Designing a Soft Gripper for a UAV

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MSc Robotics and Computation

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Abstract

In this paper, four grippers are designed the grippers will be made using PnueNet soft tendons that will be attached to a gripper base, these grippers are designed to be used as attachments to an unmanned aerial vehicle. The grippers will be different by the number of tendons used, the grippers will have two, three, four and five tendons. These gripper will be similar in design and have mainly the number of tendons as the differences. This paper's focus is on the tendons and their ability to be used to grasp objects of different shapes, sizes and weights. The grippers designed in this paper are tested on a linear actuator and are their grasping abilities are tested using a foam rectangle, a beaker and a circular silicone.

Contents

Chapter 1

Problem Statement

Soft robotics has had a lot of development in recent years, with a lot of research done around the field. With recent developments it has become rather simple to develop soft tendons that can be used in many cases. In this project soft robots will be explored in order design and compare four grippers to find which gripper or grippers are most suitable to be used as an attachment on a UAV. The reason soft robots are being studied are due to their light weight and low cost nature. The soft grippers have two main benefits to them their flexible nature which allows them to deform around objects creating a very comfortable, stable grasp, and their ability to grasp onto fragile objects due to their soft nature where the tendons do not damage the fragile objects being grasped.
The tendons individually will be tested by firstly testing the curvature limits and secondly a test will be completed to test the grasping and lifting ability of one tendon. Thereafter, grippers will be designed using the tendons, the four grippers designed will be tested by attaching them to a linear slider and test their ability to grasp and lift objects of different weights, shapes and sizes. These tests will help identify which grippers would be suitable for use on a UAV.

Chapter 2

Introduction

The problem being addressed in this study is finding the optimal soft gripper to be integrated with a UAV. Soft grippers are a lightweight, flexible, and agile alternative to the standard grippers being used on UAVs in recent years. The optimal soft gripper will be studied by designing, testing and comparing 4 soft grippers each using the same tendons, but with increasing amounts. This study will compare the feasibility of 4 Pneumatic grippers, with 2 tendons, 3 tendons, 4 tendons and 5 tendons these grippers will vary in weight and in strength as the number of tendons increases. There has been very minimal research done on soft grippers on UAVs.

Aerial grasping has been a very heavily researched field in robotics In recent years and a lot of progress has been made in the field with successful aerial grasping midflight by UAVs. However, a lot of the research and grasping has been for specific scenarios due to grasping limitations on a drone, for that reason a soft robotic gripper with high flexibility, and agility could be a suitable match for the drone. UAVs in general have a very difficult time keeping stable and accurate during flights and with most grippers tend to need very accurate readings and specific measurements to make accurate pick and place procedures, but a soft gripper does not need exact measurements as long as the object is in a certain range of accuracy the gripper will adapt to the object and should achieve successful picking.

Soft robotics is a novel and distinct approach to thinking outside the box and rethinking robot mechanics. In robotics, a "soft robot" is a device constructed of soft elastomeric materials or a device comprised of hard components with a number of hard actuators working in concert to exhibit soft robotic qualities[1]. Soft robots have shown great promise in recent research and development have shown great promise in the field. While opposed to their stiff counterparts, soft robots have a number of benefits when doing specific activities. They are excellent for use in minimally invasive surgery, search and rescue operations, and gripping activities where items may be delicate because to their very compliant nature resulting from the extensible materials used in their construction and compact size[2]. Meanwhile, the lack of internal sensors and the simplicity of actuation methods allow for far more sizing flexibility than typical rigid robots. When attached to an air supply, pneumatic manipulators effectively consist of a series of chambers that allow for deformation; cable-driven soft robots are controlled by an external motor separate from the manipulator. Smaller centimetre-sized soft robots with pneumatic or hydraulic actuation via an off-board pump mechanism have also been developed[3]. However, because of their hyper-redundancy and absence of discrete, programmable joints, model-based control of soft robots remains an unresolved problem. Because soft bodies are continuous and malleable, there is no clear way to express the system using state variables that describe the body as it changes while in motion. Traditional rigid robots, on the other hand, have established control systems based on classical mechanics that regard the robotic body as a chain of stiff links and joints that may be either rotating or sliding.[2] In this study we will be looking at the different types of soft grippers and their advantages and disadvantages and find the optimal soft grip for it to be used on a UAV. in general the system being designed is not intended to be used only for one purpose the system is intended to adapt to many different pick and place scenarios whether it is aerial construction, last mile delivery or even food delivery. Since this soft gripper is soft in nature it is excellent at handling fragile objects such as food and others.

With the scenarios being aerial construction can be achieved by picking and placing bricks however this is quite difficult to do with a single UAV and for that reason the UAV being used in this study is part of a swarm of UAVs which means that it is a group of UAVs working In sync with each other to achieve a goal. This swarm system works by allocating different quadrants of a build goal to each UAV and the UAV will share charging docks that can be used while other UAV's are in the process of picking and placing.

On the other hand, last mile delivery and food delivery is definitely a great use case of the UAV since having a robot complete mundane task such as delivering product from point A to B is much more efficient then having a human deliver the products.

in this study we will be comparing three soft grippers attached to a UAV, the success rate of grasping, the payload of the gripper and the weight of the gripper will be the main factors that will be looked at in this study.

Preliminary testing of the tendons will be done by testing firstly, the curvature of the tendons, we will compare the curvature of three tendons and ensure that they are the same since their manufacturing is the same ideally, the curvature should be the same, this is also a very important test since it can aid the design of the base by knowing the curvature limits of the tendons. Additionally, a general gripping test will be made by connecting one tendon to a linear actuator and testing to see if the tendon individually has the strength to lift a 250 ml beaker, this is an important test to help us compare the ability of a single tendon to a group.

Further experimenting will be done using a linear actuator where the various grippers will be tested on their ability to successfully grasp objects of different sizes, shapes and weights to test their ability to adapt, and payload. These are the key identifiers to look at for these grippers. further experimentation will be done for this gripper on one drone at the start to test the feasibility and the technology, and in the future the scope can be expanded to have the gripper be attached to the swarm of drones which helps in efficiency and total workload that can be done. During experiments, a set of 20 cameras are used surrounding the working area, which helps us accurately track the position of the drone. The drone also has a vision system quipped which is used to locate the object that is needed to be picked up and fly towards the target, Unfortunately, due to time limitations the grippers were not able to be tested on a UAV.

Chapter 3

Literature Review

This chapter will cover and feature the main literature that have been referred to and have built the foundation of this project. This project focuses on incorporating a soft robotic gripper on a UAV to preform aerial manipulation and achieve aerial building. This project is designed to determine the optimal soft gripper for aerial manipulation. The UAV used in this project will be the one designed by D. Darekar [21], the UAV designed explored the options of aerial grasping using, a claw gripper and a electromagnetic gripper which displayed relatively good results but needed improvement for the UAV to be used for reliable aerial manipulation.

3.1 Swarm Robotics

"Swarm robotics is an approach to collective robotics that takes inspiration from the self-organized behaviors of social animals" [4]. The grippers developed in this project are to be integrated to a swarm of UAV's that have been developed by [21]. sectionAerial Construction The use of robots for construction has shown promising results and has encouraged a great deal of research in the field. One of the approaches that can be taken is construction using bricks [5][6], this has proven to simplify the building process since picking and placing bricks side by side and on top of each other leads to a simple and easy pick and place mechanism. However, the drawback of using simple brick construction is that it leads to gaps in between the bricks which does not guarantee stability and structural integrity. Additionally, there is another approach which makes use of small sub cubic structures and special nodes [7], the cubic structures are connected to each other using the node. this results in a cubic structure that is very stable and has structural integrity. However, these structures or very complex in comparison to building using blocks since there are different orientations of the rods and the addition of a node which will require a precise and complex mechanism.

3.2 UAV Control

Controlling a UAV is difficult when considering the variable payload due to having two pick and place objects. Grasping an object while in flight proves to be the most challenging problem of controlling the UAV but this can be overcome by using a PID controller [8]. Being able to grasp while in flight is crucial for efficient aerial construction. Additionally, using a PID controller is necessary for instances where the payload is not centered perfectly which would result in unbalanced forces, the PID controller can offset the imbalance [9]. There are many different UAVs that have developed unique grasping mechanisms, such as [10] a UAV with a jaw as a gripper in the center, the mechanism works by clamping over an objects and grasping it. Another, method UAV made for grasping tubes and spherical objects has a gripper with a circular shape to grasp on to tubes[11]. Additionally, a UAV [12] with a soft gripper that makes great use of the soft limitations and shows very promising results for soft grippers for UAVs. Furthermore, there is a quadcopter that uses a 3 degree of freedom manipulator that has a gripper at the end of the manipulator, this design allows for a great range for the gripper and adds flexibility to the UAV's grasping ability[13]. Finally, there is a UAV that makes use of a soft gripper that is used by surrounding the object and then inflating the soft gripper around the object completely inside the universal jamming soft gripper[14].

