DESIGN AND DEVELOPMENT OF VARIABLE STIFFNESS TAPERED TYPE SOFT ROBOTIC GRIPPER FOR FRUIT PICKING APPLICATIONS

Project Report

Submitted by

VEDANT NATH
200929005

SIDHARTH KUDUPUDI
200929028

Under the guidance of

DR. ANKUR JAISWAL
Assistant Professor
Department of Mechatronics
MIT Manipal

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DEPARTMENT OF MECHATRONICS

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CERTIFICATE

This is to certify that the project titled **DESIGN AND DEVELOPMENT OF VARIABLE STIFFNESS TAPERED TYPE SOFT ROBOTIC GRIPPER FOR FRUIT PICKING APPLICATION** is a record of the bonafide work done by **VEDANT NATH** (*Reg. No. 200929005*) and **SIDHARTH KUDUPUDI** (*Reg. No. 200929028)* submitted in partial fulfillment of the requirements for the award of the Degree of Bachelor of Technology (B.Tech.) in **MECHATRONICS** of Manipal Institute of Technology, Manipal, Karnataka, (A Constituent unit of Manipal Academy of Higher Education), during the academic year 2023-2024.

Dr. Ankur Jaiswal
Internal Guide
Assistant Professor
Department of Mechatronics
MIT Manipal

Dr. D. V. Kamath
Professor & HOD,
Department of Mechatronics
MIT Manipal

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ABSTRACT

The development of a tapered soft robotic gripper for fruit harvesting provides a practical solution for modern agriculture. With the growing need for automation in agriculture, soft robotics solutions such as grippers with adjustable stiffness can prove to be effective. This gripper can handle fruit efficiently and gently during the picking process. These innovative grippers enhance the efficiency of the task and reduce labour expenses. The project's goal is to develop, model, produce, and incorporate a gripper with variable stiffness and a tapered shape for precise and gentle fruit manipulation. This work is important as it tackles the challenges encountered in traditional fruit-picking techniques.

This study involves a thorough literature review to understand current soft robotics gripper designs for fruit picking. The process involves selecting an optimal model based on simulations, considering factors like total deformation, bending angle, force reaction, etc. Using Fusion 360, CAD enables detailed design iterations. ANSYS is used for FEA simulations and parametric analysis to ensure structural integrity and performance optimisation. Tensile tests following ASTM standards are performed to obtain material properties for the fabrication of the gripper. 3D printing technology was utilised for the rapid prototyping of gripper moulds and UR5 robot arm mounts, expediting the fabrication process. Integration with the UR5 bot involves mechanical assembly, electrical and pneumatic connections, and programming for control systems.

The results highlight the gripper's ability to delicately handle fruits, but limitations in vertical operations, smaller fruit sizes, and material durability are identified. The project's future scope includes addressing these limitations through further design refinements, material enhancements, and automation advancements for broader agricultural applications.

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LIST OF ABBREVIATIONS

PPE	: Personal Protective Equipment
LCA	: Life Cycle Assessment
FEA	: Finite Element Analysis
SMA	: Shape Memory Alloy
SPA	: Soft Pneumatic Actuator
PNA	: Pneumatic Network Actuator
SRF	: Soft Robotic Finger
RWS	: Reconfigurable Workspace Soft
FS	: Fully Soft
TPU	: Thermoplastic Polyurethane
APA	: Antagonistic Pneumatic Actuator
FFF	: Fused Filament Fabrication
COBOT	: Collaborative Robot
CAD	: Computer-Aided Design
CAE	: Computer-Aided Engineering
ASTM	: American Society for Testing and Material
LSR	: Liquid Silicone Rubber
UTM	: Universal Testing Machine
PLA	: Polylactic Acid
UR	: Universal Robot

CHAPTER 1

INTRODUCTION

Manual fruit picking is a tedious task. To counter this problem, robotic tools and grippers have been developed. However, these grippers had a drawback. Traditional grippers used in crop picking are often rigid and can crush delicate produce. Crop picking requires grippers specifically designed to handle fruits delicately. Hence, the need for a variable stiffness gripper arises.

A soft robotic gripper has been developed for harvesting fruit. Its tapered shape enables secure grasping of fruits of various sizes. This differs from traditional rigid grippers by being soft and adaptable to different crop shapes and sizes, reducing the risk of fruit damage.

The development process included design, analysis, simulation, fabrication, and integration. Special flexible materials with unique mechanical properties were utilized to create the gripper, allowing for adjustable firmness. 3D printing and moulding techniques were employed in the production of the gripper. The firmness of the gripper's grip on the fruit is controlled by pneumatic systems. The gripper was attached to the UR5 robot arm for precise fruit picking.

In summary, the new soft robotic gripper for fruit harvesting represents an innovative application of soft robotics in agriculture. Its flexibility and tapered design make it a practical solution for fruit harvesting, potentially revolutionizing the efficiency and productivity of fruit picking.

1.1 Present Day Scenario

Previously, fruit handling in agriculture relied on manual labor and inflexible grippers. The traditional rigid grippers lacked adaptability and precision, causing inefficiencies and crop damage. Human workers physically harvested, sorted, and transported crops, depending on their skill and strength.

Unlike the old stiff grippers, soft grippers are more flexible and adaptable, capable of adjusting to various shapes and sizes of harvest, minimizing the risk of damage. They can also apply different levels of force, allowing for more delicate handling. Another advancement is the development of versatile gripper designs suitable for different types and sizes of fruits thus improving crop handling efficiency.

Innovative production methods like 3D printing and moulding have led to the creation of intricate gripper designs that offer improved performance. Advanced materials, such as silicone rubber and elastomers, have enhanced gripper flexibility and durability.

In the realm of automation, agricultural grippers now incorporate algorithms and sensor systems for independent operation. These systems utilize sensor feedback to adjust grip strength, position, and orientation in real-time, enhancing precision. This reduces the dependency on manual labor.

1.2 Motivation

- Addressing Shortcomings in Previous Work: The project aims to fill gaps identified in the literature review. This includes the integration of pneumatic actuators with a tapered design in grippers.
- Documentation and Validation: The project aims to validate the gripper design through simulations and experiments.
- Improving Productivity: The project aims to reduce damage to crops during fruit picking. The soft robotic gripper design enhances productivity and adaptability.
- Potential for Revolutionizing Agricultural Practices: The project aims to reform sustainable farming practices by meeting the demand for precision farming technologies.

1.3 Relevance of the Project

The project is focused on improving the grippers used in fruit harvesting applications to minimize crop damage and enhance grip precision.

The soft robotic gripper with a tapered design meets the demand for grippers that delicately handle fruits, unlike traditional rigid grippers and manual labor methods. The project aims to optimize these tasks.

The project aims to promote sustainable farming practices and meet industry’s demand for efficient, safe, and environmentally friendly agricultural technologies. By doing so, it can maximize yield and minimize environmental damage.

The safety precautions followed, the environmental aspects considered, and the uniqueness of the methodology adopted are explained in this section.

1.4 Impact of the Work on the Environment, Safety and Other Factors

This section includes the safety precautions followed, the environmental aspects considered, and the uniqueness of the methodology adopted.

1.4.1 Safety Precautions Followed

When developing a soft robotic gripper, it's important to prioritise strict safety measures to protect operators and the environment. This project strictly follows safety protocols to reduce potential risks and hazards.

- Material Selection: The gripper components are constructed from non-toxic and food-safe materials to comply with standards for handling fruits. Additionally, these materials are long-lasting and resistant to deterioration, reducing the potential for contamination.
- Fabrication Processes: Precautions are implemented to ensure the safety of all individuals involved during fabrication. Guidelines are in place for the use of machinery such as 3D printers and laboratory equipment to prevent accidents and damage. While working team members adhere to wearing protective gear for their safety.
- Testing Procedures: The performance and dependability of the gripper are assessed during testing. Measures such as equipment calibration and emergency shutdown procedures are utilized to mitigate risks during testing. The testing environments are carefully controlled to prevent mishaps.

1.4.2 Environmental Aspects Considered

The development of the soft robotic gripper emphasizes environmental sustainability. The project considers the impact of the grippers on the environment and incorporates measures to minimize their ecological footprint.

- Selection and Disposal of Materials: Environmentally conscious materials were used to manufacture the gripper. Our goal is to minimize waste and maximize material reuse. All materials are disposed of in an environmentally friendly manner.
- Material and Energy Efficiency: The project prioritizes reduced material usage and energy consumption in gripper manufacturing. For operation, pneumatic actuators were used.
- Life Cycle Assessment: The environmental impact of the gripper is assessed using life cycle assessment (LCA) techniques across its entire life cycle, from raw material extraction to end-of-life disposal. This evaluation helps identify ways to reduce the gripper's environmental impact at each stage of its life cycle.

1.4.3 Uniqueness of the Methodology Adopted

The project's focus is the development of a flexible robotic gripper with 10 chambers. By utilizing pneumatic actuation and design, the gripper is designed to provide improved control and versatility. Its use of soft materials and pneumatic actuators makes it well-suited for a variety of agricultural tasks.

Incorporating PneuNet technology into the gripper design offers several advantages, including efficient and lightweight construction. The gripper's capacity to adapt its grasp through pneumatic actuators and structure reduces harm to crops, rendering it suitable for precision agriculture. Using soft materials, the gripper can conform to different fruits, potentially leading to more efficient, productive, and sustainable farming practices.

CHAPTER 2

LITERATURE REVIEW AND OBJECTIVES

Detailed Literature Review, the Objective, and the Scope of the project is included in this section.

2.1 Literature Review

Soft robotics is an expanding area that focuses on making robots using soft and flexible materials like elastomers and shape memory alloys. These materials enable grippers to be more flexible and safer when in agricultural environments. The latest development in this field is the creation of soft robotic grippers. They are capable of grasping and moving objects with irregular shapes. PneuNet structures utilize pneumatic systems to generate motion. The flexible nature of the material helps the gripper to bend easily and grip fruits. This opens new possibilities for enhancing how grippers handle objects.

2.1.1 Design and Finite Element Analysis

Researchers have explored the impact of the size and shape of soft robotic grippers. The focus has been on multi-chamber pneumatic soft actuators. They are effective for grasping irregularly shaped objects. By understanding these factors, researchers can create improved grippers with better-grasping abilities [1].

Tennakoon et al. have devised a new method to modify the width, height, and wall thickness of PneuNet chambers [2]. They used this approach and combined finite element analysis (FEA) to calculate bending angles. According to their research, altering the chamber width had the most significant effect on the bending angle. Their study offers valuable insights for designing PneuNets with specific bending angles.

Wang et al. tackle the challenges associated with bending and twisting in Pneu-Net actuators. They introduce a new design approach aimed at enhancing their flexibility [3]. FEA and testing methods were employed to investigate the adjustment of chamber angles for complicated movements. This study aims to improve the control and adaptability of soft robotic systems. C. H. Liu et al. focus on increasing the bending capabilities of soft grippers. Two-fingered and three-fingered soft grippers were used. Their performance was compared to a commercial SRT soft pneumatic actuator [4]. The results show improvements, with the newly developed bending actuator achieving an average bending angle of 111° and an output force of 9.45 N.

Wang and Hirai [5] have optimized the chambers of a bellow-type soft actuator. Simulations and real-world testing were used to determine the optimal parameters for actuator bending and force application. Hu et al. [6] have developed Pneu-Net actuators (PNAs) through simulations. Global Analysis of Variance (ANOVA) was used to study the impact of different factors on the gripper’s performance. The current research has been focused on creating mathematical models to understand gripper functionality. Fujun Wang et al. [7] constructed a mathematical model for PneuNet, considering the bending of the gap layer and the movement of the chamber walls.

Zhao et al. [8] introduced a new design for the bending actuators of PneuNet. This enables increased bending while maintaining consistent pressure. FEA and multi-objective optimal were used to design and explore the influence of beam and chamber size on bending. Peng et al. [9] improved soft pneumatic grippers by integrating rigid supports. This resulted in a 150% increase in lifting force. Glick et al. [10] combined air chambers for soft finger movement with a rigid endoskeleton for transmitting gripping force. This ensured precise and adaptable grasping for a wide range of object sizes and shapes.

Liu et al. [11] examined how geometric and material parameters affect the bending angles. The partial derivative of the bending angle is calculated for each parameter in the model. Hao et al. [12] developed a soft robotic gripper with four fingers. This allowed for adjustable finger lengths and reversible control modes for object manipulation. The prototype shows the optimal selection of finger length. Simultaneously, Jain et al. [13] designed a reconfigurable workspace soft (RWS) gripper. FEA was used in the study to determine the gripper's actuators and select materials. The RWS gripper can adapt its workspace to grasp a wider range of objects, increasing its grasping workspace volume by 397%.

Elgeneidy et al. have introduced a new way to predict and control the bending response of SPAs using resistive flex sensors [14]. The study is supported by empirical models and a PID controller, which allows for precise tracking of reference signals to manipulate objects accurately. This offers valuable insights into embedded sensing for soft grippers. Alici et al. [15] have developed an analytical model to estimate the quasi-static bending displacement. To increase the bending angle, the actuator chambers have been partially separated with a gap between them. The numerical bending angle from the proposed gray-box model aligns well with the corresponding experimental results, indicating the model's accuracy. Dong et al. introduce a multi-finger soft gripper that adjusts its initial grasp postures and incorporates fingers with tapered angles, the gripper achieves a wide gripping range [16].

In another study, Gu et al. propose a model and design approach for a type of soft actuator called gPNSAs. They specifically focus on bending and twisting deformations [17]. Their model, based on the minimum potential energy method and continuum rod theory, provides insights into how geometric parameters, material properties, and external forces affect the deformations of gPNSAs. In their research, Sachin et al. have created a tailored analytical model for Pneu-net soft actuators [18]. Based on the Euler–Bernoulli finite strain hyperelastic thin cantilever beam theory, their model addresses two distinct states of the actuator and considers axial stretch and applied forces.

2.1.2 Innovative Designs

Researchers are developing new types of soft robotic grippers to improve grasping tasks in different fields. Zhu et al. [19] have created a hybrid finger design that combines soft and rigid elements, inspired by the flexibility of the human finger. They use parallel actuators to activate high force and softness as needed. In a different study, Xie et al. [20] look at the intricate structures of octopus arms to improve gripping capabilities. Additionally, Natarajan et al. [21] have designed a SPA inspired by natural locomotion mechanisms, precisely by studying the salamander's gait.

Wu et al. [22] have developed the E-Gripper, an innovation that separates the muscle actuation and force-bearing functions within the gripper. This design can achieve a maximum force of 35 N, which is significantly higher than traditional fully soft grippers (FS-Gripper) in both force and response time. Seongmin et al. [23] focus on improving fingertip force and actuation speed simultaneously in their hybrid gripper design, demonstrating superior performance compared to conventional SPAs. Li et al. [24] propose an innovative gripper design that integrates air chambers and a rigid endoskeleton. Shouyi Yu et al. [25] and Zhang et al. [26] introduce a modular gripper design that integrates features from regular and herringbone actuators. [27-28] have developed a new hand rehabilitation glove using soft actuators designed to mimic human finger movements. The approach aims to provide safe and effective hand rehabilitation.

