Title
Soft Compliant Gripper for Perching UAVs

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Publication Date
2017

Peer reviewed|Thesis/dissertation

UNIVERSITY OF CALIFORNIA, SAN DIEGO

Soft Compliant Gripper for Perching UAVs

A Thesis submitted in partial satisfaction of the requirements for the degree Master of Science

in

Engineering Sciences (Mechanical Engineering)

by

Kishan Kumar Sachdeva

Committee in charge:

Professor Thomas Bewley, Co-Chair
Professor Michael Tolley, Co-Chair
Professor Frank Talke

2017

The Thesis of Kishan Kumar Sachdeva is approved and it is acceptable in quality and form for publication on microfilm and electronically:

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University of California, San Diego

2017

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ACKNOWLEDGEMENTS

I would like to acknowledge Professor Thomas Bewley for his support as the co-chair of my committee. By providing helpful advice and resources, his guidance has proved to be invaluable.

I would like to acknowledge Professor Michael Tolley for his support as the co-chair of my committee. Through multiple weeks of advising and problem-solving, his guidance has proved to be invaluable.

I would like to acknowledge Professor Frank Talke for his time, effort and feedback as a committee member.

I would also like to thank all my labmates in UCSD Coordinated Lab and Bioinspired Lab at UCSD who have helped in getting over various hurdles on path to this work.

ABSTRACT OF THE THESIS

Soft Compliant Gripper for UAV Perching

by

Kishan Kumar Sachdeva

Master of Science in Engineering Sciences (Mechanical Engineering)

University of California, San Diego, 2017

Professor Thomas Bewley, Co-Chair

Professor Michael Tolley, Co-Chair

Current battery technology only enables a flight time of less than an hour for UAV applications. Several applications in surveillance and surveying benefit from ability of UAVs to perch at strategic locations. Existing mechanism designs on perching UAVs either require specialized manufacturing techniques or are disproportionately heavy and hence decrease the flight time. Current work utilizes advances in soft materials to achieve a compliant mechanism capable of perching on a variety of surfaces. The work begins with

a description of design, manufacturing and modelling of a tendon driven soft actuator. The actuator is then utilized to construct a claw-like perching mechanism suitable of rotor-based UAVs.

Introduction

Unmanned Aerial Vehicles, popularly known as UAVs, have seen an exponential growth in adoption over the recent years. The ability to have sensing technology onboard a small aircraft is immensely valuable for various industrial and military applications. But, current battery technology permits flight times of around an hour for low-weight (<1 kg) UAV platforms [1]. Given that various applications in surveillance, autonomous surveying etc. are require that the missions last for long durations (several hours to a few days). Specifically, there is a need for systems with ability to reach a location of interest and perch at a desired surface for an extended period of time. The underlying idea is to minimize energy consumption on hovering and thus achieve longer mission times using the current battery technology. Another potential area of application is to build autonomous systems which can perch at recharging locations and thus minimize human intervention during operation phase.

There have been various approaches at achieving a perching UAV. The work at MIT's CSAIL focuses on perching fixed wing glider on power lines. The work goes in depth in modelling dynamics and solving the control problem to achieve perching on power lines[2]. The work at Stanford's Biomimetics and Dextrous Manipulation Lab uses a Shape Deposition manufacturing technique to mimic sharp claws of bird and perch on vertical walls[3]. The work at Telerobotics lab at University of Utah takes a passive approach to perching using a compliant mechanism to perch on varied variety of surfaces[4]. The work at Yale uses a compliant mechanism to pick up object while hovering onboard a 3.5kg RC-helicopter platform[5].

In terms of non-soft gripper designs, there exists considerable efforts in mimicking human hands for gripping. Some of the well-executed gripper systems include Model Smart Motor Hand by Shadow Robot Company Ltd [6], EHI Milano Hand by Prensilia Srl[7], Actuated Sheffield Hand[8] & Elu-2 Hand[9] both manufactured by Elumotion Ltd. In realm of soft robotics, pneumatically actuated 4-fingered grippers by SoftRobotics Inc are state of art[10]. Another system of gripping capable a wide variety of materials Modular Soft Robotic Gripper by MIT CSAIL[11]. Versaball by Empire robotics uses jamming based actuation to pick up a wide variety of objects by pulling a vacuum over granular materials[12]. Although each of these systems have their own niche to operate, most of them are really slow in untethered applications due to actuation methods they rely upon.