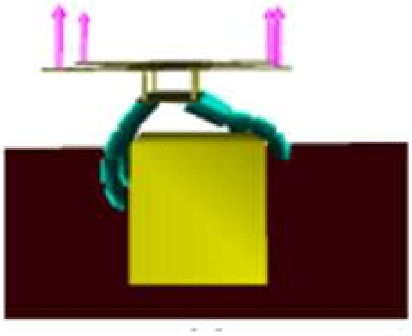


Figure 3.1: Soft tendon driven UAV [12]

Figure 3.2: Quadcopter with a 3 D.O.F manipulator [13]

Figure 3.3: UAV designed for tube grasping [11]

Figure 3.4: UAV with a Claw gripper [10]

Figure 3.5: UAV with universal jamming soft gripper[14]

3.3 Soft Robotics

Soft robotics is a new and unique way of breaking past the boundaries of the box and re-thinking the mechanics of robots. A "soft robot" in robotics can be defined as, a machine made of soft elastomeric materials, or a machine made of hard components that consists of multiple hard actuators that function in together and demonstrate soft robotic properties [1]. Soft robots have gathered a lot of attention in recent years, majority of the research within the field can be categorized as: granular jamming [15][16], electro- and magnetorheological materials [17], shape memory polymers [18][19], low melting point materials [20][21] and pneumatic actuation [22]. Soft robots are hyper redundant and contain an infinite degrees of freedom in theory, this is due to their nature being very deformable and them having continuous bodies their bodies contain n joints, with n tending to infinity. They have the ability to bend, stretch, buckle etc. which can be viewed as having infinite degrees of freedom [23]. In reality, this is not the case as motion of soft robots are often constricted through various methods, for example pneumatically actuated soft robots are limited due an in-extendable layer that is embedded in the soft deformable body. Soft actuators have been studied in recent years for usage in a variety of applications. This involves the use of soft micro robots for medication administration to inaccessible portions of the human body that cannot be accessed with typical surgical equipment, such as the inner sections of the brain. They are particularly adapted to this role since they may be made of biodegradable and biocompatible materials that can deform to move through the body's vasculature, guided by ultrasound, temperature, or magnetic fields. They have also been utilised to create unique hand rehabilitation wearable devices since their compliant nature lends itself well to responding to human motion and the actuators may be tuned to match the range of motion produced by individual fingers[24]. [25] Highlights and displays different types of soft robots and soft actuation focusing on their benefits for certain scenarios. All these methods are a great approach to the technology, and all serve a purpose for certain scenarios. For this scenario, the design mainly adopts key characteristics of pneumatic actuation.

Gripper Type	Advantages	Disadvantages
Cable Driven	Optimal weight and space	Control Complexity
Vacuum	Highly flexible Clean	Some operational issue
Pneumatic	Small dimension Low weight Clean	Not precise enough High operating cost
Hydraulic	High force	Not clean enough high maintenance cost
Servo-Electric	Highly flexible Low maintenance cost Easily controllable Clean	Low force

3.4 Soft Gripper Integration

Gripper Type	Image	Payload	Weight	Success Rate
Tendon Driven [12]		Medium	Low	High
Soft Tendons Actuated by Cable [19]		High	Medium	High
PneuEA Gripper [14]		Low	Low	Medium
Tendon Driven [11]		Medium	Low	High

Figure 3.6: Grippers

Soft robotics has been newly introduced to aerial use such as [26][27] which are both used for pipe maintenance which isn't directly related to what this scenario, however many of the main challenges faced are the same. On the other hand there is one case where a soft robot has been used with UAV's for general pick and place similar to what is to be achieved in this report, in [28] they add four soft fingers at the bottom of a quadcopter and is intended for general pick and place of deformed and irregular objects, the interesting part of [11] is that the gripper's fingers are initially actuated to be lifted up as to not add to the collision space of the copter. There are many grippers designed that can be applied to given case such as [29] which is a tendon-driven soft robot based on [30] which is a hybrid approach where small tubes are used inside the tendon to actuate the gripper, as well as [1] which is a pneumatically actuated silicone gripper which with slight design adjustment can be implemented to aerial use. Additionally, in [31] the design of the gripper is long adhesive rectangular block which surrounds the object, this design could be implemented in the current scenario by adding second actuator which could then manage to carry a higher and bigger payload.

The soft gripper does face challenges, these include robustness, speed, sensor integration, and control. Many of these challenges can be overcome with advancements and upgrades in the material (elastomers, etc.) used in the soft robots [32]. However, soft robots are also very advantageous, such as the pneumatic actuated grippers (which is going to be used in this report), are lightweight like most other soft devices, high gravimetric specific power, easy to install and smooth motion, and it is clean and safe [33]. The requirement for sensory feedback is another barrier to effectively modelling control for soft robots. Encoders will be installed at each joint of rigid robots to monitor displacement, velocity, and acceleration. They may also have cameras, LIDAR, and a variety of other sensors to help them navigate their surroundings utilising odometry or dead reckoning. Soft robots do not always have access to these suites of sensors, not only because of their typically tiny size, but also because integrating these non-deformable, hefty sensors into their soft bodies is problematic[34]. Because of the uncertainty associated with the adaptable materials utilised, whose deformation relies on the surrounding environment and the interaction between this environment and the soft body, sensory feedback is critical for soft robotic closed loop control. Because the soft body is very pliable, it adapts to its environment, resulting in unique positions that can only be assessed by sensory data. The current research in this field is still relatively new but is showing great development and progress in the gripper field there are already efficient and effective soft grippers in industry, however there is very limited research done on the implementation of soft robotics for aerial use. The lightweight and flexible nature of a soft gripper would suggest being a great match for a UAV, since the margin of error is high, and the payload is low.

3.5 PnueNets Bending Actuator

The Whitesides Research Group at Harvard is credited with the initial development of the PneuNets (pneumatic networks) class of soft actuators. They consist of several chambers and passages contained within an elastomer. When under pressure, these channels expand and move. By altering the shape of the embedded chambers and the composition of their walls, the nature of this motion can be altered. When a PneuNets actuator is pressured, expansion takes place where it is least stiff and most compliant. For instance, the thinnest structures will experience the maximum expansion if the PneuNet is made of a single, homogenous elastomer. The behavior of the actuator can be programmed in advance by designers by choosing the wall thicknesses that will provide the desired motion. The PneuNet actuator described here is made up of a row of chambers, with the wall sections between each chamber having the thinnest walls. The base contains a piece of paper that acts as the strain-limiting layer.

3.5.1 Design

The thin walls between the chambers protrude the most when the device is inflated, which causes the chambers to enlarge. As a result, instead of the actuator expanding in the axial direction as would be expected, the strain-limiting layer contracts, causing the actuator to bend. The actuator is made up of two parts: an inflatable main body and a base with an inextensible paper layer

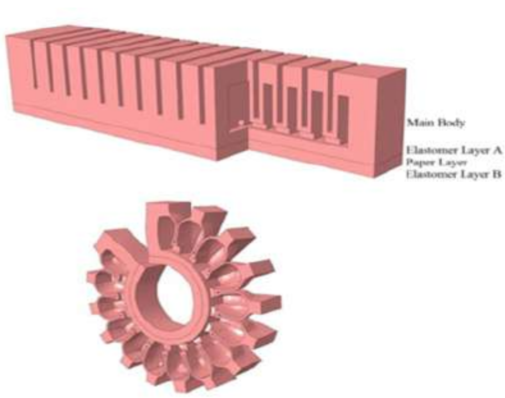


Figure 3.7: Actuator Cross-section

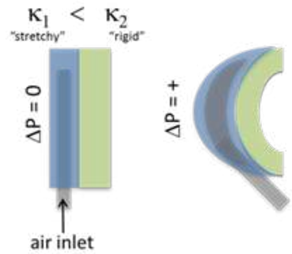


Figure 3.8: Actuation Diagram

immersed in elastomer. The main body and the base are separately cast and then assembled to

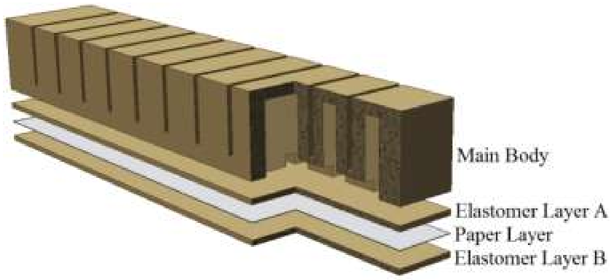


Figure 3.9: Actuation Diagram

create this actuator. The actuator's base is a simple rectangular plate. In the two-part mold seen here, the more intricate main body is cast.

