Soft Robotic Gripper with Tunable Stiffness and Multi-Modal Bending Enhancing Gripping Ability

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Abstract. Soft pneumatic grippers, structures created from soft material like silicone rubber and powered by air pressure, can grip and transfer fragile items safely and stably. These grippers are widely applicable under medical situations, especially during surgery. Other applications include automated laboratory operations, underwater gripping, food delivery, extraterrestrial exploration efforts, etc. However, traditional soft grippers face serious difficulties with gripping objects of different volumes and weights. This study proposed a novel layer-jamming mechanism of tuning the stiffness of soft grippers to increase its weight capacity. The study also proposed a novel bellowed-pipe structure for soft grippers to incorporate dual-mode gripping. The process of gripping was automated through the introduction of a camera and recognition algorithms capable of computing the size and depth of the detected object. Experiments conducted in room conditions, using the variable stiffness mechanism, the gripper could grip objects 120% heavier than without using the mechanism, indicating a significant advancement from traditional soft grippers. Further research could be done with making the gripper smaller and applicable under surgical conditions.

Keywords: Soft Robotics, Stiffening, Multimodal, Increased Load, Increased Gripping Range.

1. Introduction

Soft robotics emerged as a rising field of technology, contributing lightweight systems, multiple degrees of freedom, and reduced control complexity to many structures, as they may improve significantly in performance dealing with delicate, fragile items compared to traditional rigid-body robots. Such designed soft material may be used as energy harvesters, impact absorbers, or gripping devices in fields of laboratories, manufacturing industries, medical centers, surgery robots, underwater missions, disaster rescuing missions, etc.

Soft grippers, specifically, uses compliant materials and pneumatic actuation to grip objects of various shapes and fragilities robustly. One of the materials used commonly is the colloidal precipitate of silicone rubber that condenses at very specific ambient conditions. The method of pneumatic actuation leverages closed air channels that soft surfaces enclose, allowing the addition of pressure to deform the film as adequate pressure had been applied to fill the space. Soft grippers are usually inspired by the flexibility and dexterity found in nature—such as the trunks of elephants, the tentacles of squids, and the suction cups of octopi—where soft, organic tissues demonstrate remarkable adaptability and force distribution, allowing these creatures to garner food and thrive in nature [1].

Though the softness and compliance of soft grippers allows them to manipulate delicate objects safely, these same properties impose limitations on stiffness and the range of achievable gripping forces. The principle behind this is because the inherent stiffness and compliance soft materials have limited their stiffness that helps help grip heavier objects [2]. For example, the highest weight capacity of a Soft Bionic Grasping Device proposed by Gai and Zong can grasp objects to 500g under a maximum air pressure of 100kPa [1]. The largest object this SBDG can grip remains a small, 1-size basketball [1]. This suggests that there is significant room for improvement, which inspires my study's procession. Furthermore, designs of current soft gripping devices also bear considerable flaws that impact their airtightness, therefore their durability. Many current designs use silicone rubber and pneumatic actuators sealed by a single film, some later glued with strong metal adhesives. However, these configurations easily cause bulging in the inflated film, when stress concentration occurs at the bounded edges by the film's sides, increasing its relative chance of leakage. In soft robotics, if one spot leaks, the entire air channel loses usability.

To resolve the posited challenges, work must be done to modify both the design and stiffening mechanism of the soft gripper. The design of the gripper must help mitigate the problem of stress concentration. It also can be compatible of multiple gripper modes to enlarge the range of objects available to grip. Concerning the gripper's weight capacity, mechanisms can be implemented such that its stiffness is not solely supplemented by the change in internal pressure. To fill the chamber with something denser than air became an initiative to alter the chamber's innate stiffness. As Gai proposed, soft grippers must incorporate variable-stiffness mechanisms to expand their utility beyond gentle handling, to increase their weight capacity and potential applications [1]. Huang and Zong added that active control of structural jamming could bridge the gap between adaptability and force output [3].

Building upon these insights, this paper presents the design, principle, and fabrication of a soft gripper with integrated layer-jamming, multimodal gripping, and vision-based automation. The study further explores detecting algorithms, relay circuits, microcontrollers, and experimental validation to prove the feasibility of this system in real-world applications. This study will first introduce the foundations to the design and principle of the proposed system, followed by its control, testing, and discussion of results. Ultimately, this work aims to advance the field of soft robotics by enabling soft grippers to achieve large-scale, adaptable gripping with tunable stiffness.

2. Design, Principle, and Fabrication

2.1. Design

The author designed the gripper to achieve the following objectives:

1) Design of soft gripper prototype with enlarged gripping range allowing the gripper to grab objects larger than its own size.

2) Stiffness modulation (layer-jamming) mechanism to dynamically adjust the gripper's weight capacity.

3) Vision-based automation of the gripping process using detection algorithms, micro-controlled circuits, and subsequent enclosed airway reacting to signal transmission.

The author's design is expected to meet all the criteria above.

2.1.1 The Design of the Soft Gripper

The soft gripper this study designed aims to achieve the following: to assemble an airtight gripper compatible with multiple modes of gripping that enlarge the gripper's range of operation, and a variable stiffness design allowing the gripper to grip heavier objects robustly.

The developed soft gripper adopts a hybrid sandwich architecture combining pneumatic, jamming, and suction mechanisms to achieve multi-modal manipulation [4]. The assembly consists of two opposing silicone-based pneumatic fingers, a central layer-jamming unit for tunable stiffness, and a suction cup integrated at the base. This design enables the gripper to bend inward, bend outward, and attach via suction for stable handling of delicate or irregular objects. Each finger is configured as a bellowed actuator, designed to bend predictably due to an intentional asymmetry in material constraints. One side of the actuator is laminated with an inextensible fabric cut from a lab apron, while the opposite side remains unreinforced. Upon pneumatic pressurization, the unreinforced side expands radially, whereas the constrained side resists elongation. This differential strain induces curvature toward the reinforced side, yielding precise, repeatable bending. By arranging two mirrored bellows around the central axis, the gripper achieves bidirectional actuation, while the layer-jamming unit allows real-time stiffness modulation during grasping.

