NUST COLLEGE OF ELECTRICAL AND MECHANICAL ENGINEERING

Soft Robotic Gripper for Optimizing Picking & Placing in Food & Fruit Industry

A PROJECT REPORT
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We would also like to express our deepest gratitude of appreciation for our friends and family who have been a source of great inspiration and support throughout our project. Lastly, we hope that this project provides an initiative to add value to peoples live and become a part of future of this technological world.

ABSTRACT

Industrial robots are an integral part of automated processes in the present era. End effector is part of the robot which grasps the object and limits the type and nature of object which can be picked. Food handling can be an impossible task for conventional end effectors as they are unable to adapt to soft, delicate & uneven surfaces. Soft end effectors on the other hand are inspired from nature and offer an alternative solution to grasping of soft delicate objects. They can work in unstructured environments and can handle variety of objects without the need for reprogramming & redesigning if the objects to grasped are changed.

In this project we have developed a soft robotic gripper made of combination of soft end effectors based on a class of hyper elastic materials. For the soft end effector two different designs were made and their analysis and testing were performed. The designs were modeled in Solidworks, and analysis was carried out using ANSYS workbench. After analysis the designs were fabricated then tested and then the soft robotic gripper was assembled. We have also developed the actuation system for passing pressurized air through the end effector. Arduino UNO was utilized for the actuation system.

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CHAPTER 1: INTRODUCTION

1.1 Overview

Human life thrives on fostering creative solutions to the problems posed in the living world. The world in recent decades has had many different innovations and technological advances which have helped to complete tasks efficiently. The task of grasping objects and placing objects has helped a lot in this continuous enigma of innovation. Robots capable of picking rigid and heavy objects from one assembly line to another or in any other process have been used for many years now and they offer effective grasping for rigid & heavy objects found in industries.

End effector is the part of robot which grasps the objects and is the one which limits the type and the nature of objects which can be grasped by the robot. Robots used in manufacturing industry to pick & place objects have end effectors which are designed and programmed to be able to interact within a very structured environment and grasp only the objects they have been specifically designed and programmed for. Such robots cannot be used for objects having soft, delicate, slippery, and uneven surfaces. To grasp the objects having soft, delicate & uneven surfaces we need such end effectors which can effectively adapt to such surfaces without any damage to them.

Conventionally rigid end effectors have been used, they perform effectively for rigid and heavy objects, but they cannot be used for soft, delicate, slippery and objects having uneven surfaces. To counter this problem “Soft End Effectors” or “Soft Actuators” can be used because of their compliant behavior. The Soft End Effectors are made of materials that can adapt to unstructured surfaces and objects having different density and surface rigidity, thus showing compliance. This field of robots having soft end effectors comes under the domain of “Soft Robotics” which is a subdomain of Robotics itself.

1.2 General Background

Whenever someone mentions the word “robot”, the first thing that comes to our minds is that of superficial robots which can be either from a sci-fi movie or real robots from Honda or Sony. Robots are sometimes imagined and sometimes made up of rigid links, mechanical gears, different kinds of motors, sensors, and other heavy metal parts. Robots in the industry has been a success, these robots have worked alongside humans, Robots are extremely accurate and fast in their operations, something which humans often lack. While hard robotics has been successful and has become a part of our lives there are still some limitations accompanied by hard robots. It is quite difficult for a hard robot made up of stiff metal parts to copy the flexible and dexterous motion of human muscles, also their heavy weight brings up a difficulty for them in running, walking, standing and thus makes them less exciting for field explorations.

From L Frank Baum's early conceptions to Karel Apek's coining of the name "robot" and Pollard and Roselund's first industrial robots in the 1930s, robots have been around for almost a century. Manufacturing, medical, cooperative activities, and exploration are among areas where robots are used. Most robots are built according to a few well-defined formulae. Typical definitions are based on well-established mechanical principles inherited from the industrial revolution. While these tactics have helped grow the worldwide robotics industry to more than $100 billion in revenue, there remains a limit to what these machines can accomplish.

Conventional robots are made of mostly stiff materials, which limit their range of motion and practical uses while aiding control and determinism. If a rescue robot made of stiff materials enters a collapsed structure, it will become trapped. Traditional electromagnetic actuation technologies, which are costly and hard to manufacture and hinder scale-down, are used in conventional robots. Toxicology and long-term environmental damage are often overlooked in favor of the urgent work at hand—many robots use materials that are harmful to the environment. As a result of this toxicity, any robot that is released into the environment must be collected and returned for safe recycling or disposal at the end of its useful life. The number of robots that can be released into the environment safely is severely limited as a result of this. Despite an outer element of biomimetics, these restrictions illustrate how conventional robotics operates very differently from the notions that are so deeply rooted in biological beings.

Soft Robotics, on the other hand, has been working to address these issues over the past decade, with important advancements in autonomous robotics, smart skins, soft computation, and energy autonomy.

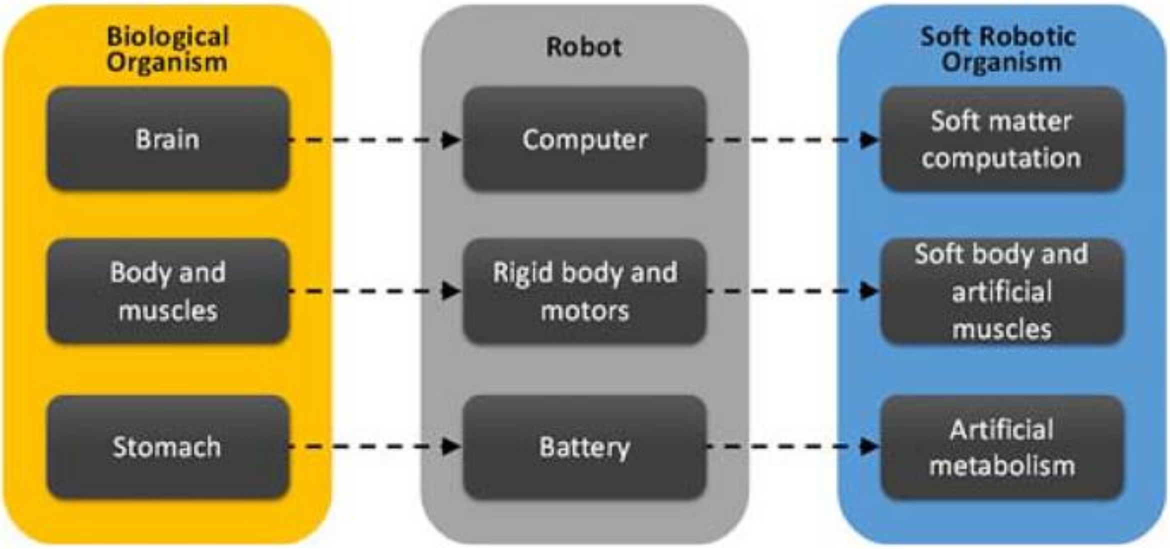

Figure 1. An equivalent Comparison of organisms, robots and soft robots

Soft Robotics is a new and emerging field of robotics, which plans to provide a solution to the problems encountered by hard robots. It plans to do so by making use of intrinsically soft parts, which gives them an edge of being extra lightweight, different motion ranges – even capable of doing human like motion, and with all of that they can be fabricated at a much lower cost as compared to the hard robots. Actuation in these soft robots can be achieved through different ways, be it pneumatics, electrical stimulation, or fluidics. Soft Robotics plans to change the way robotics has worked till now and take the field of robotics to a next step.

Figure 2. Octopus under immense ocean pressure (inspiration of soft robotics)

Bio-inspiration, which has sparked debate in the robotics world for years, is undoubtedly one of the forerunners of soft robotics. Bio-inspired systems, which are supposed to replicate animal or human characteristics, have traditionally been built with rigid-body designs and soft parts. Pioneering work in soft robotics can be found in research projects that suggested to draw inspiration from natural features while also imagining novel ways to manufacture them. In a review dating back from the early period of soft robotics, well emphasized the very close relationships between manufacturing evolutions and the design and fabrication of systems of a totally novel generation. Soft robots are systems built from materials with mechanical properties similar to those of living tissues, designed and manufactured in a very innovative way rather than artificially assembled by serial or parallel arrangements of elementary blocks, as it was the case for rigid-body robots.

Figure 3. Example of bio inspired octopus tentacle.

Compliant geometric designs, in addition to intrinsically soft materials, can enable soft devices from rigid materials. Self-adaptive mechanisms are an example of a compliant geometric design from the beginning.

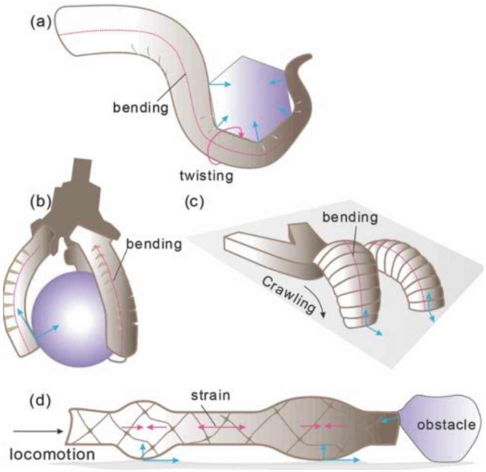

Figure 4.Soft Robots showing various forms of motion

1.3 Problem Statement

In the food industry we have objects poultry/meat and bakery products like buns which are slippery and have uneven surfaces. Similarly, in fruit industry we have some objects like strawberries, tomatoes, plums, apricots which are fragile, soft and have uneven surfaces. Furthermore, each of the object within a certain class (let's say plums) we have different sizes. The products of these industries need to be in market in different packaging sizes, have proper hygiene and the time between making (for fruits, harvesting) the products to the market should be minimum, for the consumers to buy.

So, the fast and careful grasping of such objects and placing them into small packaging size can be done by soft end effectors. Like most things in the world of science and technology soft robotics is inspired from nature and its compliant behavior. Nature is not rigid, yet it achieves it goals in most auspicious manner. The motivation thus inspired, is to design and fabricate a soft robotic gripper that can optimize picking and placing in food handling processes.

1.4 Objectives

The objectives include:

- Design of Soft end effectors
- Simulation & experimental results of soft end effectors
- Fabrication of Soft Robotic Gripper
- Design & implementation of Soft Robotic Gripper

1.5 Intended Audience

The intended audiences for our project include the following:

1. Project Group

   To ensure that they are developing the system according to its required requirements and specifications.

2. Test Persons (Project Group, Supervisor)

   To check the features and functions of the project against its requirements.
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3. Project Supervisors (Dr. Raja Amer Azim)

   To get to know about the various requirements of the system and its design features. Which technologies will be used in the system, what fabrication procedures will be followed and what failures and bugs can happen while its testing.

4. Project Evaluators (DME, CEME, NUST)

   To know the scope of the project and evaluate the project throughout the development for understanding & grading.

1.6 Scope

The Soft Robotic Gripper will be a pneumatically driven system made up of nature inspired soft actuators (end effectors) and will be capable of grasping a range of food and fruits consisting of bakery items, small fruits and meat cuts without any physical and hygienic damage to them. It will be a plug and play system that can be equipped with a manipulator quickly and operate with an actuation system that provides controlled pressurized pressure. It aims to provide solutions for small packaging sizes, filled with clean and hygienic food items.

For	Grasping and placing soft, delicate, uneven surface objects in food handling process.
What	A Gripper for application of food handling of delicate items.
The	Softy Grip (Soft Robotic Gripper)
Is	Pneumatically Actuated.
That	Picks and places food items of ranging sizes with effective compliance for each.

1.7 Working Principle

The basic working principle is that when two materials are binding together and pressurized air is passed through it, we have a phenomenon of different kinds of motion in space. To achieve this phenomenon, one of the materials should be a hyper elastic material and the other material should have Young’s modulus within proximity to that of the hyper elastic material. In this way due to different elastic behavior the materials under the effect of pressurized air respond differently, the hyper elastic layer expands more while the relatively rigid layer does not and thus combinedly they show different kinds of motion in space such as bending, twisting etc.

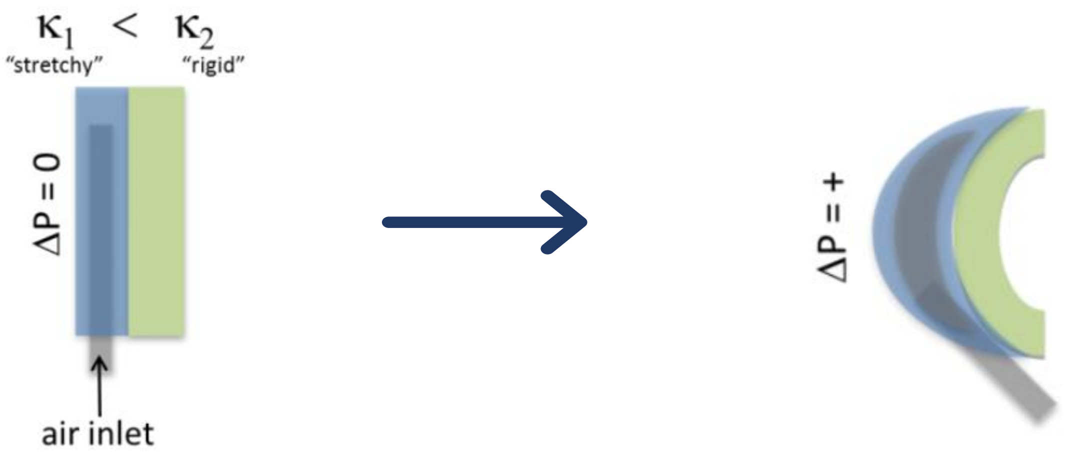


Figure 5. Working Principle (Bending motion displayed)

By controlling the motion through different designs and through different material we can utilize the motion to our benefit.

1.8 Actuation System Design

The actuation system is built keeping in the mind the following design requirements:

1. The pressure range of the pump should be between from 0 – 145 kPa.
2. The Soft Robotic Actuator must be able to inflate and deflate using the pressure control system.
3. Air transfer should be maintained for rapid actuation.
4. An airflow of around 3cfm must be maintained for fast operation of Soft Robotic Actuator.
5. Airflow should be steady and there should be no significant air losses in any connections.

These requirements were fulfilled by assembling different components which were able to produce the desired output, here we will be going through some of the components and how each component adds to the overall actuation system.

An air compressor is needed which will compressor the air at standard atmospheric pressure to a pressure 100 above KPa, so that the actuator will properly inflate and hold onto the desired object, for this a suitable air compressor was selected which has been discussed in Chapter 6 of this paper.

For the steady air flow, it needs to make sure that there is no leakage in piping, connections, etc. To get an airflow of 3cfm, a suitable air compressor should be selected which is capable of offering such an airflow, the air compressor discussed in Chapter 6 is capable of doing this.

CHAPTER 2: LITERATURE REVIEW

Soft Robotics is a new and emerging field of Robotics, and the research has been increasing in design of different soft robotic end effector, design of end effectors for gripping mechanism, design for their use in medicine & in rehabilitation tasks, design for terrain robots and others as such. The research is also in materials i.e., soft robotic materials. The research is done for how different materials can be used for different application areas or for different designs which are mentioned above. The research is also on types of actuation systems and how different actuation systems can be used for different materials and application.

2.1 Materials

The research on materials in soft robotics is of vital importance. Elastic and Viscoelastic properties are essential considerations during material selection for a soft robot. Typically used material classes in soft robotics are silicone elastomers, urethanes, hydrogels, braided fabrics, hydraulic fluids**[1]**, among these silicone elastomers are the most used. Moreover, it has been researched those materials that are to be used in soft robotics should have low stiffness (have an elastic modulus of (10^2-10^9 Pa).

2.1.1 Hydrogels

A network of water and hydrophilic chains is built in a structured form which makes up Hydrogels**[2][3]**. Hydrogels are three dimensional elastic solids, which go under a mechanical strain of up to 1000%**[4]**, temperature change (volumetric changes due to temperature changes)**[5]**, light changes etc**[6]**. Different types of actuation techniques for hydrogels are shown in figure 2.