3.5.2 Simulation

Simulations regarding soft robotics are done on Abaqus CAE, the actuator is simulated in this software. Abaqus is a finite element method (FEM) simulator that can be used to assess how soft robots behave when forces are applied onto them its main attraction is the amount of data that is gathered is very effective and useful. After input data regarding, density, elasticity, Young's modulus, Passions Ratio and Yeoh strain energy potential depending on the material, since the actuator in this project is made of elastosil and paper, there are only two sets of data needed. The soft body is split into 3 parts, one section is the top body, with the chambers, second section is the bottom part of the body and then the third is the paper. that is placed inside the bottom section. Unfortunately, due to the limitation of student version of the software the model needed for this project was not simulated since the full model used over 30,000 nodes which isn't permitted in the Abaqus student software. However, there are many other studies that have completed the simulations on the same tendons used in this project.

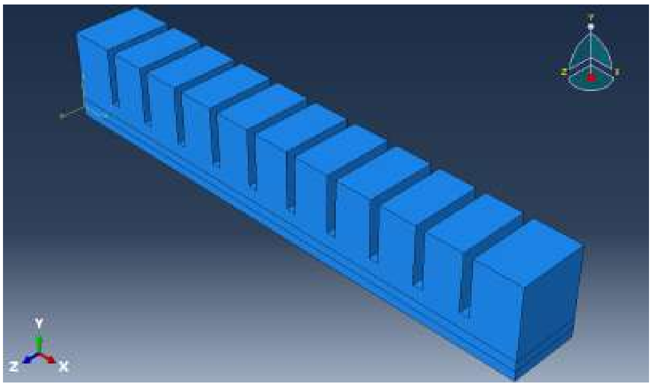


Figure 3.10: Image of Simulated PnueNet Tendon

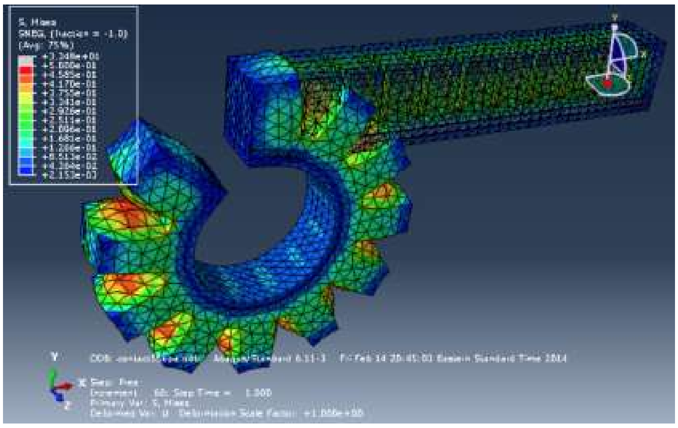


Figure 3.11: Image of expected deformation at 0.055 MPa

3.6 PnueNets Usage

PnueNets have been used for different purposes, an example that has proven to be show successful results is using it as a soft pneumatic glove for hand rehabilitation [35]. This study outlines the initial steps taken to create a soft glove for hand rehabilitation. Geometric analysis and FE model simulations were used to evaluate pneumatic actuators built on the PneuNet architecture. A soft silicone material with good elongation properties was used to manufacture the chosen geometrical patterns that came from the FEM. Findings from experiments monitoring the actuators' tips the capacity to curl more than 320 degrees, as well as create pressures that are strong enough to help a pair of passive human impaired fingers that are slightly or not at all stiff. The results proved the feasibility of the project and of the glove.

Figure 3.12: PnueNet Glove

Additionally, another approach to an assisted gripping glove is [36] where the study uses complex deployable soft pneumatic networks (D-PneuNets) actuator with chambers created using an origami technique.An initial compact form and low actuation pressure of the produced robotic glove make it advantageous for grabbing a variety of commonplace things, according to the trial and demonstration.

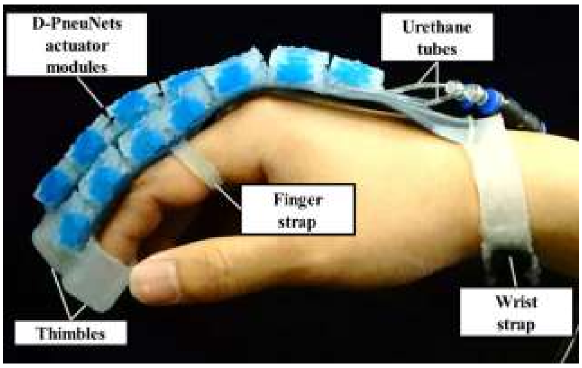


Figure 3.13: D-PnueNet Glove

Chapter 4

Equipment

4.1 Tendons

Tendons are made using Silicone Elastosil Wacker M 4601, it is a two-component addition-curing silicone that vulcanizes at room temperature. A reddish synthetic rubber is the ultimate product. The silicone is made by mixing product A and B of the mixture in a ratio of A:B = 9:1. This is completed by using a scale. There are three molds, the bottom mold is a simple rectangle plate. However, the top molds are more complex they are meant to be combined and used as one mold. The chambers of the actuator are made by the extruded walls on the bottom part.

The tendons are designed to have 11 chambers. However, only 10 will be in use, the gripper is designed to hold on to the tendon using one of the chambers in an enclosed space in order to keep it firmly attached to the gripper base. As can be seen in the figure 4.1, the air chambers required to actuate the tendon are made using the walls as mentioned previously, also there is a small ridge in between the extruded wall that connects these chambers, this ridge allows for resulted mold to have a gap to allow air to flow through the chambers.

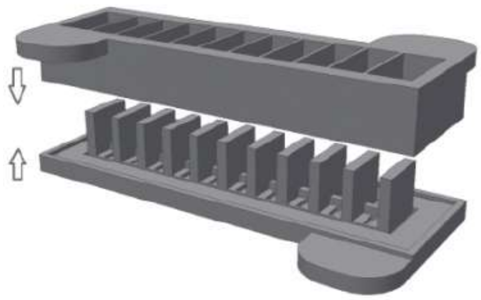


Figure 4.1: CAD Design of top mold

Figure 4.2: CAD design of bottom mold

4.1.1 Fabrication

The actuator is molded in 5 steps, the entire process takes 48 hours to complete one tendon. The top and bottom mold are done at the start, they are then left to cure for 18-24 hours, then using the silicone as adhesive the top and bottom mold are combined, after curing the actuator is completed.

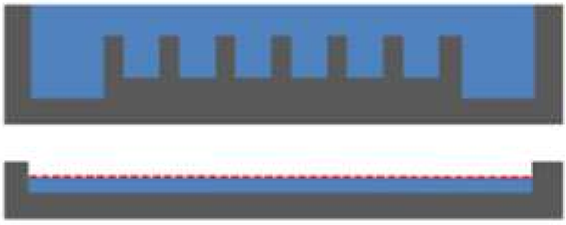
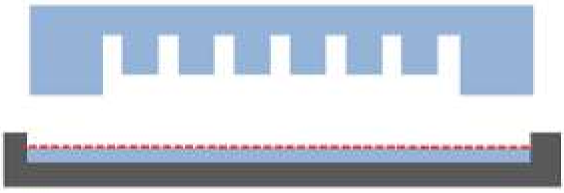
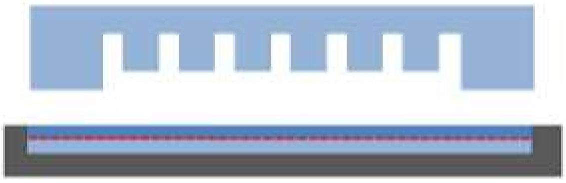
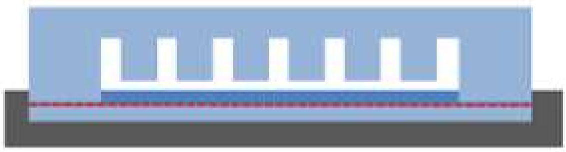
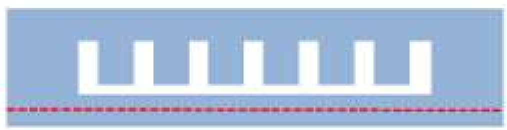
	Elastomer mixture is poured into the molds. Completely fill the main body mold; half-fill the base mold, then top it with a piece of paper to act as a strain-limiting layer.
	Cure the two pieces, then remove the main body mold.
	Uncured elastomer is poured into the remaining half of the base mold.
	Bond the main body piece to the foundation using the uncured elastomer as adhesive.
	Cure the two pieces together. Final actuator