Hancu et al. [29] have developed a data-driven approximation kinematic (DAK) model to estimate the shape of PneuNet’s soft grippers. This model uses experimental data and digital image processing for accuracy. Mondini et al. [30] have introduced Antagonistic Pneumatic Actuator (APA) PneuNet and APA FRA-Fiber-Reinforced Actuator which show bi-directional motion and increased load-bearing capacity. Miriyev et al. [31] have developed self-contained electrically-driven soft actuators with high strain density.

Zhou et al. gripper design has three soft bending fingers and an adaptive palm [32]. This allows it to conform to diverse object shapes and sizes. It can grasp objects with a force ten times its weight while operating at low pressure. Tao et al. gripper design includes a variable stiffness layer inspired by the flexible and tough scales of pangolins, as well as a toothed pneumatic actuator for power supply and increased stiffness. Experimental results show that the gripper can handle a wide variety of objects with stiffness more than twice that of conventional SPAs without variable stiffness structures [33].

2.1.3 Material Used

Soft robotic grippers often use flexible materials like elastomers or silicones. The choice of materials greatly affects how well the gripper performs [34]. J. Kim et al. [35] looked at different materials for soft actuators and their suitability for robotic applications. The review covers how these materials are made, how they perform, and what their limitations are. Haibin et al. [36] tackled the problem of grippers needing to have different levels of stiffness. They suggested a model for grasping force that uses shape memory alloys (SMAs). Gariya et al. evaluated three SPA designs using EcoFlex material and showed that the fast Pneu-net (fPN) design bends better than other designs under similar conditions [37].

Saduk et al. [38] studied how different materials affect how grippers bend in industrial settings. It is found that materials with a low Young's modulus tend to bend more. This finding can help pick the right material that improves industrial gripper performance. Manns et al. [39] looked for more flexible solutions for human-robot interaction. They explored using soft silicon grippers actuated by PneuNet, which uses 3D printing to make grippers more durable.

2.1.4 Fabrication Techniques

Soft robotic grippers can be created using different methods, such as 3D printing, moulding, and casting. These methods offer flexibility in design and material customization. Wilhelm et al. [40] used 3D-printed TPU to produce soft robotic actuators, improving force capabilities and simplifying manufacturing. Giuliano et al. used 3D printing to create pneumatic actuators for delicate fruit harvesting tasks. They focused on a new structure with a porous inner filling and a dense airtight chamber [41]. Ge et al. were the first to develop a desktop digital light processing (DLP) 3D printer for producing soft pneumatic actuators with high speed and precision [42]. Gianni et al. concentrated on achieving airtightness in 3D-printed soft actuators, particularly using fused filament fabrication (FFF) methods [43].

2.1.5 Fruit Harvesting Applications

The study by Navas et al. demonstrates how soft robotics can be used in precision agriculture, specifically in the selective harvesting produce [44]. They added a soft gripper to a two-armed robot for farming tasks. This helps with labor-intensive challenges and adds to our knowledge of automation and precision agriculture [45]. Jizhan et al. [46] studied ways to detach fruit, emphasizing the need to understand how force is transmitted, the effects of bending on fruit stems, and how the load affects fruit detachment. Gao et al. designed a pneumatic finger-like tool for picking cherry tomatoes [47]. Their tests showed that using a rotating motion instead of pulling reduced the force and shaking, so they used the rotating design in the tool.

To meet the increasing demand for efficient fruit harvesting solutions, Wang et al. [48] introduced a specialized soft robotic gripper tailored for apples. Their design integrates four tapered soft robotic fingers (SRF) and a multi-mode suction cup. In another study, Ji et al. proposed an adaptive impedance control strategy to enhance apple harvesting robot capabilities, aiming for compliant grasping to minimize mechanical damage to apples [49]. They analysed three grasping modes to mitigate plastic deformation during harvesting by establishing a Burgers viscoelastic model for apple rheology. Autonomously harvesting iceberg lettuce is tough because the lettuce is easily damaged and hard to spot. Birrell et al. made Vegebot, a system for testing and improving the harvesting process [50]. It has a smart vision system, a special tool, and unique software.

The authors predict that the future development of fruit and vegetable picking grippers will involve multi-sensing, variable stiffness, multi-functional composite materials, as well as control strategies of fusion intelligence, with the progress of micro-sensors and biomaterials [51-52].

2.1.6 Literature Summary

The field of soft robotics focuses on creating flexible and adaptable robotic systems that imitate living organisms. Soft robots use elastomer materials, allowing them to do gentle tasks without causing damage to the payload. Adding mechanisms to change variable stiffness makes soft robotic grippers more useful for handling many different things. Using flexible materials and good fabrication techniques are needed for developing soft robotic grippers. The grippers can be improved through testing and iterating. By integrating appropriate materials, CAD design, FEA simulations, and control systems, these grippers show significant promise in automating activities such as fruit harvesting.

2.2 Objectives

Primary Objective: To Design and Develop a Variable Stiffness Tapered Type Soft Robotic Gripper for Fruit Picking Applications

Sub-Objectives:

- To develop a tapered soft robotic gripper, focusing on compliance, adaptability, and efficient handling of fruits of various sizes and shapes.
- To utilise finite element analysis (FEA) to simulate and validate the gripper's design by evaluating total deformation, stress, strain, strain energy, and bending angle under various loading conditions.
- To conduct material testing to validate the material's performance in controlled environments.
- To employ advanced fabrication techniques, like moulding and 3D printing, to fabricate the gripper.
- To integrate the developed gripper with an existing UR5 COBOT and conduct tests to measure the gripper's adaptability to various crop types and sizes.

2.3 Scope

Shape memory alloys (SMAs) and control systems can be incorporated into these grippers. They can adjust their stiffness based on sensory input in real time, allowing them to work effectively. This also helps by automating physically demanding tasks, which addresses labour shortages.

The grippers can be improved by designing them to handle different types of fruits. Adding sensors and control systems will help to automate the task. This would make the fruit-picking process better. Soft robotic grippers are a big step forward in farming automation. They can help increase productivity, cut labour costs, and deliver top-quality fruit.

CHAPTER 3

THEORETICAL BACKGROUND

This section provides a thorough explanation of the theoretical foundations relevant to the project.

3.1 Theoretical Discussion

Soft robotics combines concepts from engineering, material science, and biology. It is used to develop robots that can interact with delicate objects and environments. In fruit-picking applications, soft robotic grippers are used as they can adapt to the shape of the fruit. A detailed understanding of soft robotics is required for the development of a variable stiffness tapered type soft robotic gripper.

Significant challenges are encountered during the design of soft robotic grippers. For efficient operation, it is important to find the right balance between stiffness and compliance. Stiffness determines grip force, and compliance allows for delicate handling. Material property and design influence the gripper's performance.

3.2 General Analysis

In designing a PneuNet soft robotic gripper the gripper's geometry and the material used are considered. The gripper's geometry is crucial for its flexibility. For better flexibility and the ability to conform to the shape of fruits, hyperelastic materials like silicone and elastomers are preferred as they provide good grip.

The tapered design of the gripper enhances its ability to grasp objects. It's important to understand how the gripper behaves under different types of pressure to improve its performance.

Pneumatic systems are used to actuate the gripper. This is because they are simple and cost-effective. However, they can be slow and imprecise. For increased precision, control systems and sensors are used. provide Alternatives to traditional materials, including shape-memory alloys and dielectric elastomers.

3.3 Mathematical Derivations

Total deformation for a soft robotic gripper is calculated using beam theory and FEA. Deformation is influenced by the applied loads, material properties, and gripper geometry. Strain measures the gripper deformation with respect to its original size. Stress measures internal resistance to deformation. Strain energy is the energy stored in the gripper due to deformation. The bending angle indicates the degree to which the gripper can bend under actuation. This affects its ability to conform to and grasp objects of various shapes and sizes.

Assume, the soft robotic gripper acts like a cantilever beam. Therefore, one side has a fixed support. Its behaviour can be predicted using principles of mechanics. The following equation describes the total deformation of the gripper:

$$\Delta = \Delta l + \Delta\theta z \tag{3.1}$$

Where, Δl is the longitudinal deformation and Δθz is the angular deformation. The longitudinal deformation is calculated using the following equation:

$$\Delta l = \frac{1}{E} \times \frac{FL}{A} \tag{3.2}$$

Where, E is Young's modulus, F is the force applied, L is the length of the gripper, and A is the cross-sectional area. The angular deformation is calculated using the following equation:

$$\Delta\theta z = \frac{Ml}{EI} \tag{3.3}$$

Where, M is the bending moment, and I is the moment of inertia. The following equation describes the strain of the gripper:

$$\varepsilon = \frac{\Delta l}{L} \tag{3.4}$$

Where, ε is the strain, Δl is the longitudinal deformation, and L is the length of the gripper. The following equation describes the stress of the gripper:

$$\sigma = E \times \varepsilon \tag{3.5}$$

Where, σ is the stress, E is Young's modulus, and ε is the strain. The following equation can describe the strain energy of the gripper:

$$U = \frac{1}{2} \times \frac{FL^2}{EA} \tag{3.6}$$

where U, is the strain energy, F is the force applied, L is the length of the gripper, E is Young's modulus, and A is the cross-sectional area.

The following equations are used to analyze the behaviour of the gripper. The outcomes are used to optimize the design. The desired deformation and force exerted can be modified by modifying the gripper's length, cross-sectional area, and material properties.

The gripper's position is determined by the bending angle. This enhances grip precision and adaptability. Improving the bending angle enables the gripper to grasp fruits of various shapes and sizes with precision.

A mathematical approach is implemented to calculate the gripper's bending angle. The simulation results are used for the position coordinates of the upper and lower edges of the gripper on a 2D plane. The coordinates (x_1,y_1) denote the upper edge of the gripper, and (x_2,y_2) represent the lower edge of the gripper.

The height of the gripper is added to the upper edge's Y-coordinate. This height-adjusted coordinate provides accurate measurements and analysis of the gripper's configuration on the vertical axis. The height of the gripper is denoted as h.

$$y_1{}' = y_1 + h \tag{3.7}$$

The differences in x_1, x_2, and y_1, y_2 values are calculated, representing changes along the horizontal and vertical axes, respectively. These are denoted as Δx and Δy.

$$\Delta x = x_2 - x_1 \tag{3.8}$$

$$\Delta y = y_2 - (y_1 + h) \tag{3.9}$$

Then the slope of the line connecting the upper and lower edges is calculated using:

$$m = \frac{\Delta y}{\Delta x} \tag{3.10}$$

This slope (m) helps understand the gripper's inclination. Next, the arctangent function (ATAN) is applied to calculate the bending angle in degrees. θ represents the gripper's bending angle. This angle is used to assess the gripper's flexibility and adaptability.

$$\theta = ATAN\,(m) \tag{3.11}$$

Finally, adjustments are made to the angle θ based on the quadrant in which the gripper edge lies. Depending on the quadrant, 90° or 270° degrees are added to the ATAN value to ensure accurate representation relative to the coordinate axes.

$$If\ \ x2 > x1\ (1st\ or\ 4th\ quadrant):\ \theta = \theta + 90° \tag{3.12}$$

$$If\ \ x2 < x1\ (2nd\ or\ 3rd\ quadrant):\ \theta = \theta + 270° \tag{3.13}$$

The Yeoh-III hyperelastic model was the most suitable for describing the material properties. The strain energy density function is defined as:

$$W = \sum_{i=1}^{n} C_i\ (I_1 - 3)^i \tag{3.14}$$

Where, C_i are material constants, I_1 is the dependence and is applicable to purely incompressible materials.

CHAPTER 4

METHODOLOGY

The development of the soft robotic gripper began with visualising the grippers working. A thorough analysis was done to understand the requirements and challenges of fruit picking. A strong foundation was formed by understanding the techniques used in the industry. This was crucial in setting the objectives for the gripper's development.

Following this, the project moved into a literature review stage. This was to gather insights from past research in development in soft robotics and fruit-picking applications. Through this review the challenges and research gap in fruit-picking tasks were understood.

Next, the developmental process proceeded on to the design exploration phase. Various designs were created using CAD based on the insights from the literature review. The designs majorly focused on utility and adaptability. These were further evaluated through Finite Element Analysis (FEA) to assess total deformation, stress, strain, strain energy and bending angle. Later a parametric analysis was conducted to determine the optimal model based on maximum deformation and maximum force exerted. Additionally, a second gripper model with a teeth-type structure was designed to improve the bending and force capabilities.

The fabrication phase started by selecting the appropriate material. Both gripper models were manufactured in moulds using 3D printing. The fabricated grippers were then integrated with the UR5 COBOT using 3D-printed mounts. Mechanical, electrical, and pneumatic connections were used to fasten and control the gripper. The gripper was then tested using various fruits for its working.

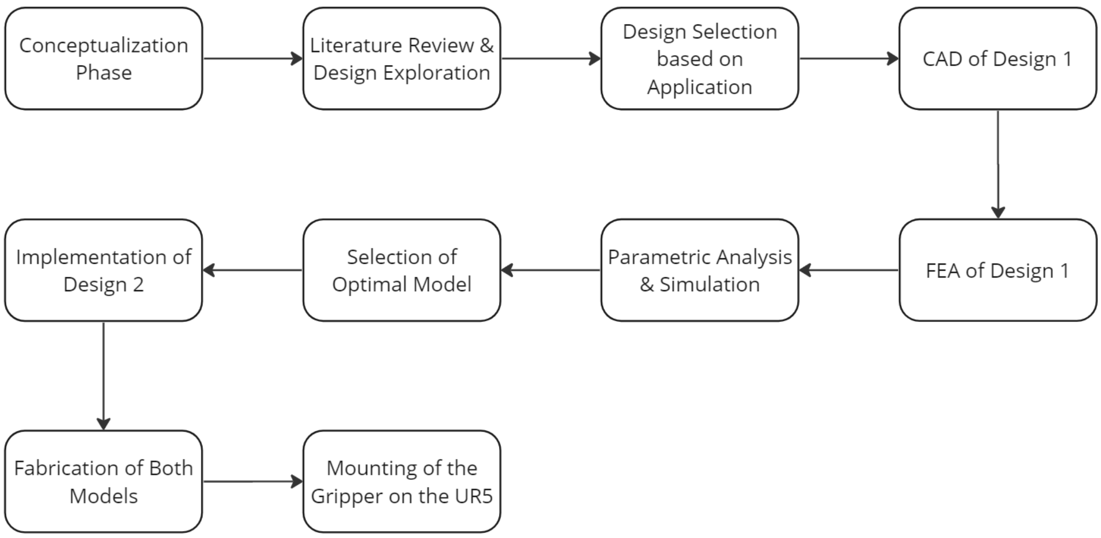


Fig. 4.1: Flowchart of the Workflow

4.1 Design Iteration of Gripper Model 1

The project began with a review of existing literature. Inspired by the design from [2], design parameters were selected to tackle the challenges of fruit picking. A 10-chamber gripper design with a taper angle (α) of 1° was chosen to adapt the various shapes and sizes of fruits. This design was set as the standard for future design iterations. The design parameters are:

Table 4.1: Design 1 Parameters of the Gripper [1]

Taper Angle (α)	1°
Length	130 mm
Height	22 mm
Width	25 mm
Chamber Thickness	4 mm
Chamber Height	15 mm
Wall Thickness	3 mm
Gap	2 mm

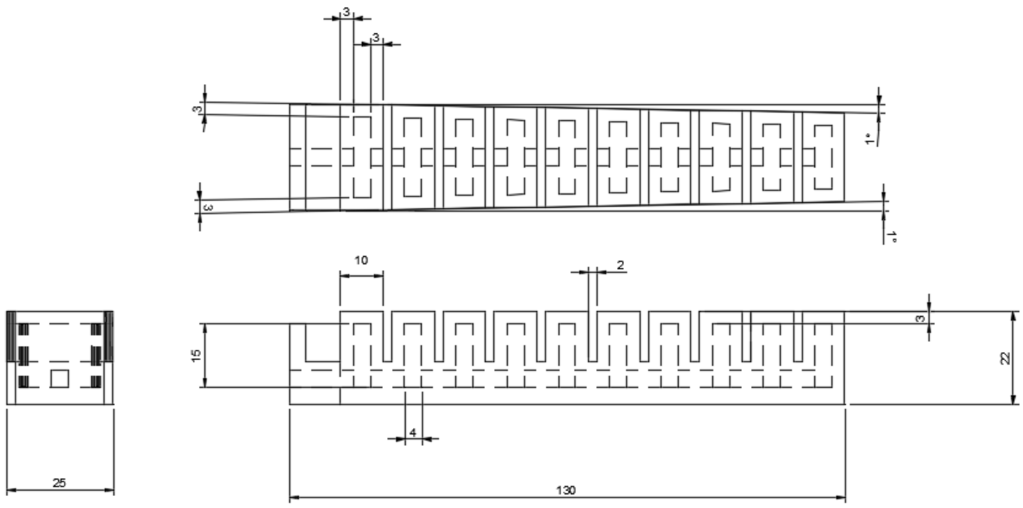


Fig. 4.2: Orthographic View of the Gripper

The design was created using CAD in Fusion 360 capturing the accurate modelling of the gripper's geometry.