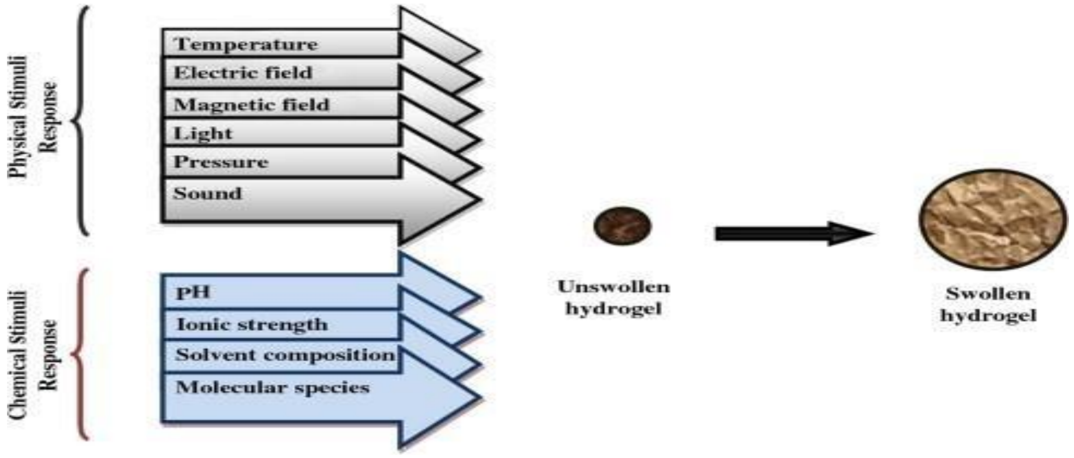


*Figure 6. Hydrogels Graphical Representation***[7]**

With all the fascinating abilities of hydrogels, research shows, there are a few spaces in which it needs to be improved. Since hydrogels can be stimulated by different methods such as PH change, temperature change, etc. Multi-Stimulation is a feature which can greatly enhance the area of applications of hydrogels, but there are some issues which are caused due to this feature as well, due to multi-stimulation capabilities of hydrogels it can become confusing sometimes for a hydrogel whether to respond to a desirable stimulation or to an undesirable stimulation causing unnecessary motion, therefore hydrogels need to be capable of distinguishing between the two types of stimulations**[8]**.

There are also some problems related to the durability of hydrogels, they can get dehydrated which can cause problems in actuation**[9]**. Hydrogels are also slow in operation, and electrochemical stability is another concern while using hydrogels as electrochemical reactions inevitably occur while using hydrogels that are actuated using electricity.

2.1.2 Silicone Elastomer

Silicone Elastomers are widely used for making soft robots, as they are cheaper than hydrogels and in comparison, to other dielectric elastomers exhibit faster response time and lesser viscoelasticity along with strong stability, scalability, and biocompatibility**[10]**. A big advantage of using silicone elastomers is that they can be actuated using air, and since air has low viscosity it permits rapid actuation, also air is available everywhere, easy to store and environment friendly. Popular silicone elastomers which are used in soft robotics are Dragon Skin 10, MEDIUM, Dragon Skin 20, Dragon Skin 30, Dragon Skin, FX-Pro, Ecoflex 00–10, Ecoflex 00–30, Ecoflex 00–50, and Elastosil M4601.

2.2 Manufacturing Process

Subtractive manufacturing processes like drilling, milling, etc. cannot be used for the manufacturing of soft robots, as these robots are made up of different materials and often have complex shapes**[11]**. But instead, advanced manufacturing processes are being developed to manufacture soft robots, such as SDM, SCM, 3D printing, and soft lithography.

2.2.1 Shape Deposition Manufacturing (SDM)

SDM was first developed in 1990 for rapid prototyping. It is a combination of subtractive and additive processes used in sequence to produce the desired shape. It allows to compose rigid and flexible materials into one part, using SDM various parts i.e., sensors, circuits, wires etc. can be embedded in during the manufacturing process. It allows us to make compliant structures with advance level of functionality**[12]**.

2.2.2 Smart Composite Microstructure (SCM)

SCM uses micro laser machining to cut out a flat composite and polymer film into the desired shape and laminates different materials for creating an integrated structure. This process combines rigid bodies of Carbon Fiber Reinforced Polymers (CFRP) with flexible polymer ligaments where the flexible polymers act as joints for skeleton. This process is typically employed for manufacturing of meso-scaled robots**[12]**.

2.2.3 Three-dimensional Printing

3D printing enables digital fabrication of pneumatic silicone actuators, a wide range of fully functional soft robots have been manufactured using 3D printing. The structures made from 3D printing can produce motions such as bending, twisting, grabbing, and contacting motion. This process is quicker, easier and avoids some of the drawbacks caused by conventional**[13]** machining routes. Most used techniques for 3D printing are Stereolithography and Selective Laser Sintering (SLS) which are based on selective solidification of a liquid or powdered material in order to create the desired shape. 3D Printing also allows to manufacture multi-material components using techniques such as FDM and inkjet processes by the inclusion of multiple printing heads each loaded with different material. New techniques using additive manufacturing are emerging which use materials such as shape memory polymers, when these materials are exposed to certain type of interactions such as exposing then to water or ultra-violet rays they conform to the desired/programmed shape**[14]**

3.2.4 Molding

3D printing is being used for preparation of molds in the case of PneuNet and fiber reinforced actuators, the mold is prepared using 3D printing. The silicone elastomer is operated to be cured at room temperature, Part A and Part B of the elastomer are mixed and the air bubbles generated during the mixing are removed by extracting air in a vacuum chamber. The prepared solution is poured into the 3D printed mold to get the final actuator**[15].**

2.3 Actuation Method

For different applications and materials, different types of actuation methods can be used.

2.3.1 Magnetically Responsive Actuator

Materials such as papers, gels, polymers, and fluids can be actuated when exposed to a magnetic field**[16]**, it is considered interesting because of the ease of quickly controlling the direction of magnetic field. This type of actuation is used in soft robotics by the insertion of magnetic fillers, the magnetic fillers align themselves to the direction of magnetic field and generate different modes of actuations such as deformation, bending, elongation and contraction**[17]**.

2.3.2 Thermally Responsive Actuator

Thermal stimulation provides actuators that are safer than UV light or electrically activated actuators especially for medical applications, but they tend to be slower, and less efficient than other modes of stimulation. Shape Memory Alloys, Shape Memory Polymers, Synthetic Hydrogels and Liquid Crystal Elastomers are some of the material classes which can be actuated using thermal stimulation**[18]**.

2.3.3 Pressure Driven Actuation

Soft actuators can be stimulated by external forces or pressure to generate the desired deformations. Research is being carried out on producing small scale pressure driven actuators**[19]**. Soft actuators can be stimulated by external forces or pressure to generate the desired deformations. Research is being carried out on producing small, scaled pressure driven actuators.

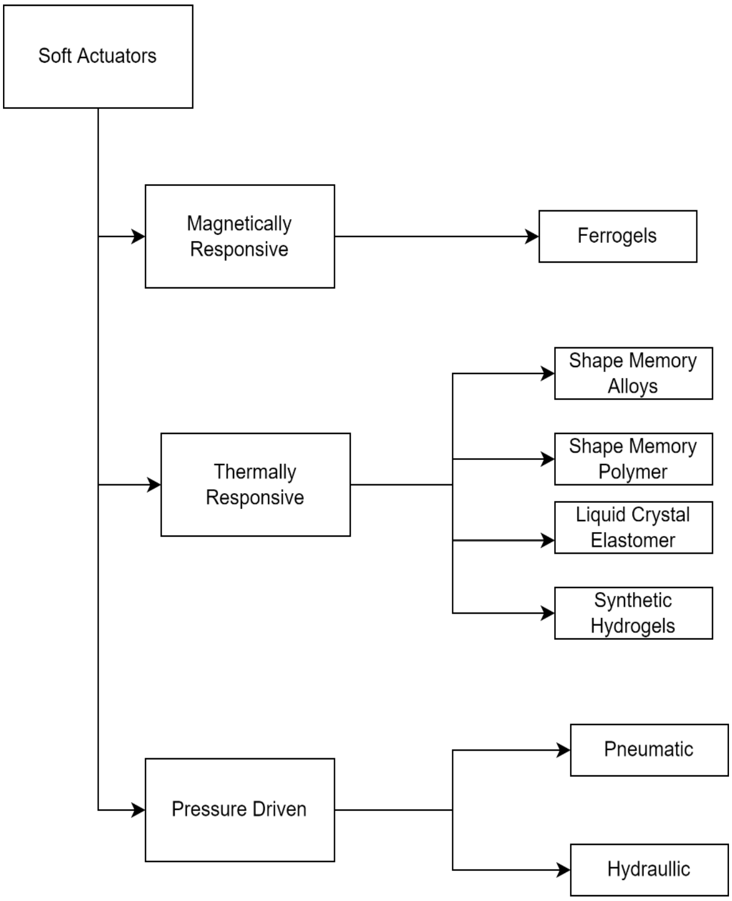


Figure 7. Types of Soft Actuators

2.4 Control of Soft Robotics

Contrary to the control of rigid or hard robots, the movements of which can be described fully by six degrees of freedom (three axes for rotational motion and three axes for translational motion), the motion of soft robotics cannot be fully defined by planar motion. Soft Robots have infinite degrees of freedom, they can bend, twist, stretch, compress, buckle, wrinkle and so on, this sort of motion makes it very difficult to control these robots using conventional techniques.

2.4.1 Kinematics & Modelling

Soft Robots have a very different motion as compared to rigid robots; the final shape of a soft robot can be described using a continuous function and modeling them requires continuous mathematics. Soft robots do not have well understood models or planning and control algorithms yet. Different approaches are used to define the kinematics of soft robots, some of them make use of Bernoulli-Euler beam mechanics to predict deformation**[20]** another model develops a relationship between the joint variables and the curvature arc parameters**[21]** and a third presents models that describe the deformation of robots actuated with low pressure**[22]**.

2.4.2 Low-Level Control

These models have been used by researchers to develop new approaches to low-level control. The controlling of a soft robot using pressure transducers or volume control using strain sensors is often called Low-Level control. Most soft robots use open-loop valve sequencing to control their motion, open-loop valve sequencing means that a valve is turned on for some duration of time to pressurize the actuator and then turned off to either hold or deflate it, this type of control is used in many soft robots**[23]**.

Recently work has been carried to develop control elements for pneumatic soft robots, which do not require electrical control signals; passive valves with memory allow the control of many soft robots from a single controlled pressure source**[24]**.

CHAPTER 3: DESIGN METHODOLOGY

3.1 Material Selection

3.1.1 Introduction

Soft actuators are the fundamental components of soft robots. The soft fluidic actuators, which uses hydraulics or pneumatics to actuate, is the most common type of soft actuator. The soft actuators are typically fabricated with silicone rubbers after a 3D molding process, though they can also be 3D printed directly. Silicone rubber is a highly flexible/extensible elastomer with good biocompatibility, high temperature resistance, and low temperature flexibility. Elastomers can withstand massive strains of more than 500 percent without deformation or fracture.

3.1.2 Literature Review

DragonSkin (Shore Hardness 10–30 A), Ecoflex (Shore Hardness 00-10 to 00-50), Smooth-Sil (Shore Hardness 36–60 A), and Elastosil M4601(Shore Hardness 28A) are mostly used silicone rubbers in the soft robotics community. Figure 1 shows a hardness scale, and Figure 4 shows the results of uniaxial tensile testing of different materials.

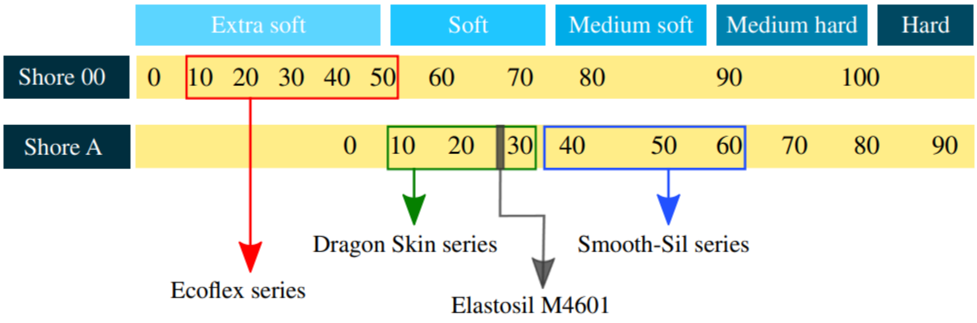


Figure 8. Shore Hardness scale for Silicones

Material selection is very difficult in these actuators due to peculiar behavior of hyper elastic materials and irregular shape of actuator. According to literature review material stiffness affects that how much air pressure is required to bend the actuator. High strain (low durometer) materials deform more than low strain (high durometer) materials for a given pressure. By using combination of high strain/low and strain/high durometer leads to varied actuator behavior.

Table 1. Commercial high Strain/Low durometer materials

Material	Manufacturer	Youngs Modulus	Shore Hardness A
Ecoflex 00-30	Smooth on	0.1 MPa	30
Elastosil M4601	Wacker Chemie AG	7 MPa	28

For making base of actuator low strain material like PDMS silicone, Fabrics (e.g., fiberglass) and Paper can be used with combination of high strain materials for main body.

Table 2. Commercial materials for base of actuator

Material	Model	Coefficients
Kevlar Fiber	Elastic	E = 31 067 MPa, ρ=1440kg/m^3, υ = 0.36, diam = 0.1778mm
Fiber yarn	Elastic	E = 103 GPa, υ = 0.34
PBO Fiber	Elastic	E = 5.8GPa, υ = 0.3
Silicone O-ring	Elastic	E = 31 067 MPa, υ = 0.36
Paper	Elastic	E = 6.5GPa, ρ=750kg/m^2, υ = 0.2
Paper	Elastic	E = 1.2GPa, υ = 0.2
Fiberglass	Yeoh	$C_{combined}$ = 7.9MPa

3.1.3 Material Decision Matrix

The actuators made with softer materials having low Youngs modulus like Ecoflex exert less force and bend slowly than material having high Youngs modulus (stiffer material) like Elastosil M4601. Since Ecoflex is a high strain material it shows a greater increase in volume under the same pressure. Actuator made of soft material like Ecoflex have one advantage that they can be operated at low pressures.

The actuator's strain and force are another important parameter to consider when choosing a material. When choosing materials, there is always a compromise between force and strain.

High-strain materials work at lower pressures and can't exert a lot of force. Low strain materials, on the other hand, can handle a lot of force, but they have a lot of pressure requirements.

A design matrix for material selection is created. The strain value, operable pressure, availability, and cost are all important considerations in material selection.

Table 3. Decision Matric for Material Selection

Property	Elastosil M4601	EcoFlex 20	Dragon Skin	PDMS
Strain Value	High	High	High	Low
Working Pressure	Low	Low	Low	High
Cost	Moderate	High	High	High
Availability in Pakistan	Locally Unavailable but can be Imported	Locally Unavailable but can be Imported	Locally unavailable but can be Imported	Locally unavailable but can be Imported

By the design decision matrix**, Elastosil M4601** is selected for the actuator. It has low working pressure, expands much less upon actuation and most importantly it can be easily imported to Pakistan and its price is much cheaper than the other materials.

3.2 Actuator Design Selection

This heading covers the research carried out for selecting the design for our soft actuator. Soft actuators made from elastomers and hydrogels and can be made into different shapes. Moreover, soft actuators can be made by different manufacturing methods. How a soft actuator is made depends on the design requirements and application area.

3.2.1Pneunet Design

First is PneuNet actuator design, it consists of two parts, upper and lower part. The upper part consists of a given length of actuator divided into chambers that are connected. On the inside they have channel to allow the air passage from the first till the last chamber. The lower part consists of two materials having different young’s modulus. These two parts are connected and when air is passed through the channel, the chambers get pressurized and thus motion is achieved.

The PneuNet design actuators can be made from materials like elastosil, ecoflex and dragon skin. This design can be made through molding. The molds for the design consist of only three parts and can be made easily by 3D printing**[25]**

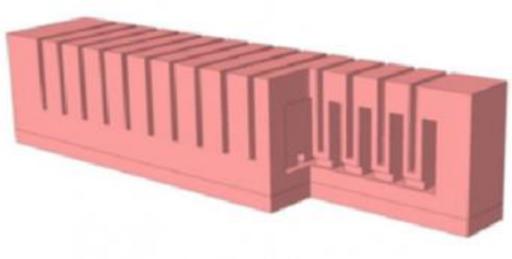


Figure 9.Pneunet Soft Actuator

3.2.2 Fiber reinforced Design

Fiber reinforced actuator_consists of an elastomer bladder wrapped around with inextensible reinforcements. The inner bladder acts like a typical balloon and expands in all directions when expanded. Wrapping the bladder with inextensible fivers constrains it from expanding radially; thus, when inflated it expands in only axial direction. Adding a sheet of inextensible material prevents the actuator from expanding in the region of that sheet; since one side expands axially and one doesn't, the actuator bends when inflated**[26]**.

