to the geometry parameters, we use different simulation programs to check that the results obtained is true.

As we need the gripper to be with the existing geometry characteristic, accordingly we will change the actuator shape and design to check if it will withstand the supplied pressure or not.

5.1 Design 2

This design will be investigated using the half rounded chambers consist to check if it will with stand with the supplied pressure and give the required bending angle or not

4.2.1 Concept design

As we stated above, the design is based on the half rounded chambers. On the other hand, this design does not have any inverse kinematics equation to check the design before simulation step. According to that we have to check each change done in the design parameter with the finite element analysis software, and re-iterate the design for each simulation results.

4.2.2 Design details

The drawing sheet provided with all dimensions of the actuator is shown in the figure 24

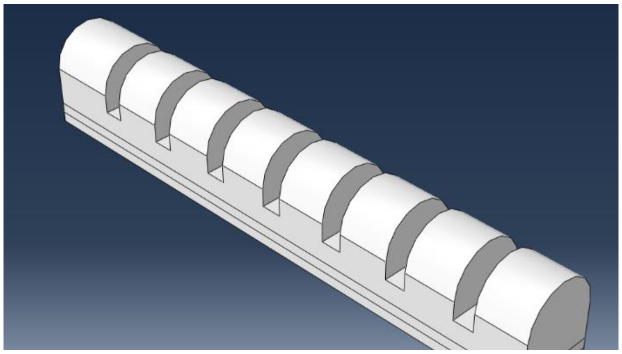


Figure 22 half rounded chamber first design

4.2.3 Gripper simulation

Using the finite element analyses (FEA) to check the stress on the actuator when the pressure is applied the following results were obtained

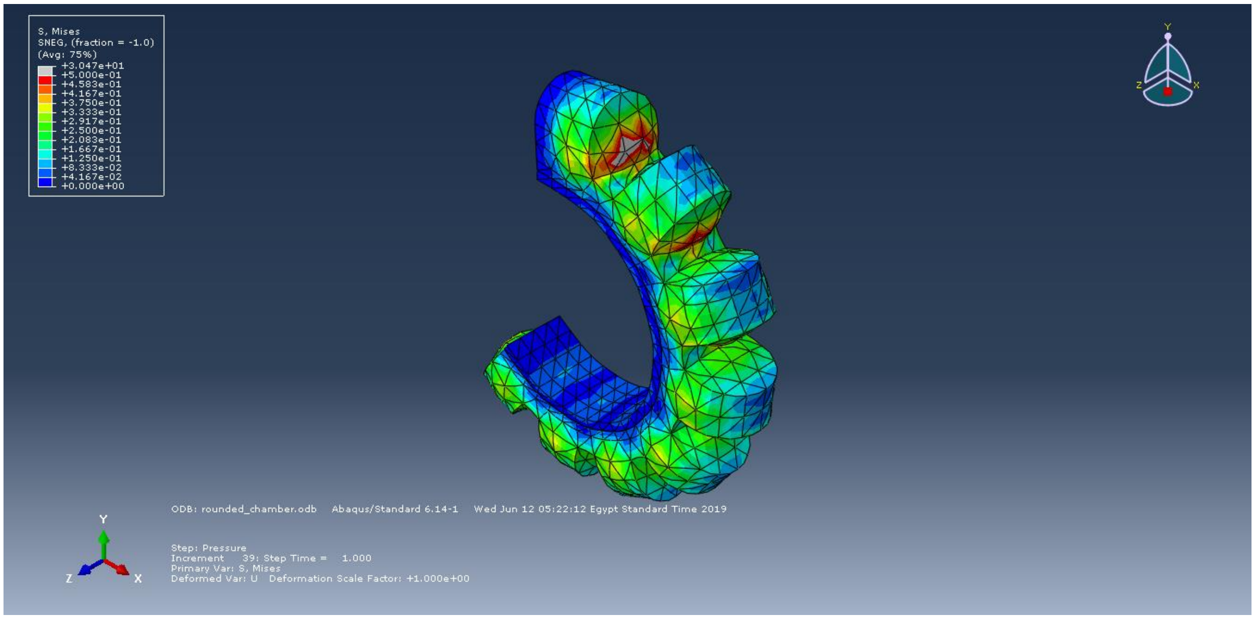


Figure 23 half rounded chambers simulation isometric

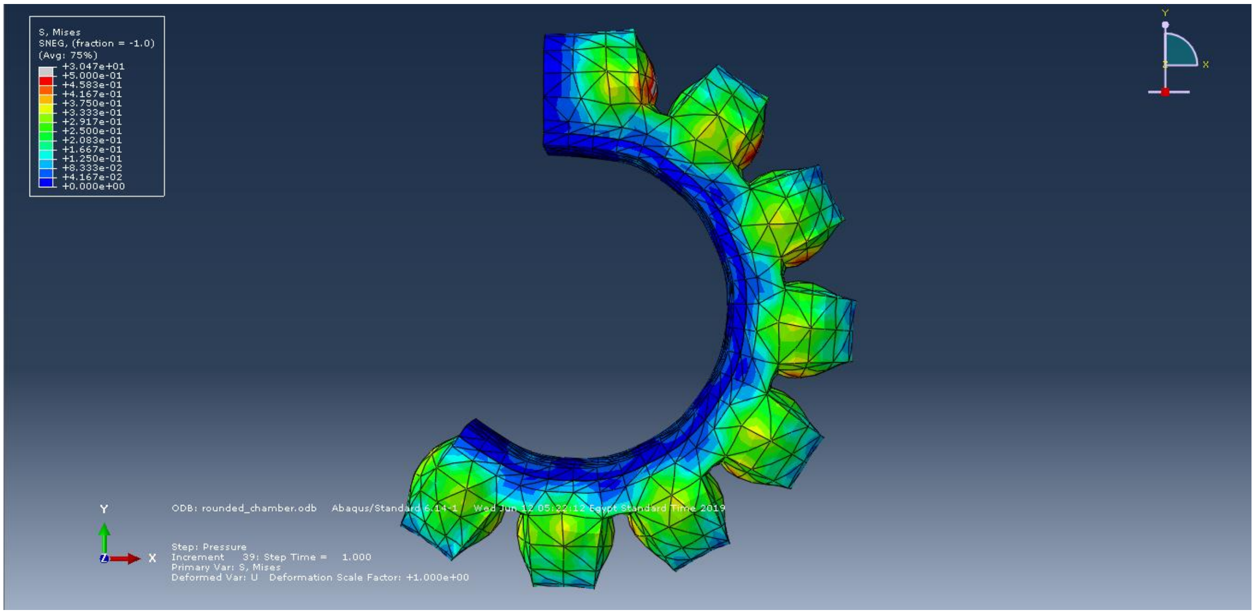


Figure 24 half rounded chambers simulation

As shown in the simulation, the design is safe and does not exploded, in the other hand we have to increase the number of chambers in order to get a higher bending radius which will help us to carry various objects.

5.1 Design 3

This design is only an update to design that stated above by increasing the number of chambers and get the actuator width smaller.

4.3.1 Concept design

After the pervious simulation step, we reorganise that we have to increase the number of chambers to increase the number of chambers as the actuator length only increase by changing the number of chambers or the distance between chambers. On the other hand we reach the optimum distance between the chambers. According to that we are allowed only to increase the number of chambers in order to get the actuator longer. Also to keep the ratio of length and width acceptable we will decreased the actuator width and check that design in the simulation

4.3.2 Design details

The drawing sheet provided with all dimensions of the actuator is shown in the figure 27 and 28