4.2 Analysis and Performance Evaluation of Gripper Model 1

Following the design phase, FEA and simulation were conducted to evaluate the mechanical behaviour of the gripper under pressures ranging from 40KPa to 120KPa. Ansys Workbench, a CAE and simulation software, was used to run the simulation. The material used was SORTAClear 40 as used in [2], to validate the result. The properties of the material are:

Table 4.2: Material Properties of the SORTAClear 40 for the Analysis of the Gripper [2]

Density	1100 Kg/m³
C10	0.255 MPa
C20	-0.0283 MPa
C30	0.0269 MPa

The Yeoh-III hyperelastic model was identified as the most suitable for describing the material properties. It provided accurate simulations of the gripper's response to varying pressures [2].

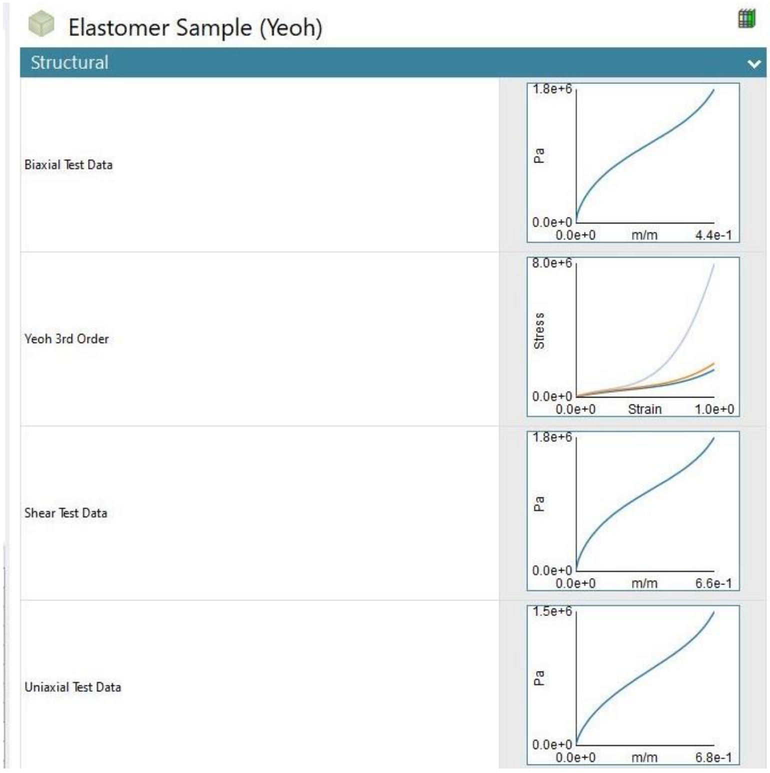


Fig. 4.3: Yeoh Model Graph

In Ansys, a static structural analysis was done to measure various metrics under static load conditions. The meshing process involved defining meshing sizes and refinement to ensure that the computational mesh accurately captures the details of the gripper's geometry. To capture the geometry details effectively, a refinement of 1 was applied. Refinement specifies the maximum number of times an initial mesh should be improved for faces, edges, and vertices [39]. The meshing details are:

Table 4.3: Meshing Details of the Gripper

Physics Preference	Mechanical
Element Order	Program Controlled
Element Size	3 mm
Refinement	1

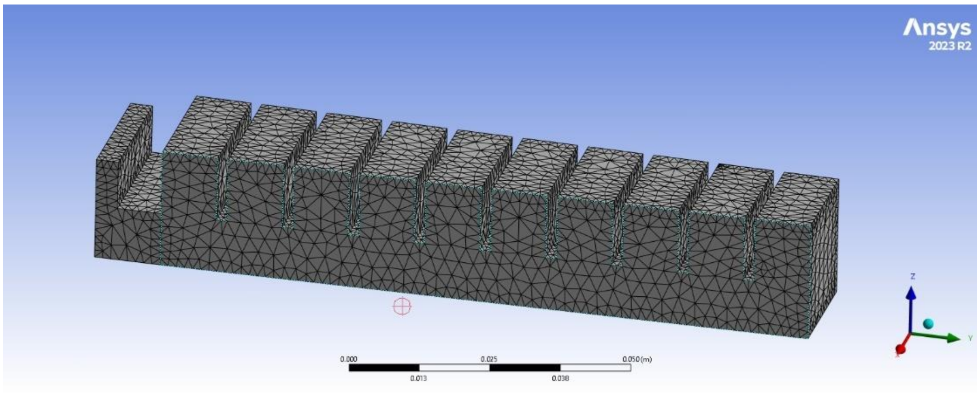


Fig. 4.4: Mesh Display of the Gripper

A parametric study was conducted using Ansys Workbench to optimise the gripper design by varying specific parameters such as [6]:

Table 4.4: Variable Parameters of the Gripper [6]

a	Chamber Wall Thickness
b	Intermediate Layer Thickness (the layer through which the pressure port passes)
c	Top Wall Thickness
d	Bottom Layer

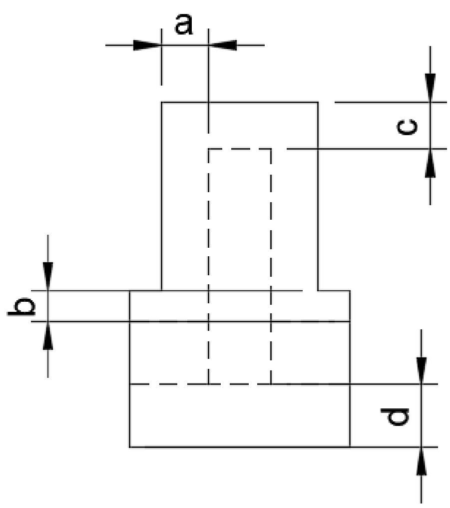


Fig. 4.5: Sub-Section View of the Gripper

Ansys was used to study metrics such as total deformation, equivalent stress distribution, equivalent elastic strain, strain energy, and the bending angle of the finger. The analysis subjected the gripper to pressures varying from 40 KPa to 120 KPa. evaluating its structural integrity and performance characteristics. Fixed parameters were set in Ansys to simulate real-world scenarios. The fixed parameters are Standard Earth Gravity, Fixed Support and Pressure [39].

Subsequently, force analysis was performed in Ansys to assess the forces exerted by each gripper model at various points. This was one of the main metrics to determine the optimal model. The forces calculated were:

- Force Reaction 1: Plate Top Face Force
- Force Reaction 2: Edge Force
- Force Reaction 3: Bottom Face Force
- Force Reaction 4: Contact Region Force

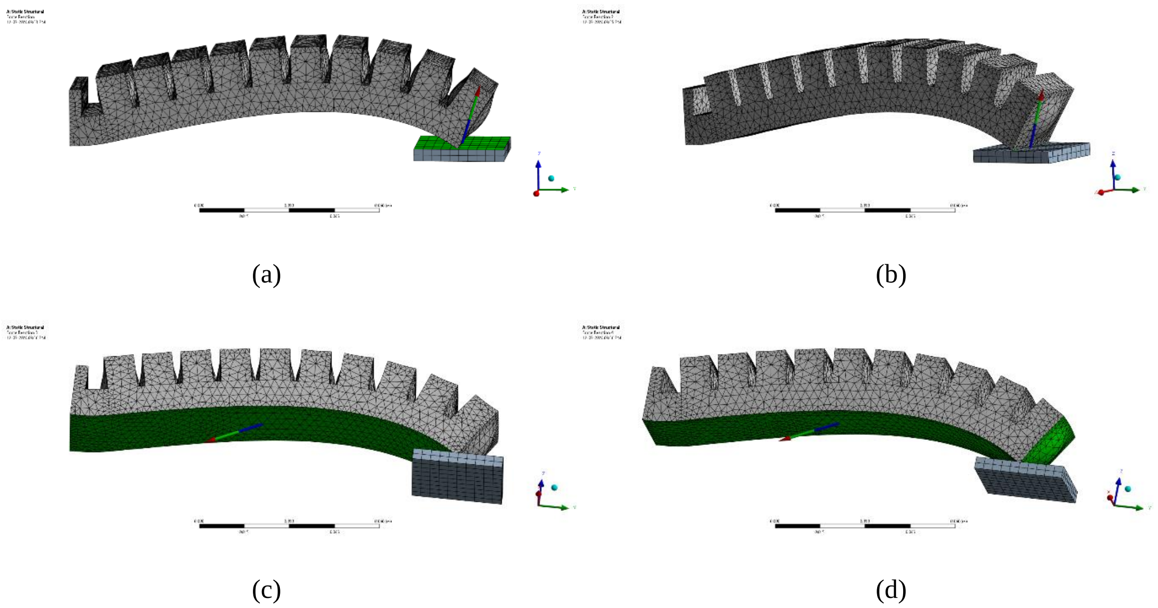


Fig. 6: (a) Force Reaction 1 (b) Force Reaction 2 (c) Force Reaction 3 (d) Force Reaction 4

The observations from the above analyses formed the base for further iterations. This resulted in a gripper design that met the requirements of maximum deformation and maximum force exerted.

4.3 Design Refinement and Innovation for Gripper Model 2

Following the analysis of the gripper models, an optimal design was selected based on the total deformation and force exerted. The parameters of this optimal model are as follows:

Table 4.5: Parameters of Design 2

Chamber Wall Thickness	3 mm
Intermediate Layer Thickness	2 mm
Top Wall Thickness	2 mm
Bottom Layer	4 mm

This model displayed the highest deformation and force results among the other models evaluated. Inspired by the optimal design of the first model, a second gripper model was designed. This new design incorporated a teeth-type structure [33] which increases the bending and force results. This addition further improves the gripper's performance in fruit-picking applications.

Table 4.6: Design Parameters of Design 2

Taper Angle (α)	1°
Length	130 mm
Height	22 mm
Width	25 mm
Chamber Thickness	4 mm
Chamber Height	16 mm
Chamber Wall Thickness	3 mm
Top Wall Thickness	2 mm
Intermediate Layer Thickness	2 mm
Bottom Layer Thickness	4 mm
Teeth Dimensions	2.5 mm × 2.5 mm
Gap	0.5 mm

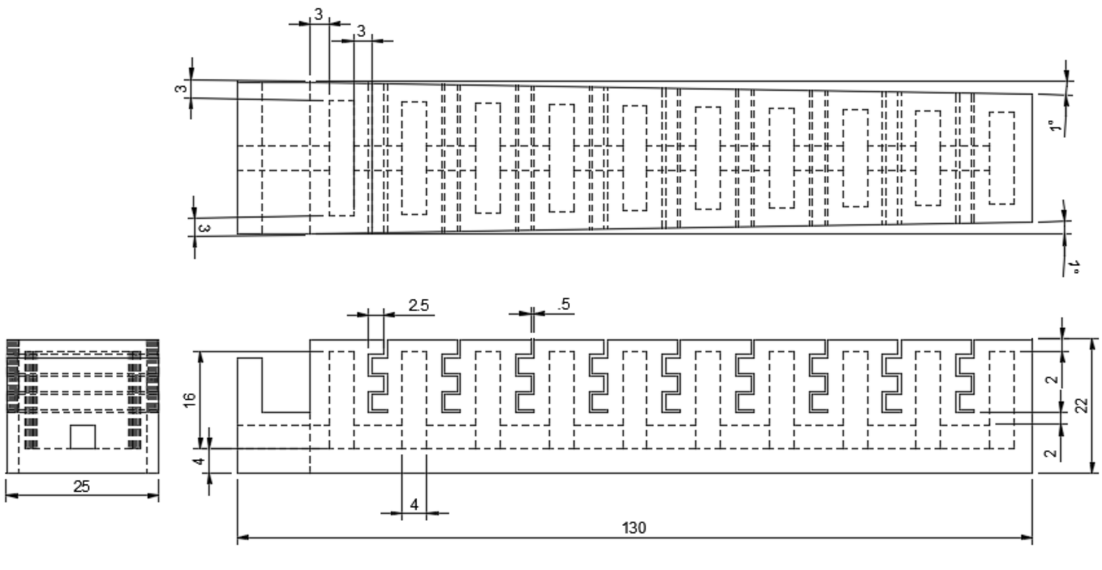
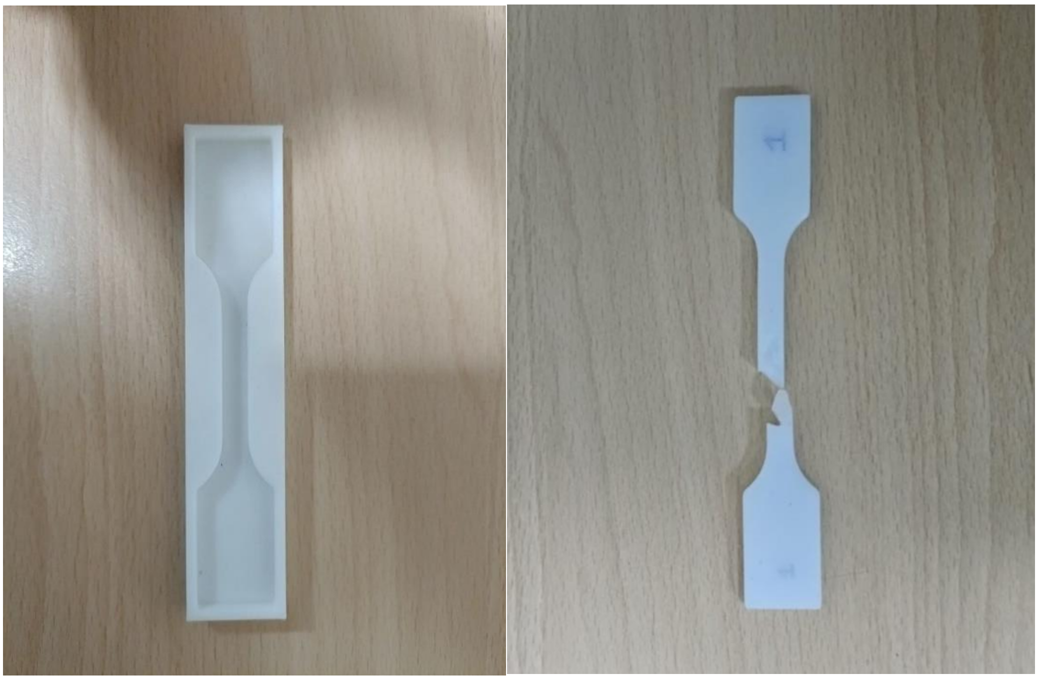


Fig. 4.7: Orthographic View of Design 2

4.4 *Material Testing*

LSR2 was selected for fabricating the gripper. Its properties were similar to SORTAClear 40 [2]. A uniaxial tensile test was conducted following the American Society for Testing and Materials (ASTM) D412 Standards. Dog bone samples were made from LSR2 following the specifications mentioned in the ASTM D412 standard.