The fiber reinforced design actuators can be made from materials like elastosil, ecoflex and dragon skin. This design can be made through molding. The molds for the design can be made from 3D printing.

Figure 10. Fiber Reinforced Soft Actuator

3.2.3 Extensible Actuator

Extensible actuator design consists of a length of actuator which has a cylindrical design with curved ends on the outside. Inside it consists of numerous small chambers. One end of the actuator is sealed, and the other is connected with a source providing pressurized air. When provided with pressurized air, the chambers are arranged in such a way that they expand causing the actuator to extend many times over its standard length**[27]**.

The extensible actuator design can be made from materials such as Ecoflex, Dragon skin. They are made through molding method.

Figure 11. Extensible Actuator Design

3.2.4 The Selected Design

Our application area is food and fruit picking i.e picking of delicate objects. We have selected the PneuNet design for this application. The reasons include:

1. PneuNet actuator design provides good enough force within a certain pressure range that will help in providing a good grip.
2. PneuNet design only provides bending motion, and we require only this motion for picking of objects. Other designs provide various motions that are not required for our application area.
3. It can be made with elastosil, a material that when paired with paper provides for good bending and moreover this material is food grade, thus PneuNet design is a good option.
4. In our case molding technique is a better approach because the materials which can be 3D printed are not good for our application area.

3.3 Morphology Selection

The Soft Robotic Gripper is designed to be used in picking and placing operations in food industry. The design parameters of the soft actuator were set keeping in view the application of soft robotic gripper, the design constraints are limited by surface of subject items, shape and size, and weight. The surface of an object can be rough, slippery, hard, etc. and the soft robotic gripper was designed to grasp a range of food items.

3.3.1 Length of actuator

To determine the length of the actuator, we took a sample of objects that can be grasped with the gripper and measured their heights.

Table 4. List of sizes of objects

Objects	Average Sizes (Height)
Strawberries	3cm to 5cm
Apple	5cm to 8cm
Guava	5cm -9cm
Muffin	4cm to 7cm
Chicken piece	2cm to 6cm

These object size helped us to determine the length of actuator of our actuator. So based on average width of objects, length of actuator was set to about 11.2 cm.

3.3.2 Height of actuator

We have selected the Pneunet type of soft actuator for our application area, food handling. In Pneunet design to select the height of our actuator we must balance between the height of internal chambers and the total height of the actuator. The height of actuator must be balanced enough so that the actuators work as desired, and the actuator also gives a good look. Since the design is nature inspired and if we look our fingers most have height of about 1.3 to 1.7 cm. Thus, we decided upon the total height of actuators to be about 1.5 cm.

3.3.3 Air Channel

To ease pressure in all the chambers without any problem, air channel is introduced at the bottom base line of the actuator. To ensure that the air goes through smoothly and also that is not blocked at any point we kept the height of air channel to be 2 mm.

3.3.4 Chambers

The internal chambers of the soft actuator were designed on basis of the constraint that length of each chamber except for the chamber where the pipe for pressurized air is to be inserted, should be nearly the same for even actuation of the actuator which is required in our application domain. Thus, we designed 11 chambers for the actuator length of about 11.2 cm with all the chambers except for the ends are of the same length.

CHAPTER 4: FEA METHODOLOGY

4.1 Imperative Reasoning

Due to the large nonlinearities associated with soft robotic systems, modelling soft structures, actuators, and sensors is difficult. Finite element modelling (FEM) is a useful tool for representing soft and deformable robotic systems with geometric nonlinearities caused by large mechanical deformations, material nonlinearities caused by the materials' inherent nonlinear behavior (i.e., stress-strain behavior), and contact nonlinearities caused by the surfaces that come into contact during deformation. Prior to the manufacture of such soft robotic systems, FEM may be used to predict their behavior efficiently and correctly under a variety of inputs and optimize their performance and topology to satisfy specific design and performance requirements.

Soft robotic structures must be meshed with caution due to their significant nonlinearities and large deformations. Soft actuator FEM simulations are time demanding and have a significant computational cost. While a small mesh size improves the accuracy of the results, it also lengthens the simulation time. As a result, a trade-off is made between the precision of the results and the simulation time.

4.2 Models for Hyper Elastic Materials

Silicone rubber is assumed to be isotropic and incompressible in hyper elastic models. All inelastic processes, such as viscoelasticity and stress-softening, are also ignored. These models are used to describe the elastic behavior of hyper elastic models. Some hyper elastic models for soft actuator are shown in table. Each model consists of certain parameter which are determined experimentally to describe the elastic behavior of material.

Table 5. Models for Hyper Elastic Materials

Model	**Stress-stretch equation**
Mooney-Rivlin	$\sigma = 2(\lambda^2-\lambda^{-1})(C_1 + C_2\lambda^{-1})$
Ogden	$\sigma = \Sigma^n{}_{p=1}\, \mu_p(\lambda^{\alpha p - 1} - \lambda^{-(\alpha p/2 + 1)})$
Yeoh	$\sigma = 2(\lambda^2-\lambda^{-1})\, \Sigma^n{}_{i=1}\, iCi(\lambda^2 + 2\lambda^{-1}-3)^{i-1}$
Neo-Hookean	$\sigma = 2(\lambda^2-\lambda^{-1})C_1$

The models show here have assumption of incompressible rubber, i.e., I3 = 1 and Di = 0, where Di = 0, are material constants describing the bulk compressibility.

With data from simple uniaxial testing, the Yeoh model accurately represents elastic behavior over a wide range of strains and can predict stress–stretch behavior in various deformation modes. On the other hand, limited testing data, such as uniaxial tension, should not be used with the Ogden model.

4.3 Settings for Analysis of Actuators

The soft actuator's finite element analysis is carried out using Ansys Software v19.2. The study is carried by using a typical static structural model. The Fluid-structure interaction (FSI) problem is defined and solved. The following is a summary of the stages involved in FEM:

1. Actuator 3D modelling

2. Define the material

3. Identifying components' interconnections

4. Defining boundary conditions

5. Meshing

6.Calculation of the Solution

4.3.1 Material Definition

Silicone M4601 and Paper were used as design materials. In Ansys, the materials are modelled as follows:

1. **Elastosil M4601**

   The silicone rubber Elastosil M4601 is made up of two parts: part A and part B. Both ingredients must be blended in a 9:1 ratio. The parameters of the combination after 24 hours of curing at 23 degrees Celsius are listed in the Table 6.

Table 6. Elastosil Properties

Material Properties	Value/Features
Color	Reddish Brown
Density	1.13 g/cm3
Hardness Shore A	28
Tensile Strength	6.5 Mpa
Elongation at break	700%
Tear Strength	>30 N/mm

Elastosil is a neo-Hookean material with the following potential strain-energy constants for FEM:

a) Density = 1.13 g/cm3
b) C10 = 0.11 MPa
c) C20 = 0.02 MPa

Yeoh model for hyper elastic materials is used to simulate the material because it accurately explains the behavior of hyper elastic materials like rubber. C10 and C20 are the half initial shear modulus and half initial bulk modulus, respectively.

2. **Paper**

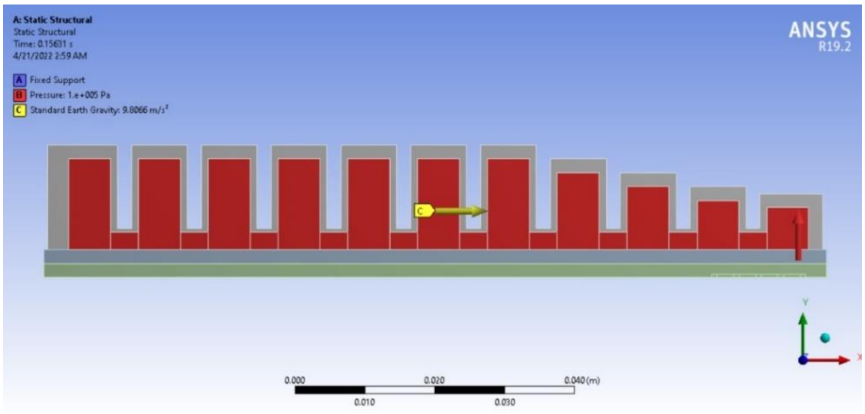
a) Density = 750 Kg/m^3
b) Young’s Modulus = 6.5 GPa
c) Poisson’s ratio = 0.2

4.3.2 Boundary Conditions

The two boundary conditions in the analysis of elastomer are:

a) Internal Pressure
b) Fixed Support
c) Earth Gravity (9.8 m/s2)

Fixed Support was applied at the end of actuator and pressure was applied at internal surface of actuator by ramped effect. Earth gravity was introduced along the longitudinal direction of actuator.



A: Static Structural
Static Structural
Time: 0.15631 s
4/21/2022 2:59 AM

A Fixed Support
B Pressure: 1.e+005 Pa
C Standard Earth Gravity: 9.8066 m/s²

Figure 12. Boundary Conditions Applied

4.3.3 Meshing

Larger the number of elements more accurate will be the solution but large numbers of elements will take large time and computational power. A balance is maintained between the number of elements and accuracy of the solution. To create this balance a mesh convergence study was performed on the actuator. A relative error of 2% is set for the deformation for mesh convergence study. After the convergence following mesh settings are used for the analysis:

a) Element size of 1 millimeter
a) Physics Preference is set to Nonlinear Mechanical
b) Element order is Quadratic
c) Displacement Error is 5.2e-3 for convergence.
d) 535425 nodes and 313521 elements.

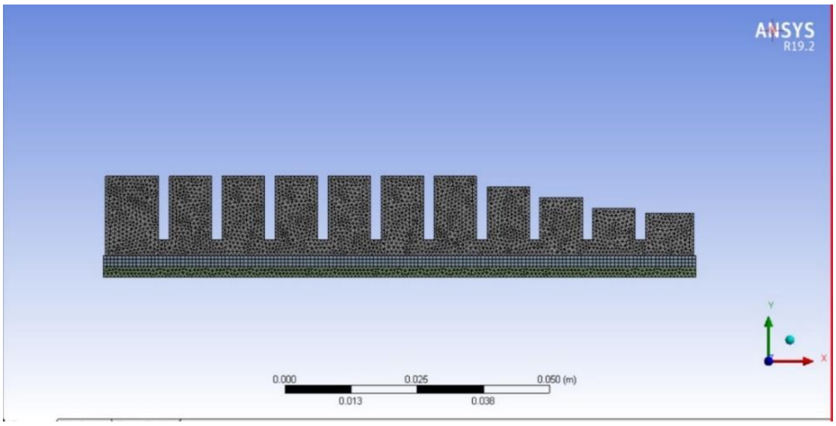


Figure 13. Mesh Generation of Soft Actuator

4.3.4 Solution Settings

Large Deflections were set ON for simulation to cater the peculiar behavior of hyper elastic materials. For convergence and volumetric compatibility auto time stepping is set ON.

Table 7. Solution Settings

Minimum Time Step	0.1 s
Maximum Time Step	1e-4 s
Initial Time Step	1 s

CHAPTER 5: SOFT ACTUATORS

5.1 1st Soft Actuator

5.1.1 Design of Actuator

In first design all the chambers height, width of chambers in between the first and last, and wall thickness were same as shown in the Figure 14.

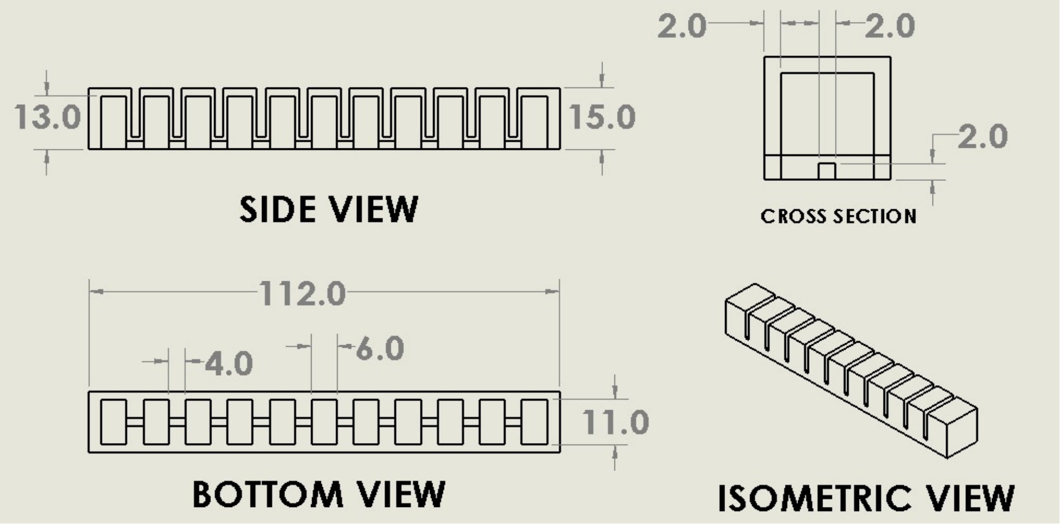


Figure 14. First Actuator 2D Drawings

5.1.2 Design of Mold

A mold for the curing of hyper elastic material, such as Elastosil m4601, is required to produce an actuator. The dimensions and design of the actuator are used to develop and model a mold. In our scenario, a mold is created utilizing the 3D printing technology. Solidworks was used to develop the CAD model for 3D printing. Three components were modelled and produced, and we needed molds to put them together. Another mold was made to make the bottom layer of the actuator. PLA filament was utilized to make the molds because it is simple to 3D print and inexpensive.

(a) (b)

Figure 15.(a)Mod of Actuator Upper body (b) Mold for bottom layer

5.1.3 Analysis of Actuator

From a design perspective of our PneuNet designed actuator we needed to determine the following:

a) The force that is applied by the actuator at different intervals of time corresponding to different pressures within the actuator.

b) The deformation at different intervals of time corresponding to different pressures in the actuator.

1. **Deformation**

   By FEA analysis of our design, we were able to determine the deformations and how they vary with change in time.

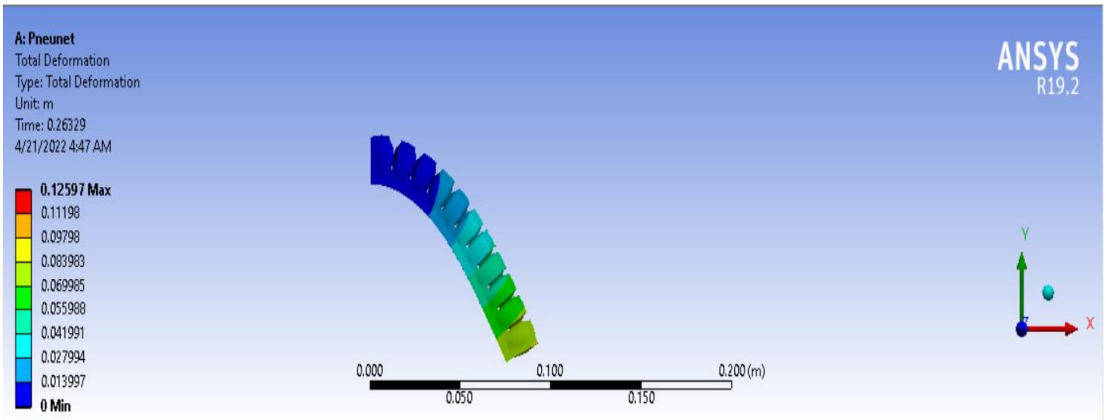


Figure 16. Deformation as shown by FEA

Correspondingly we have given the data for deformation obtained in tabular form.

Table 8. Table showing deformation of soft actuator

No.	Pressure (kPa)	Maximum Deformation(mm)	Average Deformation(mm)
1	60	75.219	29.695
2	80	82.731	32.601
3	95	90.032	35.411
4	105	97.115	38.122
5	110	103.98	40.732
6	115	110.64	43.24

2. Force

By FEA Analysis of our soft actuator, we were able to determine forces exerted by the soft actuator. The forces obtained in different axes corresponding to Pressure applied were found out through analysis.