2.1.2 Multi-Modal Bending of the Gripper

The sandwich structure of the gripper was designed to achieve inward, outward, and suction gripping capabilities. Powered by pressure, an air channel will deform by expanding its soft film as much as possible. In the case of this study's bellow, each half of the sandwich has its own pipeline supplying pressure, and as one side is made stationary, the other will bend naturally. This bending mechanism takes inspiration from elephant trunks that bend when the elephant needs to roll grass to eat, filling their trunks with air such that they bend [5].

Figure. 1 Elephant trunk bending in Action (https://www.newscientist.com/article/2305489-elephants-trunk-may-be-one-of-most-sensitive-body-parts-of-any-animal/)

Taken inspiration, this study expects each finger to bend in response to input pressure [6]. To this end, this study attached an inextensible piece of cloth cut from a kitchen apron to one end of each half of a finger, making one side of the finger stationary, allowing the other side to bend as pressure accumulates. Inward gripper is then achieved by powering the outside set of halves of fingers, such that the side taped with cloth will curl inward, exerting a normal force, therefore a friction force to the object that needs to be gripped. Outward gripping is achieved by activating the inner pair of halves, that the side with cloth faces outward and curling in that direction, gripping larger objects. In addition to the two horizontal modes, the gripper is equipped with a vertical gripping device, namely a suction cup made from silicone rubber attached to the bottom of the sandwich structure. This suction cup also has a connected pipeline to a vacuum pump. Used to grip flat, smooth surfaces, the suction mode of gripping functions act as an alternative, gripping objects vertically.

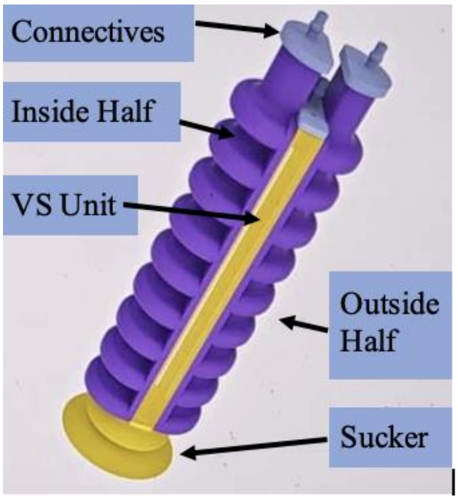

Figure. 2 Iterated Design of the Gripper created by Finalist, 2024.

One significant problem with creating soft robotics by hand is leakage—especially due to high input pressures, the soft structure may tear small holes if the precipitate's surface is not uniform [7]. To lower chances of leakages, this study made iterations and modifications to the shape of the gripper, allowing it to form smoothly and evenly, distributing pressure equally across the surface. The bellow was employed because of, again, bionic inspirations from the human finger that is segmented into different joints, each region separated by joints having a bulge to increase contact area, hence friction, to grip objects stably. Such that each dip between bulges of the bellow is rounded, reducing a phenomenon called stress concentration, which accumulates stress on sharp edges. Specifically, a round corner of 2mm is installed on every edge that the gripper could possibly have, limiting stress concentration.

Beyond creating a set of functioning grippers, this study aimed to build a mechanism inside the sandwich structure that enables the gripper to change its innate stiffness. The rationale of this came from a string of deductive thoughts. Three components impact the gripper's weight capacity: amount of input pressure, area of contact, and the innate stiffness of the gripper. The input pressure may not exceed 100kPa, or the durability of the gripper will be significantly impacted [3]. Or, if the study chose stiffer silicone rubber solutions, the solidified air channels will withstand more pressure, but at the same they lose the desired deformability and compliance that soft robots typically exhibit, defeating the purpose of using soft material. Similarly, the gripper's area of contact with the object is pre-determined by the gripper's design—not much more area could be added by anyhow manipulating the gripper's structure using mechanisms. Therefore, the only option left is altering the gripper's innate stiffness, as such a technique leverages jamming—placing materials other than air into the gripper's chamber, creating friction inside of the film, achieving dynamic stiffening. Section 2.2 will detail the principles of jamming and how they impact the gripper's performance with different stiffnesses and loads. The gripper and its molds are designed from SolidWorks 2024.

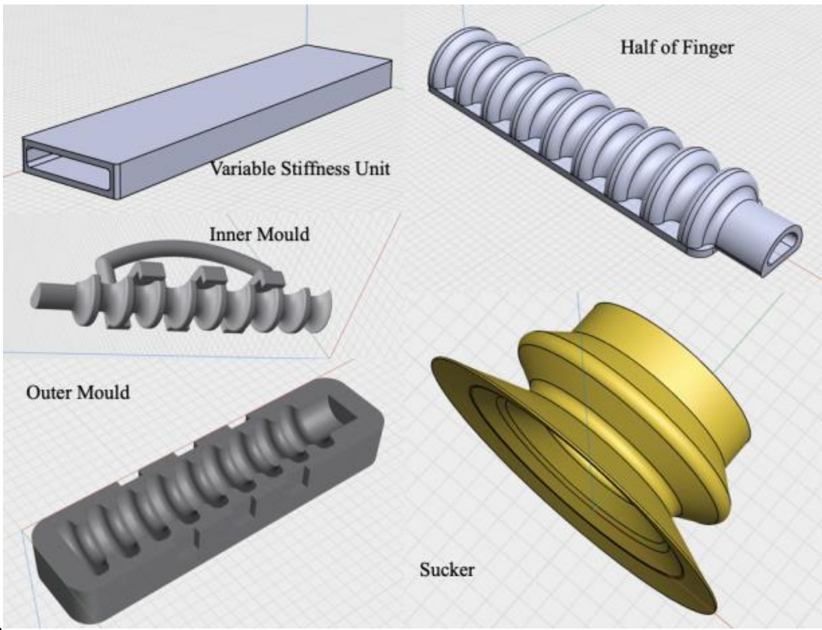

Figure. 3 Molds for the fingers, variable stiffness unit, and suction cup created by Finalist in Solidworks, 2024, displayed in Shapr3D.

2.2. Principle of Variable Stiffness Mechanism

To change the internal stiffness of the soft gripper, a layer-jamming mechanism is applied to increase the Young Modulus of the material's surface, allowing it to exert more friction to hold objects of greater weight. This section will explain how Layer Jamming achieves a dynamic increase in weight capacity from the theoretical standpoint, and how the mechanism takes place in this study's system.