A mould was designed using Fusion 360 and 3D printed to fabricate dog bone samples. This mould was used to produce multiple dog bone samples. This ensured consistency and accuracy in testing procedures. The tensile tests were conducted using the EZ-SX Texture Analyzer, a Universal Testing Machine (UTM) designed particularly for material testing.



(a) (b)

Fig. 4.8: (a) Dog Bone Sample Mould (b) Dog Bone Sample after Testing

During the tensile tests, data was collected as the samples elongated from 35 mm to 119 mm till the point of failure. The data collected was analysed using ANSYS to study the material's behaviour under stress and strain conditions.

Fig. 4.9: Tensile Test using UTM.

This analysis revealed that the Yeoh-III order model best fits the stress-strain graph. Therefore, LSR2 was deemed the most appropriate material for the gripper. Based on the tensile tests, the material properties of LSR2 are:

Table 4.7: Material Properties of LSR2

Density	1080 Kg/m³
C10	0.030246 MPa
C20	0.0033434 MPa
C30	-6.6095E-05 MPa

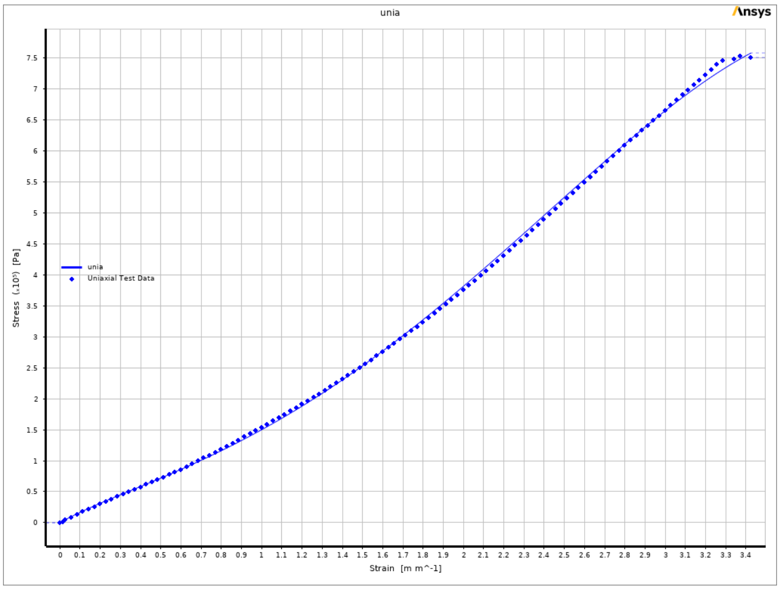
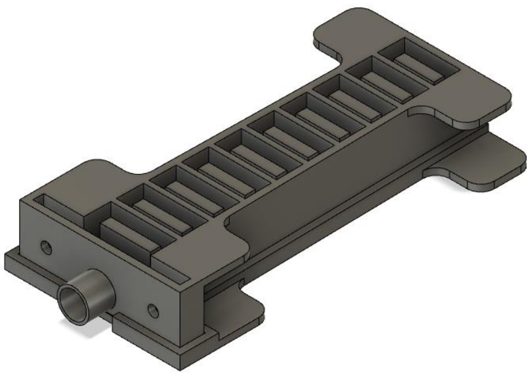


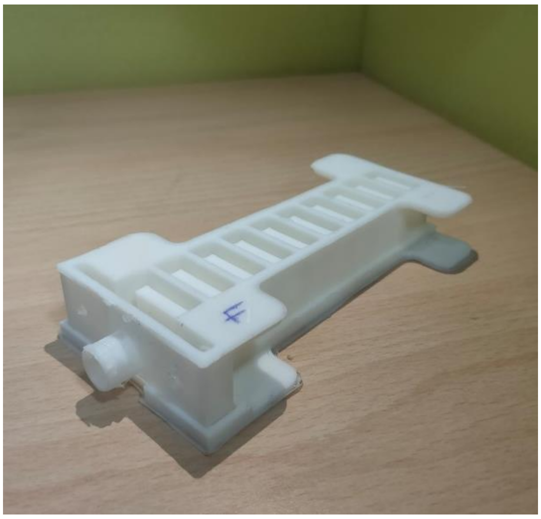
Fig. 4.10: Yeoh III Order Graph for LSR2 based on the Tensile Test

4.5 *Fabrication of Gripper Model 1 and Model 2*

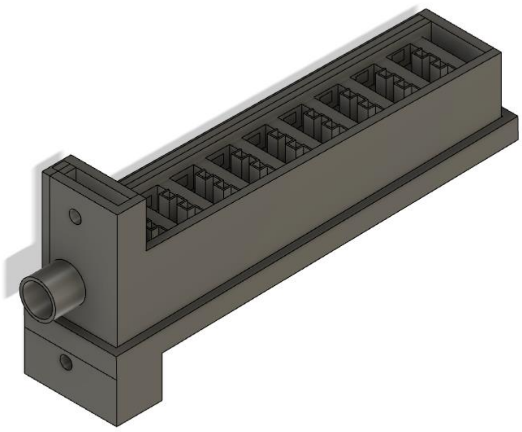
For the fabrication of Model 1 and Model 2 prototypes, accurate moulds were designed using Fusion 360, ensuring precise geometries and dimensions. Tolerances were provided to ensure a perfect fit between the gripper and the moulds. Polylactic Acid (PLA) was selected as the material for 3D printing the moulds due to its ability to create intricate and rigid structures.



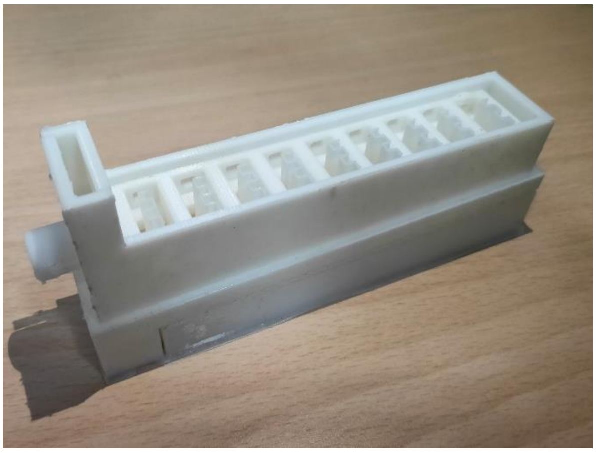
(a)



(b)



(c)



(d)

Fig. 4.11: (a) CAD of Design 1 Mould (b) 3D Printed Mould of Design 1
(c) CAD of Design 2 Mould (d) 3D Printed Mould of Design 2

Once the moulds were printed, the grippers were fabricated using Liquid Silicone Rubber (LSR2) mixed with a catalyst (CAS) for the curing process. The material was mixed in a specific ratio of 5g of CAS for every 100g of LSR2.

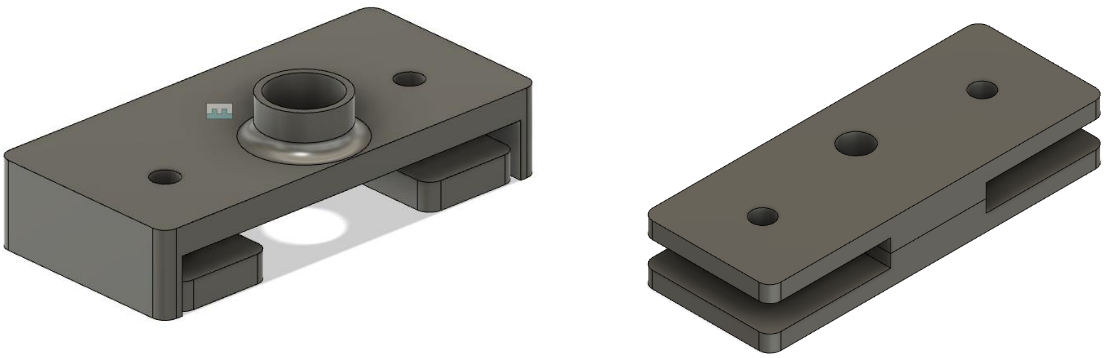
(a) (b)

Fig. 4.12: (a) LSR2 Material (b) CAS Catalyst

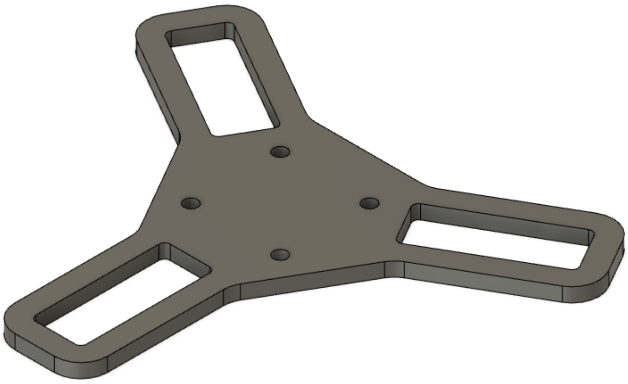
The mixture was gently poured into the moulds to prevent the formation of bubbles. After pouring, the mixture was left untouched, allowing the material to cure. Upon completion of the curing process, the moulds were carefully removed to avoid any damage to the fabricated gripper prototypes. Tabs were designed at the sides of the moulds for the easy removal of the gripper from the moulds.

4.6 *Mounting the Gripper*

For integration with the UR5 COBOT, the gripper will be oriented in a 3-claw configuration. This configuration involves mounting three fingers onto a gripper mount. This mount ensures stability by securely fixing the fingers. The gripper mount will be attached to a slider mount. As a translating joint, the slider mount is connected with a variable 3-claw mount at an angle of 120°. The distance between the fingers can be varied using by adjusting the slider mount.



(a) (b)



(c)

Fig. 4.13: (a) Gripper Mount (b) Slider Mount (c) Variable 3-Claw Mount

All the mounts in the assembly will be fabricated using PLA. This mounting assembly enables the integration of the gripper with the UR5 COBOT. The COBOT allows precise control and manipulation of objects using electric and pneumatic systems.

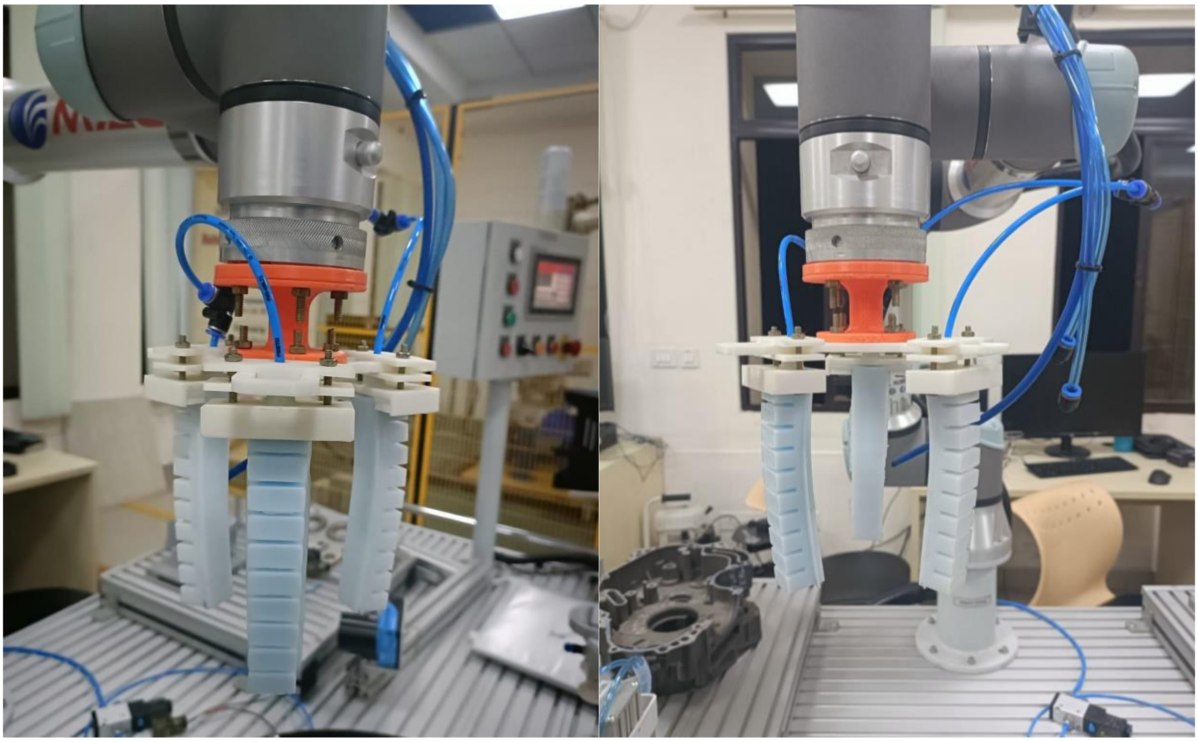


Fig. 4.14: Gipper Mounted on the UR5 COBOT

4.7 Pneumatic Setup and Actuation

The soft robotic gripper's pneumatic system was designed to provide consistent and controlled airflow, which is necessary for its operation. The setup included a compressor that can provide air at various pressures, which is ideal for handling delicate items like fruits. The air flows from the compressor to the gripper through standard pneumatic pipes.

A flow control valve was installed in the system to adjust the airflow. This allows for precise adjustments to the gripping force. The inclusion of the flow control valve was needed for a secure and gentle grip for various types of fruits. The setup underwent testing to check for leaks and ensure that consistent pressure was supplied.

The pneumatic system was then integrated with the UR5 COBOT along with the gripper. During testing, the gripper securely held the fruits without causing any damage. This shows that the pneumatic system is effectively controlling the gripper.

4.8 Nature of the Project

The development of the soft robotic gripper employs a multi-disciplinary approach. It includes CAD design, FEA simulation, material testing, 3D printing, moulding, and testing with the UR5 COBOT.

The project uses software tools such as Fusion 360, Ansys Workbench, and MATLAB. Fusion 360 is used for designing gripper geometries. Ansys is used for FEA simulations and parametric analysis to assess the mechanical behavior of various gripper iterations.

Material testing of LSR2 is conducted using the EZ-SX Texture Analyzer. Gripper components are fabricated using 3D printing and moulding. These components are then integrated with the UR5 COBOT for testing.