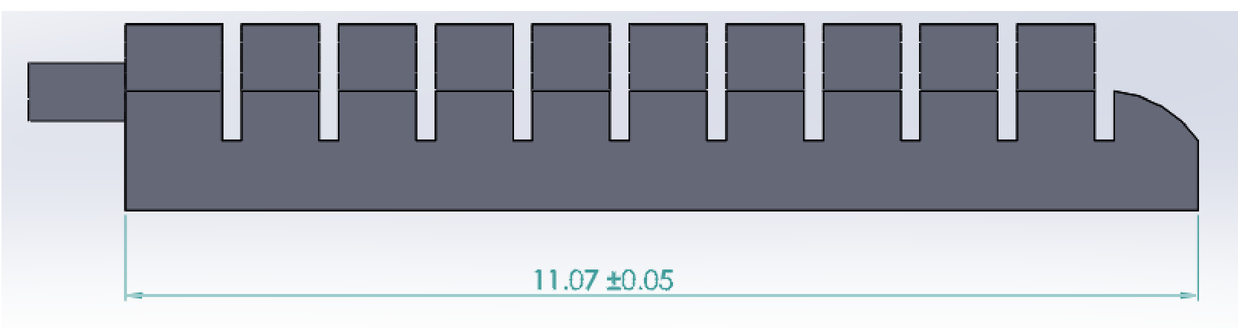


Figure 25half rounded design 2

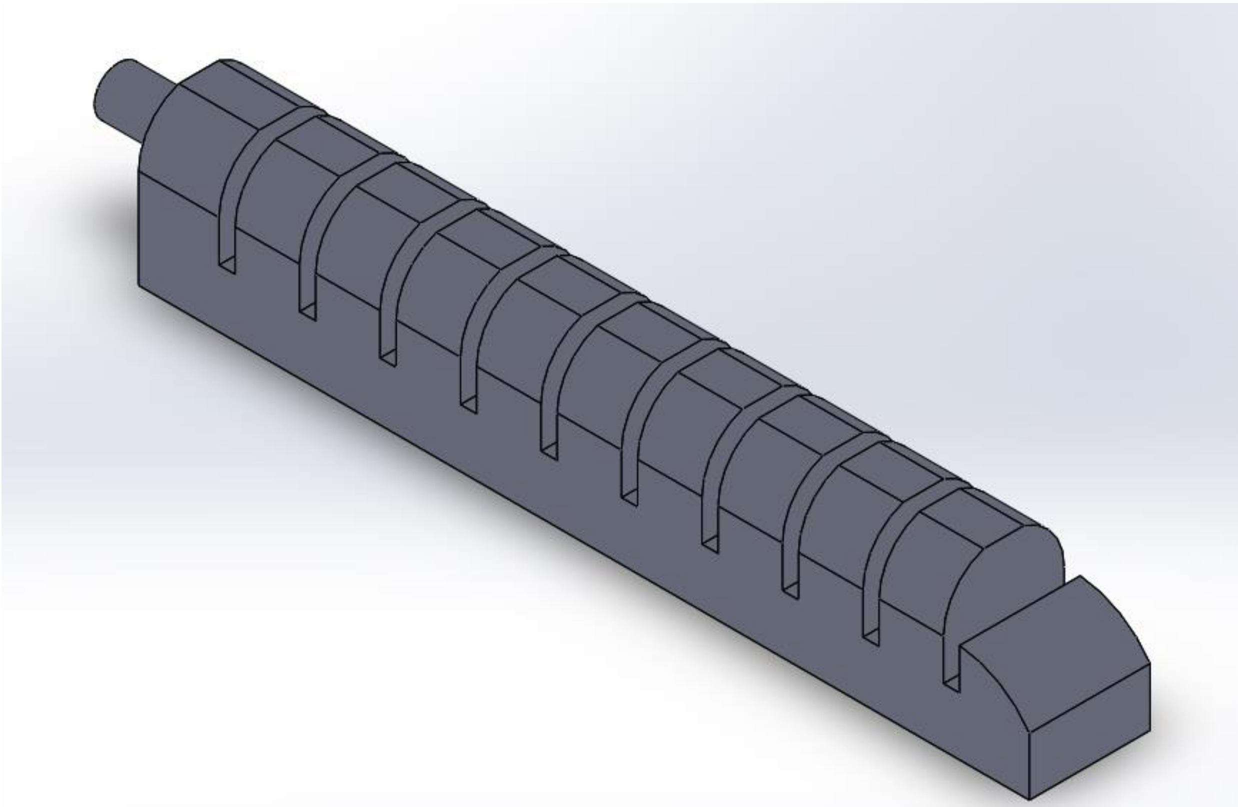
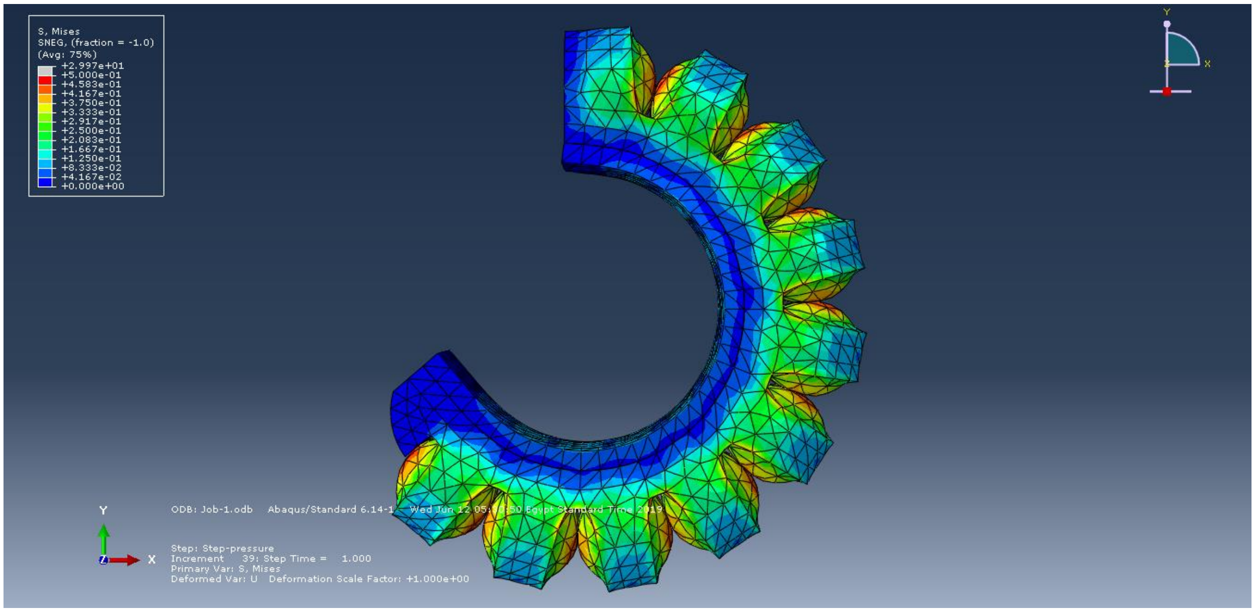


Figure 26 half rounded design 2 isometric

4.3.3 Gripper simulation

Using the finite element analyses (FEA) to check the stress on the actuator when the pressure is applied the following results were obtained



As shown in the simulation, the design is safe and does not exploded, also the banging radius is quit acceptable so we have to start with the fabrication process.

Chapter 5 Fabrication and control system

5.1 Fabrication process

The fabrication process will be conducted on the final design which is the half rounded with 11 chambers as its simulation results was acceptable. The first step in the fabrication process to make the mold for the designed actuator.

5.1.1 Mold design

According to what stated in the experimental work chapter, we take into consecration the recommendation regarding the mold design.