2.2.1 The Relationship Between Stiffness and Effective Modulus

Understanding the mechanical relationship between stiffness, elasticity, and weight capacity is essential for quantifying how soft robotic grippers perform under different loading conditions. These properties determine how a soft actuator responds to external forces and how design changes—such as layer jamming—affect its ability to lift heavier objects.

In soft materials, stress (σ) is defined as the internal force per unit area:

$$\sigma = \frac{F}{A}, \tag{1}$$

where F is the applied load and A is the cross-sectional area. The corresponding strain (ε) measures deformation relative to the original length:

$$\varepsilon = \frac{\Delta L}{L_0}, \tag{2}$$

where ΔL is the change in length and L_0 is the original length. For linear elastic materials, Hooke's Law relates stress and strain through Young's modulus (E):

$$\sigma = E\varepsilon. \tag{3}$$

Thus, the stiffness of a material depends directly on E. In soft grippers, where the primary material is silicone rubber, E typically ranges between 0.1 and 3 MPa. However, when the gripper's internal layers undergo jamming, interlayer friction increases the effective modulus E_{eff} which can rise to several tens of MPa depending on vacuum pressure [3]. Combining equations (1), (2), and (3), the axial stiffness (k) of a gripper finger can be expressed as the ratio of applied force to resulting deflection:

$$k = \frac{F}{\Delta L} = \frac{AE}{L_0}. \tag{4}$$

From this equation, it is clear that increasing E through jamming directly raises k, reducing deformation for the same applied load. This principle underlies the enhanced rigidity and load-bearing capacity of layer-jammed grippers. We may then model the bending of the soft gripper as a cantilever beam, approximated by a cylinder.

The bending deflection at the tip for the cylindrical cantilever beam is empirically given by:

$$\delta = \frac{FL^3}{3EI} \text{ [2]}. \tag{5}$$

Deflection decreases as E increases, meaning that the jammed state not only increases gripping force but also stabilizes the structure during operation. Because deflection is not significant, which the Poisson effect accounts for only a small part of the deflection, the effective modulus E_{eff} increases through jamming, which makes the allowable load increase almost linearly, explaining why jammed grippers can lift several times the weight of unjammed ones [1].

Now, to quantify how the stiffness of two vertically oriented soft grippers affects their ability to hold an object, we begin by considering the force balance at the contact interface. When the gripper fingers bend inward symmetrically, each finger applies a normal force F_n on the object. Friction between the gripper surface and the object provides the tangential holding force F_t, which prevents the object from slipping downward due to gravity. We have the frictional component F_t equaling:

$$F_t = \mu_s F_n, \tag{6}$$

where μ_s is the static friction constant. Such that the object does not fall, equilibrium is established by having Weight W reach its maximum:

$$W_{max} = 2F_t = 2\mu_k F_n. \tag{7}$$

The normal force is related to the gripper's internal stiff linearly: $F_n = k\Delta L,$ where k is the finger stiffness and ΔL is the inward displacement. Combining equations (4), (14), and (15) yields:

$$W_{max} = 2\mu_s k\Delta L = \frac{2\mu_s A E_{eff} \Delta L}{L_0}. \tag{8}$$

This result shows that the maximum holdable weight depends on the effective modulus tunable through layer jamming, the contact area A, the static friction coefficient μ_s, and the ratio of deformation $\frac{\Delta L}{L_0}$.

2.2.2 The Effect of Laying Jamming on Young Modulus

Layer jamming is a variable stiffness mechanism that enhances the structural rigidity of a soft actuator by boosting frictional coupling between multiple flexible sheets of polymers. The principle is that when internal particles or layers are compacted under vacuum pressure, relative motion is restricted, and the system transitions from a compliant to a rigid state. In the context of the soft gripper, this process dramatically increases the effective Young's modulus E_{eff}, which we had proven is linearly correlated with the weight capacity of the gripper.

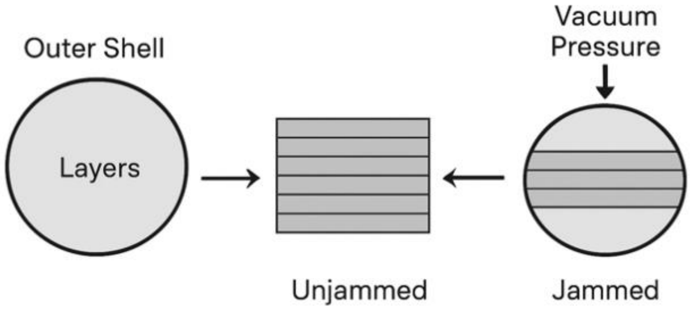

Figure. 4 Figure created by ChatGPT on the action of layer jamming, 2025.

In the unjammed state, the layers inside the jamming module are loosely packed, allowing them to slide freely over one another. When vacuum pressure P_v is applied to the polymer stack, the air between layers is removed, and an interlayer normal pressure develops. This compression produces frictional resistance to shear and bending. The frictional shear stress τ_f generated between layers can be expressed as:

$$\tau_f = \mu_{polymer}|P_v| = G\gamma \ [2], \tag{9}$$

where $\mu_{polymer}$ is the static friction between polymers, G is the shear modulus, and γ is the shear strain concerning angular deformations between the stack of polymers.

As observed, the shear stress is influenced by the amount of vacuum pressure, which then increases G (the shear modulus), which linearly correlates with the modulus of the gripper:

$$E_{eff} = (1 + 2\nu)G \ [2]. \tag{10}$$

Any increase in G due to interlayer friction directly increases E_{ff}. To quantify by how much the effective modulus has increased, we model the mechanical transition as a continuous stiffening process. Initially, when no vacuum is applied, the stack behaves as a low-modulus lamina that only follows the base silicone's elasticity E_0. As the vacuum increases, the frictional coupling between layers grows until the layers are fully locked, at which point the composite behaves like a rigid laminate with a much higher bending stiffness. We can estimate the effective modulus of the jammed structure using the following relation:

$$E_{eff} = E_0(1 + k_f P_v) \ [2]. \tag{11}$$

The stiffness constant k_f refers to the stiffness that was improved by interlayer jamming on each layer, which depends on the number of layers in jamming action, the friction coefficient between layers, and the contact area. Empirically, k_f can range from 0.10.1–1.0 kPa, meaning a vacuum of −50 kPa can increase the modulus by several times its unjammed value [3]. As the effective modulus positively correlates with weight capacity, this study expects a proportionate increase in weight capacity such that any current structure can have increased load by percent.