Figure 4.3: Fabrication Step

4.1.2 Procedure

The combined total of actuators needed for the manipulators in this project is 14, since we need two for 2-gripper, three for the 3-gripper, four for the 4-gripper and five for the 5-gripper. This process can be very time consuming so to -be more efficient 8 top molds and 12 bottom molds are used to complete the tendons in 10 days. Accounting for the unsuccessful tendons, about 32 tendons were made during this project. The main reason the tendons were unsuccessful is due to blockage in the air chamber this occurs during the penultimate stage where the top mold and the bottom mold are to be combined. In the combination step it is important to have enough elastomer for the they elastomer to act as a strong adhesive and keep the pieces attached. During initial Implementation a strategy was found to be very helpful in ensuring that blockage doesn't occur, this was to combine the top and bottom bodies and then after two to three hours simply lift the top piece slightly to make sure that the elastomer is not creating the blockage and not in contact with the inner walls of the top body. During the first batch of molds there was a success rate of about 20 percent which is what encouraged the development of the new strategy which showed promising improvements to about 70 percent success rate. The molds seen below are an example of the molds used in this project, the molds are all 3D printed. They are in groups of three since the top mold is made of two of the pieces and the bottom mode is a simple rectangular plate. The elastomer is applied into the mold and left to cure as can be seen in the figure 4.5. It

Figure 4.4: Example of 3D printed mold

can also be seen in the rectangular mold that there is a piece of paper acting as a tough surface for the actuator to move around. An important step that is commonly overlooked is ensuring that air bubbles found in the elastomer are popped, inevitably there will be air bubbles that remain in the final actuator, however, they must be avoided since they can create weak points in the actuator which will later lead to leakage. It is important to note that since an elastomer is being used if an air bubble or a leak was to occur it can be fixed by mixing some more elastomer to block the leak.

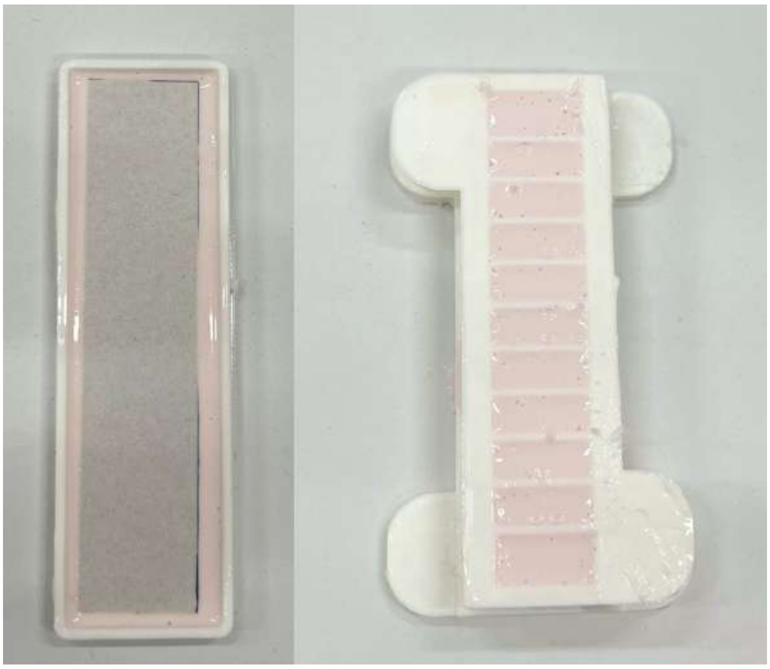


Figure 4.5: Example of mold curing

4.1.3 Actuator

The figure 4.6 shows the final version of the tendon/actuator. As can be seen in the figure there is a PVA tube attached into the tender this is achieved by finding a metal rod that is between two to three millimeters in diameter and placing it inside a tube of four millimeters diameter and then using the metal in the tube to poke a hole into the top of the tendon which will create a tight gap for the PVA tube to fit in therefore creating an area for air to flow into the actuator.

Figure 4.6: Example of tendon

4.1.4 Actuation

The tendon is actuated using a 12 volt peristaltic pump, as seen in the figure below. A peristaltic pump is a type of positive displacement pump used for pumping a variety of fluids. A flexible tube that is inserted inside the circumference of the pump casing houses the fluid. Although linear peristaltic pumps have also been created, rotating motion is how most peristaltic pumps operate. The flexible tube is compressed while the rotor rotates by many "wipers" or "rollers" that are attached to its outside circumference. The compressed portion of the tube is sealed, forcing the fluid to pass through it. More fluid is sucked into the tube when it opens to its original condition after the rollers pass. The peristaltic pump has two tubes, one to suck fluids and one to pump

Figure 4.7: Peristaltic pump

out fluids. The flow direction can be controlled using an H-bridge, where depending on the user's command the tube connected the tendon can either suck air in or pump air out. Therefore, by controlling the flow we can control the actuation of the tendon; the tendon when air is pumped into it will compress itself and deflate which is extremely useful for the application of drone usage and drone manipulation. Having the tendon compressed as seen in the figure below allows the manipulator to achieve a larger workspace, and allows for a higher margin of error. Furthermore,

Figure 4.8: Tendon when air is sucked out

the tendon can be actuated by blowing air into it, and that can be achieved again by controlling the pump and directing the current so that the tube connected to tendon can blow air into it. This is the most crucial step of the tendon, since this is the actuation that will grip the object. as can be seen in the figure below the chambers expand and with the help of the piece of paper in the bottom part of the tendon, it will form into the shape seen below, as can be seen in the figure the chambers are expanding and colliding into each other and forcing the tendon to form this shape.

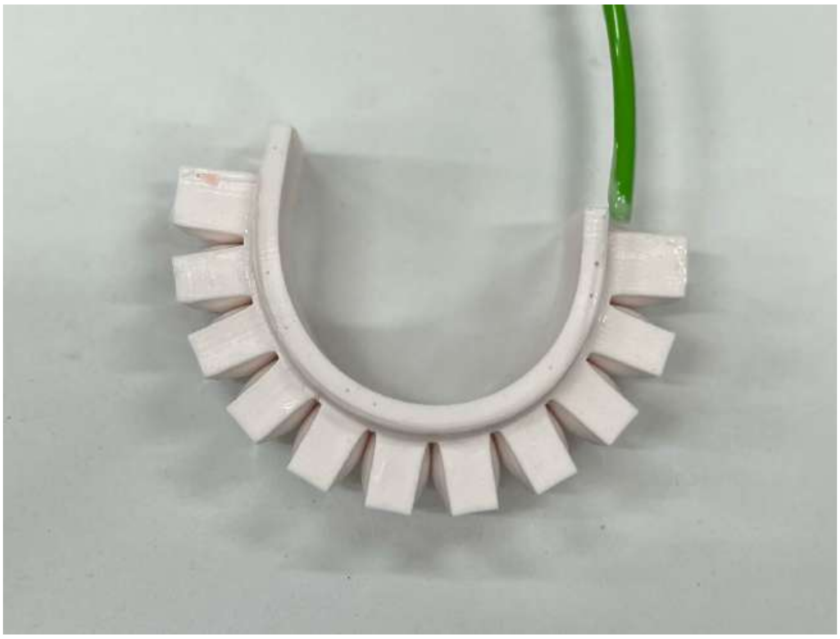


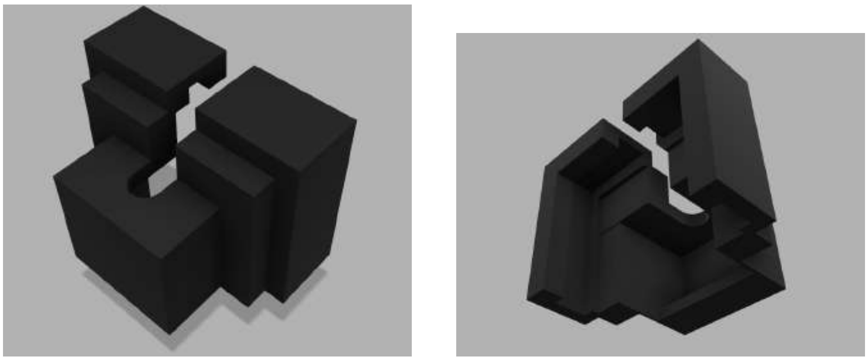
Figure 4.9: Tendon when air is blown into it

Therefore, by combining both actuation states a smooth gripping motion can be achieved. while the drone is flying around air is sucked out of the tendons which results in a compact shape, and when the drone is in the correct position to grip an object it will blow air into the tendon and the tendon will wrap itself around the object.