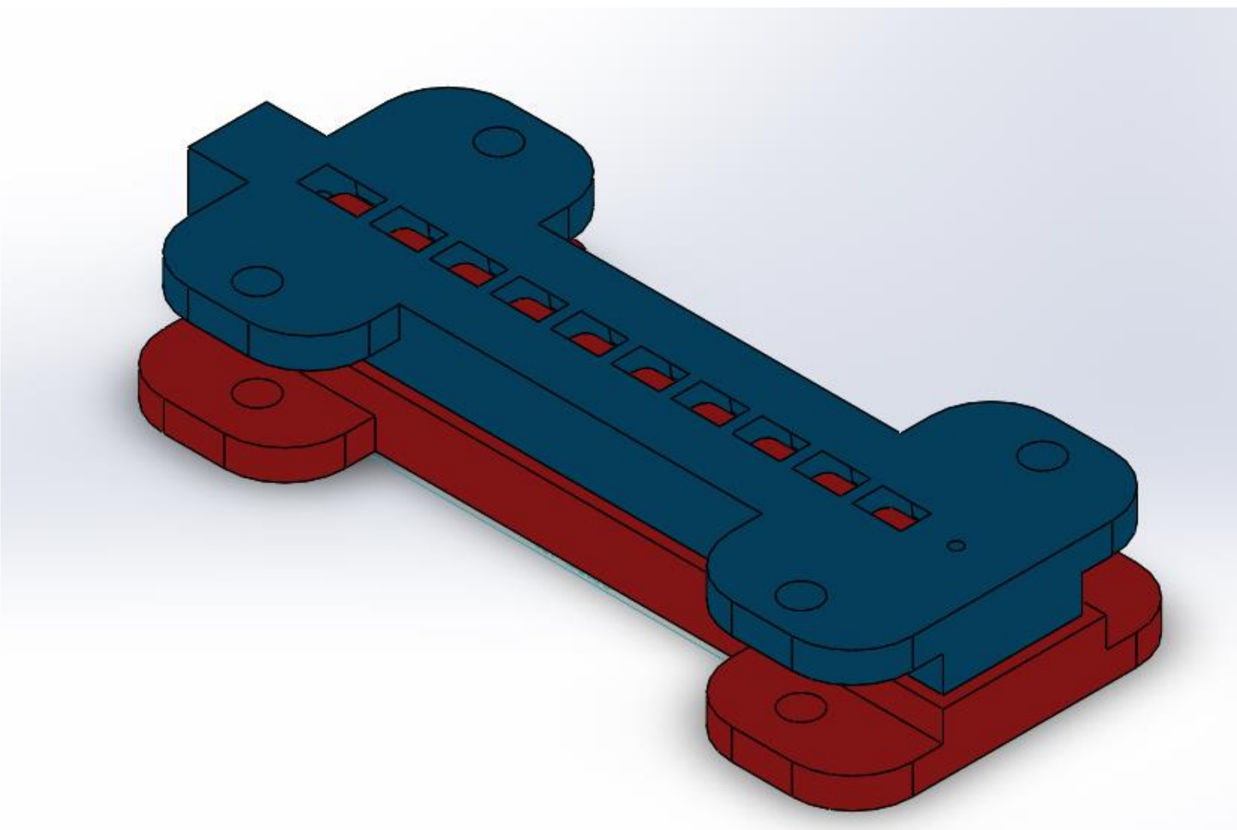


Figure 27 mold for the half rounded cross-section

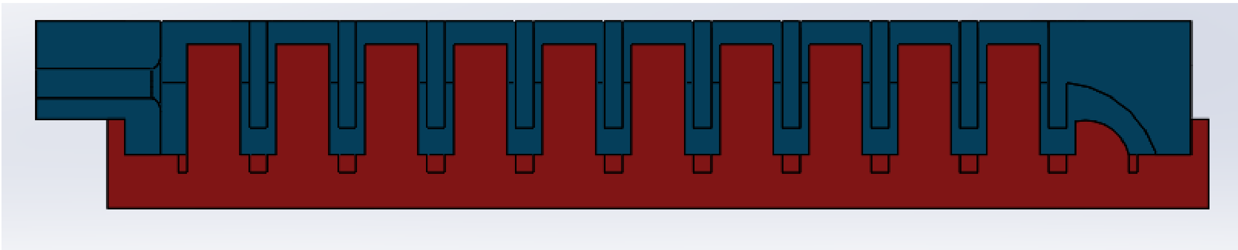


Figure 28 mold cross-section

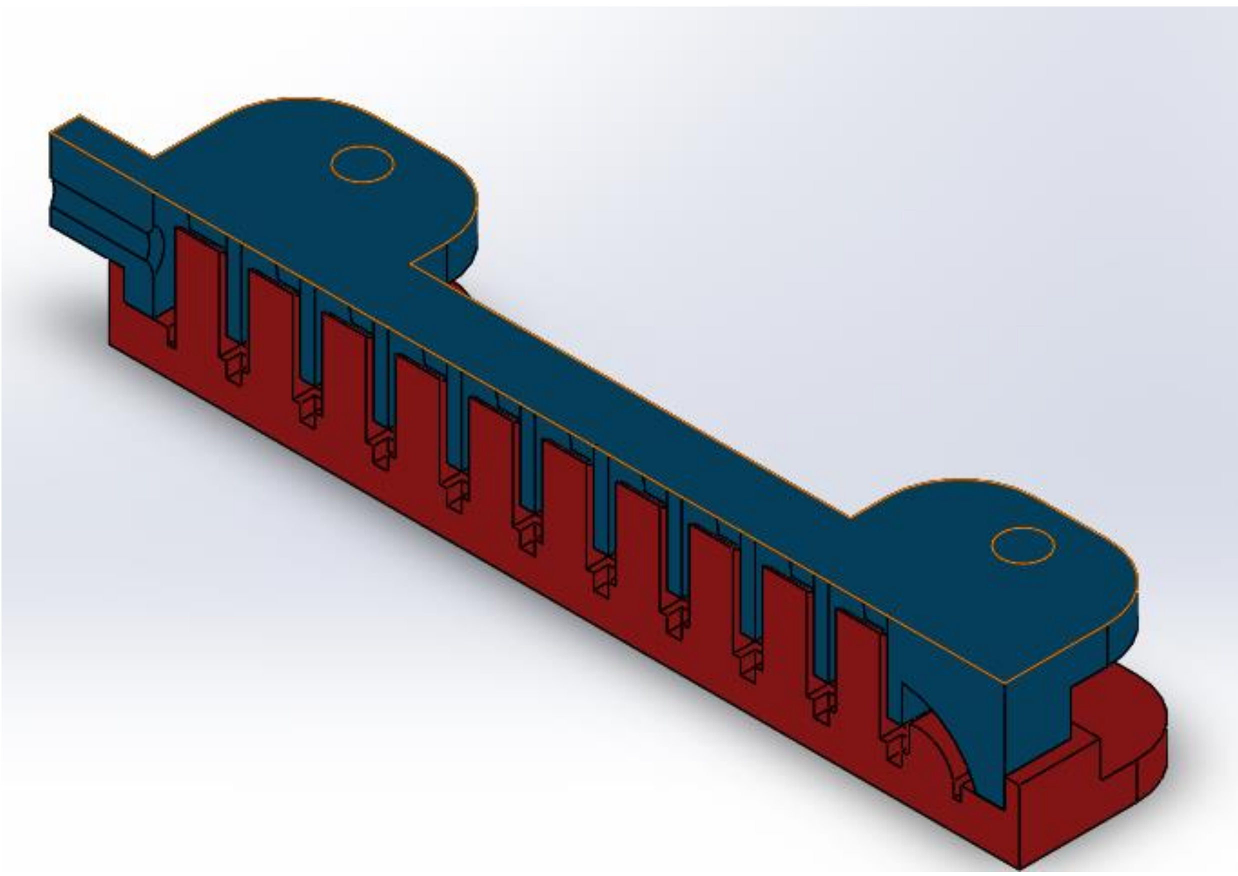


Figure 29mold section view

As shown the modification done in the mold is that we increase the cavity supply and attach air tubing location in the mold. Also the base mold was improved by making vents acts like anti slip layer.

5.1.2 Casting

After the mold is fabricated we will strain in the actuator fabrication by casting Martials into the new mold.

By following fabrication steps stated in the fabrication chapter the actuator is casted.

The casted parts are shown in the following pictures:-

Figure 30defected casted part

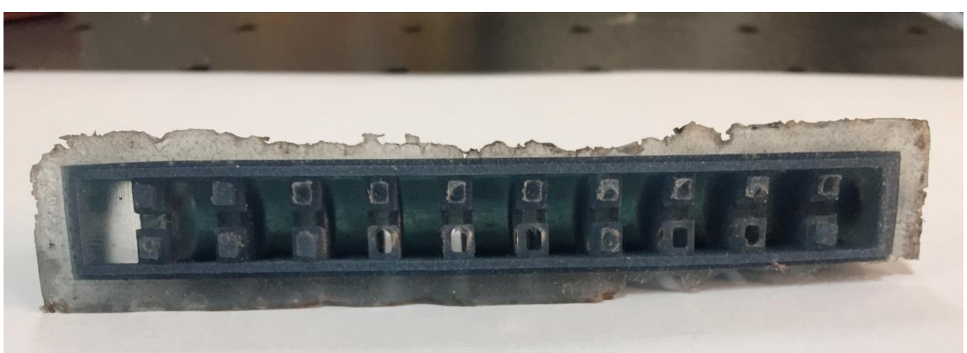


Figure 31defected casted actuator bottom view

As shown there was some defects in the casted parts as we use the centrifugal mixer and did not cool the container, accordingly the material cured before it fills all the mold cavity creating air bubbles.

As a modification process of casting technique it is require either to use a refrigerator with the centrifugal mixer, or to not use the centrifugal mixer as we do not have a refrigerator in the laboratory. According to that we will mix the material manually then make the degassing process then all fabrication process stated in the fabrication chapter remain the same.

After that modification the following casting result were obtained.

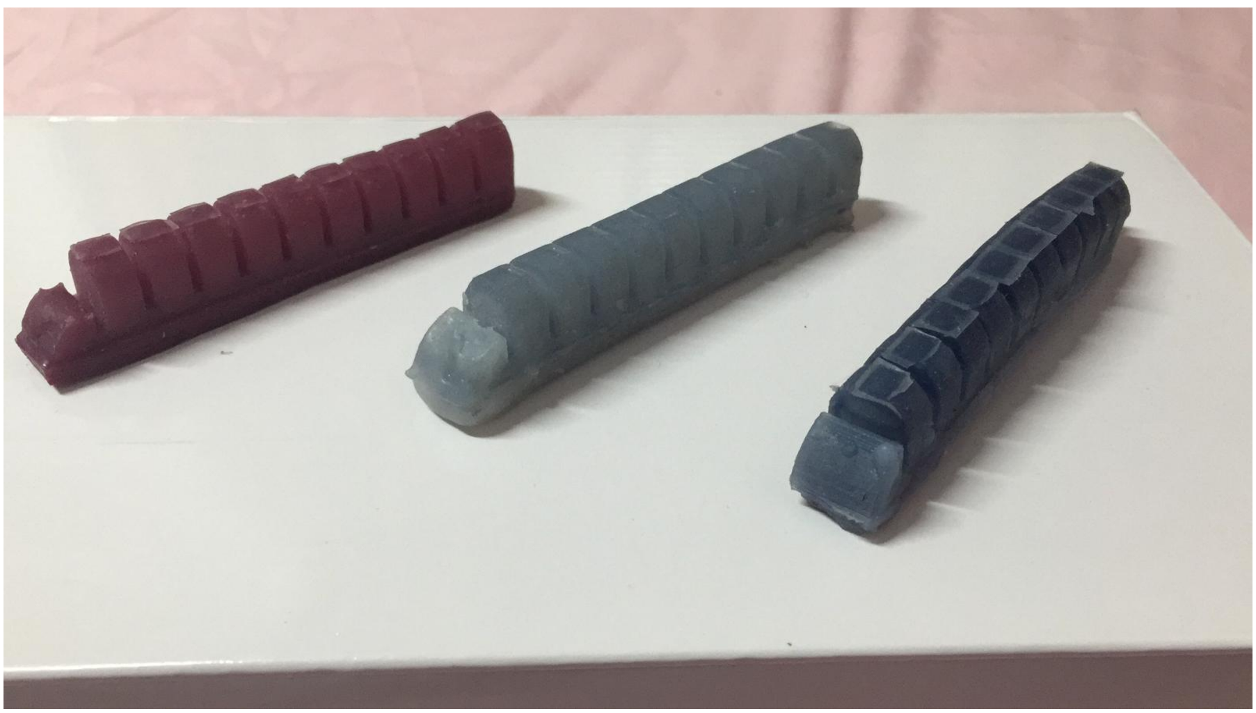


Figure 32modified casted actuators

In the base part we will attach the strain limiting layer as fabric paper and as starch sensor.

After some trails we found that if we will attach a stretch sensor to the actuator we do not have to put the fabric paper as the sensor stiffness is much higher than the dragon skin material.

The assembled actuator with the sensors is shown in the following figures.

Figure 33casted actuator base with the sensor attached

5.2 Gripper fabrication

The concept design of the gripper is consist of three actuators with a cam to change the distance between the actuator smoothly while operating in order to grip various objects with different shapes. Also it is important to prevent object from slipping by increasing the number of degrees of freedom. The concept design is shown in Figure 36