During experimentation, an analog model of layer jamming was constructed by inserting layers of A4 paper inside an air channel right next to the gripper itself. In this case, slips of A4 paper are the stacked polymers, and the addition of a vacuum outlet in this air unit allows for slips of A4 paper to press against each other vigorously, increasing the effective modulus of the gripper adjacent to the air unit that was jammed. Results of load increase would be discussed in later sections.

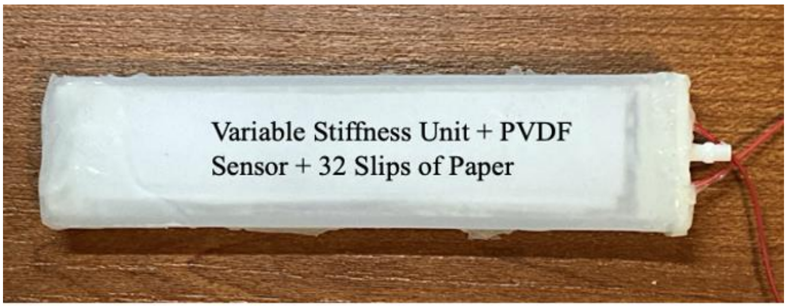

Figure. 5 Air channel with A4 paper as the variable stiffness unit created by Finalist, 2024.

2.3. Fabrication of the Gripper

2.3.1 Silicone Rubber Solidification Principle

Once the design of the soft gripper prototype is established, creating the gripper, specifically solidifying silicone rubber into the gripper's shape becomes the next step. Solidifying an organic fluid usually takes the reaction of:

$$A_{(l)} + B_{(l)} \rightarrow C_{(s)} \tag{12}$$

where A is called the curing agent and B is called the base, as the two bonds to strengthen intermolecular attractions, holding silicone rubber molecules together as a solid C [8]. To solidify silicone rubber into its colloidal precipitate, a mold is needed to hold the mixed elastomer in place, allowing the base and curing agent to mix sufficiently. The principle behind the reaction in (12) is a phenomenon called cross-linking, when chains of silicone polymers connect to form a network, which the product takes the form of a solid condensing from the liquids in the reactants [8]. This reaction is widely used because no byproduct is produced—despite the backward equilibrium reaction, the liquid base and curing agent almost fully reacts to yield significant amounts of solid product.

Vinyl-functional silicone rubber, the base in this case, takes the chemical formula of a lengthy chain of polydimethylsiloxane, which are long, flexible repeating the unit of:

$$CH_2 = CH - [Si(CH_3)_2 - O]_n - Si(CH_3)_2 - CH = CH_2. \tag{13}$$

The double bonds between CH_2 and CH is the reactive site where the cross linking occurs. Vinyl silicone is then mixed with the curing agent, Hydride-functional silicone rubber, in the form of:

$$H - [Si(CH_3)_2 - O]_m - Si(CH_3)_2 - O - H. \tag{14}$$

Now, the hydrogen atom at the end of the curing agent connects to the CH_2 at the end of the base, breaking the double bond to connect with it. This solidification process is called Hydrosilylation, where the vinyl group of the base silicone forms an extra Si-C bond with a hydride group of the curing silicone, connecting two polymer chains [8]. The newly formed bond looks like:

$$\text{[Base]}\equiv Si - CH_2 - CH_2 - Si \equiv\text{[Curing Agent]}. \tag{15}$$

Such that when these bonds form, the silicone rubber curves and connects into a network with a remarkable number of London Dispersion Attractions that makes silicone rubber a solid, despite high ambient temperatures that are used as catalysts to accelerate the reaction [8].

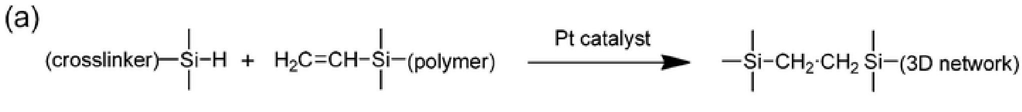

Figure. 6 Hydrosilylation reaction causing cross-linking in silicone rubber complex. (https://www.researchgate.net/figure/a-Hydrosilylation-reaction-and-b-condensation-reaction-for-the-preparation-of_fig2_339037545)

2.3.2 3D Printing

With the Hydrosilylation reaction in place, to create molds to fine precision that will form thin, smooth soft structures, this study employed 3D printing to create the required molds. This study selected resin as printing material since resin is heatproof, that it remains at solid state up to 100 degrees Celsius ambient temperature—the surrounding heat serves as a catalyst to the solidification reaction. The precision of the molds was selected to be 5mm, as that yields sufficient precision for the silicone to smoothen in the molds, instead of having small bumps and cavities on its surface, like the 10mm precision would engender. The orientation of the molds in the 3D-preview is landscape, so no additional supports need to be printed, there wasting resin and giving potential for making the surface less smooth.

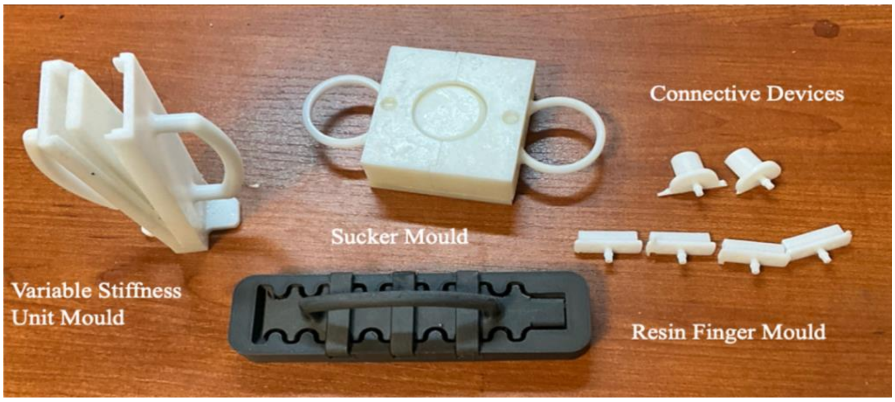

Figure. 7 3D-printed molds and connectives created by Finalist, 2024.