4.9 Tools and Resources Used

The soft robotic gripper project uses tools and software for the design, analysis, and fabrication. To design the tapered 10-chambered gripper, Fusion 360, a CAD software, was used. Fusion 360 helped create detailed geometries of the gripper's components and its iteration. Multiple iterations of the gripper were designed with varying parameters such as chamber wall thickness, top wall thickness, intermediate layer thickness and bottom layer thickness for the parametric analysis.

For FE Analysis and simulation of the gripper's behavior under varying pressures, Ansys, a CAE and simulation software, was utilized. Fixed parameters such as Standard Earth Gravity, Fixed Support, and Pressure applied to the inner walls were defined to simulate real-world scenarios. Using Ansys, the gripper’s behaviour under various pressure ranges was analysed. This led to the selection of the optimal design.

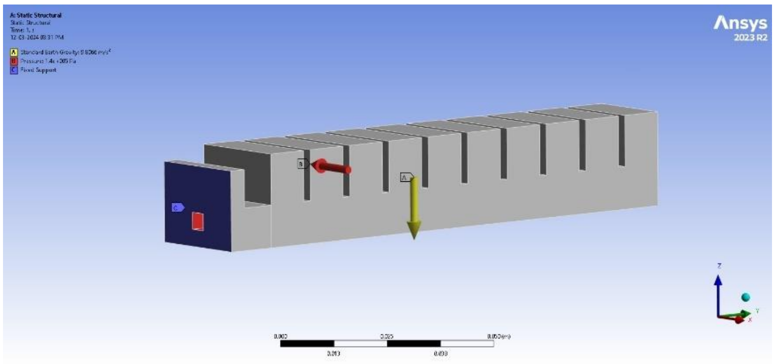


Fig. 4.15: Fixed Parameters applied on the Gripper.

MATLAB was used to analyse data and plotting graphs. The graphs provided visual insights into the simulation results. Material testing is conducted to measure the material properties and use those values to simulate the gripper model accurately. This is done using a Universal Testing Machine (UTM) - EZ-SX Texture Analyzer, an instrument used to evaluate materials' properties under tension, compression, or bending. For this project, a uniaxial tensile test is performed according to the ASTM D412 standards.

To fabricate prototypes of the optimal gripper design, 3D printing was used. A mould was designed using Fusion 360 and 3D printed using PLA. The mixture of Liquid Silicone Rubber (LSR2) with the CAS catalyst is poured into the mould to fabricate the gripper prototype.

The gripper prototypes were integrated to the UR5 COBOT using a custom mount that was designed and fabricated with precision. The mounts were created using Fusion 360 and 3D printed with PLA to perfectly fit the UR5 end effector slot.

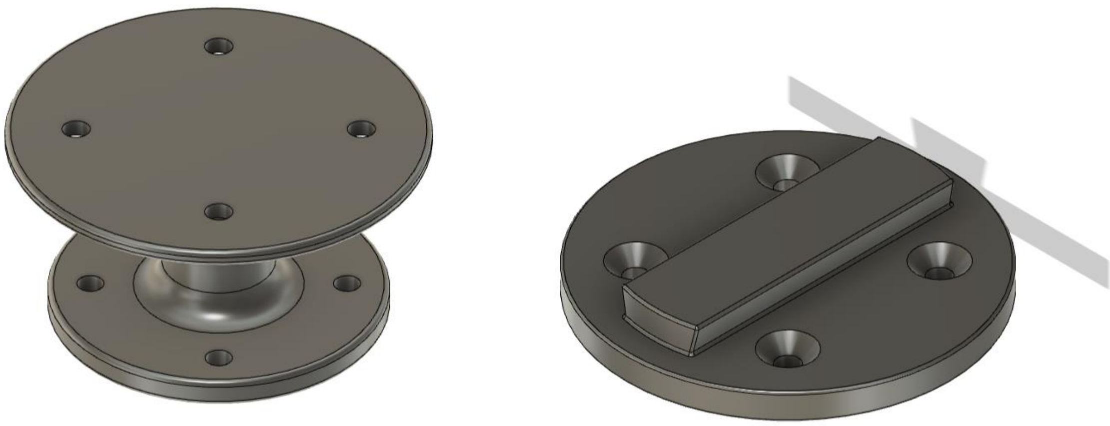


Fig. 4.16: Mounts that Accurately attaches to the UR5 COBOT

CHAPTER 5

CONTRIBUTION OF EACH STUDENT

5.1 Contribution of Vedant Nath

- Literature Review

A thorough literature review of the existing research was conducted. The review focused on types of soft grippers, materials used, fabrication, actuation, and design for achieving variable stiffness. It also identified current research gaps and their impact on performance.

- Optimal Model Selection

Various design configurations and materials were evaluated to identify the best gripper model. Factors such as flexibility, strength, and the ability to pick up were considered. The model enhances performance and durability, by grasping different types of fruits.

- CAD Designing in Fusion 360

A CAD model of the tapered shape gripper was created using Fusion 360. This model served as a blueprint for enabling precise fabrication and assembly of gripper components. Gripper geometry, material properties, and actuation mechanism were considered.

- Parametric Analysis and Design

Parametric analysis techniques were used to optimize the design parameters. The design was refined by adjusting parameters such as material thickness, stiffness gradients, and actuation angles.

- 3D Printing of Gripper Moulds and UR5 Mount

3D printing technology was used to produce moulds for gripper fabrication and mounts for integrating the gripper with the UR5 robot arm. Complex geometries and fine details were captured.

- Fabrication of Grippers

LSR2 was the selected material to ensure that the gripper met the required standards. The gripper components were fabricated with precision and consistency using 3D-printed moulds.

- Integration with UR5 Bot

For extensive testing to be conducted, the gripper is integrated with the UR5 robot arm creating a mechanical assembly and setting electrical and pneumatic connections.

- Documentation of Data

Documentation ensures that the project can be replicated, reviewed, and referenced in future research. Detailed records of literature reviews, design models, simulation results, material testing data, and fabrication processes were maintained from the start.

5.2 Contribution of Sidharth Kudupudi

- Literature Review

A thorough literature review of the existing research was conducted. The review focused on types of soft grippers, materials used, fabrication, actuation, and design for achieving variable stiffness. It also identified current research gaps and their impact on performance.

- Optimal Model Selection

Various design configurations and materials were evaluated to identify the best gripper model. Factors such as flexibility, strength, and the ability to pick up were considered. The model enhances performance and durability, by grasping different types of fruits.

- FEA Simulations in ANSYS

Finite Element Analysis (FEA) simulations using ANSYS were conducted to predict the behaviour of the gripper under different pressures in a defined loading condition. The simulations helped in understanding stress distribution, deformation, and potential failure points.

- Simulation Result Analysis

After receiving data obtained from FEA simulations, result analysis was done to understand the data and draw meaningful conclusions about the gripper's performance. Comparison of simulation results with experimental data was also done.

- ASTM D412 Tensile Test

LSR2 material's mechanical properties were known by conducting an ASTM D412 tensile test. Using a Universal Testing Machine, samples of the material were subjected to controlled tension until failure. The data obtained from these tests was needed to validate the suitable hyperelastic material model.

- Fabrication of Grippers

The gripper components were fabricated with precision and consistency by pouring the LSR2 mixture into the 3D-printed moulds.

- Documentation of Data

Documentation ensures that the project can be replicated, reviewed, and referenced in future research. Detailed records of literature reviews, design models, simulation results, material testing data, and fabrication processes were maintained from the start.

CHAPTER 6

RESULTS AND DISCUSSION

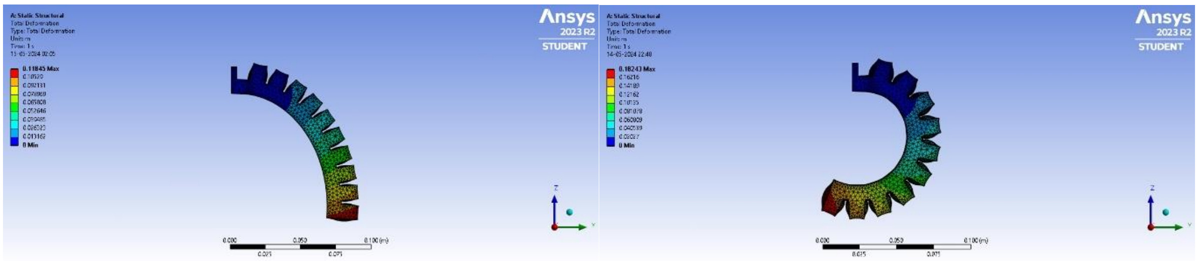
This section shows the results of the conducted study, followed by a detailed analysis and conclusive remarks.

6.1 Preliminary Data Analysis

After completing a literature review, the gripper with parameters $\alpha = 1$ and $\beta = 0$ is chosen. α and β represent the taper angles of the width and height of the gripper, respectively [2]. This design was chosen because it minimizes deflection and maximizes stability when holding a fruit.

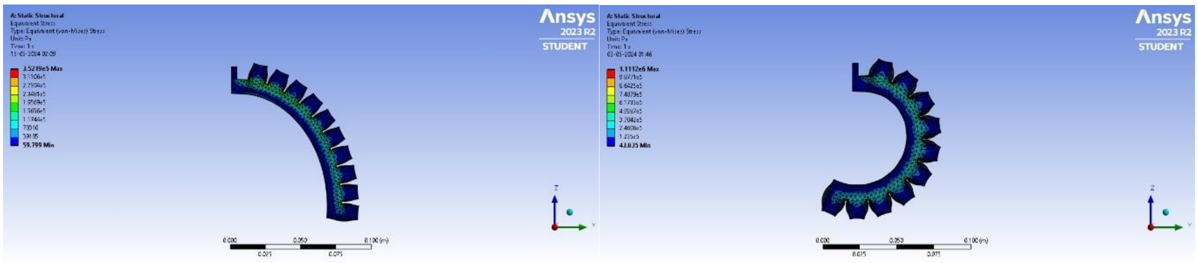
Each configuration was simulated across a range of pressure values from 40-120 KPa. The values for total deformation, equivalent stress distribution, equivalent elastic strain, strain energy, and bending angle on the gripper were noted from the simulation results [2]. The optimal design was selected which showed the highest force value.

Total deformation is determined through FEA. Strain indicates how much the gripper deforms compared to its original size. Stress measures the gripper's internal resistance to deformation caused by applied forces on its cross-sectional area. Strain energy measures the energy stored due to deformation. It is calculated by integrating stress-strain relationships across the gripper's volume. The bending angle assesses the gripper's ability to deform under different pressures. This helps assess the gripper's ability to conform to and securely grasp objects of different shapes and sizes.



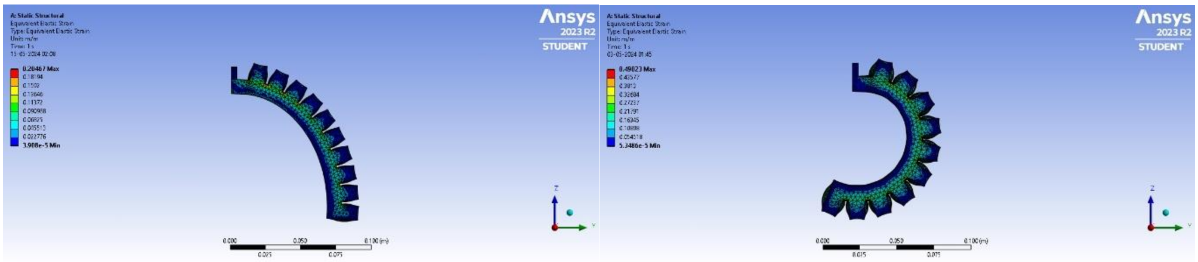
(a) (b)

Fig. 6.1: Total Deformation at (a) 40 KPa (b) 120 KPa



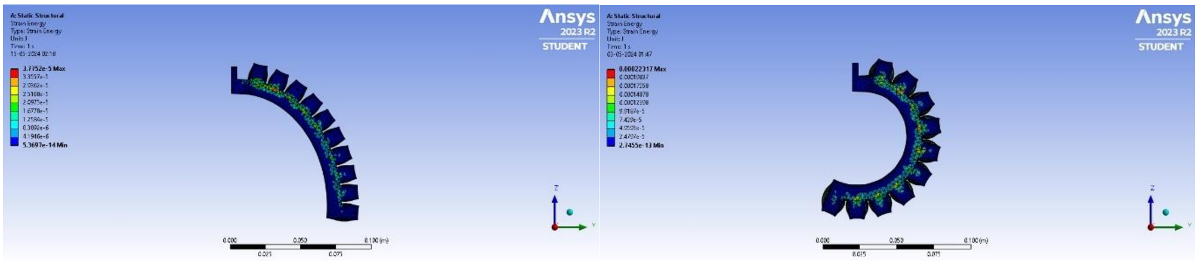
(a) (b)

Fig. 6.2: Equivalent Stress Distribution at (a) 40 KPa (b) 120 KPa



(a) (b)

Fig. 6.3: Equivalent Strain Distribution at (a) 40 KPa (b) 120 KPa



(a) (b)

Fig. 6.4: Strain Energy at (a) 40 KPa (b) 120 KPa

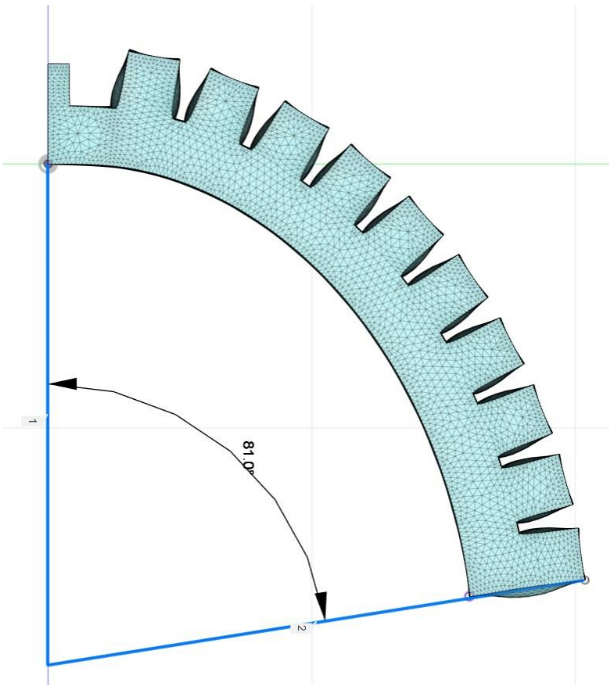


Fig. 6.5: Bending Angle at 40 KPa

6.2 Parametric Analysis

The criteria for choosing the optimal design focused on increasing the maximum total deformation and force reaction at the selected pressure range. To achieve this, four key design metric variables were systematically varied and analysed: Chamber Wall Thickness, Intermediate Layer Thickness, Top Wall Thickness, and Bottom Layer.

A total of 81 (3^4) different models were analysed, with almost 405 (81×5) simulations conducted in ANSYS Workbench Static Structural across pressure ranges from 40 to 120 KPa. This approach led to the identification of the optimal design configuration.

After reviewing the simulation results, we noticed that the thickness of the chamber wall was important in classifying models during the parametric analysis. This design factor directly affected the flexibility and bending of the gripper. Changes in the chamber wall thickness directly impacted the pressure distribution on the chamber wall area.

MATLAB-generated graphs of the simulation results helped provide valuable insights into the relationship between design and performance metrics.