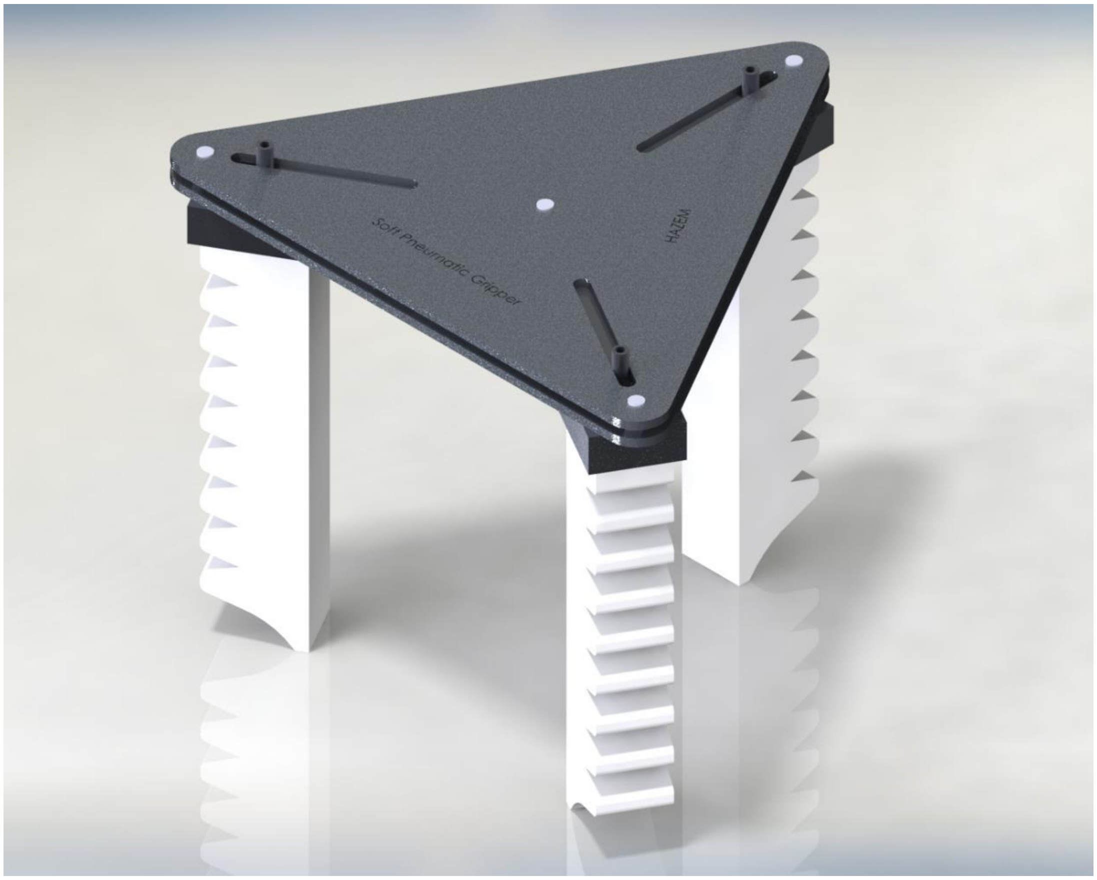


Figure 34 concept design for the gripper

5.2.2 Cam design

The chosen cam type is “Cycloidal Cam” because it has best dynamic characteristics with low vibration, noise and shock impact. The cam profile is shown in Figure 37

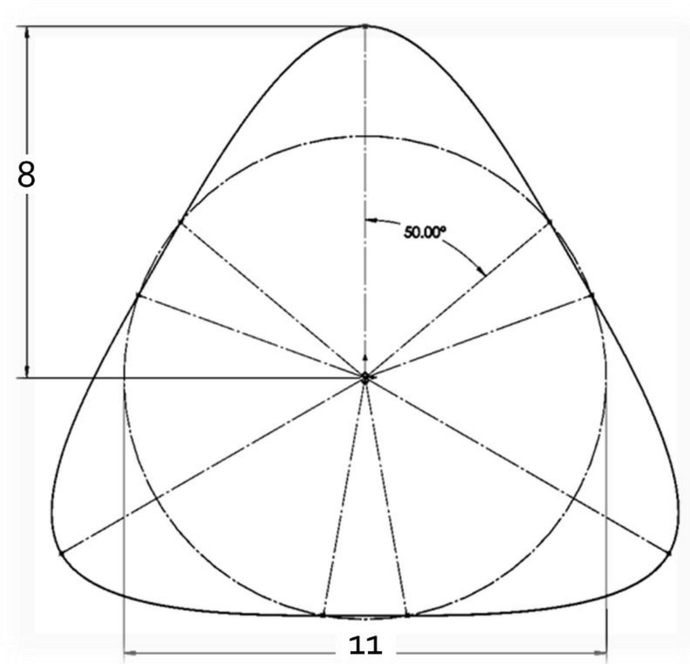
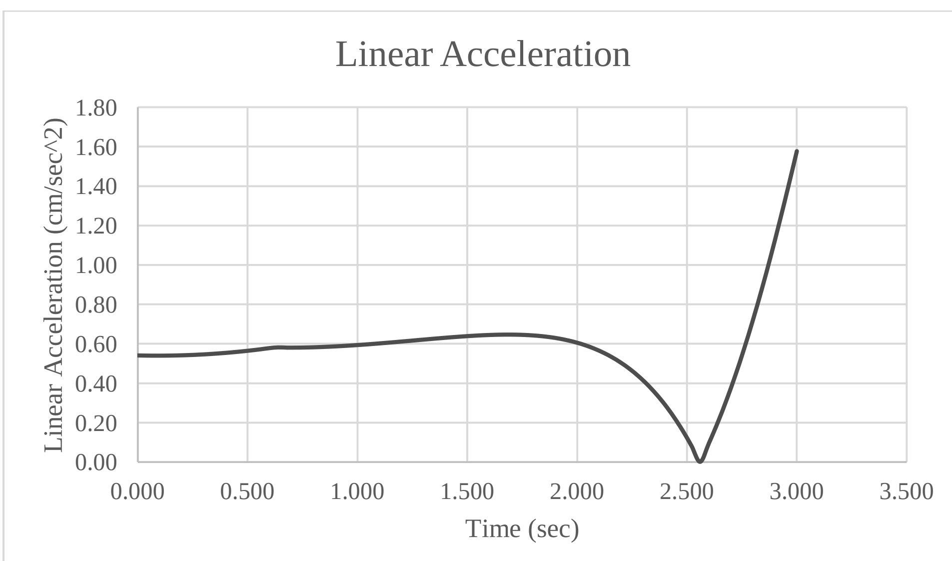
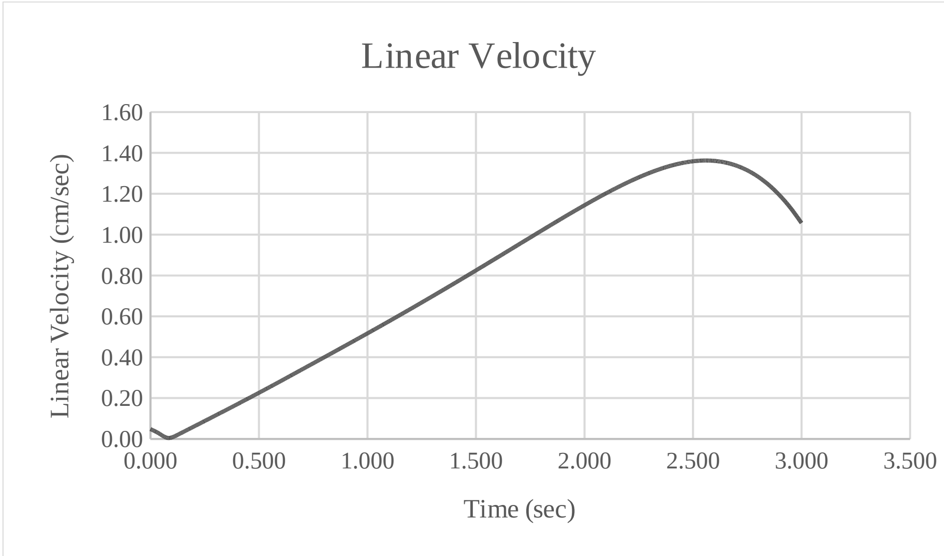


Figure 35 Cam profile

Using "Solid works" analysis to get the cam characteristics the flowing results were developed.





5.2.2 Fabrication

After the design is finished all component are checked, we fabricate the gripper using 3d printing. The printing material is PLA with infill of 30 %. The fabricated gripper is shown in the following pictures.