There have been numerous previous attempts at tendon-driven soft structures for various applications. Researchers have explored applications ranging from Wearable robotic hands for assistance[13] to prosthetic hands[14]. In terms of grasping mechanisms, the work ranges from octopus-inspired tentacles[15] to bio-inspired soft grippers for adaptable grassing[16]. The iRobot-Harvard-Yale hand is a dexterous manipulator capable of picking up a wide range of objects with a focus on the stability of fingertip grasping, ability to adjust the force exerted on grasped objects using high impedance actuators and underactuated fingers[17].

Soft materials and additive manufacturing techniques can give rise to a mechanical gripper capable of picking and gripping a wide variety of everyday objects. The gripper design so formed should perform better than existing grippers in terms of actuation and compatibility with range of objects while being able to be mounted on untethered systems. Thus, the system should have low energy consumption per actuation cycle.

The current work addresses the need to have a light-weight (sub-100gram) mechanical design which is robust to perch on variety of surfaces, low energy consumption and cheap to manufacture preferably on a low-cost commercially available desktop 3D printer. This is achieved by leveraging advancements in soft materials and rapid additive manufacturing. The current work starts with development of tendon driven soft actuators. Details on the design, fabrications and analysis of the finger-shaped actuator is laid down in Chapter 1. Chapter 2 discusses the application of the actuator for robotic gardening manipulator. Chapter 3 discusses the design and results for UAV perching. Finally, Chapter 4 concludes with a discussion on results and scope of future work.

Chapter 1

Tendon-driven Soft Actuator

1.1 Mechanical Design

1.1.1 Material

NinjaFlex® was chosen for printing because of elongation properties (660% max elongation[18]) and variable flexibility properties by tweaking 3D printing parameters (explained in 1.2). The latter enabled fine-tuning of the design by varying the effective modulus of elasticity to achieve desired characteristics such as maximum force, twist, bending moment etc. Since NinjaFlex® is a polyurethane, the structures manufactured function well even after few surface ruptures and cuts. This acts a huge advantage over pneumatic based systems which are highly susceptible to tear by sharp objects and thus have shorter lifecycles in such applications.

1.1.2 Design

The macroscopic dimensions were derived keeping in mind the target object. The target object was tomatoes in case robotic gardening (Chapter 2) and a PVC tube of diameter 42mm (Chapter 3). This influenced total length, width and thickness of each finger. The angles were derived to attain a bend angle 90°. Other design constraints included eliminating need for support material, remove stress concentration points and maximize contact force at the tip of finger. The dimensions for fingers for both applications are mentioned in the appendix.

The shape of the actuator was inspired mostly from human-fingers. Human fingers are made of three sections which get their rigidity from the bones. The tendons and the muscles in the joints enable relative turn of the various sections of the human finger. Moreover, 3D – printed NinaFlex® with medium infill density (0.15 – 0.3) bends at the cross-section of the minimum thickness. This can be explained by thinking of the actuator as a series of cantilever beam under a uniform load. The deflection a cantilever beam is inversely proportional to thickness in direction of the load. Hence, maximum bending occurs at the cross-section with minimal thickness. This gives rise to the notches in the finger design (Figure 1.1)

One key difference in mechanical design for robotic garden and perching UAV was location of bottom-hole on the finger. For the perching UAV, the servos were situated in front of the finger. On the other hand, for the gardening robot, the motors were placed below the surface. This dictated the position and shape of the bottom hole.