2.3.3 Experimental Conditions to Solidify Silicone Rubber

The silicone elastomer (product C in equation 20) was prepared by mixing base (type B) and curing agent (type A) silicone solutions at a 1:1 weight ratio, mixing fully with a chopstick, and degassing in a vacuum chamber for two minutes to eliminate entrapped air bubbles during the mixing process. Degassing was especially crucial for thin-walled bellows, like the gripper this study attempts to create, to ensure airtightness and durability in later use.

Figure. 8 The base and curing agent in silicone formation bought by Finalist, 2024.

During the fabrication process, molds were filled slowly to avoid bubble entrapment, and as the fluid remains tape was attached around each mold to ensure the molds are in a state of relative rest. The cast samples were cured at 25 °C for 4 hours, in later trials thermally accelerated at 70 °C, depending on silicone viscosity and part thickness. Environmental parameters such as temperature (±10 °C) was maintained using heaters to ensure consistency of curing, such that a part does not solidify earlier than its surrounding parts, partially distorting the shape of the cast.

Figure. 9 Fabrication environment using heat of the Finalist, 2024.

Following the molding process, the solid product was demolded by force (pulling across the handles assembled on the molds). Sometimes the solidified samples were difficult to remove, such that the author placed a thin layer of white Vaseline on the mold's surfaces touching the silicone solutions before pouring the solution, creating a nonpolar barrier preventing unnecessary London Dispersion attractions. The halves of fingers were later assembled with the central jamming module and suction system using silicone adhesives prepared by heating a. In the openings of the silicone air channels, 3D printed connective devices that tightly cling to soft pipelines were installed and adhered with the 5800-metal adhesive, sealing the air channels to be used for durability testing. Each gripper was subjected to pneumatic leak testing—pumping 100kPa of pressure for 30 seconds, observing potential leakage--prior to assembly to ensure airtightness was secured. Four samples of weights 40g, 40g, 35g, and 35g, out of 21 passed this test, which was just sufficient to produce two fingers in gripping action.

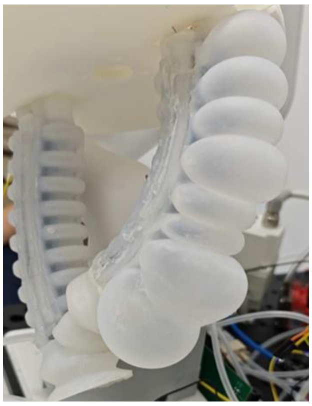

Figure. 10 Gripper that failed the air pressure test produced by Finalist, 2024.

2.4. Overall Process of Automation

2.4.1 The Flow of the System & Detection Algorithm

The system of gripping requires multiple stages. First, the system must identify an object to grab, using a vision-mimicking device. Next, the system must choose how to grab the object, whether using inward, outward, or suction gripping as the available options. Following that, the system moves the pair of grippers above the object, this motion directed by the 6-DOF (degrees of freedom) robotic arm through the logic of inverse kinematics. Finally, the gripper lands at the same elevation as the object, then powered by air pressure to grip the object using the identified mode of gripping, lifting it up for 5 seconds to see if the object drops.

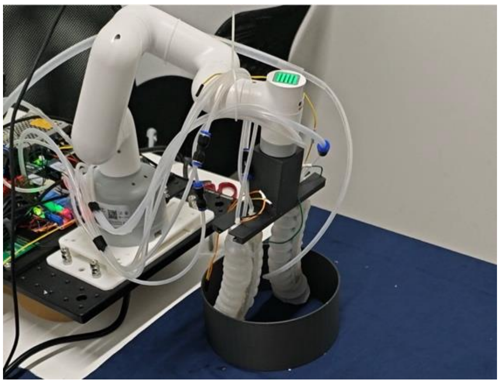

Figure. 11 The gripper-robotic arm complex in action taken by Finalist, 2024.

Throughout this process, operation of three systems is required to fully automate the gripping process: the camera-robotic arm complex, the airway, and the electric circuit. Using pre-programmed functions, the camera-robotic arm complex needs directions given from a microcontroller to adjust the position of the gripper. The instructions required are given by the detection algorithm, which captures the object's size and depth, helping the system select the optimal method of gripping. The airway will manage two tasks: which pair of fingers are bending and whether to use the variable stiffness function during gripping. The electric circuit delivers signals received from the microcontroller to electric relays, then opens the correct airways so pressure could be delivered to the right pair of fingers, achieving full automation.

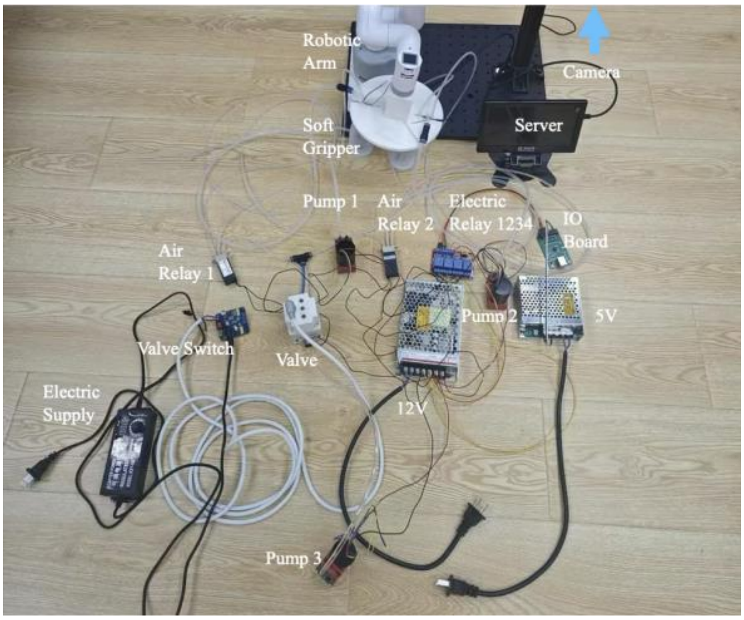

Figure. 12 All the parts present for automation taken by Finalist, 2024.

2.4.2 Detection Algorithm

To see the dimensions of the object the gripper intends to grip, this study implemented a double-eye depth camera that mimics the human eye, using the distance between the "eyes" to determine the distance of the object from the table. The built camera provides a 30frame/second video stream of the object, helping the detection algorithm capture the approximate shape and size of the object, to determine where it is and how big is it. The purpose of capturing depth is to help determine which gripping mode to use. The algorithm knows how high the camera is from the table, as it is the length of the camera frame. If this distance roughly equals the distance between the camera and the object, then the object is either flat, meaning we can use suction gripping, or hollow, that we can use outward gripping. If the object has a significant height, then inward gripping would work best, though outward gripping would also work for a very specific radius of the object. The algorithm selects inward gripping as default.