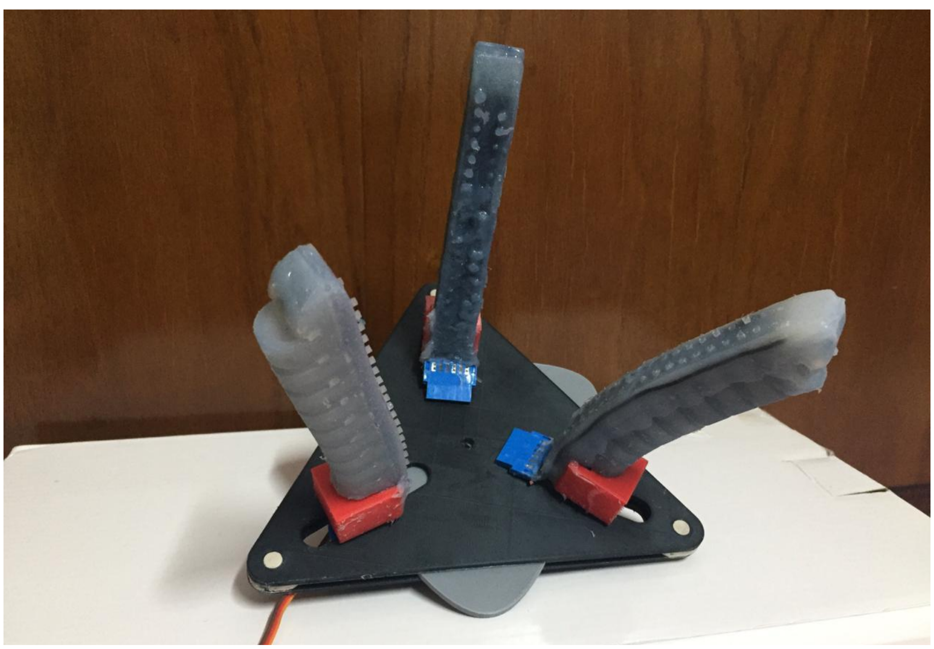


Figure 36 gripper assembly

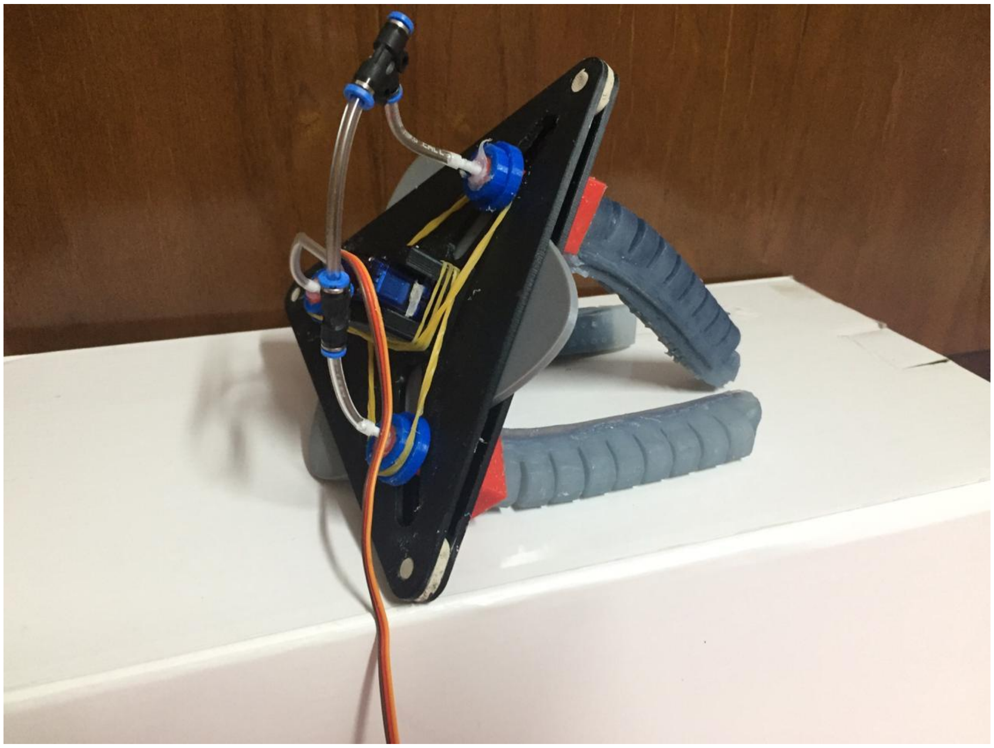


Figure 37gripper assembly another view

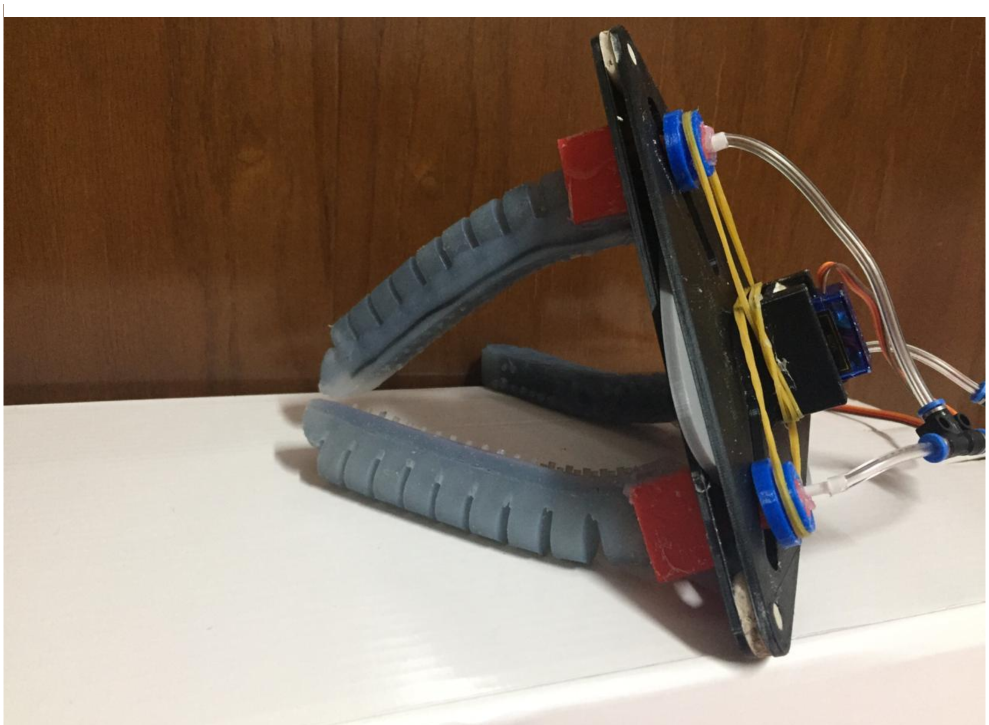


Figure 38 gripper assembly 2

5.3 Control system

5.3.2 Fluidic control board

According to what mentioned above and the attached sensors, it is required to integrate a control system that help the actuator to inflate probably, does not slip the gripped object while moment, and to not squeeze the object being gripped to fulfil the concept of soft robotics implementation. The control system is mainly divided into two main systems, firstly the test board where we can test the actuator to find any leakage, and check it's bending radios. On the other hand, the second one is that the main control board that will be integrated with the gripper with the attached sensors and support all features.

The explanation of the both control methods will be expressed in the following section.

- **Open-source control board**

  the testing board is an open source control board from "soft robotic toolkit", this board helps to quickly test the behaviour of pneumatic soft robots, also it can be used for advanced control such as adjusting the PID of inflation process and attach any external sensor and implement it to the board.

This board consist of many electric components such as air pump the supply the actuator cavity with pressurized air, solenoid valves that activate and deactivate the flow of air in the system. Also it have a set of pressure regulator system which work by the "pulse width modulation " technique in order to control the solenoid vales, in addition to that, pressure sensor is integrated in the board to monitor the actuator pressure and give feedback in order to make a closed loop control system. As the main brain of this board is Adriano micro-controller it can be run manually using the attached potentiometers and switches, or run autonomous with simple Adriano code.

The wiring diagram for this control board is quite important to be known as if we need to attach or remove sensor or electric components for advanced control level. As we mentioned above this is an open source control unit it is simply mapped to be categorized by each set of components. The main category is the board power which is mainly two power regulators one to supply logic controller with 5 volt dc current and to supply the pump and the fluid control valves with 12 volt dc current. The other categories such as pressure controller sensors are to be connected with the logic board and powered from the 12 volt terminal. Also it has some potentiometers to control the

Figure 39fluidic control board components location

speed and pressure of the air in the output, the potentiometers is to be connected to the Adriano analog pins as it give wide range of values.

It is highly recommended to check the connections of before connect the power to the board using the wiring diagram and any multi meter devise in order to avoid short circuit which can damage the whole board.

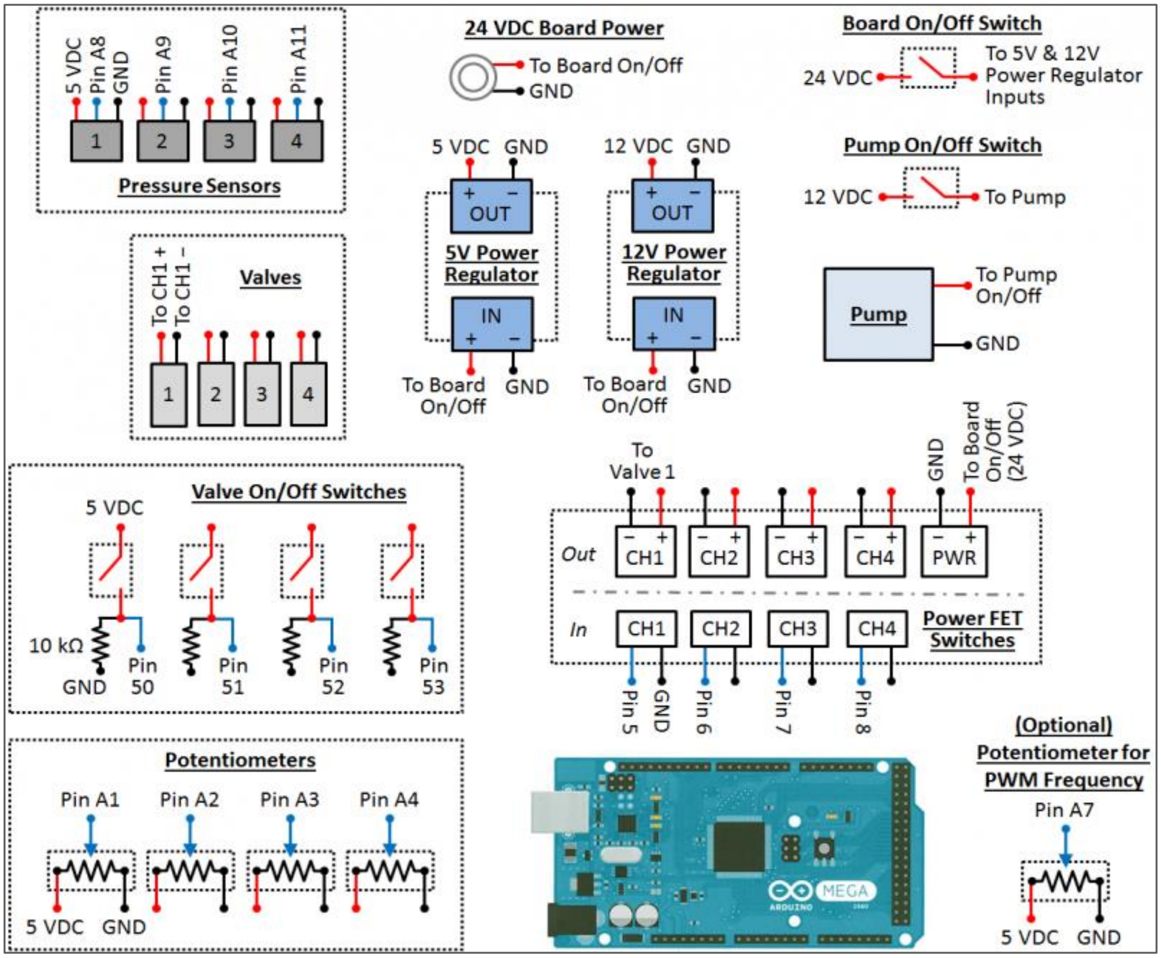


Figure 40 fluidic control board wiring diagram

How the fluid control board manually operated.

1. Plugin the power supply.
2. Switch on the control board using the On/Off button and check that the power regulator screen shows that the output volt is 5 volt for the controller and 12 volt for the pump.

3. Activate the control valves by turning the potentiometers until it click and the red LED is flashing.
4. Open the air pump form the switch in the power section.
5. Use USB cable to connect Adriano to the computer in order to get the sensors data on the serial monitor directly.