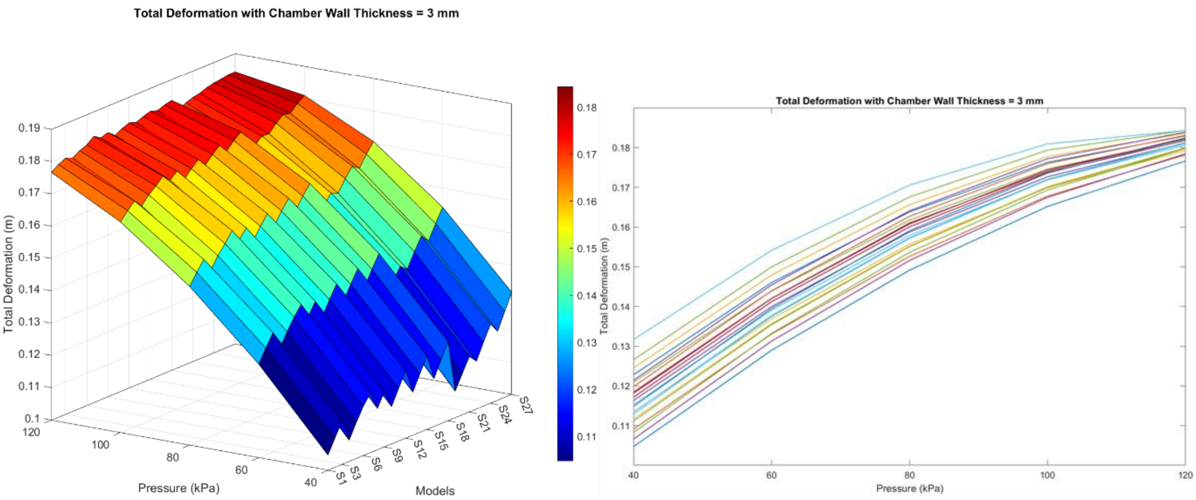


Fig. 6.6: Graph of Total Deformation with Chamber Wall Thickness = 3 mm

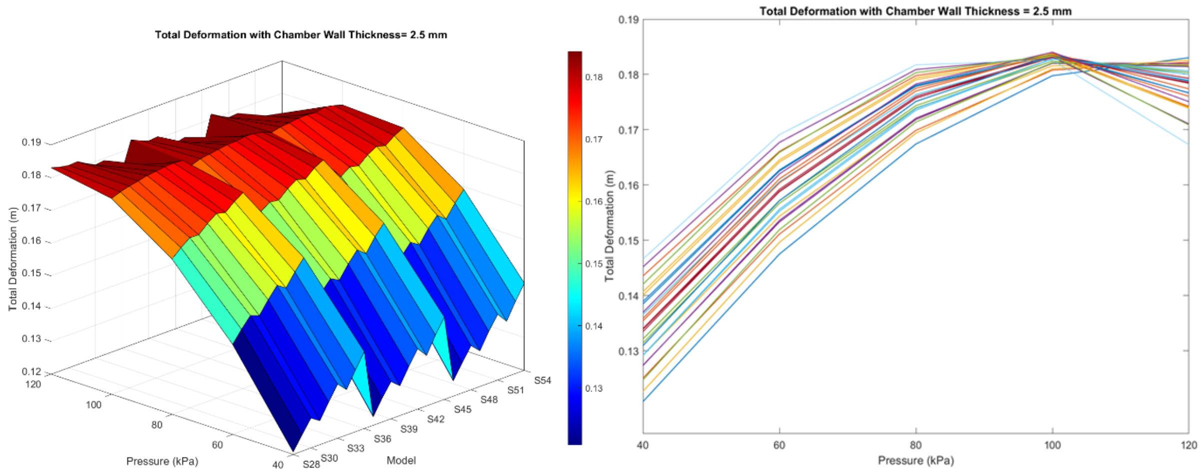


Fig. 6.7: Graph of Total Deformation with Chamber Wall Thickness = 2.5 mm

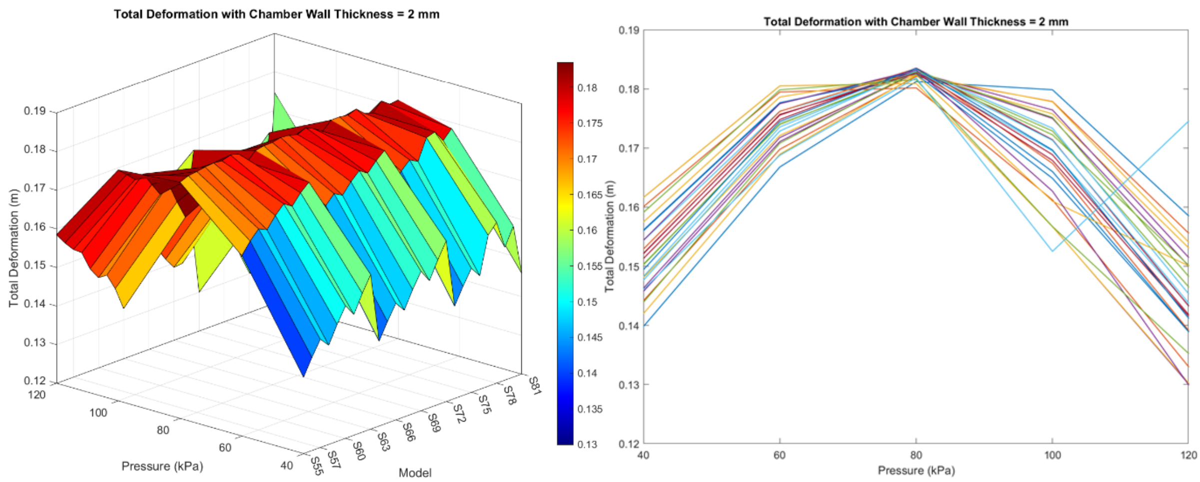
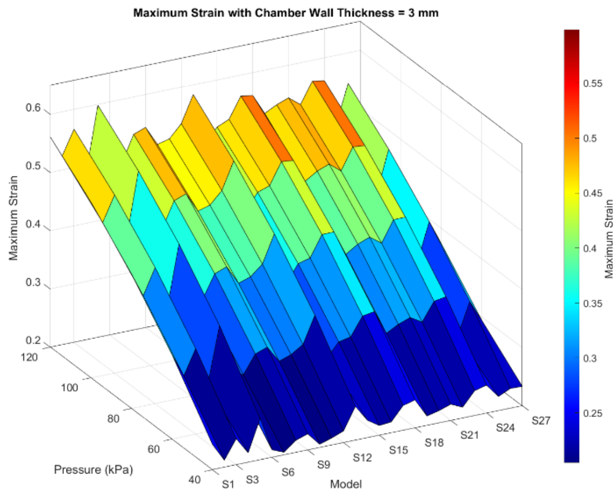
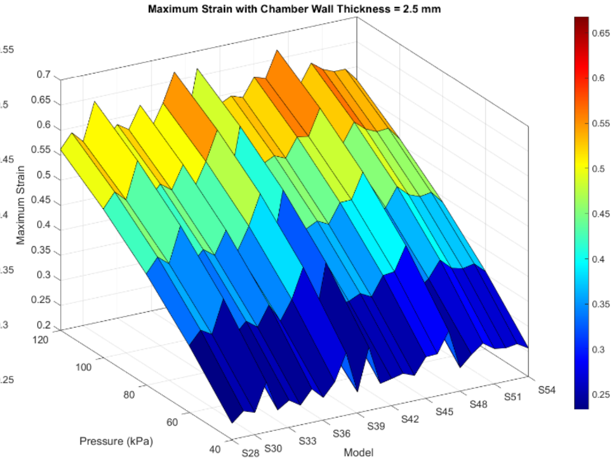


Fig. 6.8: Graph of Total Deformation with Chamber Wall Thickness = 2 mm



(a)



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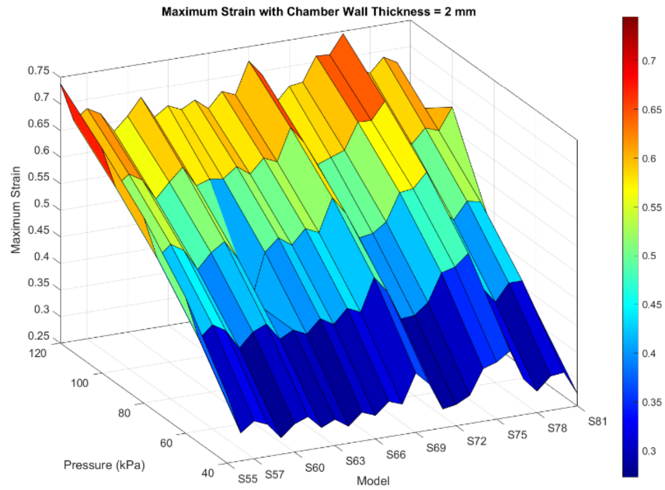
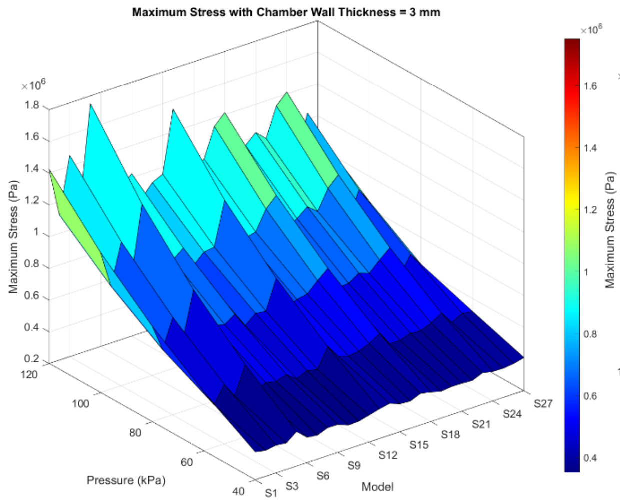
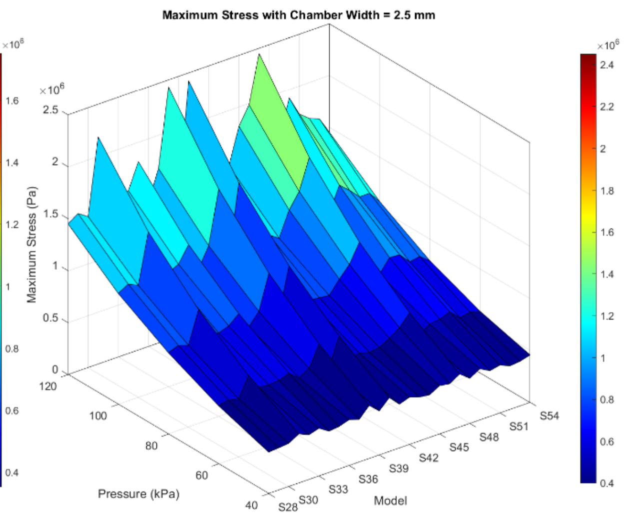


(c)

Fig. 6.9: Graph of Maximum Strain with Chamber Wall Thickness = (a) 3 mm (b) 2.5 mm (c) 2 mm



(a)



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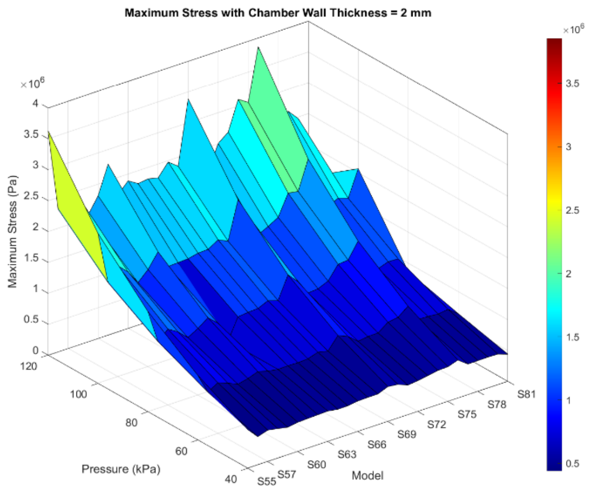
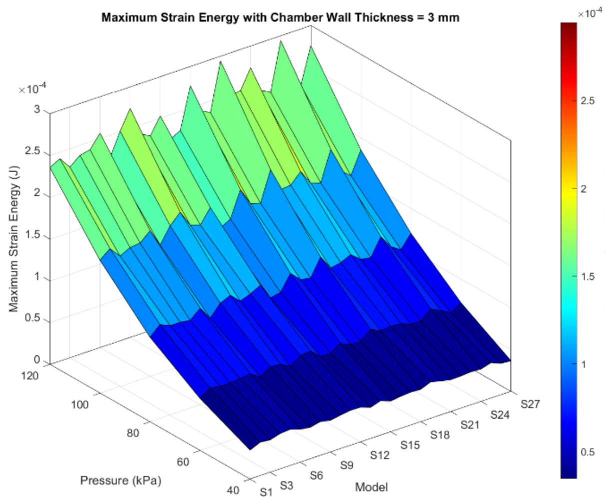
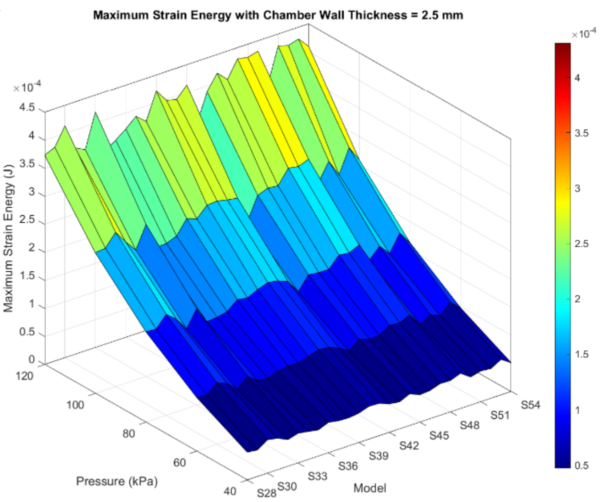


(c)

Fig. 6.10: Graph of Maximum Stress with Chamber Wall Thickness = (a) 3 mm (b) 2.5 mm (c) 2 mm



(a)