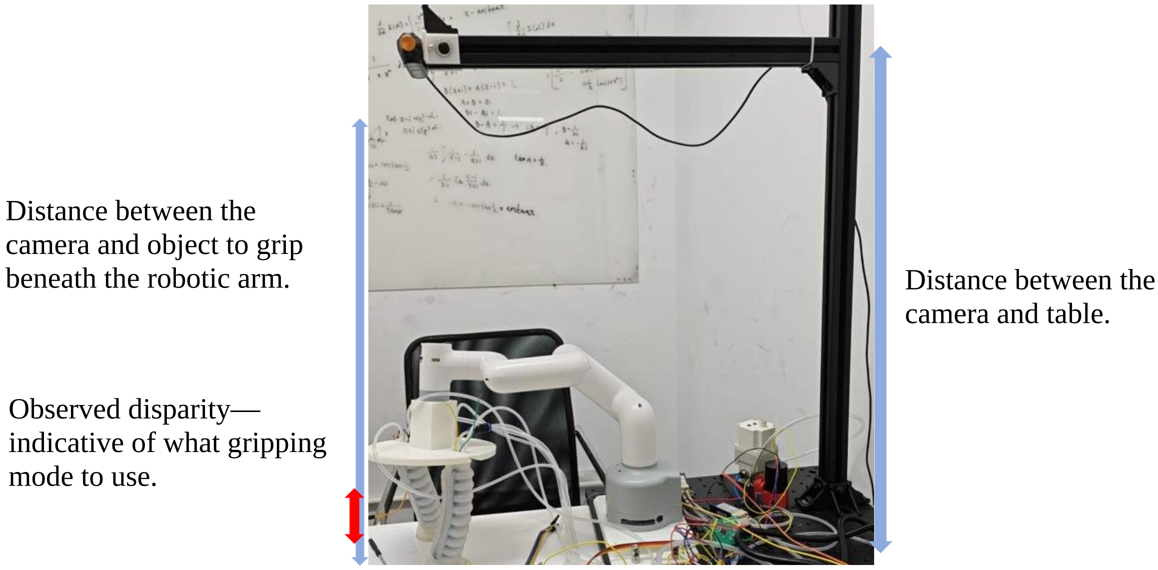

Figure. 13 How height differences affect the selection of gripping choices, taken by Finalist, 2024.

In the case of detecting the sizes of each object, the Hoff Circle Algorithm was employed to fit a circle around each object, obtaining that object's size through its radius. The algorithm functions as a parameter-space transformation method—one that mutated from the Hough transform. Edge points extracted through the Canny edge detector vote for possible circle centers and radii, which then three distinct edge points determine the circle around the object, just like how three non-collinear points determine a circle. The algorithm then identifies peaks, like what the Hough transform detects with object imperfections, which correspond to detected circular shapes. A dark blue layer of fabric is laid on the table to increase contrast and detection accuracy.Once the object's radius and center coordinates are identified, these parameters are transmitted to the control system to determine the gripping approach and alignment.

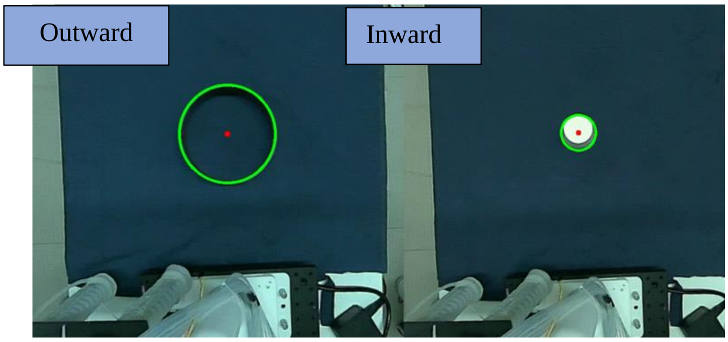

Figure. 14 Hoff Circle Algorithm handling objects of different sizes, taken by Finalist, 2024.

As the Elephant 6DOF robotic arm built a server-client relationship with the microcontroller through the former's raspberry pi, the object's relative coordinates to the calibrated center—where the robotic arm's base is at, is then taken to consideration. Knowing how to get from point A to point B the most efficiently, the robotic arm was installed with a package of Inverse Kinematics to level the pair of grippers just above the object that needs to be gripped.

2.5. Circuit

The electrical control system orchestrates the coordination between vision, actuation, and sensing modules. It consists of a microcontroller unit, electric relay, air relay (solenoid valve), Polyveldene Fluoride sensor in the variable stiffness unit, and communication interfaces connecting to the host computer. At the core of the system lies an Arduino microcontroller, selected to interpret Python code written on the host computer. The Arduino receives input signals from the detection system processed on a companion computer running YOLO. It outputs control signals to the solenoid valves and relay switches that operate the pressure valve and vacuum pump. Specifically, air channels responsible for inward gripping are labeled as the NO channel (Normally Open), and those responsible for outward gripping are labeled as the NC channel (Normally Closed). In a three-way air relay, despite the COM channel being always open to ensure air circulation, whether the NO or NC channel opens depends on whether the object's fitted radius exceeds 60mm. The airway circuit opens up pressure to be delivered anywhere, making whichever needed pair of fingers bend.

2.6. Final Flow of the System

A logic sequence governs the operation:
1.Receive object detection data from the computer.
2.Move the robotic arm to a preset height above the object.
3.Inflate pneumatic chambers to initiate bending motion.
4.When the pressure sensor indicates contact, trigger the vacuum valve for layer jamming.
5.Optionally activate the suction cup for additional adhesion.
6.Lift and transport the object; release pressure to reset.