Table 9. Forces Analysis data of 1st Actuator

No.	Pressure (kPa)	Force Reaction(X) [N}	Force Reaction (Y) [N}	Force Reaction (Z) [mN]	Force Reaction (Total) [N}
1	60	13.385	20.121	1.0527	24.167
2	80	16.437	21.349	1.1582	26.944
3	95	19.654	22.213	1.2099	29.659
4	105	22.988	22.702	1.1872	32.308
5	110	26.392	22.813	1.0513	34.885
6	115	29.822	22.547	0.77505	37.386

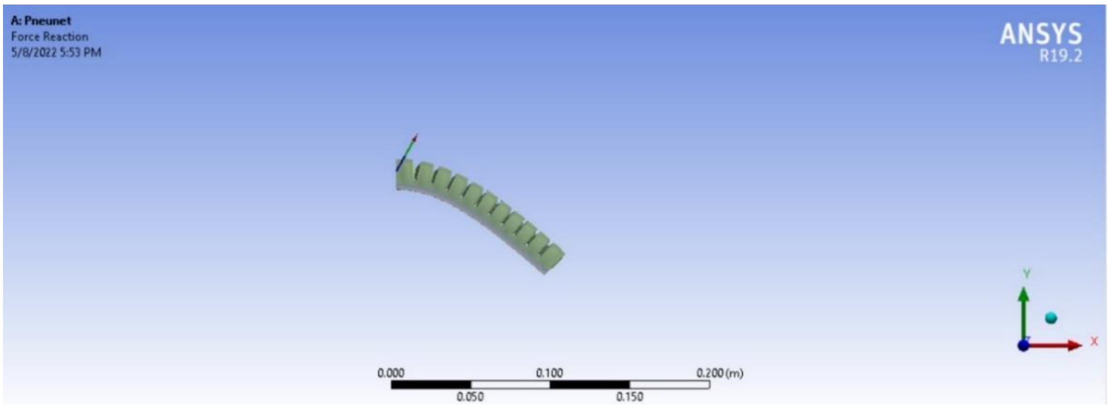


Figure 17. Forces as shown by FEA

5.1.4 Fabrication of Actuator

The Fabrication Processes involves the following steps:

1. **Preparation of Elastosil m4601**

   Elastosil m4601 comes in two parts: A and B. They need to be mixed in ratio of 1:9 (by weight) of Part A: Part B.

   We mix Part A and Part B into a uniform consistency. It can be mixed in a beaker.

Figure 18. Elastosil m4601

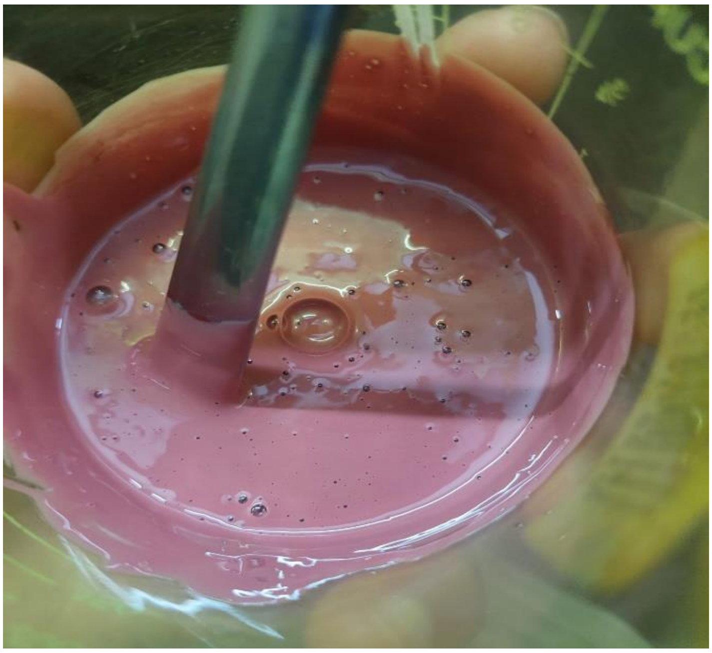


Figure 19. Mixing Process

2. **Pouring Elastosil into molds**

   Slowly pour the mixture into the main chamber mold, making sure that each chamber fills up. Also filled the base mold to half its depth with Elastosil and spread it out evenly. After that add paper on base layer. Pop any bubbles in the base mold and add the piece of paper on top of the Elastosil. Press the paper gently so it sticks, but not so hard that it gets submerged.

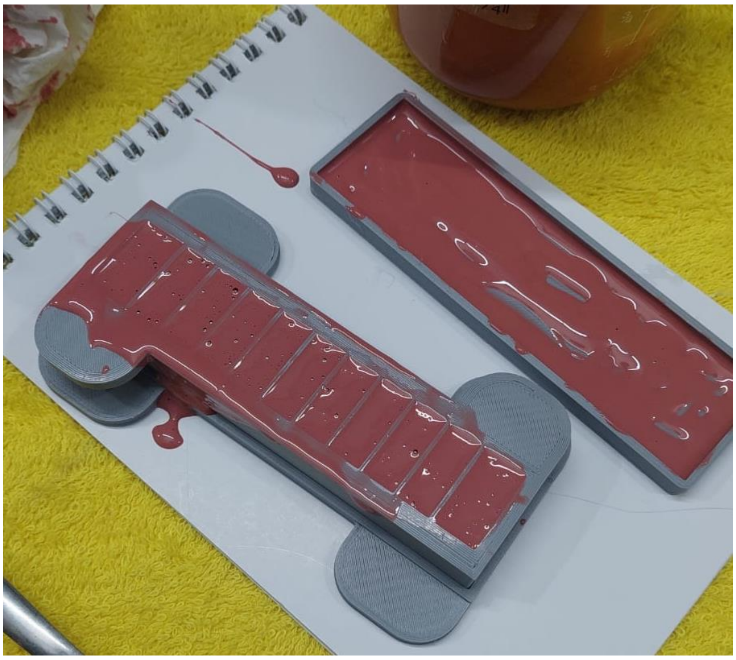


Figure 20. Elastosil poured in molds to cure

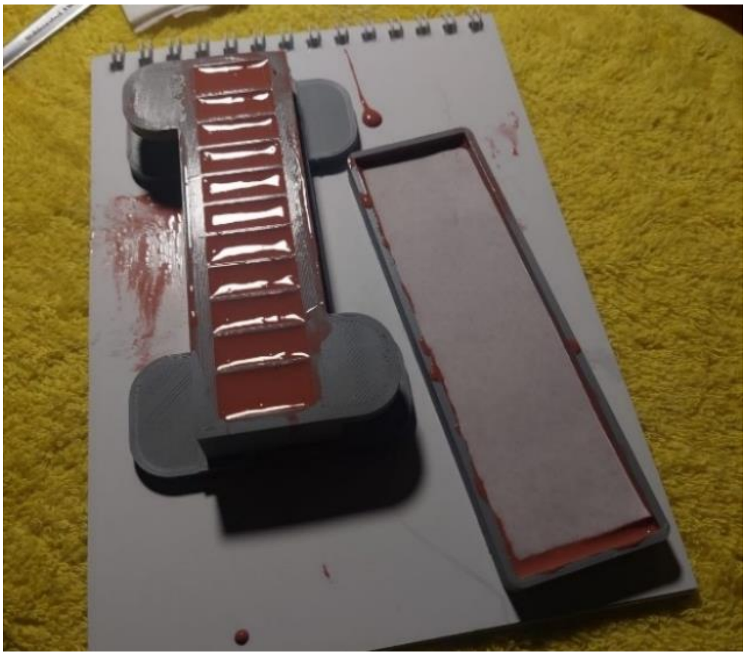


Figure 21. Paper layer on base layer

This step involves curing. This can be done either by placing the molds in oven at 65°C for 10 minutes. This is also done by curing the mold over night at room temperature.

3. Assembling the soft actuator

This involves removing the main body of actuator from the mold. use the tabs on the sides of the molds to pull the mold pieces apart. It was okay to pull hard, as this material is hyper-elastic and can stretch quite significantly before tearing.

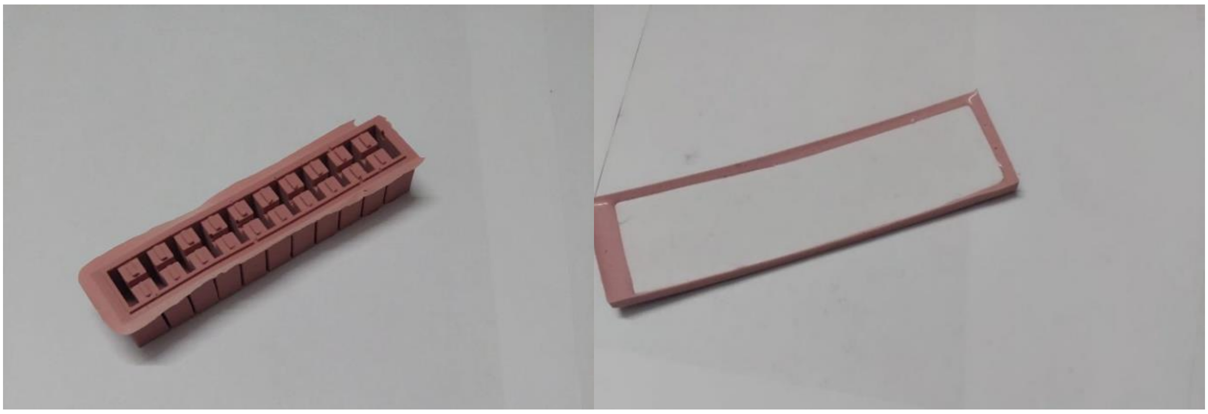


Figure 22. Top part(body) and base out of the mold

Now we have to join parts together (body and base). Place the top piece of the actuator on the base so that it settles into the uncured (freshly added) Elastosil and press down gently.

4. Connecting air source

In this step we basically insert a pipe in the Elastosil which will provide the pressurized air.

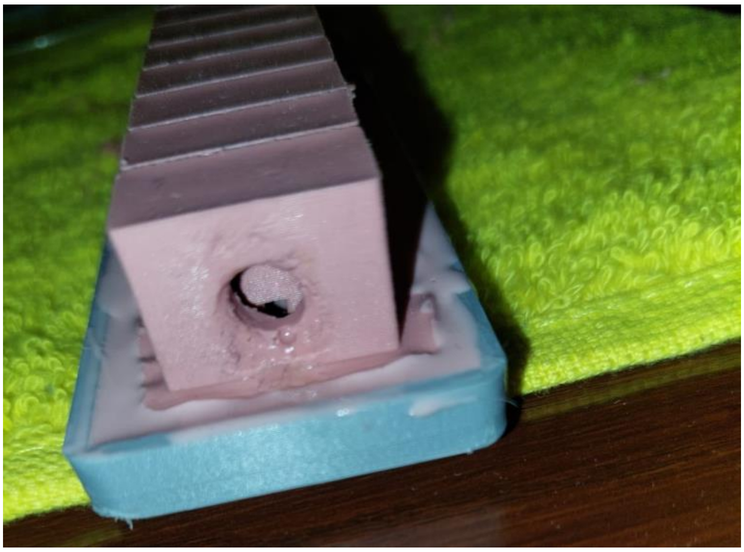


Figure 23.Hole made for connecting the air source

Figure 24. Air source(pipe) inserted

5.2 2nd Soft Actuator

5.2.1 Design of Actuator

While designing for second actuator design, the goal was to decrease the actuation time, increase the force applied, and to work more efficiently in a closed environment (in picking up comparatively small sized fruits,). Few design parameters were fixed and not changeable which are the length of the soft gripper, and material used for fabrication, therefore chamber height of the last three chambers was changed according to the design goals. The height of the chambers was gradually decreased in the last few chambers which aided in achieving the design goals listed above.

In second design last four chambers height was gradually decreased, and length and width were kept constant. We call it the 'staircase' design.

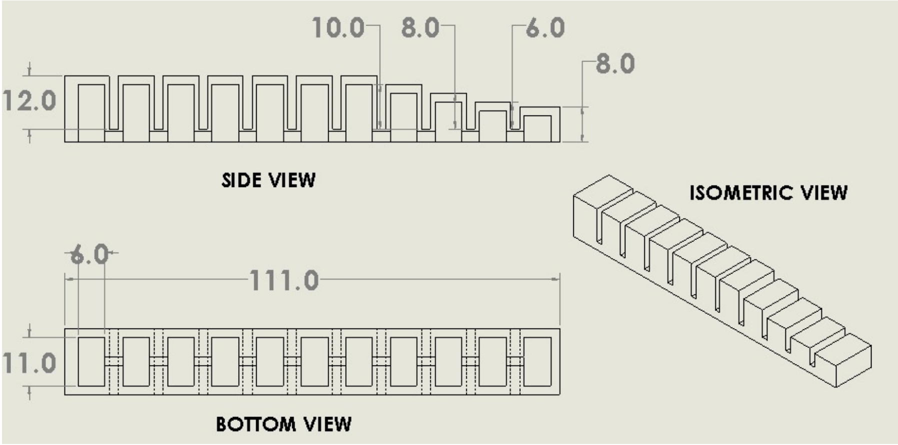


Figure 25. Design of Second Soft Actuator

5.2.2 Design of Mold

The mold for our second actuator was designed taking into consideration the design changes involved in the second actuator. Same methods and design tools were used as were done for design of first actuator.

Figure 26. 3D printed mold for Second Actuator

5.2.3 Analysis of Actuator

From the data obtained for the first design and the application area of our actuator we brought about some design changes in our actuator according to the discussed parameters in actuator design_the reason for design changes is to increase the force obtained and to achieve faster actuation time.

1. **Deformation**

   By FEA analysis of our design, we were able to determine the deformations and how they vary with change in time.

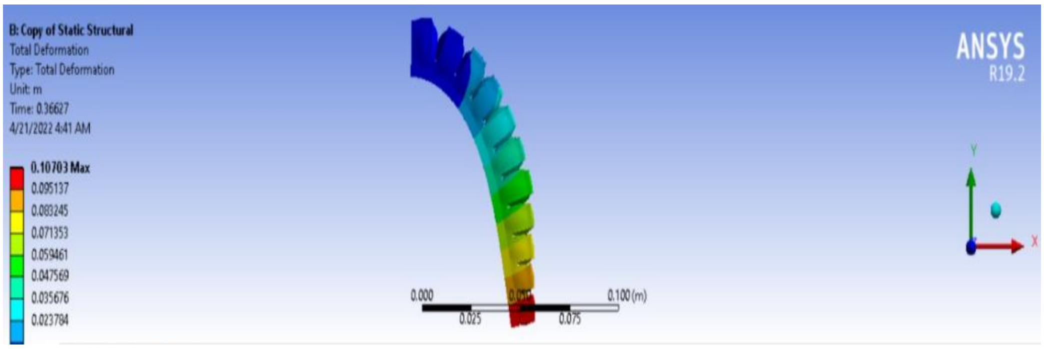


Figure 27. Deformation as shown by FEA of Actuator

Correspondingly we have given the data for deformation obtained in tabular form.

Table 10. Deformation data obtained by Analysis

No.	Pressure (kPa)	Maximum(mm)	Average(mm)
1	60	81.484	30.866
2	80	88.802	33.652
3	95	95.708	36.321
4	105	98.169	37.228
5	110	109.5	38.119
6	115	103.91	39.427

2. Force

By FEA analysis of our design, we were able to determine the force exerted and how it varies with change in time (due to the change in pressure).

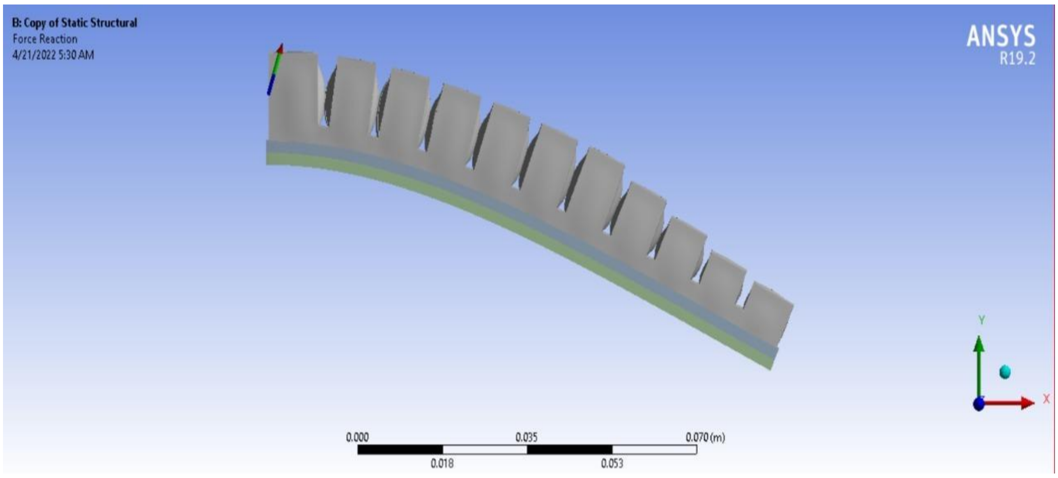


Figure 28. Force Analysis

Correspondingly we have given the data for deformation obtained in tabular form.