4.2 Gripper Base

4.2.1 Handle

The gripper base is straightforward in concept, the tendons simply need something designed to connect them all together, however, it was proven to be quite challenging to contain the tendons in place since they are deforming when actuated. So after a couple of failed attempts, a handle was designed to contain the first section of the tendon, the handle's purpose is to clamp the first chamber in and attempt to block it from expanding, but an important thing is that it also does not block the air flow between the first chamber and the others. As can be seen in the previous figures the tendon used for this project has an irregular shape which makes it difficult to contain it, so the handle designed can be seen in the figure 4.10 accounts for width of the bottom part of the tendon and also has a space at the top for the tube to ensure that airflow can still reach the tendon. Additionally, the most important part of this design is the section at the front for the chamber to be concealed in, it is a tight gap in order to ensure that the top chamber doesn't expand but also it is not too tight so the airflow can still pass through. The success of this design made it very simple moving forward with the gripper base, since all that was needed was to attach these



(a) Front View (b) Back View

Figure 4.10: Handle

handles onto a base of with a number of handles depending on how many tendons were needed for the gripper. Therefore, the 2-gripper would have two handles, 3-gripper would have three and so on. The measurements of the handle aren't designed to be the same size as the tendon, they are designed to be tight on the tendon, since the tendon is made of a soft material we are able to compress it to fit in the shape needed, this was an important lesson to learn in order to keep the tendon in place.

As can be seen in the figure 4.11, the top of the tendon is completely enclosed in the handle and the tendon is firmly in place, and the tube at the top has room for it to connect to the pump.

Figure 4.11: Example of a tendon placed in a handle

4.2.2 Base design

The general design of the base is straightforward, it is intended to be simple. The most complex part of the design is to ensure it is as light weight as possible since the gripper will be attached to a drone and needs to maintain weight below the payload. So in order to minimise the base weight, it is designed to be hollow in the center and just have it thick enough to ensure that it can maintain the weight of the tendons. Another feature that is important in the design of the base is the length in between the handles. Since the length of the tendon is 11.5 cm the length in between the handles is 12 cm to accommodate that when they are actuated and expand they will bend in and ensure that they can grip the object in the center comfortably, this length was found after the curvature experiment that will be discussed in later stages of this paper. The computer aided designs, made using AutoDesk Fusion 360, can be seen in the figures below 4.12,4.13,4.14 and 4.21.

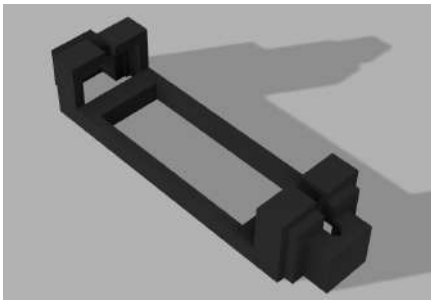


Figure 4.12: 2-Gripper Design

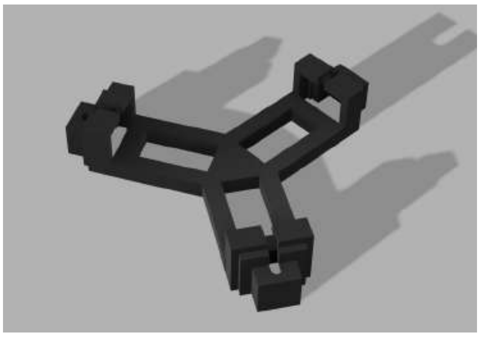


Figure 4.13: 3-Gripper Design

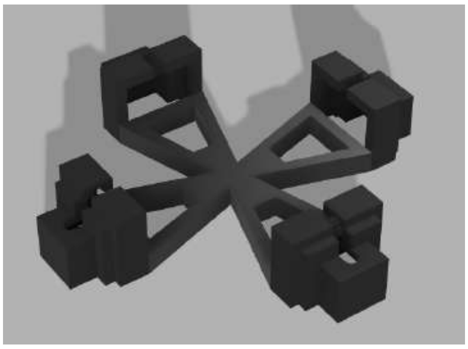


Figure 4.14: 4-Gripper Design

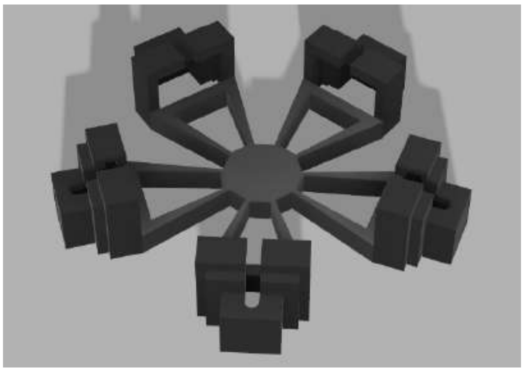


Figure 4.15: 5-Gripper Design

4.2.3 Airflow

As mentioned previously, the gripper will be actuated pneumatically by a peristaltic pump. However there is only one pump and multiple tendons for each gripper so a network of tubes has to be sorted to ensure airflow reaches the tendons evenly. Firstly, the network was made using simple 3 directional tube connectors however that proved to be ineffective for the more complex grippers since the distribution of air was not even, therefore a tube connector was designed using Fusion 360 and used.

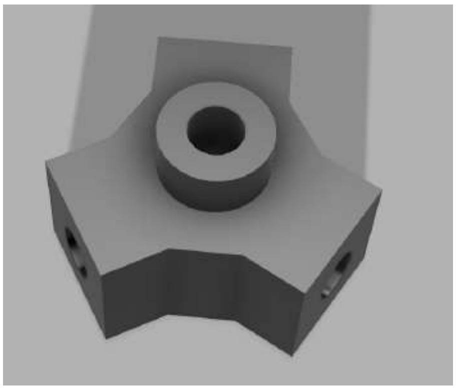


Figure 4.16: 3-Gripper connector Design

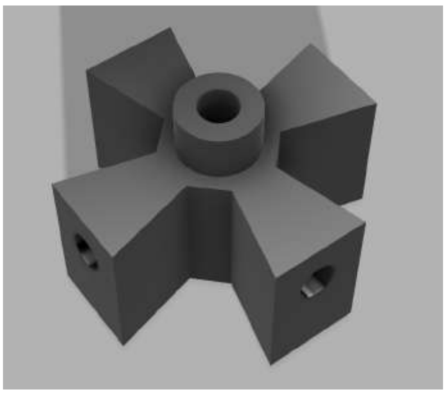


Figure 4.17: 4-Gripper connector Design

These designs are made to connect all the tendons and achieve even air distribution in order for the tendons to actuate at the same rate and increase the likelihood of a successful grip. The connector works by creating a passage for the tube connected to the pump to be placed and then has three exits for tubes that will then be leading to the tendons.

4.3 Control

To control the direction of the airflow a 'L298N Dual H-Bridge Driver Module' is used. An electrical circuit known as an H-bridge changes the polarity of a voltage applied to a load. These circuits enable DC motors to move forward or backward in robotics and other applications. The name is derived from its typical schematic diagram depiction, in which the load is linked as the crossbar and the four switching components are arranged as the branches of the letter "H." The H-bridge is necessary here so that the pump can change direction, in order to control if the tendon is either being compressed or expanded.

Figure 4.18: L298N Dual H-Bridge Driver Module

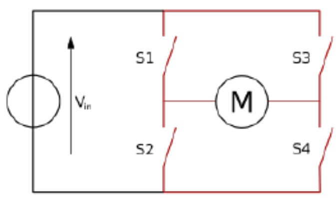


Figure 4.19: H-Bridge Schematic

The H-Bridge is then controlled by an Arduino UNO, where it is coded to change the direction of the pump on command, since at this stage with the project the gripper is not automated and does not detect when it needs to grip. Therefore, upon pressing a key on the keyboard connected to the Arduino, the pump will either switch states, or stop air flow leading to the tendon which results in the tendon remaining in the current state.

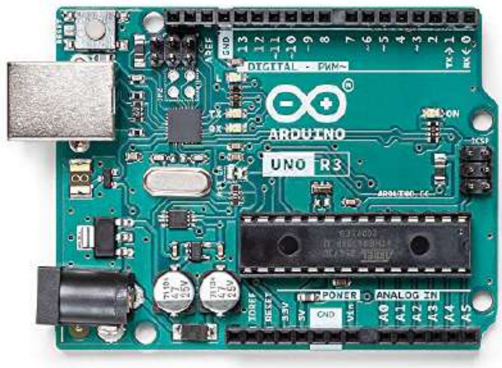


Figure 4.20: Arduino Uno

4.4 Stand

The grippers are fragile to an extent, since the tendons used on the grippers are soft, they deform very easily, and since they deform easily if they are placed in an awkward position where the tendons are held in a bent stance the tendon could deform to adapt to that shape and stance. During the project, the grippers were placed in an awkward stance for around two weeks, and in result the holes that had the tubes connected to them expanded. For that reason a stand is designed to keep the grippers in a held position where the tendons cant deform after a long time which increases their life span.