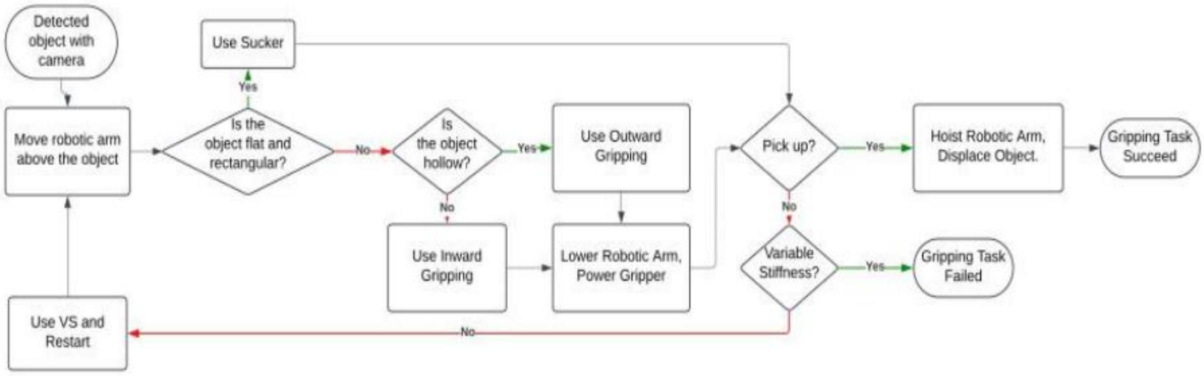

Figure. 15 Flowchart of the system created by Finalist with LucidCharts.

The control logic operates in a closed loop, continuously adjusting actuation commands based on detection feedback. The user can override automatic control via a serial command interface for manual testing and calibration. The gripping system is now ready for testing.

3. Experimentation & Effectiveness of the Gripper

3.1. Testing Each Gripping Mode

When running the flow of the system, the study attempted to test if each gripping mode functions well, with each an object matching their gripping capacities. Five trials were conducted to each object to grab, as all three gripping modes (inward, outward, and suction) succeeded in all five trials. Objects gripped exhibit a range between a cup of 50mm to a ring of 200mm, proving the effectiveness of dual mode gripping in enlarging the volume of objects available to grip and handle robustly.

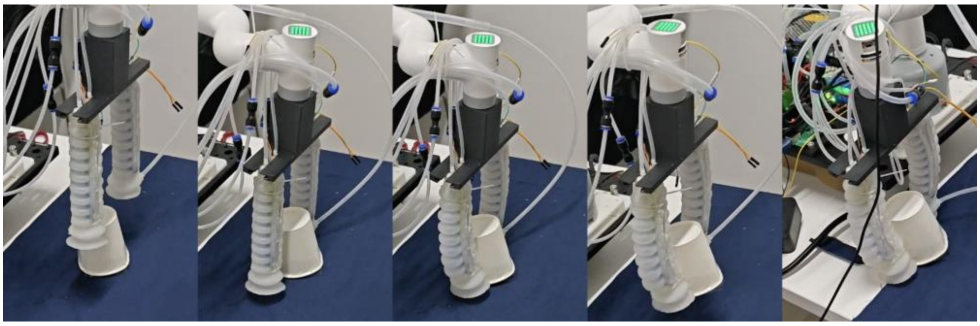

Figure. 16 Inward gripping in action taken by Finalist, 2024.

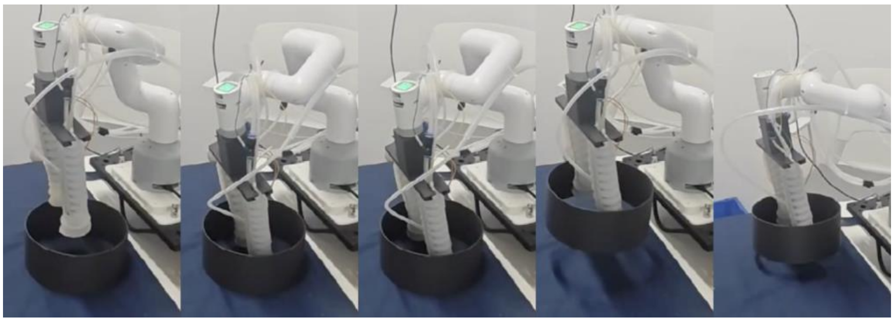

Figure. 17 Outward gripping in action taken by Finalist, 2024.

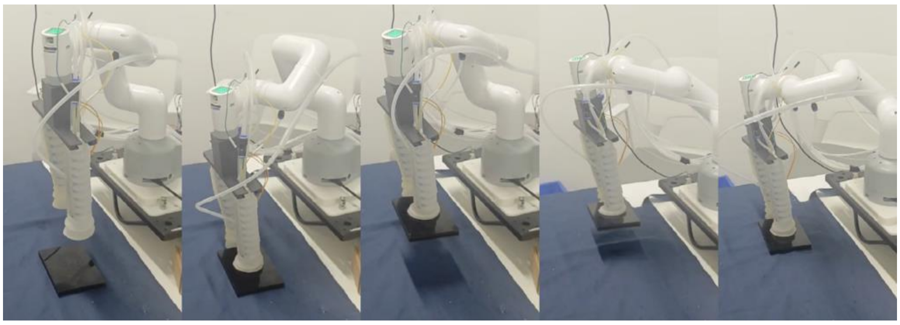

Figure. 18 Suction gripping in action. taken by Finalist, 2024

3.2. Testing the Effect of Layer-Jamming on Weight Capacity

3.2.1 Experimental Hypothesis

The hypothesis this experiment attempts to validate is activating the layer-jamming variable stiffness module will increase the soft gripper's effective modulus and thus raise its maximum reliably held load. With identical pneumatic actuation, a gripper with layer jamming engaged at −50 kPa will achieve a higher success rate and lift heavier loads than the same gripper operating without jamming.

3.2.2 Experimental Procedures & Data Analysis

Two tests were performed to compare gripper performance with and without automation, as the Elephant robotic arm limited payload capacity. With the arm, the gripper lifted a 4 g cup incrementally loaded with 2 g screws. Without the arm, identical 500 mL bottles were filled from 100 mL to 220 mL in 20 mL steps, with density assumed to be 1g/mL. Each mass increment had five trials, judged successful if the object was lifted 20 cm, held for 5 s, and released. Pneumatic pressure was fixed at +60 kPa using a pressure valve, while the variable-stiffness (layer-jamming) vacuum was −50 kPa; the control group had 0 kPa vacuum. All tests were at STP to isolate jamming effects on load capacity.