Table 11. Force Analysis of 2nd Actuator

No.	**Pressure (kPa)**	Force Reaction (X) [N]	Force Reaction (Y) [N]	Force Reaction (Z) [mN]	Force Reaction (Total) [N]
1	60	24.466	23.219	2.341	33.728
2	80	28.233	23.195	2.7814	36.539
3	95	29.556	23.082	2.9256	37.501
4	105	30.877	22.915	3.0639	38.451
5	110	32.85	22.566	3.2569	39.854
6	115	33.831	22.348	3.437	40.545

5.2.4 Fabrication of Actuator

The fabrication process of the second actuator is same as the one followed for the first actuator.

Figure 29. Mixing of Elastosil

Figure 30. Top part of actuator curing

Figure 31. Base of actuator curing

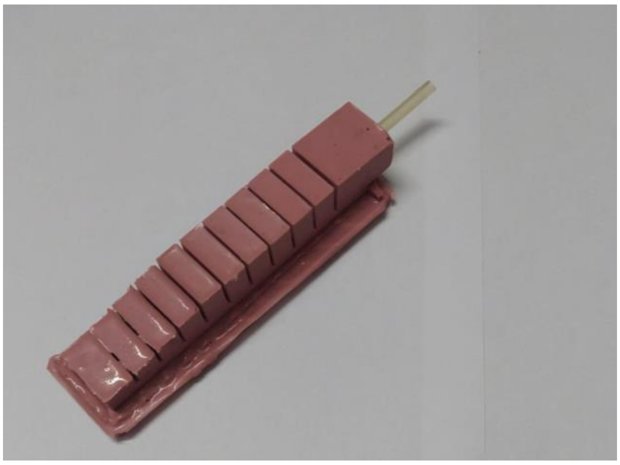


Figure 32. Actuator ready with air source(pipe)

CHAPTER 6: ACTUATION SYSTEM

6.1 Introduction

Pneumatic actuators are used to convert energy from compressed gas into a mechanical motion which regulates one or more control elements. These actuators can be used to obtain linear or rotating motion depending on the design parameters. In industry pneumatic systems are used for movement of a wide range of loads. For our application energy from compressed air is used for the rapid actuation of soft robotic gripper, air has been used as a gas because it is available in abundance, it is safe to work with and free of cost, a **diaphragm air compressor** has been used to increase the pressure of air/compress the air.

6.1.1 Diaphragm Air Compressor

The most vital component of the pneumatic actuation system is the air compressor, it is solely responsible for increasing the pressure of air for the soft robotic gripper to actuate. The air compressor used in building up actuation system is a Diaphragm Air Compressor; it is a reciprocating compressor that has a rotating diaphragm which compresses the air or gas. It works on two strokes, in the first stroke air is taken in from the atmosphere via a suction port while the diaphragm and connecting rod are below, the air from the suction port enters the gap between the diaphragm and connecting rod due to the lower pressure created as the diaphragm and connecting rod move downwards, the crankshaft is driven by the motor which helps in the rotation of the connecting rod and hence the diaphragm, once air enters into the pump chamber the crankshaft moves up and the second stroke – the delivery stroke starts and air is compressed as the diaphragm moves up, hence compressed air is delivered at the outlet.

The working of a diaphragm air compressor is like a reciprocating IC engine it is further explained with the help of a Figure 33.

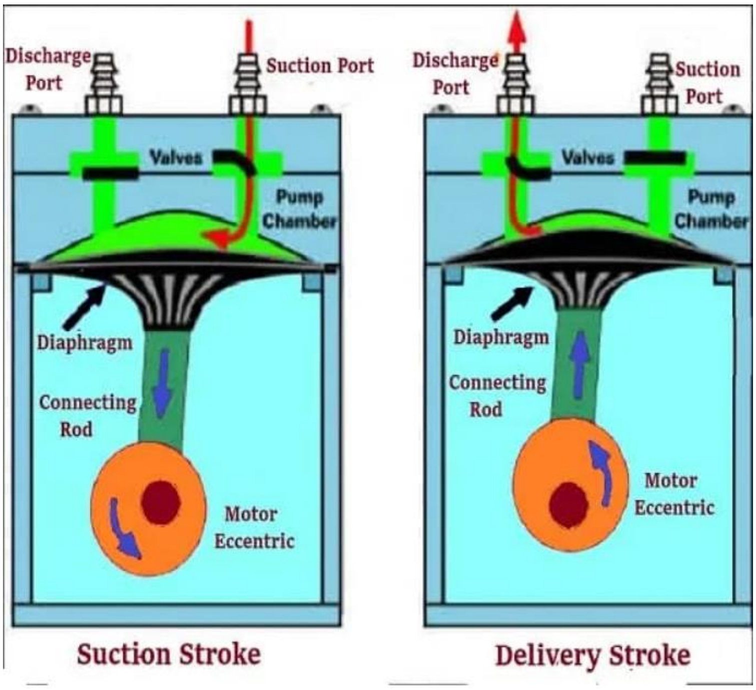


Figure 33. Working of a diaphragm air compressor

The diaphragm is made of rubber and is circular in shape. The diaphragm has a tight sealing so that ionic fluid cannot mix with the air, the diaphragm material must be able to bear the strain caused by the pumped gas.

For our application, we have used a 12V DC Diaphragm Air Compressor which can produce a maximum pressure of 100KPa with a flow rate of 15 liters/minute, the motor used in this air compressor for driving the crankshaft is Motor 555 which has a torque of 334mNm and has a no-load speed of 7400RPM while operating at 12V. The motor rotates the shaft connected with the crankshaft of the diaphragm and helps in compression of air.

6.1.2 Solenoid Valves

Usually, a pneumatic valve is used to control or modulate the flow of air in a pneumatic system. This is done by controlling the amount of air at the source, and its passage as needed into tubing, pipes, etc. A pneumatic system can be controlled by electric circuits, and a solenoid valve acts as an interface between these two, the solenoid valves act as a gate or window, they are used to block the flow passage or allow it where needed. They are often used in place of manual valves where flow is to be controlled remotely.

Solenoid valves consist of an electric coil, a plunger and sleeve assembly. In a normally closed solenoid valve the orifice is closed by the plunger spring as it holds the plunger against the orifice, for the flow to occur the electric coil is energized by current, and the magnetic field produced in this coil forces the plunger to move up which opens the orifice and flow occurs, the opposite of it applies to the normally open solenoid valve.

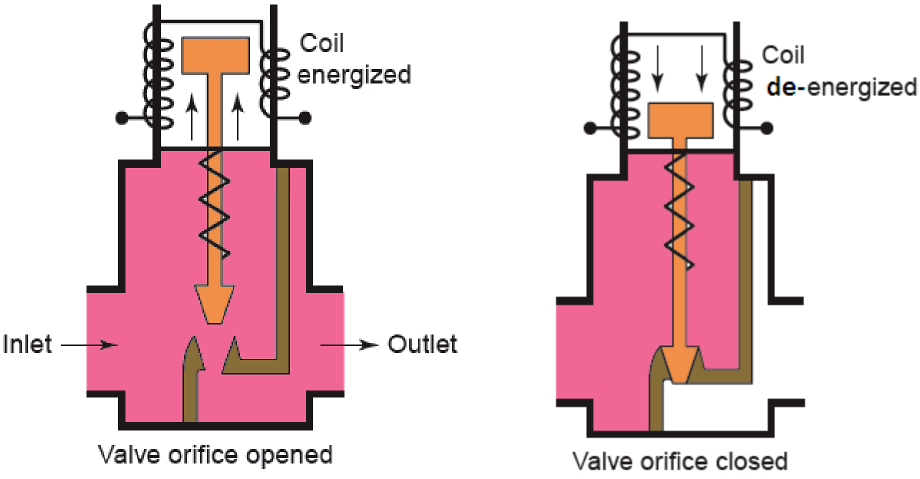


Figure 31. Working of a solenoid valve

A solenoid valve was used in our case to restrict the flow of air from the Diaphragm Air Compressor, a 6-12V DC Solenoid Air Valve was used for this purpose, this solenoid valve is suitable for air with the pressure range from 0 – 110KPa which incorporates the pressure produced by the 12V DC Diaphragm Air Compressor.

6.1.3 Transistors

A transistor is a semiconductor device which is used to amplify or switch electrical signals. Transistors are required in our case to interface the high current external devices to the microcontroller, which is Arduino for our system. The solenoid valves are connected through transistor, which is acting as a switch in our case, when the transistor pin is HIGH from the Arduino, current passes through the transistor and the solenoid valve turns on (closes) and when the transistor pin is set to LOW, the transistor acting as a switch is open and no current flows through it, hence the solenoid valve is turned on (open). TIP120 Darlington transistors are used in our application to account for the greater current drawn by the solenoid valve.

A Darlington transistor is actually a pair of transistors that act as a single transistor with a high current gain, it is able to produce a high current gain since it has a multi-transistor configuration meaning that it is a circuit consisting of two bipolar transistors in which the emitter of one transistor is connected to the base of the other, which results in the current amplified by the first transistor to be amplified further by the second transistor. TIP120 transistors were used in the making of this control board. The internal circuit of a TIP120 transistor is shown below, in which it can be seen that it consists of two transistors bundled together as a single transistor.

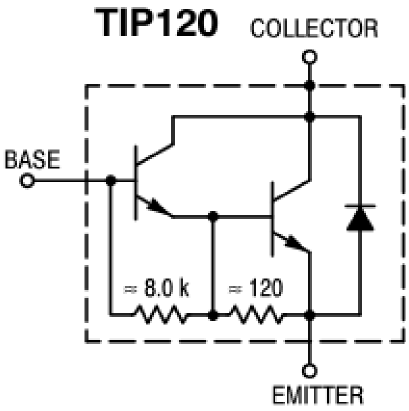


Figure 34. Internal circuit of TIP120 Darlington transistor

6.1.3 Diodes

Diodes are used when the solenoid valve is subjected to a large change in current as in case when the transistor switches, the inductor solenoid valves present a large back-emf. This large voltage spike could be harmful, so diodes are used as flyback diodes to dissipate the spike. To explain it more, since a solenoid has an inductive coil around it and acts on the principle of magnetic field generation when current passes through a coil, a diode needs to be connected across its ends. This diode helps in eliminating transient voltages which are caused when a magnetic coil (found in a motor, relay, or solenoid) suddenly loses power.

In case there is no diode placed across the ends of the solenoid valve, the transient voltage spike can damage other elements of the circuit. The diode is placed from the negative side of the coil to the positive side. Since diodes only allow current to flow in one direction, we will be somehow controlling the current flow and not allow it to hurt other elements in the circuit due to the back emf produced. 1N4001 diodes were used in the construction of this control board, the pinout of a 1N4001 diode is attached below, it allows the current to flow in only one direction.

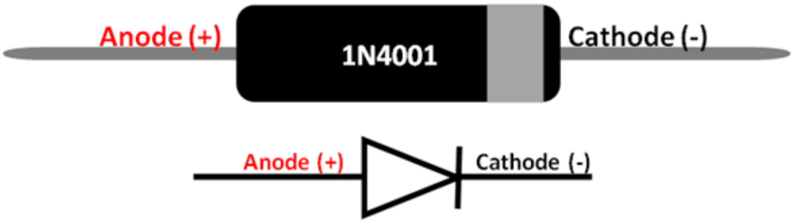


Figure 35. Pinout of a diode

6.1.4 Switching Voltage Regulator

A buck voltage converter acts to step down the voltage, it takes the voltage from a DC source and steps it down to the desired voltage, the output voltage is set by tightening the screw mounted on the buck converter. In our case, the voltage regulator has been used to drive the solenoid valve. Since the solenoid valve used in this control board operate on 6V and the Arduino microcontroller works at 5V, a voltage regulator had to be used to provide 6V to the DC Pump and Solenoid Valves. A switching voltage regulator was used over a linear voltage regulator because a significant amount of current is required for the solenoid valve when circuit is in operation which generates a significant amount of heat. The LM2596 DC-DC Switching Adjustable Step-Down Voltage Regulator Buck Converter was used for this purpose.

6.1.5 Microcontroller

A microcontroller acts as a brain of the regulator system, for our project we have chosen Arduino UNO. Commands to inflate/deflate the soft robotic gripper, turning on/off air compressor, solenoid valve are written and embedded on Arduino which then guides each component connected in the system.

6.2 Components Decision Matrix

The following decision matrix depicts the reason of choosing these components over other components which could have been used to serve the purpose.

Table 12. Component decision matrix

Component	Purpose	Availability	Reasons for selection
12V Diaphragm Air Compressor	To increase the pressure of air	Locally available	Cheap, available in the market, has a suitable pressure range.
6V DC Solenoid Valve	To control the flow direction	Locally available	Cheap, easier to set up, works at low power.
TIP120 Transistors	Works as a switch for the solenoid valve due to their current requirement.	Locally available	Able to switch loads up to 60V with a peak current of 8A and continuous current of 5A, which makes it ideal for solenoids.
1N4001 Diode	Acts as a flyback diode, prevents	Locally available	Cheap, acts as a safety for important components in the circuit, can handle

	components from getting burned due to large back emf produced when current change occurs.		current up to 1A and voltage up to 50V.
LM-2596S Switching Voltage DC-DC Buck Regulator	It is used to step down voltage from 9V to 6V for smooth operation of pump and solenoid valve	Locally available	A switching voltage regulator was used over a linear voltage regulator because a significant amount of current is required for the solenoid valve when circuit is in operation which generates a significant amount of heat.
JQC-3FF-S-Z Relay	Acts as a switch for the diaphragm air compressor	Locally available	Cheap, easy to setup, helps to run the air compressor without getting hot.

6.3 Working

On our control board we have 1 Diaphragm Air Compressor, 1 solenoid valve, 2 switch buttons, LED light, relay, voltage regulator, Arduino microcontroller, toggle switch and a power supply. All these components are connected as shown in the figure below. The Arduino sketch for the actuation system is given in the Appendix. The working of the components of the actuation system in accordance to the Arduino sketch is explained in the following paragraphs.

When the power supply is turned on, a green light will be shown, a 12V 10A output from the power supply is connected to the solenoid valve through the voltage regulator and to the diaphragm air compressor through the relay, at the start of the circuit a toggle switch is placed which acts the parent switch, toggling it to OFF will disconnect the electric supply to the whole circuit whereas toggling it to ON will supply the power to the whole circuit. Once the parent switch is turned ON, power has reached the control board now we have placed two push buttons in the circuit, these buttons will restrict the current flow to the air compressor and the solenoid valve, when the 1st push button is pressed it retains its state due to the code uploaded on the microcontroller, when it is pushed the Arduino pin to which it is connected is set to HIGH and current flows through it, the 1st push button is placed before the solenoid valve, when it is on it turns ON the solenoid valve, now the solenoid valve used in this circuit is normally open, when current is supplied to it, the solenoid valve is closed, an LED light is also placed in the circuit besides the transistor which will show us that the push button is set to ON. Now after the solenoid has been turned OFF and closed, we will push the 2nd button which will activate the diaphragm air compressor through the relay, the air compressor will inflate the soft actuator and turn off after a set time, which varies from application to application, once the soft actuator has been inflated, we will again push the 1st button which will stop the current flow towards the solenoid valve and the solenoid valve since it is normally open, will open, and the air from the soft actuator will move out causing them to deflate and return to their original state.