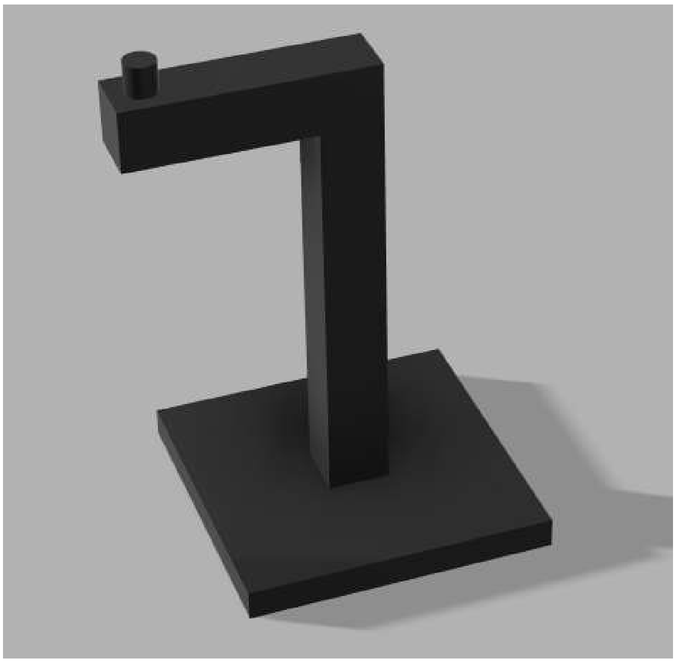


Figure 4.21: Stand for the grippers

The stand is designed to keep the gripper elevated, so the stand is 15 cm tall, since the tendons plus the handle have a height of 13cm. The stand also has an extrusion the size of the hole in the center of the gripper, that was previously designed to be used in order for the gripper to be attached to the linear actuator.

4.5 Issues Faced

A main issue faced in the gripper is leakage. Leakage is a problem across all pneumatic devices that is encountered commonly, it is an issue that is quite detrimental to the tendon since any leakage will lead to the tendon not actuating to it's final state or not actuate at all since all air is escaping, another result of leakage is the inability to maintain the state of the tendon when actuation is off, which means that when an object is grasped the pump actuating the tendons can be switched off and the object can remain grasped, this is a very functional feature that saves energy.

Leakage was mainly faced in early stages of manufacturing the tendons after numerous attempts the reason for the leakage was found and steps were taking to counteract the leakage. Additionally, leakage was also an issue in later stages of the project. Unfortunately during the final stages of testing I tested positive for Covid-19 and was unable to attend the lab and complete the testing during that time, during this time the grippers were left in the lab where they were moved around in order to make space for other members of the lab, unfortunately, the tendons were placed awkwardly which led to the tube connected to the top to be bent and that resulted in expanding the hole for the tube which led to the gap being larger and resulted in leakage. Which has inspired the creation of a stand, where the gripper needs to be stationed in order to protect the gripper from deforming over time. This is a vital aspect of the gripper since longevity of the gripper is crucial to its feasibility and usage. Furthermore, an issue faced while working on the gripper is linking the air supply, since only one peristaltic pump was available for use in the project the tendons must all be connected and air must flow efficiently around the the tendons, especially the more complex grippers, like when it comes to the four and five tendons, since the fluid splitters that were purchased for this project where 3 splitters. If the tubes are not correctly connected and there is a leak anywhere in the system the gripper will not actuate and result in failed gripper.

Chapter 5

Experiments

5.1 Bending Curvature Estimation

Experimenting for the individual tendons will be done by comparing the length and curvature of the tendons before and after actuation. This is relevant to assess the true final state and the tendon limitations. This is useful for designing the gripper and understanding what object sizes and shapes can be handled and grasped by the gripper.

The test will be completed on three tendons to ensure and compare consistency between the tendons. Consistency across the tendons is vital for the gripper.

5.2 Single Tendon Grasp Test

To test the ability of a single tendon, to test the strength and speed required for a tendon to complete a grasp we will test one tendon's ability to grasp a 250 ml beaker. The test will use a linear actuator that will start low at 0cm off the surface and be moved up to 30 cm to test the ability to carry the beaker. This test will use a linear actuator, an arm to attach the tendon to the slider, a power supply, an Arduino and an Hbridge to control the direction of the pump.

5.3 Linear Manipulation Test

To emulate the effectiveness of the grippers grasping objects as they are lifted by a UAV, this experiment will use a linear slider, that has an attachment that will be used to place the gripper on and allow the gripper to move vertically with the slider, the attachment has a hole in it to fit a screw threw it and the gripper, and a locking knot will be placed at the top to secure the gripper in place. The set up can be seen in the figures in the Results section of the paper. The experiment will have three stages; the first stage will be sucking the air out of the tendons in order to compress the tendons and create a larger area for the grippers to grasp on to, the gripper will surround the objects before moving on to the next stage, the next stage will be to blow air into the tendons expanding the chambers and allowing the tendons to grasp the objects, after having grasped the object the slider will then lift up the gripper to 30 centimeters. The test will be repeated for every gripper on three objects the objects are intended to be random equipment found in a lab to analyse the adaptability of the grippers. The objects chosen are a 250ml beaker,

(a) Foam (b) Beaker (c) Silicone

Figure 5.1: Objects Used for Testing

weighing 48 grams, a foam deformed rectangle weighing 9 grams and silicone remainder that was made earlier in the project when manufacturing the tendons, weighing 186 grams. The objects chosen cover a wide range of weight, shapes and sizes to ensure adaptability can be tested efficiently.

The equipment apparatus for the experiment consist of:

1. Linear slider with stepper motor
2. Gripper being tested
3. Arm attachment to hold gripper
4. Peristaltic pump to actuate the tendons
5. Bench power supply
6. Arduino and Hbridge to control actuation of the peristaltic pump
7. Object to be grasped
8. Timer

Chapter 6

Results

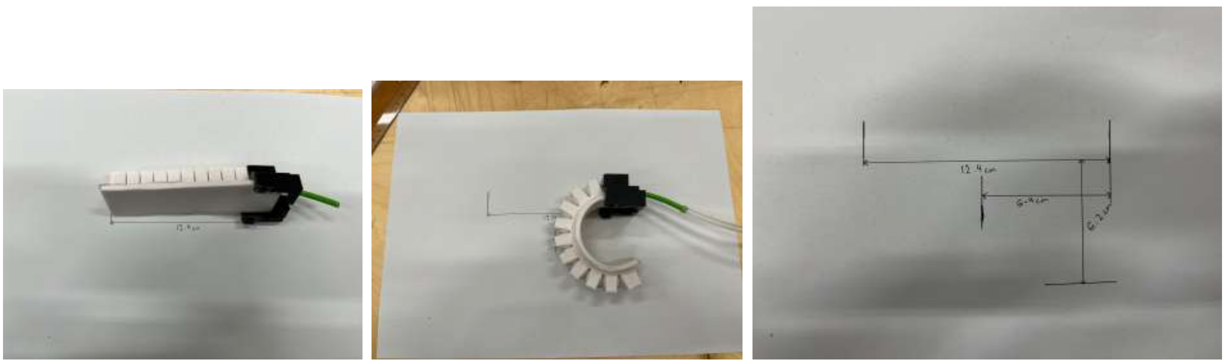
6.1 Bending Curvature Estimation

This test is completed in two phases the tendon is placed on a piece of paper and the length of the tendon is measured while the tendon is in an unactuated state and the tendon is relaxed, this is done to compare the before and after, the tendon is then inflated and the vertical and horizontal measurements are labeled. This test is completed 3 times. The test was conclusive and all 3 proved to measure exactly the same. The tendons proved to be consistent through out.