Both tests revealed a significant difference on the performance with stiffening and without stiffening. With stiffening, without the robotic arm the performance of the gripper was limited to 50g because of the maximum, thus only revealing an increase of 35% in weight capacity, once removing the outliers. The test independent of the robotic arm showed a more significant increase in weight capacity, soundly a 120% increase.

A statistical error test was conducted to observe the significance of the data, whether it proves the distribution of frequencies weight were loaded without and with using the stiffening mechanism. Pooled populations, standard errors and z-scores were computed, as z-scores of 2.68 and 5.91 correspond to p-values of 0.007 and 10^{-5}, in that high confidence of data shows layer jamming significantly increased the weight capacity by increasing the number of trials succeeded in both tests, confirming the usefulness of the variable stiffness module.

Conditions (screws)	Successful Trials	Failed Trials
Without VS	14	26
With VS	26	14

Conditions (water)	Successful Trials	Failed Trials
Without VS	4	36
With VS	30	10

Figure. 19 Summary of all trials created by Finalist, 2024.

	Without Variable Stiffness (trials succeeded)	Average/ Median/Mode Time(s)	With Variable Stiffness (trials succeeded)	Average/ Median/Mod Time(s)
5 Screws (22g)	5	30/29/30&39	5	27/25/26&25
6 Screws (26g)	4	33/33/32&34	5	30/29/30&29
7 Screws (30g)	3	34/34/34	4	31/32/31
8 Screws (34g)	1	37/37/37	5	32/31/31
9 Screws (38g)	0	N/A	2	35/35/35
10 Screws (42g)	1	38/38/38	2	38/38.5/38&3
11 Screws (46g)	0	N/A	1	40/40/40
12 Screws (50g)	0	N/A	0	N/A

	Without Variable Stiffness (trials succeeded)	With Variable Stiffness (trials succeeded)
Water bottle (100g)	3(out of 5 trials without the robotic arm)	5(out of 5 trials without the robotic arm)
bottle + 20ml distilled water	1	5
bottle + 40ml distilled water	0	4
bottle + 60ml distilled water	0	5
bottle + 80ml distilled water	0	5
bottle + 100ml distilled water	0	3
bottle + 110ml distilled water	0	2
bottle + 120ml distilled water	0	1

Figure. 20 Data from both tests revealed in number of succeeded trials created by Finalist, 2024.

3.3. PVDF Sensor Confirming Variable Stiffness in Action

To experimentally confirm that the layer-jamming mechanism was altering the internal stiffness of the soft gripper, a polyvinylidene fluoride (PVDF) vibration sensor was integrated into the variable-stiffness channel. PVDF was chosen for its unique piezoelectric behaviors--polarizing with respect to vibration, changing the voltage. When subjected to deformation, the polymer's dipolar crystalline regions generate an electrical potential proportional to the rate of strain, making PVDF an ideal candidate for detecting vibrations that layer jamming engenders.

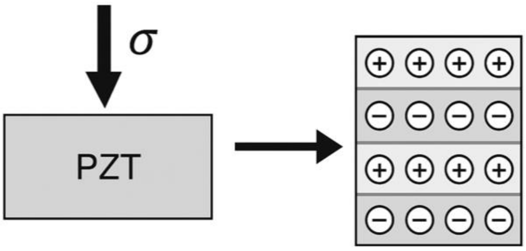

Figure. 21 piezoelectric behaviors microscopically observed, created by ChatGPT 2025.

To collect data, the analog model created in section 2.2.2 is used to provide voltage signals responding to compression. Then, an amplifier was installed to enlarge the voltage signals such that the voltmeter connected to the ends of the PVDF sensor could display an observable change, proving that layer jamming was happening to cause the observed load increase. The data for 10 trials, corresponding to 10 analog tests conducted using a voltmeter was shown:

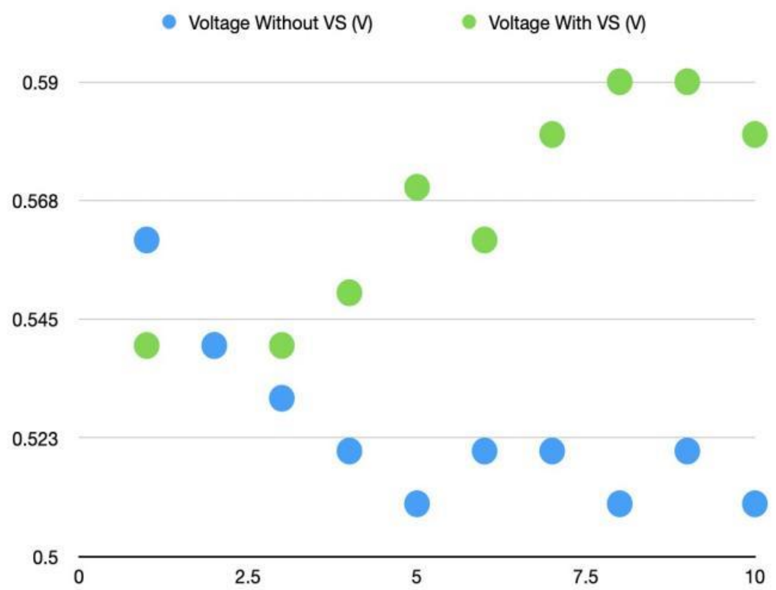

Figure. 22 Voltage Data with and without Variable Stiffness recorded by Finalist, 2024.

A maximum difference of 0.09 V was commonly observed, as the number of trials increase the disparity emerges. This difference is significant enough to prove variable stiffness was in action, and combining with the second test in this section, the effect of layer jamming on increased weight capacity.

4. Discussion

This study proposes a fully automated structure that advances the field of soft robotics through increased weight capacity using layer jamming and enlarged gripping range through multimodal gripping. The stability of gripping combines with the gentle touch of silicone to handle fragile items robustly. In addition, the increase in weight capacity was a percentage increase, as it adds specifically to any gripper's weight capacity because of effective stiffening. The precision and efficiency of this gripper provides possibilities for soft robotics to be used in more applicable situations, specifically in surgical environments which soft edges can handle organs more gently to reduce potential infections from cuts.

Some future work can be done to improve this gripper's performance include fabricating another soft finger to create stability from multiple degrees of freedom, or installing liquid metal sensors to detect the amount of force and deflection the gripper experiences. But in general, this study produced a gripper exceeding standards, with tunable stiffness and enlarged gripping range adjusted for more adaptable gripper capacities.

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