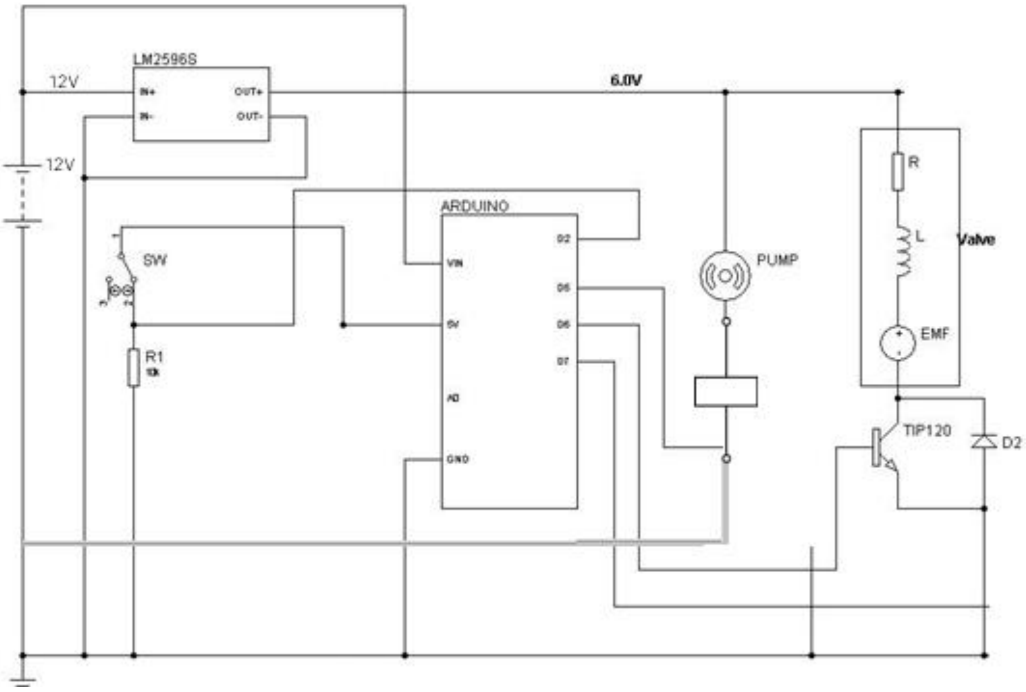


Figure 36. Circuit Diagram of Actuation System

The circuit diagram shows how different components are wired together, at the top a 6V line is passing which powers the solenoid valve, and the pump is connected through a relay to a 12V power supply.

The actuation system components are connected as per the circuit diagram, the push buttons visible in Figure 37 on the breadboard are not shown in the circuit diagram, the actuation system made from the schematic is shown in Figure 37.

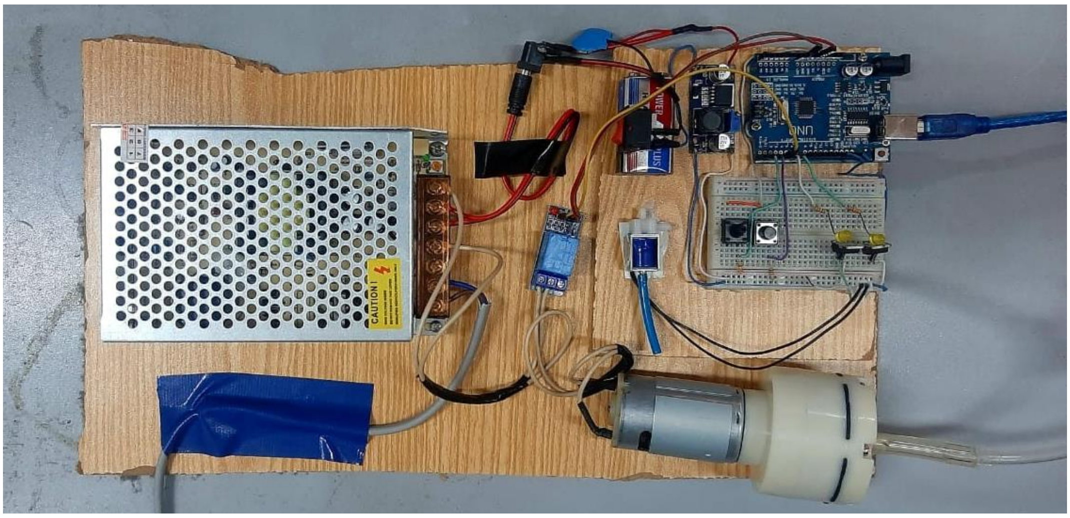


Figure 37. Actuation System picture

CHAPTER 7: MANIPULATOR

A manipulator is the part of robot which take any object grasped by the end effector part of the robot, from one position to another position. For our project the manipulator is an auxiliary part used for demonstration of effective working of the focus of the project i.e., soft robotic gripper.

7.1 Introduction

The manipulator used as an auxiliary part will consist of threaded shaft on which there will be an internally threaded nut. On threaded shaft the internally threaded nut, around which there is a moving acrylic part (on which end effector bracket is mounted) which will convert rotational motion of threaded shaft into linear motion. As a result, bracket mounted with internally threaded component will displace in a horizontal direction to the distance of about 28 cm. Two rods along with bearings will also be mounted to stabilize the system.

7.2 Designing of Components

Mountings

Two mountings are designed for catering the load of end of effector assembly and shafts. For mounting designing 2mm thick acrylic material was selected. Acrylic was selected because it was cost effective and was optimum for our application verified by FEA results.

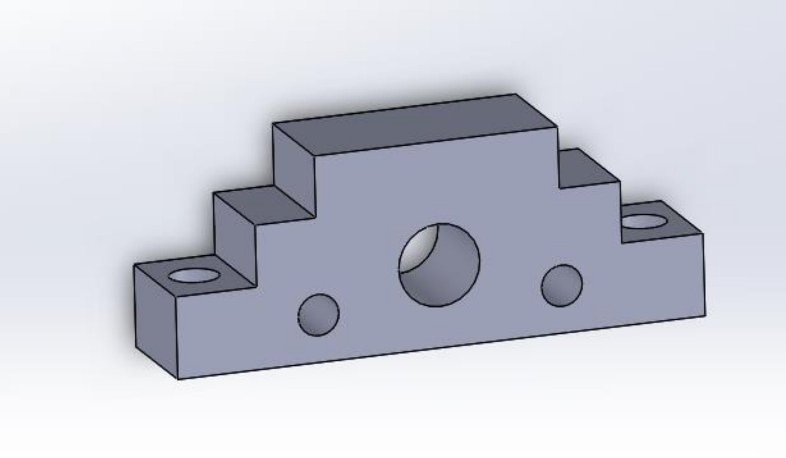


Figure 38. CAD model of side mounting

Threaded Shaft

A threaded shaft was designed to get rotating motion and the motion will be achieved when it will be connected to a DC motor. Stainless steel material was used for the fabrication of shaft.

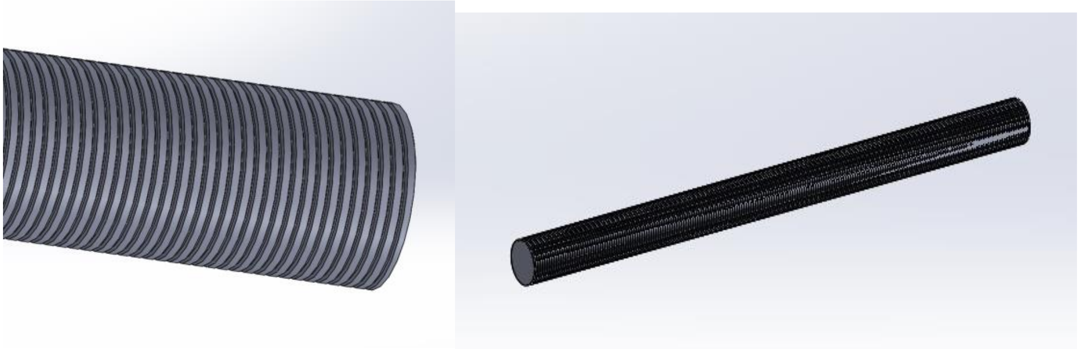


Figure 39 CAD model of Threaded shaft

Rods

Two support rods were used to make the moving bracket stable and move in only one direction.

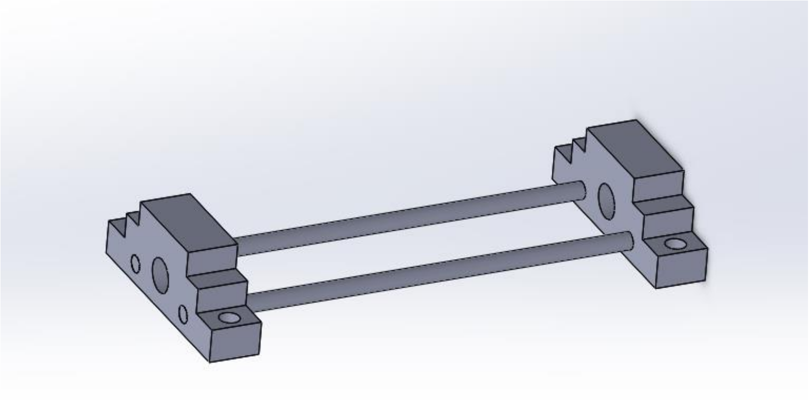


Figure 40. CAD model of support rods with side mountings

Assembly of Manipulator

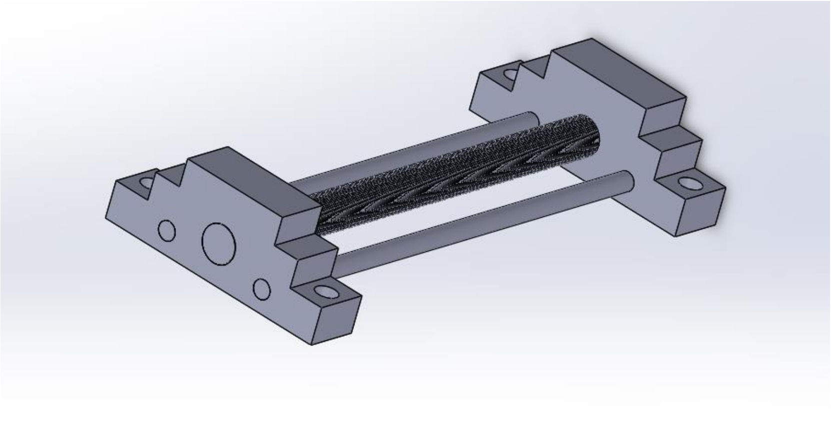


Figure 41. CAD Assembly of manipulator

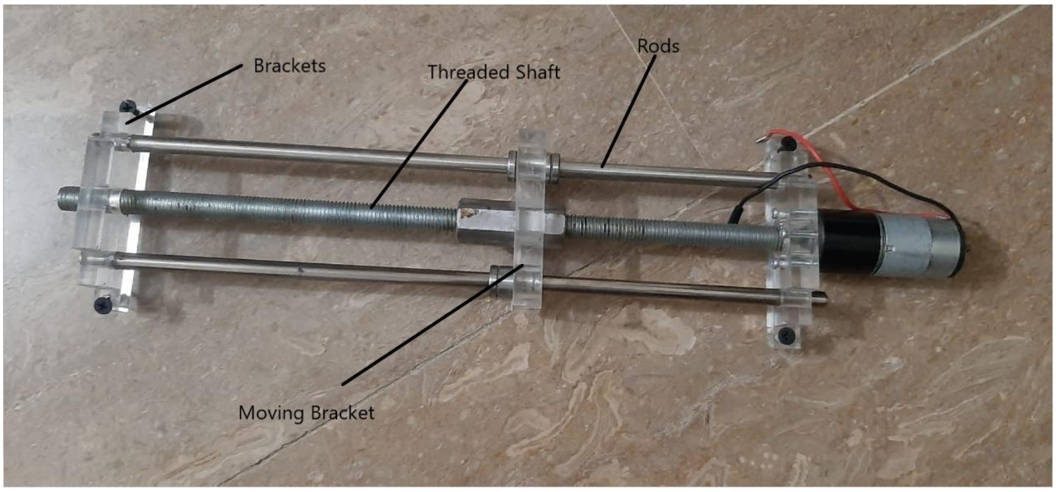


Figure 42. Manipulator Assembly

7.3 Analysis

For FEA manipulator was fixed from both sides of mountings and load of 50 N was applied on the threaded shaft to ensure the safety of manipulator. So as stress and deformation plot show that manipulator is safe for these boundary conditions and will not fail.

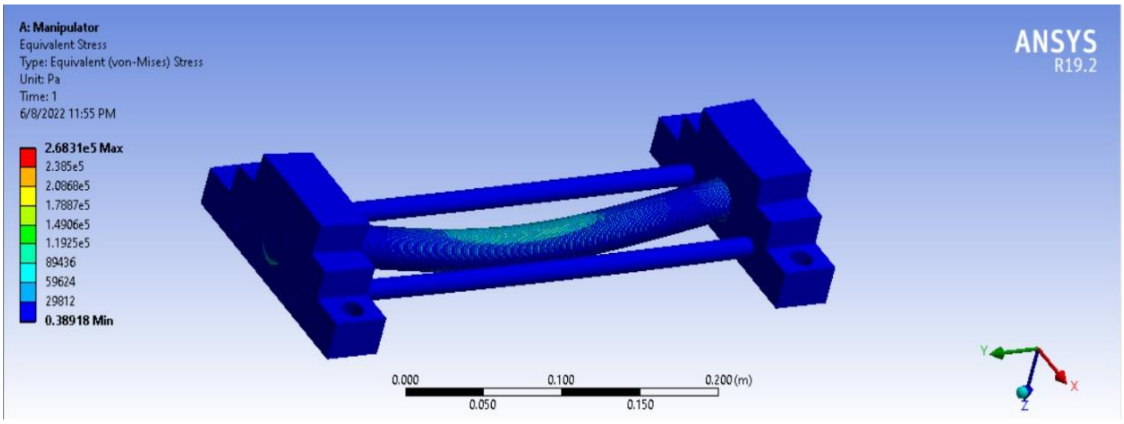


Figure 43. Equivalent stresses result

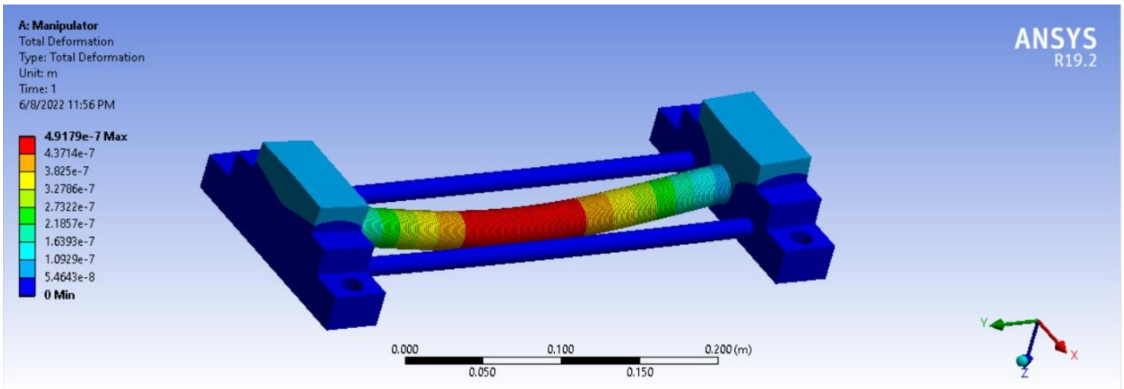


Figure 44. Total Deformation result of manipulator

7.4 Motor Selection and Control

Manipulator must be able to displace 500g of mass which include mass of three end effectors and a bracket. So, load to be transferred will be 5 Newtons.

Table 13. Motor Calculations

Power required = Torque X Angular Velocity

Power required = Load x distance x 2*pi/t

Power required = 50N * 12inch * 2pi/(25sec) = 3.6 Watt

Angular Speed = 2piN/60 = 31.4 rad/s

Torque = 0.24516625 N-m

Now for the Power Supplied = Torque X Angular Speed = 7.693 watt

Higher Power motor was used to cater frictional loads. A Double Pole Double Throw (DPDT) switch (consists of six terminals, two of which are independent input terminals) was used to change the polarity of DC battery. As the polarity changes direction of motor rotation also changes. As a result, moving bracket moves backward and forward.

CHAPTER 8: RESULTS & DISCUSSIONS

8.1 Experimental Testing of Actuators

Testing of 1st Actuator

We have tested the first design of our actuator with a lab air compressor. The actuator worked as expected and same bending phenomenon was observed as in FEA.

Figure 45. Testing of 1st Actuator

Testing of 2nd Actuator

The second design was tested and showed faster actuation.