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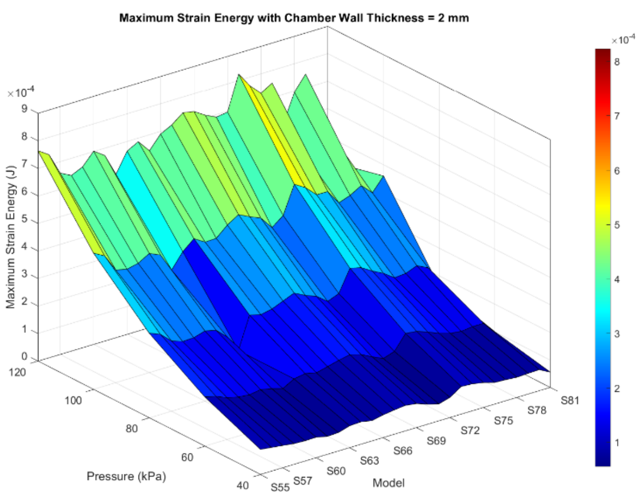
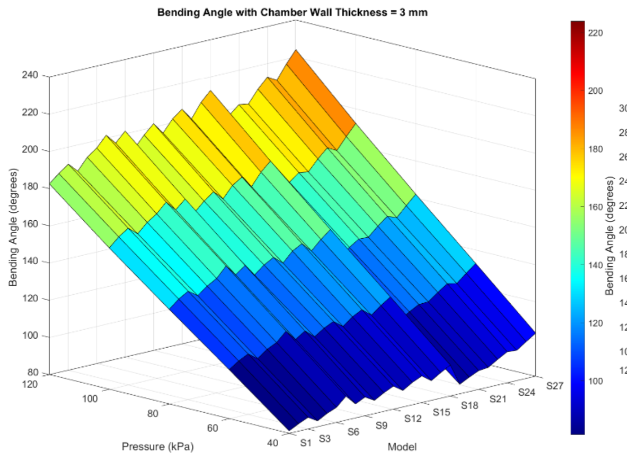
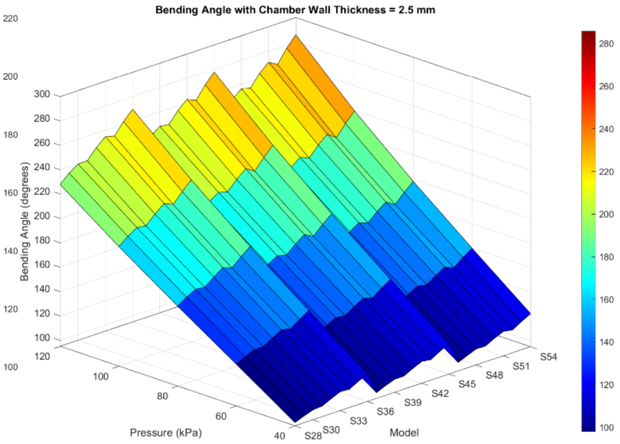


(c)

Fig. 6.11: Graph of Maximum Strain Energy with Chamber Wall Thickness = (a) 3 mm (b) 2.5 mm (c) 2 mm



(a)



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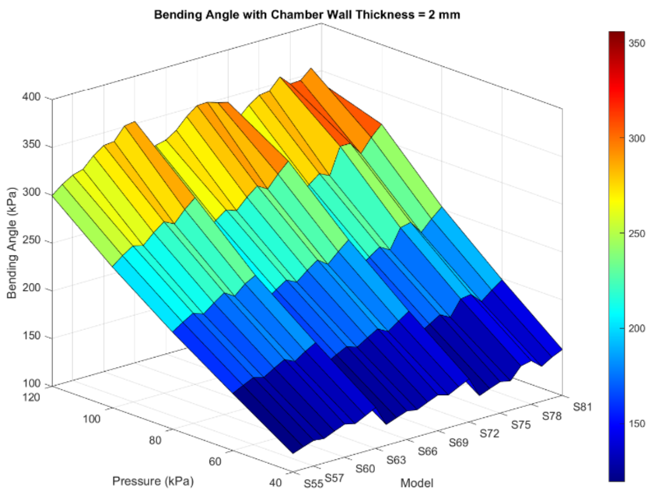


(c)

Fig. 6.12: Graph of Bending Angle with Chamber Wall Thickness = (a) 3 mm (b) 2.5 mm (c) 2 mm

It is known that hyperelastic materials exhibit non-linear elastic behaviour. At lower pressures, these materials tend to increase deformation uniformly. However, beyond a certain high-pressure value, the material begins to exhibit non-linear behaviour, which is caused due to strain stiffening. This can lead to a decrease in the rate of deformation over time. The simulation results show that a Chamber Wall Thickness of 3 mm in the gripper results in a more uniform increase in deformation compared to models with other wall thicknesses. Therefore, force analysis simulations were primarily conducted on models with a chamber wall thickness of 3 mm to take advantage of this uniform deformation behaviour.

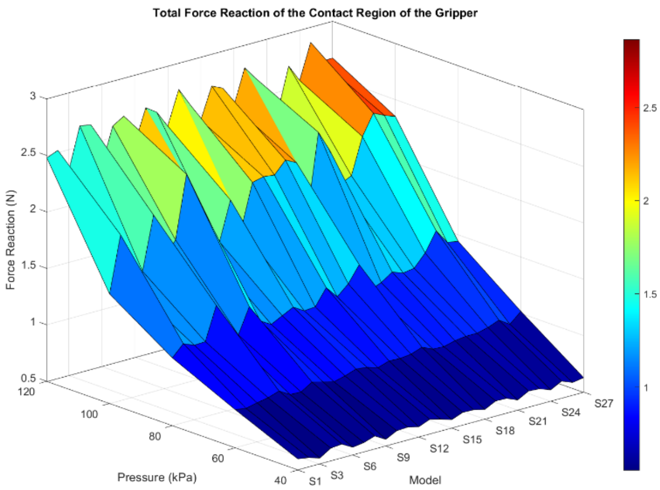


Fig. 6.13: Graph of Total Force Reaction of the Contact Region of the Gripper

After conducting extensive simulations, we have selected the optimal model for the soft robotic gripper based on the maximum force exerted on the contact region of the gripper. It's crucial to choose a model that provides the maximum force reaction on the contact region of the gripper to ensure effective and reliable gripping performance. This approach guarantees that the gripper can exert enough force to securely hold fruits, especially when a firm yet gentle grip is needed to avoid damage. By prioritising models with higher force reactions, we can identify the optimal design that balances strength, precision, and adaptability to different object shapes and sizes. The model which shows this is mentioned in Section 4.3.

6.3 Comparison between Design 1 and Design 2

Simultaneously, the simulations for Design 2 of the gripper were also run in ANSYS.

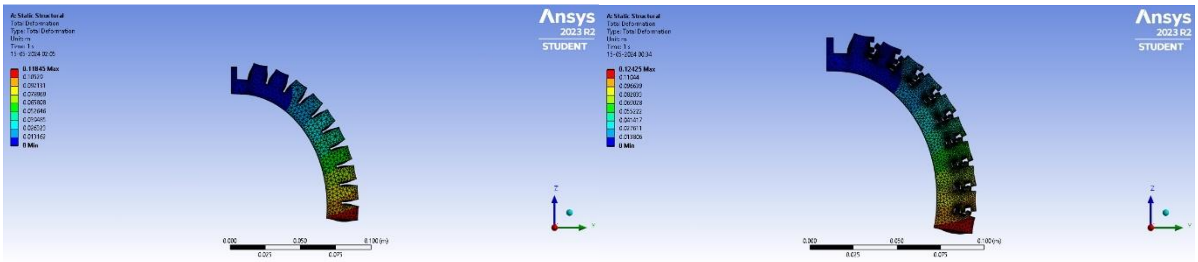
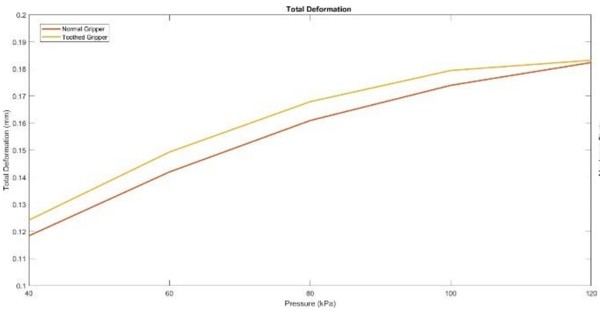


Fig. 6.14: Comparison between the Total Deformation of Design 1 and Design 2

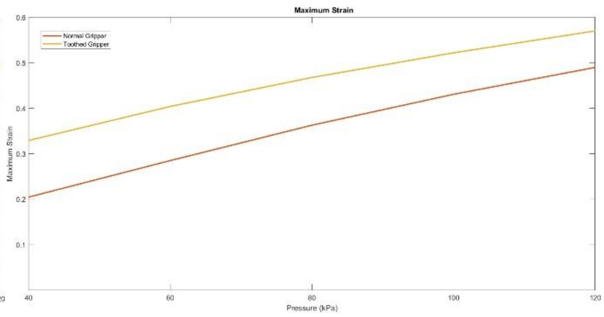
Here is a comparison of results between Design 1 and Design 2.

Table 6.1: Comparison between various parameters of Design 1 and Design 2

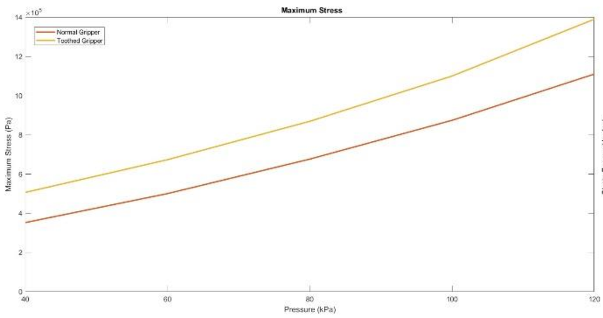
Parameters	Design 1		Design 2		% Increase
	@ 40KPa	@ 120KPa	@ 40KPa	@ 120KPa	
Total Deformation (mm)	0.11845	0.18243	0.12425	0.18326	3.60 %
Equivalent Strain	0.20467	0.49023	0.32934	0.57045	33.83 %
Equivalent Stress (Pa)	3.520E+05	1.110E+06	5.06E+05	1.39E+06	31.68 %
Strain Energy (J)	3.78000E-05	2.23170E-04	5.16E-05	3.60E-04	57.84 %
Bending Angle (degrees)	92.96376748	201.6253804	98.9316067	221.9211299	8.64 %
Force (Contact Region) (N)	0.10448	1.63610	0.289120835	1.7017	68.86 %



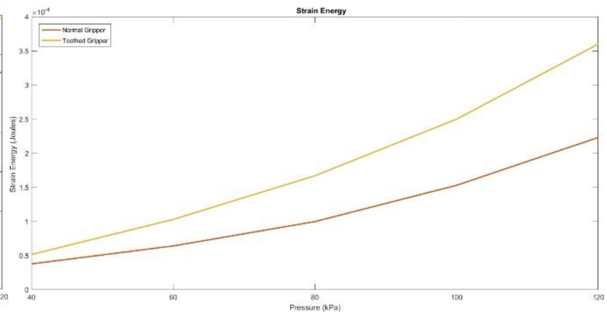
(a)



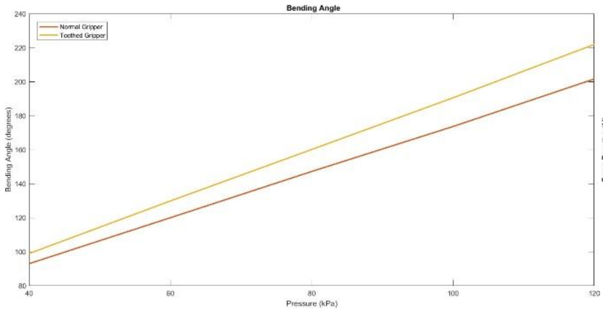
(b)



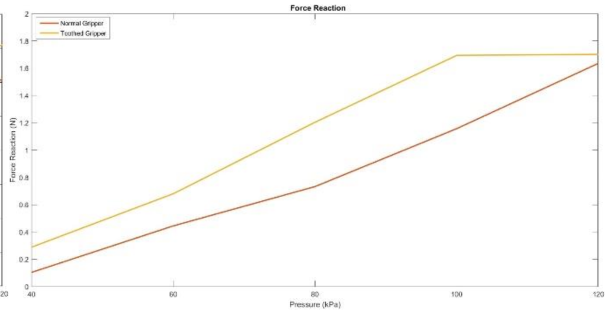
(c)



(d)



(e)



(f)

Fig. 6.15: Comparison Graphs between Design 1 and Design 2 (a) Total Deformation (b) Maximum Strain (c) Maximum Stress (d) Strain Energy (e) Bending Angle (f) Force Reaction

It is significantly clear that Design 2 shows substantial enhancement in results compared to Design 1 when assessed at 40KPa and 120KPa pressures. This includes total deformation, equivalent strain, equivalent stress, strain energy, bending angle, and force reaction. These findings indicate Design 2 performs significantly better when simulated in a similar working environment. It can function more reliably and consistently in real-world situations.

6.4 Testing of the Gripper

Both Design 1 and Design 2 gripper prototypes were attached to the UR5 COBOT. Using pneumatic systems, the gripper was maneuvered with precision. The gripper was used to pick a few fruits like apples and oranges. The gripper picked up fruits at a pressure ranging from 30KPa to 50KPa.

Fig. 6.16: The Assembled Gripper Picking up an Apple

CHAPTER 7

CONCLUSION AND FUTURE SCOPE

The objectives of this project were to develop a gripper that efficiently and safely handles fruits. A review of existing designs provided valuable insights. This review also identified the research gaps. After evaluating various design configurations, an optimal model was chosen based on deformation and force exerted.

Once an optimal model was selected, the design was created using Fusion 360. To understand the gripper's mechanical performance and structural integrity, FEA was done using ANSYS Static Structural. Parametric analysis was carried out by altering design metrics. The gripper was fabricated using LSR2. The material properties of LSR2 were verified through tensile tests that followed ASTM standards. 3D printing was used to manufacture the moulds and mounts for fabricating the gripper and integrating it with the UR5 COBOT.

Mounts were designed, and pneumatic and electrical connections were made to integrate the gripper with the UR5 COBOT. Throughout the project, records were maintained.

The project combines research, simulations, and fabrication. By introducing soft materials, the gripper was capable of handling fruits delicately. This design represents an innovative approach to efficient and damage-free fruit picking.

7.1 Limitations

This gripper has a few limitations that impact its performance. One of the disadvantages is the difficulty in operating the gripper in vertical positions. The force of gravity affects its ability to securely grasp fruit. More design considerations are necessary to ensure stability and consistent gripping force when in vertical orientations.

Additionally, the gripper faces challenges when handling smaller objects. Although it is designed to handle larger fruits efficiently, it is less effective with smaller items. Improvements in the design are required to accommodate a wider range of fruit sizes.

When using flexible materials like LSR, the grippers can be fragile. This material is less durable when used for longer periods. Careful material selection and design refinements are crucial to improve the gripper's life.

The fabrication process is complex as the materials can only be cured in a structured mould. This complicates and lengthens the fabrication process. The consistency should be maintained throughout the process of mixing the catalyst.

The identified limitations indicate areas for future development of the gripper. Overcoming these challenges would enhance the overall performance of the gripper. This will make the gripper more effective for fruit-picking applications.

7.2 Future Scope

The soft robotic gripper has many applications beyond agriculture. It shows promise in medical sample handling and warehouse object manipulation. In the medical field, the gripper's precise and controlled force application makes it suitable for delicate tasks such as handling biopsy samples. The stiffness feature allows it to conform to the fragility of biological tissues. This minimises damage during sample collection and transport.

When it comes to warehouse object handling, the grippers can streamline sorting and packing operations by handling items of different shapes, sizes, and fragility. Further, custom tools would not be required for each object. This can reduce operational costs and increase efficiency.

Future research could focus on improving the gripper's material properties to make it more durable. It could also explore expanding its operational capabilities and integrating it with advanced robotic systems for autonomous operations. These advancements will make the gripper useful in a wider range of fields beyond just agriculture.