Bending Curvature Estimation 1		
Tendon State	Vertical Length	Horizontal Length
Unactuated	0	12.4
Actuated Inflated	6.2	6.4

Bending Curvature Estimation 2		
Tendon State	Vertical Length	Horizontal Length
Unactuated	0	12.4
Actuated Inflated	6.2	6.4

Bending Curvature Estimation 3		
Tendon State	Vertical Length	Horizontal Length
Unactuated	0	12.4
Actuated Inflated	6.2	6.4

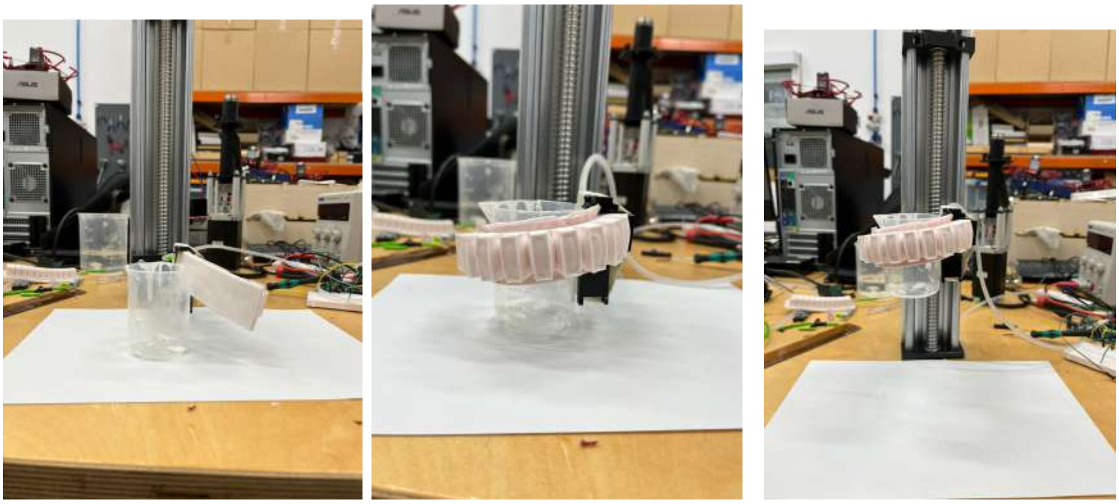


(a) Straight Tendon (b) Curved Tendon (c) Silicone Test

Figure 6.1: Final Results

6.2 Single Tendon Grasp Test

The three phases of the tendon grasping the beaker can be seen in the figures below, the first stage is the tendon deflated as to get a good wrap around the beaker, the second phase is the tendon inflated to grasp the beaker and the final phase is the linear actuator moving vertically 30 cm off the surface. This test is pass or fail and as can be seen in the figure 6.2 the tendon passed and was able to lift the beaker very successfully.



(a) Deflated Tendon (b) Grasped Beaker Bottom (c) Grasped Beaker Top

Figure 6.2: Single Gripper Test

6.3 Linear Manipulation Test

This experiment is designed to test the different grippers capabilities, this test is conducted for each gripper on three separate objects, therefore there are a total 12 tests that were completed. Each test is split into 3 phases, the first phase is the air being deflated from the tendon to surround the object to be grasped, the second phase is when the tendons are inflated, the timer begins as soon as the peristaltic pump is turned on and the tendon begins to be actuated, the timer is left on till the gripper has a solid grasp on to the object or the grasp is failed. The linear actuator is then lifted up to 30 cm to emulate lift off of a UAV after grasping.

Success / Fail Grasp			
Gripper Type	Foam	Beaker	Silicone
2 - Gripper	Successful	Successful	Failed
3 - Gripper	Successful	Successful	Failed
4 - Gripper	Successful	Successful	Successful
5 - Gripper	Successful	Successful	Successful

Time Taken To Grasp (Seconds)				
Gripper Type	Foam	Beaker	Silicone	Average
2 - Gripper	12.45	14.51	N/A	13.48
3 - Gripper	16.32	17.12	N/A	16.72
4 - Gripper	17.23	19.23	21.42	19.29
5 - Gripper	17.41	21.10	27.22	21.91

(a) Beaker Test (b) Foam Test (c) Silicone Test

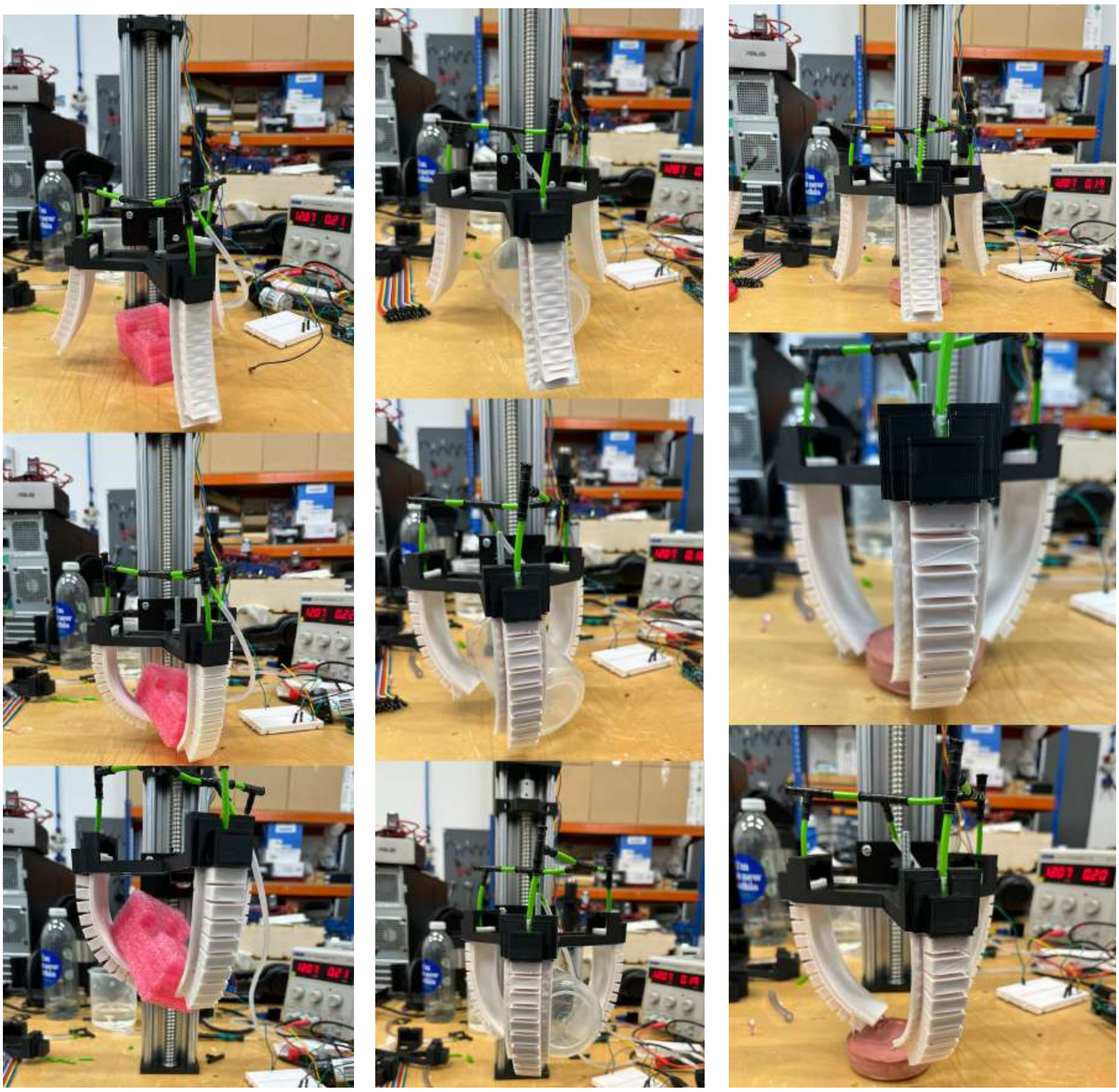
Figure 6.3: 5 Gripper Test

This is the test of the 5-gripper, the 5 gripper has the most tendons and therefore requires more time to actuate each tendon to a strength that is strong enough to grasp an object. However, the 5 tendon seemed to have the most stability once the objects are grasped since the object are completely surrounded and firmly enclosed within the tendons.