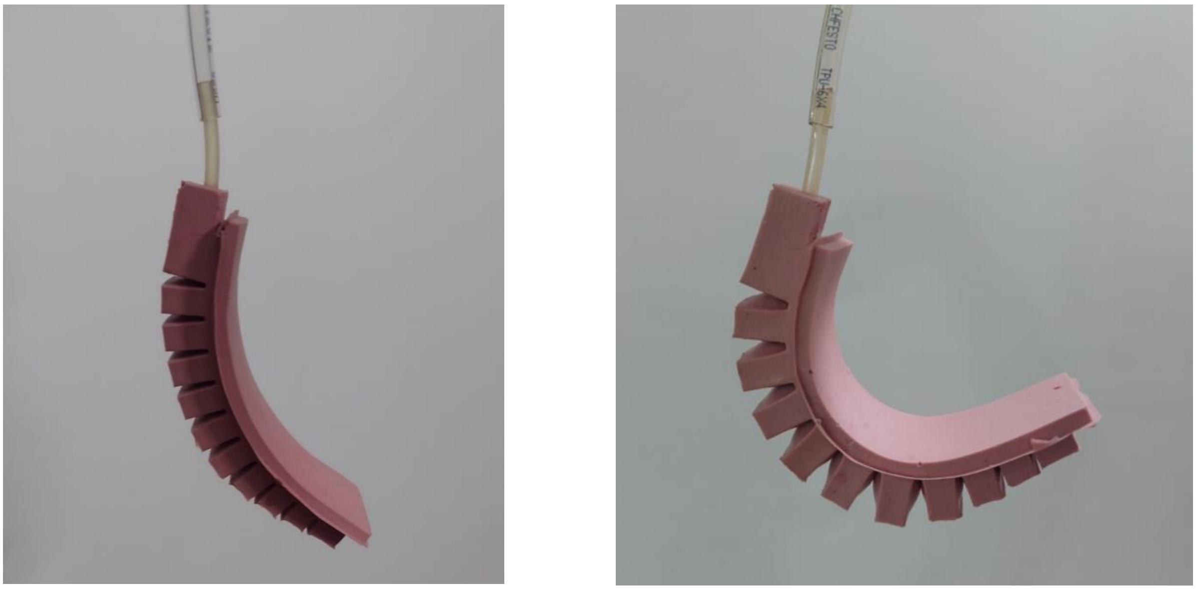


Figure 46. Testing of Second Actuator

8.2Comparison of Results

8.2.1 FEA Results of 1st & 2nd

Table 14. Percentage relative increase between 1st & 2nd design

Pressure (KPa)	**Deformation Increase**	**Force Increase**
60	4 %	2 %
80	9 %	15 %
95	8 %	11 %
105	7 %	8 %

As we can clearly see the design changed is effective and, now we have greater force as compared to previous first design.

8.2.2 Grid Independence Test

Based on the examination of multiple grid conditions, the grid independence test is a procedure used to discover the ideal grid condition with the fewest number of grids without causing a difference in the numerical results. For our simulation grid impendence was achieved at 3500000 cells. Grid independence results are shown in Table 15.

Table 15. Grid Independence table

Deflection(m)	**No. Of Cells**
0.01	200000
0.03	250000
0.05	300000
0.07	350000
0.07	400000
0.07	450000
0.07	500000

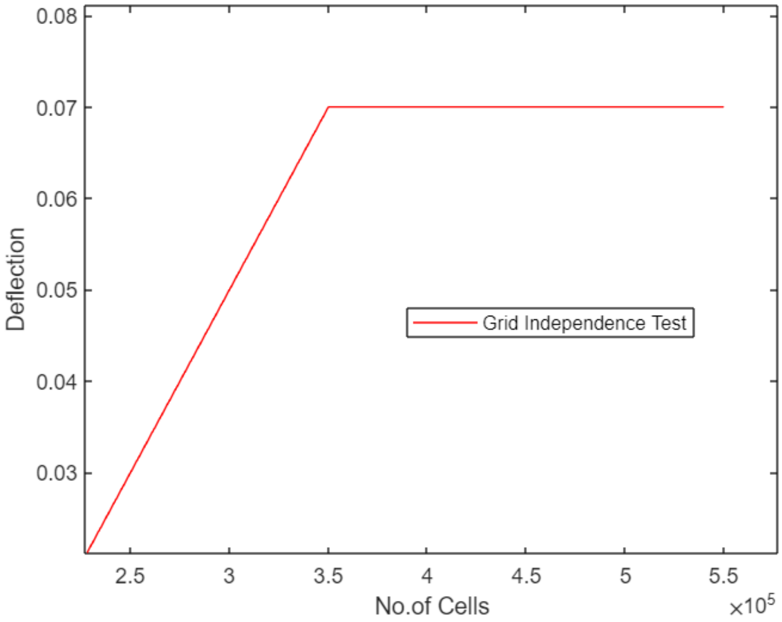


Figure 47. Grid Independence Test

8.2.3 FEA & Experimental Result of 1st Actuator

Bend angle is a significant element in actuator design. This angle indicates the actuator's behavior while it is under pressure. The bend angle is calculated as shown in the Figure.

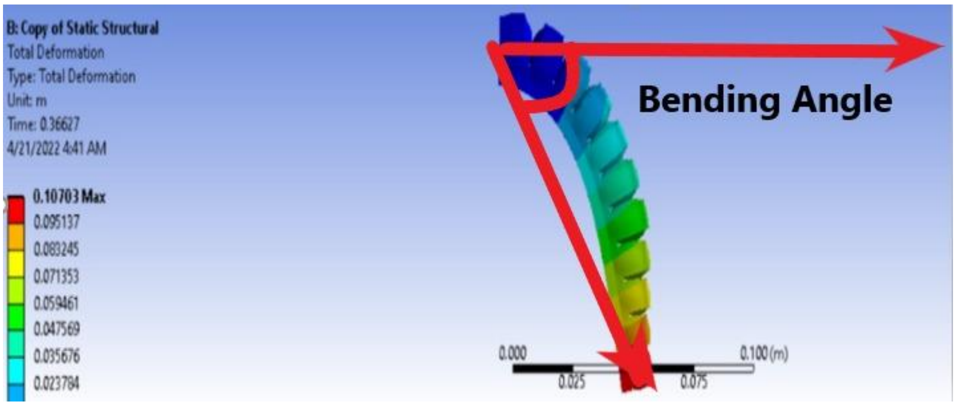


Figure 48. Bending Angle Calculations

Experimental results were compared with simulation results for the validation of results. Bending angles of actuator determined experimentally were close to the bending angle values which were found using FEA.

Table 16. 1st Actuator Result comparison

Bending Angle **(FEA) (1st Actuator)**	**Bending Angle** **(Experimental) (1st Actuator)**
30°	33°
36°	38°
42°	41°
45°	43°

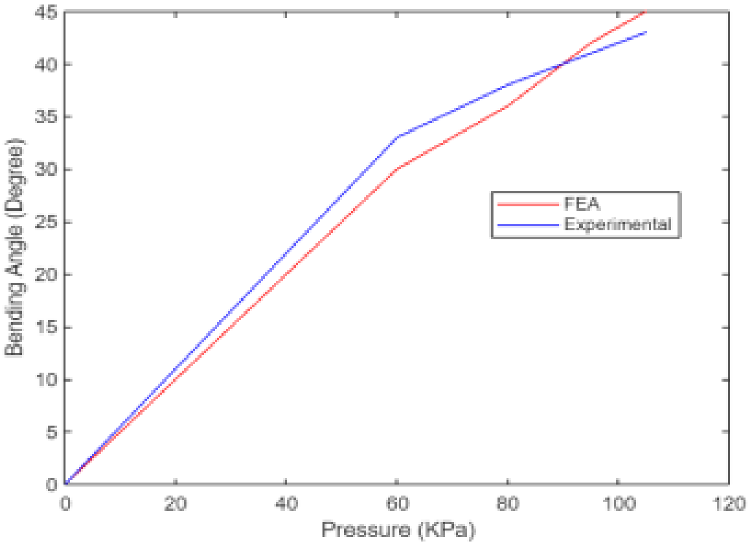


Figure 49. Graph of Results of 1st Actuator

8.2.4 FEA & Experimental Result of 2nd Actuator

Bending angle of 2nd actuator were determined experimentally and by FEA by the method illustrated in Figure.

Table 17. 2nd Actuator Result Comparison

Bending Angle **(FEA) (2^{nd} Actuator)**	**Bending Angle** **(Experimental) (2^{nd} Actuator)**
34°	36°
38°	41°
42°	45°
45°	47°

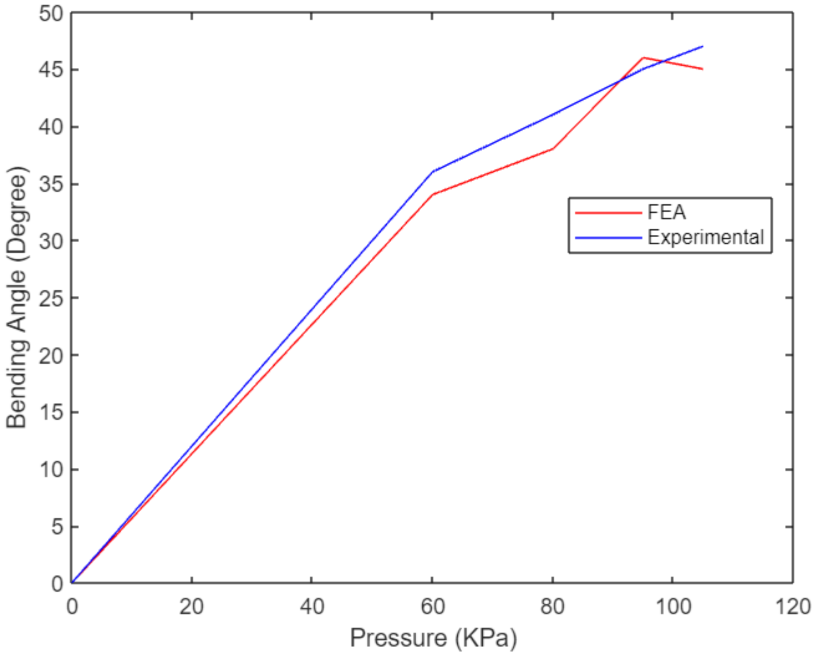


Figure 50. Graph of 2nd Actuator Results

CHAPTER 9: ASSEMBLY & WORKING

The next steps to follow the design, analysis, fabrication & experimental validation of the soft actuator is the assembly of soft actuators by means of a bracket. After that the bracket which serves as the soft robotic gripper can be attached to the manipulator system.

9.1 Bracket Design

A bracket was designed to mount the soft actuator on it. In bracket three hollow rectangles were left, each at 120 degrees to hold the actuators. Space between actuator was left according to the size of object to be grasped as explained previously. Three sliders were put in hollow rectangles to vary the space between actuators so that they can accommodate different sizes of objects. For fabrication bracket was 3d printed using PLA material.

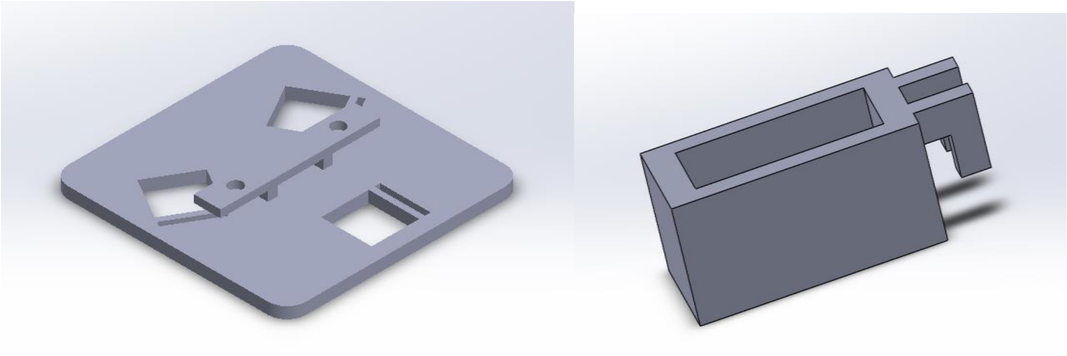


Figure 51. Bracket & Slider

9.2 Gripper Assembly

The assembly of soft robotic gripper using three soft actuators is shown in Figure 52.

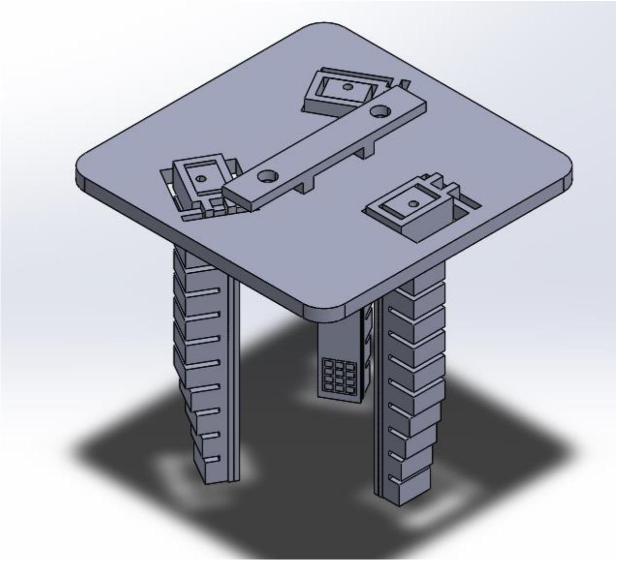


Figure 52. CAD Assembly of Soft Robotic Gripper

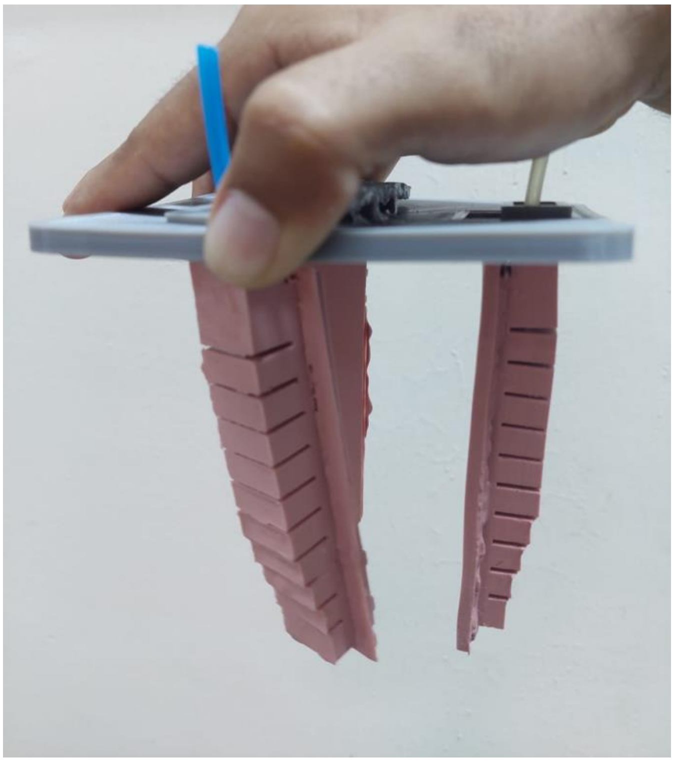


Figure 53. Assembled Soft Robotic Gripper

9.3 System Assembly

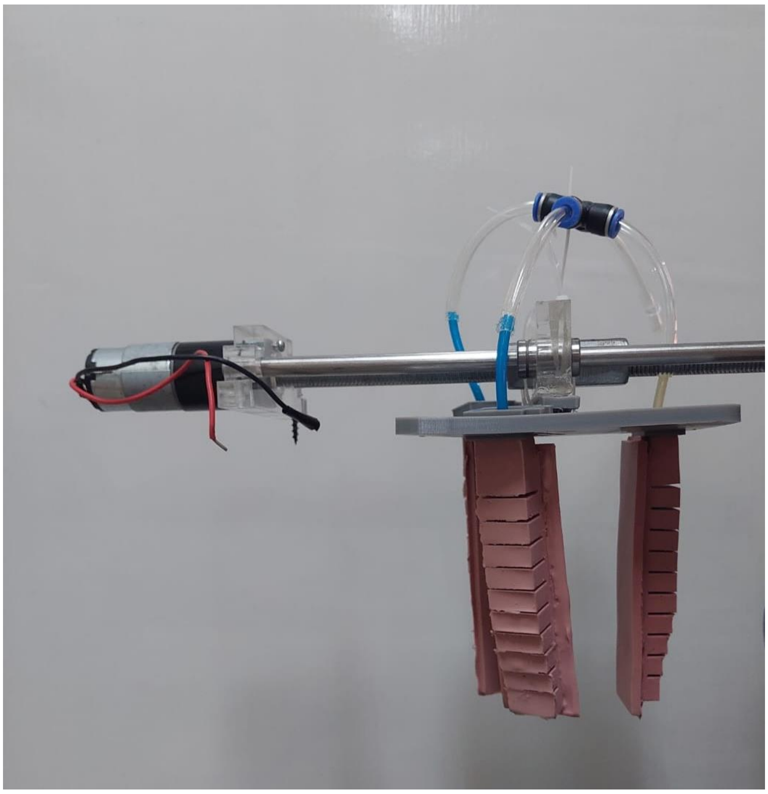


Figure 54. System Assembled (Auxiliary part & main part)