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Annexure 1

PO & PSO Mapping

Student Name: Vedant Nath / Sidharth Kudupudi
Registration No: 200929005 / 200929028

PO	✓ Tick	Page No	Section No	Guides Observation
PO1	✓	13	Chapter 3	
PO2	✓	6	Chapter 2	
PO3	✓	17	Chapter 3	
PO4	✓	6	Chapter 2	
PO5				
PO6	✓	2	Chapter 1	
PO7				
PO8	✓	4	Chapter 1	
PO9	✓	31	Chapter 5	
PO10	✓	5	Chapter 1	
PO11	✓	31	Chapter 5	
PO12	✓	46	Chapter 7	

PSO	✓ Tick	Pg. No	Section No	Guides Observation
PSO1	✓	17	Chapter 4	
PSO2	✓	17	Chapter 4	
PSO3				

Signature of Student: **Name and Signature of Guide:**
Date:

Annexure 2

<u>PLO Mapping</u>

Student Name: Vedant Nath / Sidharth Kudupudi
Registration No: 200929005 / 200929028

Note: use a tick mark if you have addressed that Learning Outcomes (LO) in your report

PLO	✓ Tick	Page No	Section No	Guides Observation
C1.				
C2.				
C3.				
C4.	✓	6	Chapter 2	
C5.	✓	17	Chapter 4	
C6.	✓	17	Chapter 4	
C7.	✓	4	Chapter 1	
C8.	✓	4	Chapter 1	
C9.	✓	4	Chapter 1	
C10.				
C11.	✓	4	Chapter 1	
C12.	✓	17	Chapter 4	
C13.	✓	17	Chapter 4	
C14.				
C15.				
C16.	✓	31	Chapter 5	
C17.	✓	31	Chapter 5	
C18.	✓	31	Chapter 5	

Signature of Student: **Name and Signature of Guide:**
Date:

Annexure 3

Address of IET learning outcomes during project period
<u>Answer the following questions with relevant to the Project Work (In-house Project).</u>

1. Explain the steps you considered to investigate and define the problem in your project work *(C4, evaluate level)*

Answer: To design a variable stiffness gripper for fruit picking, I investigated existing soft gripper actuation, materials, and challenges specific to handling delicate fruit.

2. Discuss the science, mathematics, statistics, engineering principles and other basic technology you identified for design (Mechanical, Electronic, Physics, Chemistry, Automation) in your project work. *(C1, C2, C3, Application, Analysis, Evaluation of Science and Mathematics in the project)*

Answer:

1. Science:
   - Mechanics: Understanding principles of leverage, stress & strain, and grasping mechanics to design the gripper structure and finger movement.
   - Materials Science: Selecting materials with appropriate stiffness and elasticity for variable stiffness and fruit handling.
2. Mathematics:
   - Finite Element Analysis (FEA): Simulating gripper behaviour under pressure and load to optimize design.
3. Engineering Principles:
   - Mechanical Engineering: Designing mechanisms for finger movement, actuation, and variable stiffness control.
   - Control Engineering: Developing control systems to manage pressure and gripper movement.
4. Technology:
   - Automation: Integrating sensors and control systems for autonomous fruit picking.

3. Have you considered the Environmental and Sustainability limitations in your project work? *(C7, evaluate)*

Answer: Environmental and sustainability considerations have been integral to the project's development process. The selection of materials, fabrication techniques, and operational aspects has been carefully evaluated to minimize environmental impact and promote sustainable practices. Additionally, efforts have been made to optimize energy efficiency and resource utilization throughout the project lifecycle.

4. Have you considered ethical, health, safety, security, and risk issues; intellectual property; codes of practice and standards while addressing these issues in your project work? If so, Explain in detail. *(C5, create)*

Answer: Yes, ethical considerations like responsible material sourcing and potential environmental impact during operation would be addressed. Safety concerns like unexpected actuation should be mitigated through proper design and control systems.

5. What were the esthetical issues faced and how it was addressed in your project in the design phase? *(C5, analysis)*

Answer: Aesthetics wasn't a major concern in this project.

6. Were there any health issues considered during design process? How it was addressed in your project in the design phase? *(C5, create)*

Answer: No, there were no such issues.

7. What were the safety, security and risk issues considered in the design stage? *(C10, create)*

Answer: General safety standards, nothing specific.

8. Have you come across intellectual property issues in the project phase? *(C5, create)*

Answer: There is a possibility of encountering intellectual property (IP) issues related to the novelty of the gripper design (especially the tapered aspect) and material selection for variable stiffness if similar inventions are already patented.

9. What are the codes of conduct and standards you needed to use in design phase and in other phases of your project as well? (It may include codes of practice and standards for safety, security, health, risk) Explain the legal issues, ISO standards, IEC standards, etc. *(C8, evaluate)*

Answer: Focus on safety standards and material properties during development.

10. What were the professional ethics needed to be followed in general while you are doing the project? *(C8, evaluate)*

Answer: Here are some of the professional ethics to consider while designing a soft robotic gripper for fruit picking:

1. Do no harm: The gripper design should minimize damage to fruits during picking.
2. Environmental responsibility: Use eco-friendly materials and avoid introducing harmful substances during fabrication.

11. Do you think ethics and professionalism needs to be paid attention by students during study? If, yes, explain how it can be inculcated/introduced/implemented? *(C8, evaluate)*

Answer: Yes, ethics and professionalism are important for students. Students can be taught ethics and professionalism through coursework, workshops, and by faculty modelling these behaviours. In the context of research, this means being honest about data and results, citing sources properly, and treating colleagues with respect. For the robotic gripper design, ethical considerations would focus on responsible use of the technology and avoiding unintended harm.

12. Do you think environmental and sustainability limitations; ethical, health, safety, security, and risk issues; intellectual property; codes of practice and standards are sufficiently covered in the courses you have studied in your curriculum? *(C8, evaluate)*

Answer: Yes, all the mentioned limitations and isuues, are adequately covered in the courses I have studied. These topics are addressed in relevant subject areas such as environmental science, engineering ethics, occupational health and safety, and risk management. Additionally, intellectual property, codes of practice, and standards are discussed in courses related to law, business ethics, and engineering design. Overall, efforts are made to ensure students gain a comprehensive understanding of these important considerations in their respective fields of study.

13. Have you gone through online classes, or a crash course in which you are familiarized with intellectual property rights as well as risk issues in professional environment? *(C8, evaluate)*

Answer: Yes, I have participated in online classes and crash courses where intellectual property rights and risk issues in professional environments were addressed. These courses provided valuable insights into various aspects of intellectual property, including patents, copyrights, trademarks, and trade secrets, as well as risk management strategies in professional settings. Through case studies, discussions, and practical examples, I gained a better understanding of how to navigate intellectual property challenges and mitigate risks effectively in professional environments.

14. In the beginning of your project did you evaluate environmental effects and sustainability factors in your work? *(C7, evaluate)*

Answer: Yes, at the beginning of the project, environmental effects and sustainability factors were evaluated to ensure that the project aligned with sustainable practices and minimized negative environmental impacts. This evaluation included considerations such as the selection of materials with low environmental impact, optimization of energy efficiency in design and operation, and implementation of waste reduction strategies throughout the project lifecycle. By incorporating these assessments early on, the project aimed to prioritize environmental sustainability and responsibility.

15. Did you addressed the limitations of your project work, and have you improved the results through continuous improvements in your project work? *(C5, create)*

Answer: Yes, the limitations of the project were addressed, and continuous improvements were made throughout the project work to enhance results. This involved systematically identifying areas of improvement based on initial findings and feedback, and implementing iterative refinements to the design, methodology, and implementation processes. By embracing a cycle of continuous improvement, the project was able to overcome limitations, optimize performance, and achieve enhanced results over time.

16. How did you plan your project, deadlines, maintaining dairy of each stage and improved the quality of the project? *(C14, understand)*

Answer: The project was meticulously planned with clear deadlines and milestones established to ensure timely progress and successful completion. Gantt charts were employed to visualize the project timeline, identify critical tasks, and allocate resources effectively. Additionally, a detailed project diary was maintained at each stage, documenting progress, challenges faced, and lessons learned. This documentation facilitated ongoing reflection and evaluation, allowing for continuous improvement in project quality. By adhering to the planned schedule, regularly updating the project diary, and utilizing Gantt charts for efficient project management, the project team was able to enhance project quality and meet objectives effectively.

17. Are you aware of the ethical clearance when you work in the field of health/medical applications.? *(C8, evaluate)*

Answer: Yes, ethical clearance is essential when working in the field of health/medical applications to ensure that research involving human subjects or sensitive data adheres to ethical standards and regulations. This typically involves obtaining approval from an Institutional Review Board (IRB) or an Ethics Committee, which evaluates the ethical implications of the research and ensures that participants' rights, safety, and confidentiality are protected. Additionally, researchers must comply with relevant laws, guidelines, and ethical principles, such as informed consent, privacy protection, and data confidentiality, to maintain the integrity and ethical conduct of their work.

18. Did you adopt any quantitative technique for any engineering activity related to your project? *(C3, evaluate)*

Answer: Yes, this project would likely use finite element analysis (FEA) to simulate and optimize the gripper's design for grasping force

19. What were the elements of your project work which addresses sustainable development and were you able to apply quantitative techniques to analyze and achieve your project goals? *(C7, evaluate)*

Answer: The project addressed sustainable development through material selection, energy efficiency, and waste reduction. Sustainable materials were chosen for the gripper design, considering factors like recyclability and biodegradability. Energy-efficient operation was optimized to reduce power consumption. Additionally, waste reduction strategies were implemented, including additive manufacturing to minimize material waste. Quantitative techniques, such as Finite Element Analysis (FEA), were applied to analyse project goals. FEA simulations quantitatively assessed the gripper's structural integrity, mechanical behaviour, and performance under different conditions, aiding in optimization and validation of the design. Overall, the integration of quantitative techniques facilitated data-driven decision-making and successful project outcomes aligned with sustainability considerations. All these methods were used for effective fruit picking.

20. Did your project need the understanding of relevant legal requirements governing engineering activities you carried out as a part of your project work? Explain in detail. *(C8, evaluate)*

Answer: Yes, the project required understanding relevant legal requirements to ensure compliance with industry standards, intellectual property rights, and environmental regulations.

21. What are the legal, ethical practices you followed while working on project? *(C8, evaluate)*

Answer: Legal and ethical practices were maintained throughout the project, including respecting intellectual property rights, ensuring transparency in communications, and upholding privacy and confidentiality measures.

22. Are you sure that you abide IPR/copy right issues? *(C15, apply)*

Answer: The project team ensured compliance with intellectual property rights and copyright issues by conducting thorough research, obtaining necessary permissions, and documenting sources and references appropriately.

23. What online course you attended to improve your communication skills, Report writing, Oral presentation, Software used for writing report? *(C17, apply)*

Answer: No online courses were attended to improve communication skills and report writing, and software such as Microsoft Word and PowerPoint was used for writing reports and creating presentations.

24. In your project, was it needed to tackle risk issues, including health & safety, environmental and commercial risk, and of risk assessment and risk management techniques? Explain in detail. *(C5, create)*

Answer: Yes, risk issues, including health and safety, environmental, and commercial risks, were systematically addressed using risk assessment and management techniques throughout the project.

25. How is the organization addressing a fire accident/human safety when working with machines? *(C9, evaluate)*

Answer: The organization addresses fire accidents and human safety by implementing strict safety protocols, conducting regular safety training sessions, maintaining firefighting equipment, and having emergency evacuation plans in place.

26. Process of teamwork. How each of you are involved in the team? What part the work is addressed by you.? *(C16, evaluate)*

Answer: The teamwork process involves active participation from each team member, with tasks allocated based on individual strengths and expertise. Each member contributes to different aspects of the project, such as design, analysis, experimentation, documentation, and presentation.

27. Have you filed patent, IPR, or published your work? Give more details. *(C17, evaluate)*

Answer: Yes, the project findings will be published in a paper and a patent application will be filed to protect the intellectual property associated with the project.

28. How you documented the literature review, your analysis on their results, discussion with the guide and team members, provide the documents on weekly basis. Put as one chapter in final report. *(C4, evaluate).*

Answer: The literature review, analysis, discussions with the guide and team members, and weekly progress reports were meticulously documented and compiled into a dedicated chapter in the final report.

29. Have you sensitized about inclusion and diversity in the team? If yes, what are the diversification in the team in terms of religion, gender, ethnicity, etc? *(C11, apply).*

Answer: Yes, sensitization about inclusion and diversity was integral to the team dynamics. The team comprised members from diverse backgrounds, including different religions, genders, ethnicities, and cultural perspectives, fostering a rich and inclusive environment.

30. How were you able to keep yourself updated with the technology? How you incorporated advanced technology in your project. *(C18, lifelong learning)*

Answer: Staying updated with technology was achieved through continuous learning, reading journals, research paper, and following the news on the latest technological trends. Advanced technology was incorporated into the project through extensive research and experimentation to ensure the use of cutting-edge methods and techniques.

31. Which are the laboratory skills you found applicable to your project? Explain. *(C12, apply)*

Answer: Laboratory skills such as material testing, data analysis, prototype fabrication, and equipment operation were highly applicable to the project. These skills enabled accurate testing of gripper components, analysis of experimental results, fabrication of prototypes, and the use of specialized equipment for experimentation and validation.

Annexure 4
<u>Project Work (In-house) Classification</u>

Student Name: Vedant Nath / Sidharth Kudupudi
Registration No: 200929005 / 200929028

Note: Use a tick mark to specify under which domain your project work falls into.
Table 1: classification based on project domain classification

Domain	✓ Tick
Product	✓
Application	✓
Review	
Research	✓
Management	

Note: Use a tick mark to specify societal impacts you considered during your project work.
Table 2: classification based on societal consideration

Societal Impact	✓ Tick
Ethics	✓
Safety	✓
Environmental	
Commercial	✓
Economical	
Social	

Signature of Student: **Name and Signature of Guide:**
Date:

Annexure 5

Project Details

Student 1 Details			
Student Name	**Vedant Nath**		
Register Number	200929005	Section / Roll No	A / 2
Email Address	vedant.nath@gmail.com	Phone No (M)	6290908398
Student 2 Details			
Student Name	**Sidharth Kudupudi**		
Register Number	200929028	Section / Roll No	A / 12
Email Address	sid.kudupudi@gmail.com	Phone No (M)	9398140763
Project Work (In-house) Details			
Project Title	**Design And Development of Variable Stiffness Tapered Type Soft Robotic Gripper for Fruit Picking Application**		
Date of Synopsis	23/01/2023	Date of Final Presentation	16/05/2024
Internal Guide Details, If any Co-guide			
Name of the Guide	**Dr. Ankur Jaiswal**		
Full contact address with pin code	Department of Mechatronics, Manipal Institute of Technology, Manipal – 576 104 (Karnataka State), INDIA		
Email address	ankur.jaiswal@manipal.edu		

PLAGIARISM REPORT

DESIGN AND DEVELOPMENT OF VARIABLE STIFFNESS TAPERED TYPE SOFT ROBOTIC GRIPPER FOR FRUIT PICKING APPLICATIONS

ORIGINALITY REPORT

11%	8%	8%	3%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Submitted to Manipal Academy of Higher Education (MAHE) Student Paper	2%
2	www.researchgate.net Internet Source	1%
3	www.mdpi.com Internet Source	<1%
4	hdl.handle.net Internet Source	<1%
5	Yu Shan, Yanzhi Zhao, Haobo Wang, Liming Dong, Changlei Pei, Zhaopeng Jin, Yue Sun, Tao Liu. "Variable stiffness soft robotic gripper: design, development, and prospects", Bioinspiration & Biomimetics, 2023 Publication	<1%
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