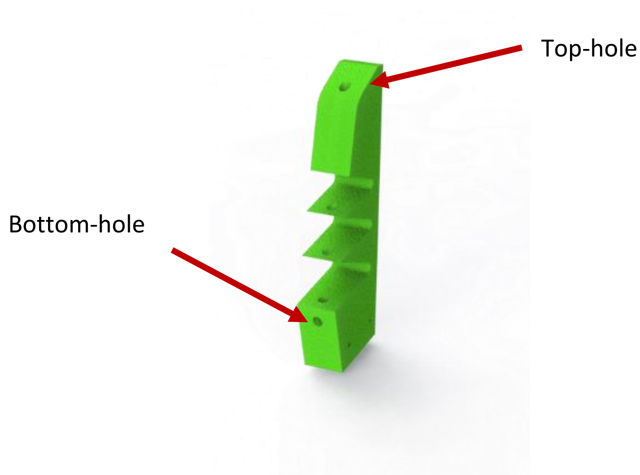


Figure 1.1: Tendon driven soft actuator for Perching UAV

1.2 Fabrication

The fingers were printed using 3mm NinjaFlex® filament using a modified Robot 3D R1 plus printer. Getting the correct structural properties is challenging when 3D printed a soft material. Since the material is by itself very soft, minor tweaks such as number of top and bottom solid layers, percentage infill, and infill orientation can cause large fluctuations in properties. For example, printing the design on its dorsal side (Figure 1.2, right) causes the infill to build up in direction of actuation. The finger thus printed, is very stiff in direction of actuation and soft in perpendicular direction, i.e. lateral side. Since the honeycomb structure is cause of the majority stiffness, direction of axis of honeycombs affects the rigidity. Hence, the design is printed on its lateral side so that the finger retains its complaint properties in direction of actuation.

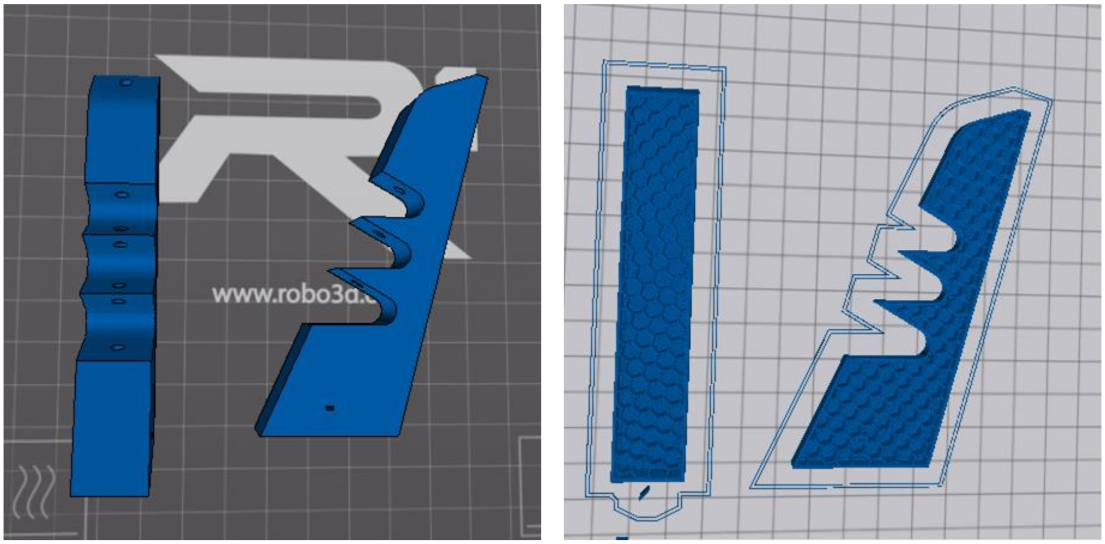


Figure 1.2: (Left) Side-to-Side comparison of fingers on the print bed. On left, the finger is placed on its dorsal side while on right it lies on it lateral side. (Right) The direction of honeycomb infill is always perpendicular to plane of printed. Section view of the infill

For the robotic garden, the final properties for printing finger were 18% infill, 7 top and bottom solid layers, 30mm/s print speed using a 3mm diameter filament. The fingers are coated with a thin layer of Dragon Skin silicone 20 to add surface friction and facilitate gripping.

For the perching UAV, the final properties for printing finger were 24% infill, 5 top and bottom solid layers, 30mm/s print speed using a 3mm diameter filament. The fingers are coated with a thick layer of thermoplastic adhesive to enhance surface friction and facilitate gripping.