5.3.2 Special control board

In order to make the gripper with its own control system we will fabricate as special control system using Adriano micro controller and by attaching some electric components and sensors it will used to control the gripper by controlling each actuator separately. This concept will help to increase the controlling efficiency and reduce slipping and error happened. Also as it have a closed loop control it will have a very high response to the actuator movement.

List of components:

The following component are the components needed in order to build up the whole control system.

Table 6 control sytem component

S/N	Component	Quantity
1	Adriano Nano microcontroller	1
2	Relay	4
3	Stretch sensor	2
4	Sensor controller	1
5	solenoid valves	3
6	Switches	2
7	Pressure sensor	3
8	Power supply	1
9	Voltage regulator	1

Stretch sensor

In order to make a closed loop gripper control system with sensor feedback to insure that the gripper will not slip the object and to reduce power consumption of air and electric, also to reduce the harm of the gripper to be exploded due to over compression, a sensor must be implemented inside the gripper.

Most of available sensors in the market are either rigid sensors or very small flex sensors, while the pneumatic actuator require that the sensor to cover all the actuator base area to give a correct reading and complete exhibit to what it is gripped.

Stretch sensors are special type of sensors made out of flexible, stretchy material in order to measure strain, bending, shear and force applied by soft structure like soft robotic actuator.

The commercially available sensor has been developed by New Zealand Company called (StretchSense). This type of sensors can be considered as flexible capacitors because it changes its value as it is stretched or squeezed and accordingly these value can be assigned to control process to control the gripper.

The sensor is made out of layers of signal and ground electrodes separated by dielectric silicon insulator as shown in the figure

based on the actuation techniques of soft gripper actuator which is to stretching parallel to one axis only, therefore ,there will be only two parameters will be changed in the sensor while actuating the actuator which are the conductive layer area and thickness, as a result of that the capacitance value increased.

As sated above the StretchSense sensor is a capacitive sensor, and measuring the capacitance is indirect process done by comparing the applied volt and actual output volt on the sensor using micro controller or a multi meter device. The type of measuring instrument used can directly affect the whole gripper control process, in order to choose the compatible measuring instrument and its working method with the sensor the sensor specification have to be studied.

In order to have a good control system there are some characteristics of the sensor will be attached to the actuator must be taken into consideration and its effect on the control quality, such as accuracy, sensitivity, repeatability , noise and non-linearity.

According to (Irish, 2005) Sensor accuracy can be defined as at which level the sensor can measure the required data in an absolute sense. While he define the repeatability as the ability of the sensor to repeat the measurement when it is putted back in the same conditions. On the other hand, sensitivity is the minimum absolute change the senor can detect and it is affected directly by the noise in the sensor which is an electromagnetic energy produced at very high frequency and low power voltage devices, the noise in the sensor directly proportional by increasing connection wires length. In order to reduce the sensor noise there are stranded method have to be followed, which are:-

1. Use shielded cables and ground it.
2. Avoid ground loops (make one ground connection to all connected sensors).
3. Put the wires fare away from the interference source.
4. Implement twisted pairs of sensor wires.

Sensor non-linearity is defined as the variance of sensor output data from the best fit straight line. And it is defined by percentage of the output range.

StretchSense provide the flowing characteristic of their silicon based stretch sensor as follow:-

Table 7 strech sensor property

Extension	62 mm
Capacitance when it is not stretched	350 pf
Capacitance when stretched	560 pF
Sensitivity	3.38 pF/mm
Load when maximum stretch	6.472 N
Operating temperature	From 10 to 30 degree Celsius

The Adriano code for the stretch sensor is stated in the appendix

Wiring diagram

The circuit schematic is shown in the following figure. The wiring is based on each component data sheet

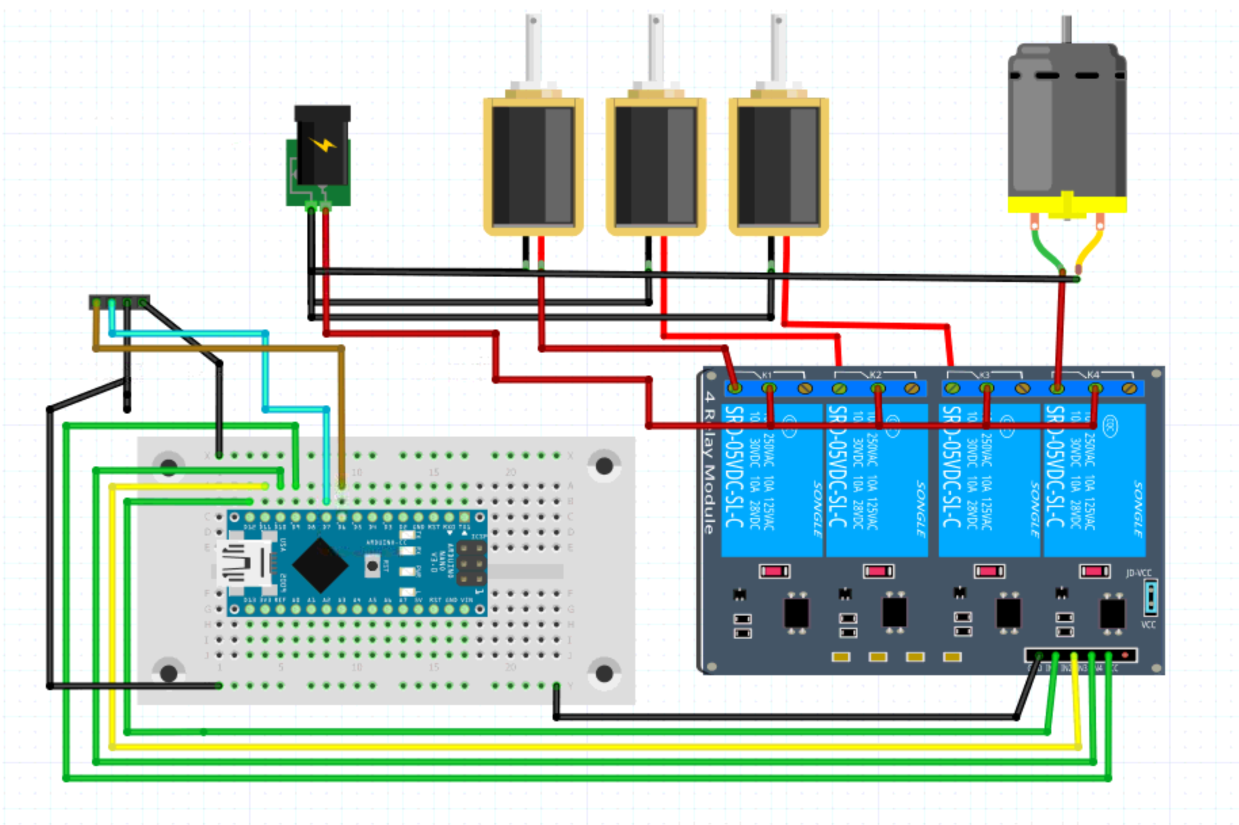


Figure 41 circuit schematic for the control system

Working principle

The working principle of this control unit is quit completed since we attach lots of sensors.

The concept is to activate the three solenoid valves with the pump when the operator push the bottom then the attached sensors will get the values and compare it with previous reading to calculate error. Once the error is too small the solenoid valve is deactivated. The process is done also for the other two actuator. Beside that the senor still working in order to track the slipping, it detect slipping if the sensor error decrease, at this time the actuator which have the slipping detected will activate its solenoid valve will activated to let air pump to supply it with pressurised air. The process is an iterative process until the user deactivate it using the unlading putt on or with the emergency bottom which will kill the whole process if any danger happened. The flow chart of the control system is provided in the following picture.

Chapter 6 Results obtained

According to the objectives listed in this research we have successfully achieve the following:

- Produce working strategy to deal with the silicon rubber material for soft robotics fabrication.
- Investigating diffract designs for the actuator based on simulation and mold design.
- Based on the fabrication, and simulation process we eliminate differ actuator design until we reach the design will fitful the requirement.
- Many modification was made in the actuator design, like attaching sensors and a fully control system
- The design concept was chosen for a gripper that can carry different shapes, weight and size object and place it in another location.
- A practical test was conducted on the actuator to check the design and proof that it can carry the design load and can deal with different object structure.
- The gripped object us shown in the figures (44,45,46)