(a) Foam Test (b) Beaker Test (c) Silicone Test

Figure 6.4: 4 Gripper Test

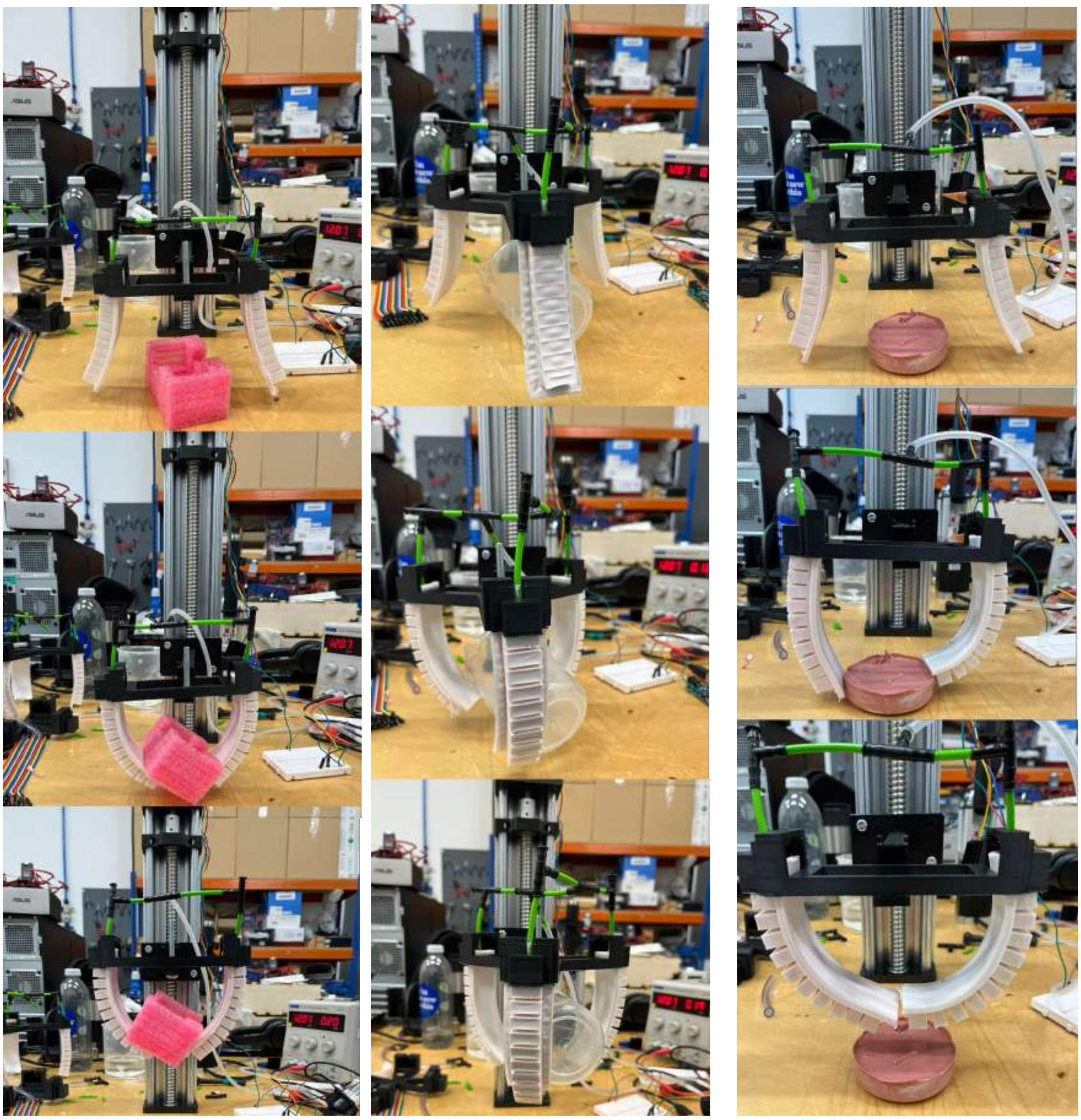
This is the test for the 4-gripper, the 4 gripper has 4 tendons which has the second most tendons which similarly to the 5-gripper the gripper requires extra time to inflate the tendons to the required inflation to grasp the objects. The 4-gripper proved to be quite stable when grasping and lifting the objects. The gripper was tested on the foam, the beaker and the silicone



(a) Beaker Test (b) Foam Test (c) Silicone Test

Figure 6.5: 3 Gripper Test

This is the 3-gripper test, the 3 gripper has the second least tendons and in comparisons needs less time to actuate to significant strength to grasp. The 3-gripper was very stable when grasping the foam but was quite unstable with the beaker. The 3-gripper failed to grip the silicone since it seemed to be too heavy for the gripper.



(a) Beaker Test (b) Foam Test (c) Silicone Test

Figure 6.6: 2 Gripper Test

This is the final test, the 2-gripper has the least tendons and is therefore the fastest at achieving significant strength to grasp the objects. The gripper was actually very stable with the foam, however unstable with the beaker due to the bigger size of the beaker. The gripper failed at grasping the silicone also due to the heavy weight of the silicone.

Chapter 7

Discussion

7.1 Bending Curvature Estimation

The bending curvature estimation test is an important test that was completed in early stages of the project in order to understand the limits of the gripper design and to help design the gripper base. After understanding how far the tendons extend vertically and horizontally the gripper bases were designed.

7.2 Single Tendon Grasp Test

This experiment helps understand the limits in strength of the a single tendon. After completing experiment we have seen that one tendon does have the strength to grasp and lift off a 250 ml beaker of 48 grams, this shows that one tendon has the ability to independently surround an object of similar size and shape. This is interesting to look at since the tendon does have the ability to grasp the beaker on its own but the issue with the single tendon is that the beaker has to be placed standing which means that the tendon isn't actually very adaptable to the object.

7.3 Linear Manipulation Test

This is the main test of the project since this experiment tests the final product of the grippers and their ability, these grippers are tested individually and each gripper is tested on separate objects, a foam deformed rectangle, a beaker and a silicone mold. These tests are designed to check time taken to grasp and if grippers are able to grasp and lift objects. After completing the experiments it is clear to see that two and three grippers are not able to grasp the silicone due to the weight. However, both of the grippers were very comfortable and able to grasp and lift the beaker and the foam. The 2-gripper was very quick at inflating the tendons and achieving significant strength to grasp the object it was successful at grasping at an average of 13.48 seconds to grasp. The 3-gripper took longer than the the 2-gripper which is to be expected, the 3-gripper averaged a 16.72 second time to grasp. On the other hand, the four and five grippers achieved great results succeeding in grasping all objects, all the grasps were very stable and there was no worry of the objects falling out of the grasp of the grippers. However, the time taken to inflate the tendons with the four and five gripper takes longer than the others, the 4-gripper averaged 19.29 seconds, the 5-gripper took even longer at 21.91 seconds to grasp the objects on average.

7.3.1 Comparison

The grippers performed quite well in general, out of 12 experiments only 2 failed at a 16.6 percent fail rate. The grippers showed great strength and stability on the successful grasps. However, in comparison the 4 and 5 grippers succeed across the board and didn't t fail at grasping any objects, which makes them much more reliable. The four and five grippers seem to be the standard moving forward if this gripper is to be used, since the reliability of the gripper is very crucial for a UAV gripper. However, between the four and five gripper the 4-gripper seems to be the most efficient gripper since it was successful in all experiments and was faster than the 5-gripper.

7.4 General

The gripper in theory provides merit, the idea of having the added flexibility for a UAV is a great advantage to have. However, a soft gripper with a small budget is difficult to control and difficult to maintain. The gripper it self is not expensive, however the gripper needs a sustainable powerful pump that can be controlled by strength and direction. Due to the rather low budget of this project the gripper was limited, as a prototype it shows promising results and proof of concept. With greater investment and more time for testing the little quirks can be fixed and can result in a promising gripper. The project faced hurdles that needed to be overcome, first being the rather small budget and second being time constraints. In an ideal world with more time many more tendons would be made to replace faulty ineffective tendons that overtime deteriorate. The gripper shows promising progress made in Pneumatic soft robotics design, a very simple design of tendons with very few materials can result in an effective pneumatic tendon. However, a very simple tendon might not be the most effective of tendons for a UAV gripper. There are multiple other designs that have been discussed in the literature review that have shown promising results, even though they are more complex and expensive to make they are more effective for the purpose.

Chapter 8

Further Work

This section explores what work can be done in the future to further develop this project and further find an efficient way of integrating soft grippers with UAVs. For future development a new tendon design can be used and tested to compare types of tendons as well as number of tendons. There are many other tendon designs and soft robotics approaches that can be taken to further test for better results. Unfortunately, due to the limited time of the project the grippers were not able to be tested attached to an actual UAV but instead tested on a linear actuator to emulate the flight of a gripper, obviously this is not an accurate evaluation since a UAV does not only move linearly and many other problems could be encountered. Further work can be done with different designs of bases, a base design can be made so that the gripper can be used horizontally, and grasp on to objects from the side instead of from the top. Additionally, a big issue faced in this project was the inability to fully simulate the soft tendons using Abaqus CAE, due to the limitation of the student software, gaining access to the full version could further allow simulation tests and allow for better understanding of the limitations of the gripper and the tendons.

Chapter 9

Conclusion

To conclude, the main aim of this project was to find a soft gripper that can be used as an attachment to a UAV that can grasp objects efficiently. The soft grippers designed in this project have proven to be successful. The grippers showed a great ability at grasping, the two and three grippers did both fail at gripping the silicone, however the four and five grippers showed great gripping ability and grasped the silicone and all the other objects very well. Ultimately, it goes down to the usage of the gripper, for lighter weight objects the two and three grippers can be used, since they are lighter weight and faster at grasping, and for heavier objects the four and five grippers have proven effective with heavier weighted objects. With further experimenting and a better air supply and control a more efficient gripper can designed to have even better results and can be more effective.

Chapter 10

Acknowledgment

I would like to firstly thank Dr Vijay Pawar for the opportunity work under his supervision and allow me the freedom in the HereEast lab. He gave me the freedom to express myself in the project and provided me with very great realistic advice and guidance throughout the course of the project. I would also like to thank Mr. Durgesh Darekar for always being there for me during the project a great, reliable and motivational member of the team who kept pushing me right to the end of the project. Finally I would like to thank all the members of the HereEast lab for welcoming me and creating such a great environment to work in.

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