1.3 Modelling and Analysis

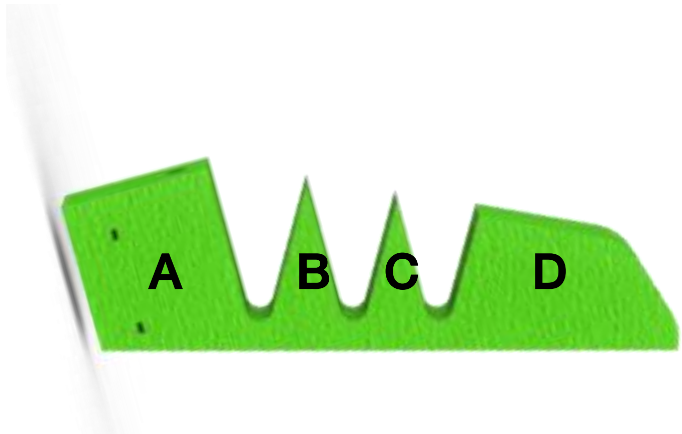


Figure 1.3: Individual notches of the finger actuator

The thin sections of the actuators divide the finger into a series of linear springs. These linear springs can be thought to be connected to each other via torsion springs. This partitioning of the finger into individual notches is demonstrated in Figure 1.3 and Figure 1.4

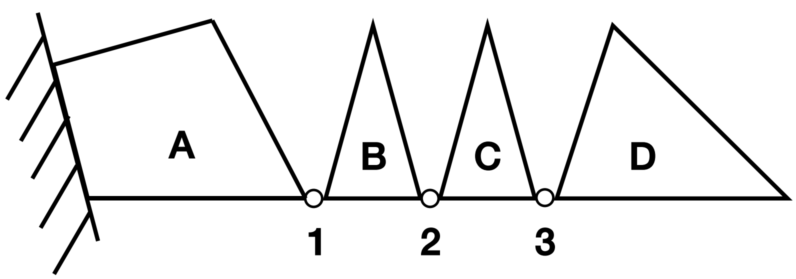


Figure 1.4: Each letter represents a linear spring, each number represents a torsion spring

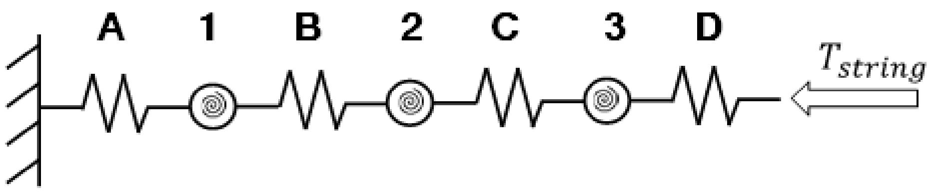


Figure 1.5: Modelling finger as a series of compression and torsion springs

In order to obtain force balance for a generic notch, the linear elasticity of the notch was discarded because $K_{linear} \gg K_{torsion}$. It was also assumed that the tension in both ends is same and the effect of cable friction is not taken into account, i.e., $T_1 \approx T_2$. The effect of gravity was ignored since the tension in cable and reaction forces are substantially larger than the gravitational pull on the element. These assumptions lead to a free-body diagram as depicted in Figure 1.6.

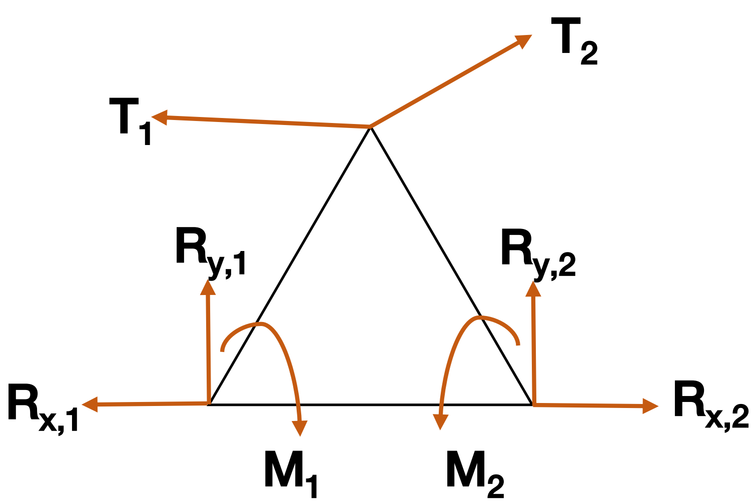


Figure 1.6: Free body diagram for a generic element

The series elastic spring enables to estimate the strain energy stored in actuator. For the actuator for perching UAV, by definition of work done -

$$Work_{net} = F_{full\ actuation} * displacement_{string}$$
$$Work_{net} = 1.8N\ * 0.041m = \mathbf{0.078\ J}$$