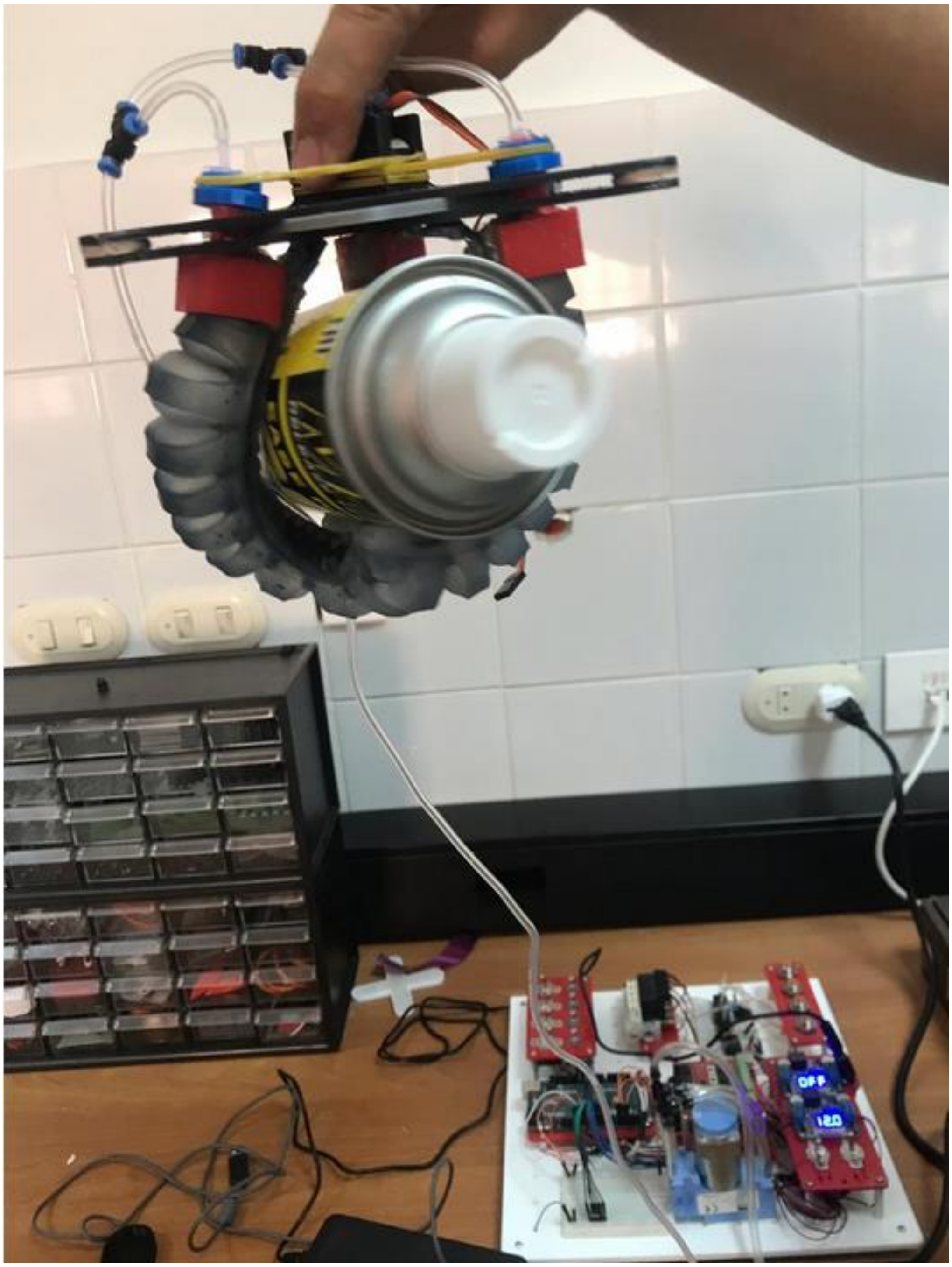


Figure 42 gripper carrying a cylindrical heavy object

Figure 43 actuator gripping a cubic object

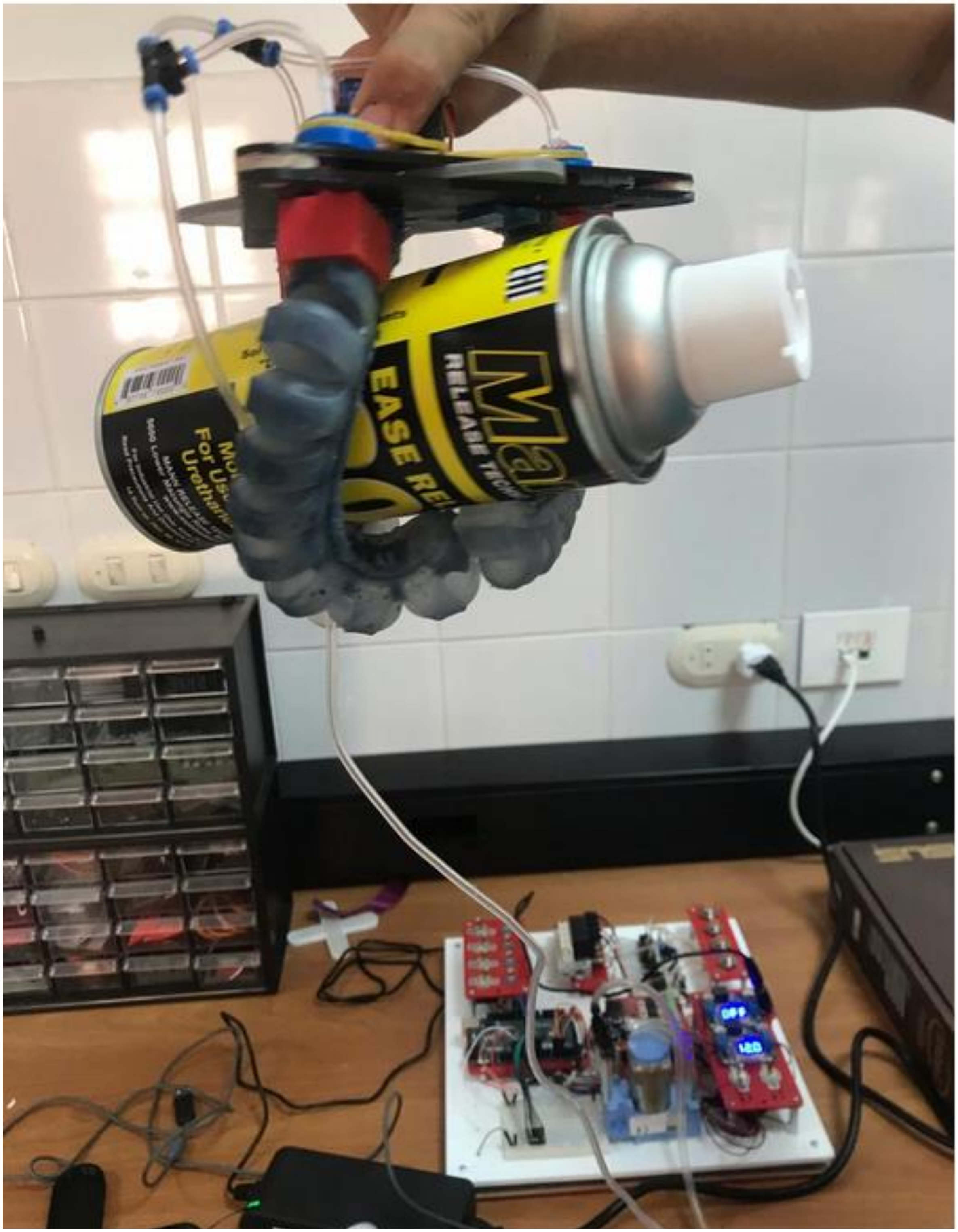


Figure 44 gripper carrying a cylindrical heavy object with different configuration

Chapter 7 Future development

In order to enhance the gripper to get better quality and better control. In the design process before fabrication the gripper itself need to be simulated from load it can carry point of view. This type of simulation is done using a special program called SOFA. This program can be produced using python script. Due to limitation in python programing language and the uses of this program we did not make tis simulation. The concept of this simulation program is to write python code to define the gripper geometry with all attached fingers, also it will define the load and environment. In addition to that the object being gripped being define with its geometry and shape.

There are some material modification can be done like use the silicon rubber that is used to fabricate the mold for casting process. This will decrease the gripper cost and due to its availability in Egypt. In order to that we have to check if the criteria we follow in mold design will work with the new material or not. The final modification process is to attach the fabricated gripper to the industrial control arm and merge the control system to proof that it will do its function.

Chapter 8 Conclusion

To conclude, this research aims to investigate the using of the soft robotics in the process of loading and unloading applications. This technology will take place in the factories as a replacement for the hard grippers which attached to the robot arm. The design concept for the investigated gripper is to use soft gripper to deal with the soft and sensitive objects that may damage with the old hard gripper. In addition to the simple control system which doesn't need per setup for the gripped part. Implementing soft grippers made the gripping process to occur at any position which make the product handling more practical. The theses of this research are based on the half-rounded cross section design. This design is been choosing according to the simulation and many elimination process in order to fulfil the requirement of selected application. Many experiments were done to test different configurations on the actuator also, to obtain a successful casting technique for the material we use which is dragon skin 20, this material s special type of platinum base silicon rubber used for such applications. The investigated gripper consists of 3 actuators and each actuator consists of 8 champers. The actuation process is done by using compressor with 30 Kpa pressure to inflate the actuator chambers for the gripping process. According to the iterations done during the design process, it is possible to carry out an object with load of 1 kilogram also, the gripped object can be with any shape and with any skin. In addition to that the gripper could be attached to the industrial robotic arm to replace the old rigid gripper to save the gripped product in material handling process. As future enhancement for the soft gripper, neural network will be attach to the control system to develop its controlling speed and to minimize the slipping by using high speed camera. This camera is used also to determine the object size before holding to prepare the gripper quickly to minimize the grasping time because it will affect the mass production for the industrial application.