9.4 Working Demonstration

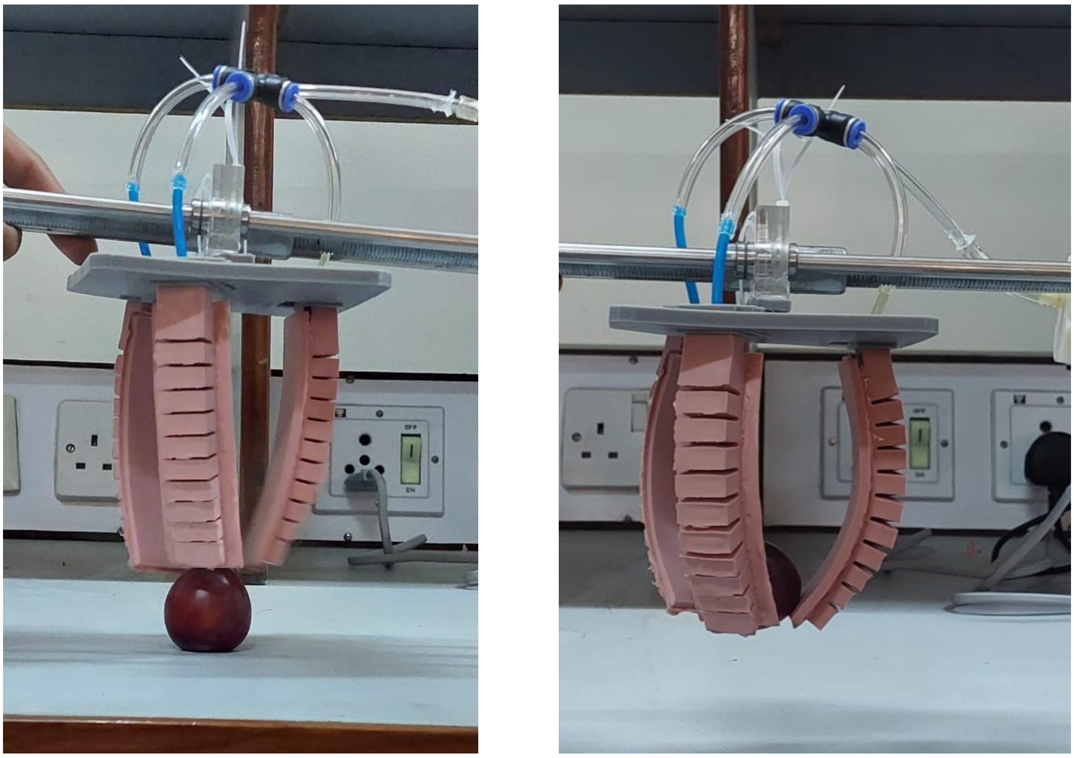


Figure 55. Grasping of Plum by soft robotic gripper

In Figure 45, we can see that even if fruit size varies for the same fruit, it can grasp the fruit easily and adapt to the surface.

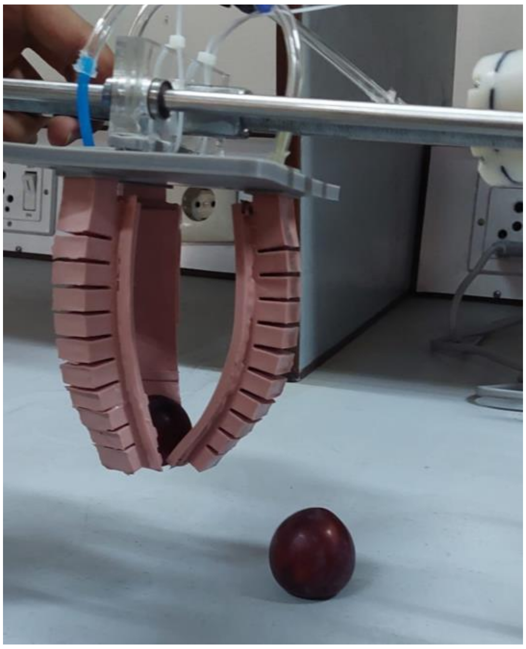


Figure 56. Grasping of small plum

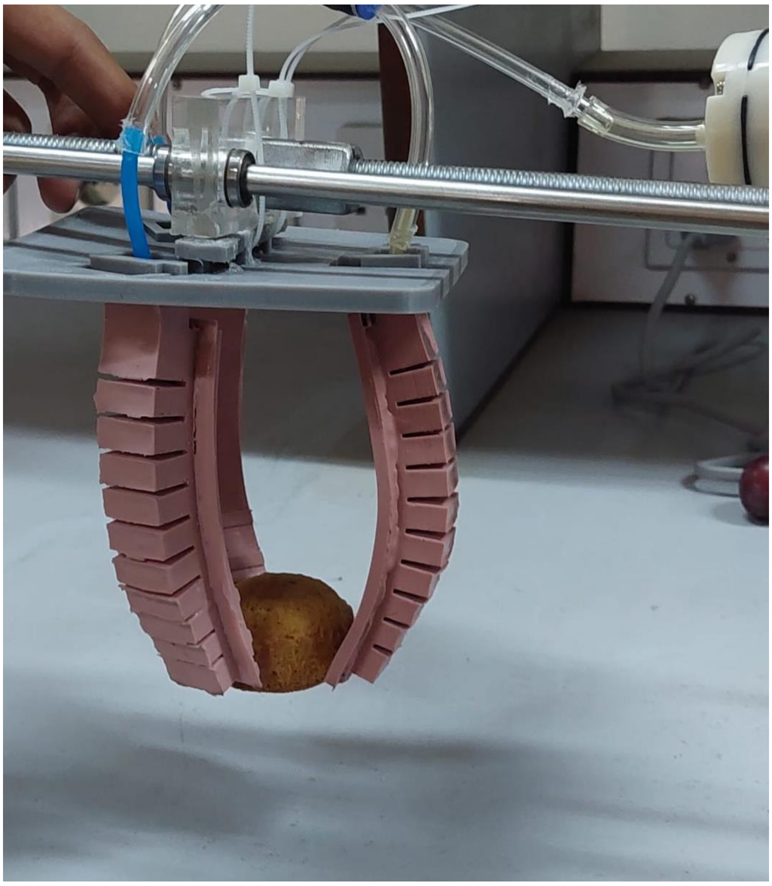


Figure 57. Bakery item (muffin) picked

CHAPTER 10: CONCLUSION

The objective of food handling through soft actuators was successfully done without any damage to objects and objects having soft, delicate uneven surfaces were successfully grasped.

By introducing design improvements in the soft actuators, we were able to achieve fast actuation and thus reduced the time for actuator to bend. The results design improvements were backed up by the analysis of soft actuator done on ANSYS. The actuators assembled to form soft gripper actuated harmoniously and operated to grasp different objects effectively.

The actuation system was designed at the minimum cost possible, and it is also very easy to implement on any pneumatically actuated system. It functions smoothly on a medium sized twelve-volt battery. It provided continuous pressurized air and almost no abnormalities were reported in the bending of soft actuators through this actuation system.

Overall, with the soft robotic gripper we were able to achieve the grasping of variety of objects having soft, delicate, and uneven surfaces with reduced system complexity and the detections systems that are otherwise required in other kinds of robotic grippers. The whole system designed analyzed & fabricated comes under the nature inspired field of Soft Robotics that has potential for filling in many different application spaces.

CHAPTER 11: LIMITATIONS & RECOMMENDATIONS

10.1 Limitations

The limitations of our projects include:

1. The actuators can only sustain a pressure of safe limit of 145 kPa.
2. The pressure can only be provided from a single point which limits the control of pressurizing only specific chambers.
3. The soft actuators are not embedded with sensors (due to cost of each sensor) that can track back data for storing and detecting object sizes in a database.
4. The computational cost of precise analysis of actuators limits the analysis procedure of our project.
5. The mass range of objects that can be grasped is 250 to 400 grams.
6. The actuation system is not fully autonomous and requires minor human input.
7. The actuation system can only be used for a single soft robotic gripper.

10.2 Recommendations for Future Work

The field of soft robotics is relatively new, and much research area is still unexplored. Our project on the design soft actuators has played a part in the development of this field and there is massive potential for growth in these areas of soft robotics. With this we have some recommendations for future work for soft actuators particularly and field of soft robotics generally:

1. Improvement in design of actuator by studying effects of volume change of chambers for a specific hyper elastic material can lead to more rapid and resilient soft actuators.
2. Utilizing better tools during fabrication process can lead to less air incorporation which makes better soft actuators overall.
3. Three Dimensional printed molds using SLA technique will give better soft actuator texture overall.
4. Utilizing ‘bend sensors’ or ‘flex sensors’ embedded at the base of the actuator to help distinguish between sizes of objects with help of data points obtained by the curvature of the actuator when it holds an object.
5. Full synchronization of whole robotic system so that it works with just a single input.

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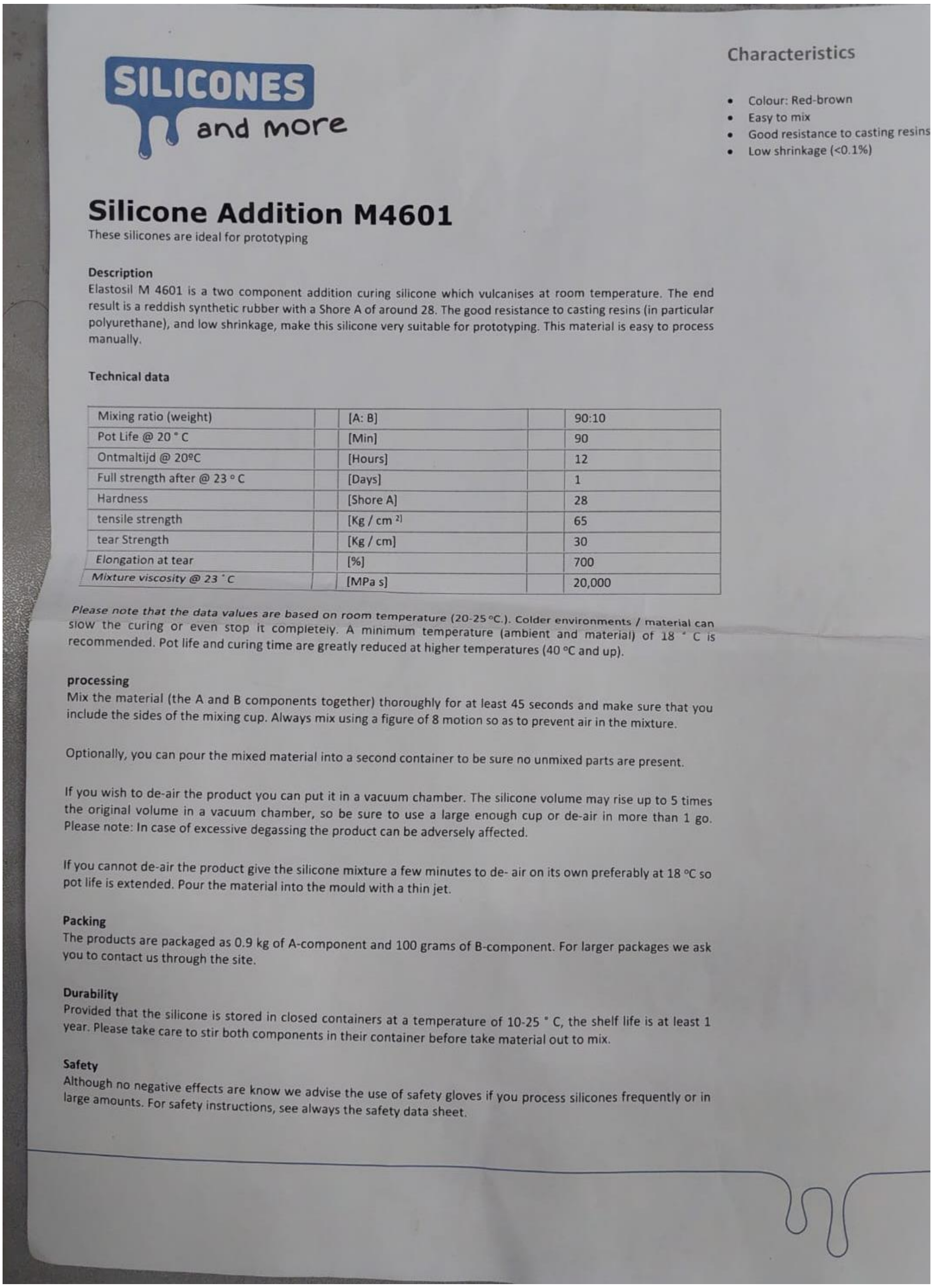
Appendix

Arduino Sketch for Actuation System

```
const int switch1 = 2;
const int switch2 = 3;
const int ValvePin = 6;
const int pumpPin = 4;

int state;
int lastState;
int newState;

int state2;
int lastState2;
int newState2;

void setup() {

Serial.begin(9600);
 pinMode(switch1, INPUT);
 pinMode (switch2, INPUT);
 pinMode (pumpPin, OUTPUT);
 pinMode (ValvePin, OUTPUT);

 digitalWrite(pumpPin, HIGH); // HIGH means airpump will be turned off
 digitalWrite(ValvePin, HIGH); // HIGH means valve be closed

}

void loop()
```

```
{
 state = digitalRead(switch1);
 state2 = digitalRead(switch2);



 if (state != lastState) {
 if (state == HIGH) {
 if (newState == HIGH)
    {newState = LOW;}
 else
    { newState = HIGH;}
 }
 lastState = state;
 }

 if (state2 != lastState2) {
 if (state2 == HIGH) {
 if (newState2 == HIGH)
    {newState2 = LOW;}
 else
    { newState2 = HIGH;}
 }
 lastState2 = state2;
 }

 digitalWrite(pumpPin, newState);
 digitalWrite(ValvePin, newState2);

 delay(20);
}
```

Elastosil m4601 Manufacturer sheet



SILICONES and more

Silicone Addition M4601

These silicones are ideal for prototyping

Description

Elastosil M 4601 is a two component addition curing silicone which vulcanises at room temperature. The end result is a reddish synthetic rubber with a Shore A of around 28. The good resistance to casting resins (in particular polyurethane), and low shrinkage, make this silicone very suitable for prototyping. This material is easy to process manually.

Technical data

Mixing ratio (weight)		[A: B]		90:10
Pot Life @ 20 ° C		[Min]		90
Ontmaltijd @ 20ºC		[Hours]		12
Full strength after @ 23 ° C		[Days]		1
Hardness		[Shore A]		28
tensile strength		[Kg / cm 2]		65
tear Strength		[Kg / cm]		30
Elongation at tear		[%]		700
Mixture viscosity @ 23 ˚C		[MPa s]		20,000

Please note that the data values are based on room temperature (20-25 °C.). Colder environments / material can slow the curing or even stop it completely. A minimum temperature (ambient and material) of 18 ° C is recommended. Pot life and curing time are greatly reduced at higher temperatures (40 °C and up).

processing

Mix the material (the A and B components together) thoroughly for at least 45 seconds and make sure that you include the sides of the mixing cup. Always mix using a figure of 8 motion so as to prevent air in the mixture.

Optionally, you can pour the mixed material into a second container to be sure no unmixed parts are present.

If you wish to de-air the product you can put it in a vacuum chamber. The silicone volume may rise up to 5 times the original volume in a vacuum chamber, so be sure to use a large enough cup or de-air in more than 1 go. Please note: In case of excessive degassing the product can be adversely affected.

If you cannot de-air the product give the silicone mixture a few minutes to de- air on its own preferably at 18 °C so pot life is extended. Pour the material into the mould with a thin jet.

Packing

The products are packaged as 0.9 kg of A-component and 100 grams of B-component. For larger packages we ask you to contact us through the site.

Durability

Provided that the silicone is stored in closed containers at a temperature of 10-25 ° C, the shelf life is at least 1 year. Please take care to stir both components in their container before take material out to mix.

Safety

Although no negative effects are know we advise the use of safety gloves if you process silicones frequently or in large amounts. For safety instructions, see always the safety data sheet.

Characteristics

- Colour: Red-brown
- Easy to mix
- Good resistance to casting resins
- Low shrinkage (<0.1%)

END.