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Appendix

Adriano code for the fluidic control board

```
int prescaler = 256; // set this to match whatever prescaler value you set in
CS registers below

// intialize values for the PWM duty cycle set by pots
float potDC1 = 0;
float potDC2 = 0;
float potDC3 = 0;
float potDC4 = 0;

void setup() {

  Serial.begin(9600);

  // input pins for valve switches
  pinMode(50, INPUT);
  pinMode(51, INPUT);
  pinMode(52, INPUT);
  pinMode(53, INPUT);

  // output pins for valve PWM
  pinMode(5, OUTPUT);
  pinMode(6, OUTPUT);
  pinMode(7, OUTPUT);
  pinMode(8, OUTPUT);

  int eightOnes = 255;  // this is 11111111 in binary
  TCCR3A &= ~eightOnes;   // this operation (AND plus NOT), set the eight
bits in TCCR registers to 0
  TCCR3B &= ~eightOnes;
  TCCR4A &= ~eightOnes;
  TCCR4B &= ~eightOnes;

  // set waveform generation to frequency and phase correct, non-inverting
PWM output
  TCCR3A = _BV(COM3A1);
  TCCR3B = _BV(WGM33) | _BV(CS32);

  TCCR4A = _BV(COM4A1) | _BV(COM4B1) | _BV(COM4C1);
  TCCR4B = _BV(WGM43) | _BV(CS42);
}

void pPWM(float pwmfreq, float pwmDC1, float pwmDC2, float pwmDC3, float
pwmDC4) {

  // set PWM frequency by adjusting ICR (top of triangle waveform)
  ICR3 = F_CPU / (prescaler * pwmfreq * 2);
  ICR4 = F_CPU / (prescaler * pwmfreq * 2);
```

```
  // set duty cycles
  OCR3A = (ICR4) * (pwmDC1 * 0.01);
  OCR4A = (ICR4) * (pwmDC2 * 0.01);
  OCR4B = (ICR4) * (pwmDC3 * 0.01);
  OCR4C = (ICR4) * (pwmDC4 * 0.01);
}

void loop() {

  potDC1 = 0; potDC2 = 0; potDC3 = 0; potDC4 = 0;

  // if statement for manual switch override
  if (digitalRead(50) == LOW) {
  potDC1 = analogRead(A1)*100.0/1024.0; // scale values from pot to 0 to 100,
which gets used for duty cycle percentage
  }

  if (digitalRead(51) == LOW) { potDC2 = analogRead(A2)*100.0/1024.0; }
  if (digitalRead(52) == LOW) { potDC3 = analogRead(A3)*100.0/1024.0; }
  if (digitalRead(53) == LOW) { potDC4 = analogRead(A4)*100.0/1024.0; }

  float potPWMfq = analogRead(A7)*100.0/1024.0; // scale values from pot to 0
to 100, which gets used for frequency (Hz)
  potPWMfq = round(potPWMfq/5)*5+1; //1 to 91 Hz in increments of 5 (rounding
helps to deal with noisy pot)

  // update PWM output based on the above values from pots
  pPWM(potPWMfq,potDC1,potDC2,potDC3,potDC4);

  // transfer function for sensor Honeywell ASDXRRX100PGAA5 (100 psi, 5V, A-
calibration)
  // Vout = 0.8*Vsupply/(Pmax - Pmin)*(Papplied - Pmin) + 0.1*Vsupply
  // Rearrange to get: Papplied = (Vout/Vsupply - 0.1)*(Pmax - Pmin)/0.8 +
Pmin;

  // read output voltages from sensors and convert to pressure reading in PSI
  float P1 = (analogRead(A8)/1024.0 - 0.1)*100.0/0.8;
  float P2 = (analogRead(A9)/1024.0 - 0.1)*100.0/0.8;
  float P3 = (analogRead(A10)/1024.0 - 0.1)*100.0/0.8;
  float P4 = (analogRead(A11)/1024.0 - 0.1)*100.0/0.8;

  // print pressure readings
  Serial.print(P1); Serial.print("\t");
  Serial.print(P2); Serial.print("\t");
  Serial.print(P3); Serial.print("\t");
  Serial.print(P4); Serial.print("\n");

  delay(200);
}
```

Arduino code of the starch sensor

```
/*
 This project was developed and tested with the Arduino/Genuino 101

 Circuit:
 16FGV1.0 sensor attached to pins 6, 7, 10 - 13:
 INTERUPT : pin 6
 NSS      : pin 7
 MOSI     : pin 11
 MISO     : pin 12
 SCK      : pin 13
 About:
 This is a demostration for how to stream data from a StretchSense 16FGV1.0
circuit in continuous mode.
 The SPI data from the StretchSense board is read in through the
Arduino/Genuino 101 circuit and then relayed
 back to a PC via the USB/Serial port.
 Note:
 Due to the relatively slow data rates available over the USB/serial comms it
will mean that the highest data rates will be limited.

 created 06 July 2016
 by Alan Deacon
 */

// the StretchSense circuit [16FGV1.0] communicates using SPI
#include <SPI.h>

// pins used for the connection with the sensor
// the other you need are controlled by the SPI library):
const int InterruptPin   =    6;
const int chipSelectPin  =    7;

// ---- DEFINITIONS ----//

// Data package options
#define DATA    0x00  // 16FGV1.0 data packet
#define CONFIG  0x01  // 16FGV1.0 configuration command

// ODR - Output Data Rate
#define RATE_OFF             0x00
#define RATE_25HZ            0x01
#define RATE_50HZ            0x02
#define RATE_100HZ           0x03
#define RATE_166HZ           0x04
#define RATE_200HZ           0x05
#define RATE_250HZ           0x06
#define RATE_500HZ           0x07
#define RATE_1kHZ            0x08

// INT - Interrupt Mode
#define INTERRUPT_DISABLED    0x00
```

```
#define INTERRUPT_ENABLED     0x01

// TRG - Trigger Mode
#define TRIGGER_DISABLED     0x00
#define TRIGGER_ENABLED      0x01

// FILTER - Filter Mode
#define FILTER_1PT           0x01
#define FILTER_2PT           0x02
#define FILTER_4PT           0x04
#define FILTER_8PT           0x08
#define FILTER_16PT          0x10
#define FILTER_32PT          0x20
#define FILTER_64PT          0x40
#define FILTER_128PT         0x80
#define FILTER_255PT         0xFF

// RES - Resolution Mode
#define RESOLUTION_1pF       0x00
#define RESOLUTION_100fF     0x01
#define RESOLUTION_10fF      0x02
#define RESOLUTION_1fF       0x03

// Config Transfer
#define PADDING              0x00

// Configuration Setup
// MODIFY THESE PARAMETERS TO CHANGE CIRCUIT FUNCTION
int    ODR_MODE        =      RATE_100HZ;
int    INTERRUPT_MODE   =     INTERRUPT_DISABLED;
int    TRIGGER_MODE    =      TRIGGER_DISABLED;
int    FILTER_MODE     =      FILTER_16PT;
int    RESOLUTION_MODE =      RESOLUTION_10fF;

//SPI Configuration
SPISettings SPI_settings(2000000, MSBFIRST, SPI_MODE1);

//Default scaling factor
int    CapacitanceScalingFactor = 100; //Default value
int    RawData[20];

///////////////////////////////////////////////////////////////
//   void loop()
//
//   @breif:
//   @params:
///////////////////////////////////////////////////////////////
void setup() {
  Serial.begin(921600);

  //Initialise SPI port
  SPI.begin();
  SPI.beginTransaction(SPI_settings);
```

```
  // Initalize the  data ready and chip select pins:
  pinMode(InterruptPin, INPUT);
  pinMode(chipSelectPin, OUTPUT);

  //Configure 16FGV1.0:
  writeConfiguration();
  //Get capacitance scaling factor
  CapacitanceScalingFactor = getCapacitanceScalingFactor(RESOLUTION_MODE);

  // give the circuit time to set up:
  delay(0.1);
}


/////////////////////////////////////////////////////////////////
//  void loop()
//
//  @breif:
//  @params:
/////////////////////////////////////////////////////////////////

void loop() {

  float capacitance =0;

  //Check if interrupt mode is enabled (in configuration)
  if(INTERRUPT_MODE == INTERRUPT_ENABLED){
    // don't do anything until the interupt pin goes low:
    while (digitalRead(InterruptPin) == HIGH);
  }

  //Read the sensor Data
  readCapacitance(RawData);

  // convert the raw data to capacitance:
  for (int i=0; i<10; i++){

    capacitance = extractCapacitance(RawData,i);
    Serial.print(capacitance);  //Output capacitance values
    Serial.print(',');          //Output data as comma seperated values

  }
 Serial.print('\n');

  //Wait for next data packet to start sampling
   if(INTERRUPT_MODE == INTERRUPT_ENABLED){
      while (digitalRead(InterruptPin) == LOW);
   }
}

/////////////////////////////////////////////////////////////////
//  void writeConfiguration()
//
//  @breif:
```

```
//  @params:
////////////////////////////////////////////////////////////////
void writeConfiguration() {

  // 16FGV1.0 requires a configuration package to start streaming data

  // Set the chip select low to select the device:
  digitalWrite(chipSelectPin, LOW);

  SPI.transfer(CONFIG);                 //  Select Config Package
  SPI.transfer(ODR_MODE);               //  Set output data rate
  SPI.transfer(INTERRUPT_MODE);         //  Set interrupt mode
  SPI.transfer(TRIGGER_MODE);           //  Set trigger mode
  SPI.transfer(FILTER_MODE);            //  Set filter
  SPI.transfer(RESOLUTION_MODE);        //  Set Resolution
  for (int i=0;i<16;i++){
    SPI.transfer(PADDING);              //  Pad out the remaining
configuration package
  }

  // take the chip select high to de-select:
  digitalWrite(chipSelectPin, HIGH);
}



////////////////////////////////////////////////////////////////
//  void readCapacitance(int raw[])
//
//  @breif:
//  @params: int raw[] - Raw sensing data from 16FGV1.0
////////////////////////////////////////////////////////////////
void readCapacitance(int raw[]) {

  // 16FGV1.0 transmits data in the form of 10, 16bit capacitance values

  // Set the chip select low to select the device:
  digitalWrite(chipSelectPin, LOW);

  SPI.transfer(DATA);                   //  Select Data Package
  SPI.transfer(PADDING);                //  Get Sequence Number
  for (int i=0;i<20;i++){
    raw[i] =  SPI.transfer(PADDING);    //  Pad out the remaining
configuration package
  }

  // take the chip select high to de-select:
  digitalWrite(chipSelectPin, HIGH);

}


////////////////////////////////////////////////////////////////
//  void setCapacitanceScalingFactor(int Resolution)
```

```
//
//  @breif: The 16FGV1.0 has an adjustable LSB resolution this function
scales raw data to capacitance based on
//  configuration settings.
//
//  @params: int Resolution_Config
////////////////////////////////////////////////////////////////
int getCapacitanceScalingFactor (int Resolution_Config)
{

  switch(Resolution_Config){
    case (RESOLUTION_1pF):
      return 1;
    break;

    case (RESOLUTION_100fF):
      return 10;
    break;

    case (RESOLUTION_10fF):
      return 100;
    break;

    case (RESOLUTION_1fF):
      return 1000;
    break;

  }
  return 1;

}

////////////////////////////////////////////////////////////////
//  float extractCapacitance(int[] raw, int channel)
//
//  @breif:
//  @params:
////////////////////////////////////////////////////////////////
float extractCapacitance(int raw[], int channel){

  float Capacitance =0;

  Capacitance = (raw[2*channel])*256+raw[2*channel+1];
  Capacitance /= CapacitanceScalingFactor;

  return Capacitance;

}
```

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