The total strain energy of the actuator can be considered as a sum of strain energy due to deformation energy in all the springs in Figure 1.5. Assuming that the linear spring undergo very small deformations ($K_{linear} \gg K_{torsion}$)

$$Total\ Strain\ Energy = \sum_{i=1}^{3} \frac{1}{2}\ k_{\theta,\,i}\theta_i^2 + \sum_{i=a}^{d} \frac{1}{2}\ k_{x,i}x_i^2$$
$$Taking,\ \theta_i = 30°\ ,\ x_i\ \approx 0,$$
$$Total\ Strain\ Energy = \mathbf{0.026J}$$

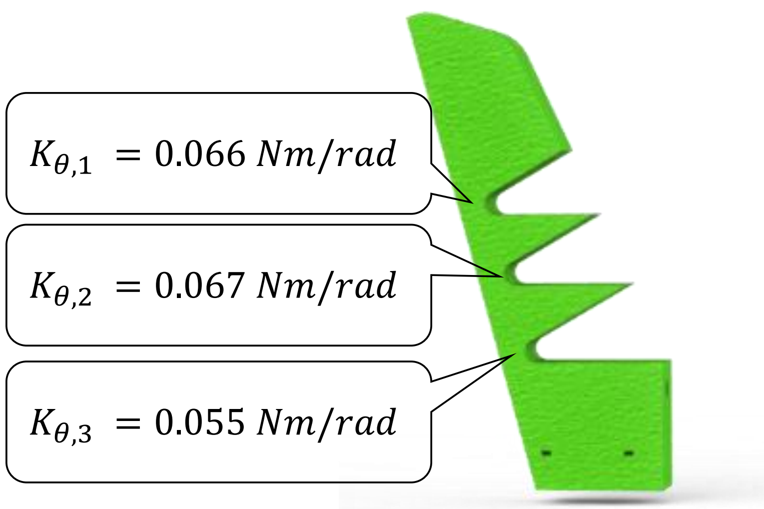


Figure 1.7: Torsional stiffness constants for finger actuator designed for perching UAV

Thus,

$$\frac{Total\ Strain\ Energy}{Work_{net}} = 33\%$$

Hence, the assumptions and model only justify a third of the work input on the cable.

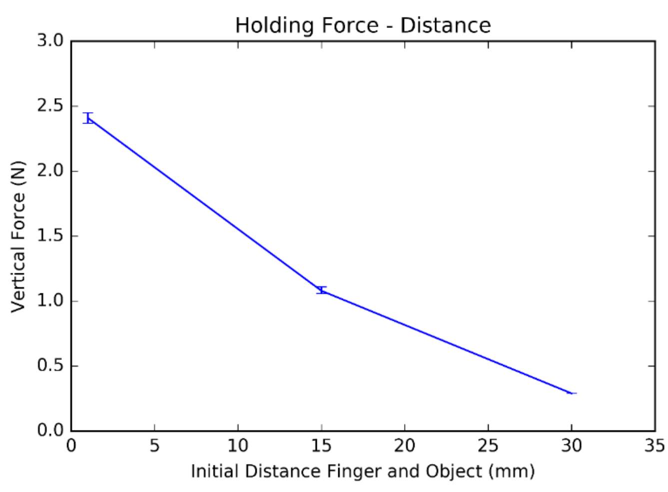
This demonstrates the limitation in current model and assumptions due to

- Exclusion of cable friction in energy balance
- Non-zero deformations in linear springs
- Exclusion of large-scale deformations effects
- Exclusion of other elastic bending modes of the actuator such as out-of plane buckling of the actuator and localized shear deformations

The vertical force generated at the tip of the finger was measured experimentally

Figure 1.8: Measuring vertical force on a measuring scale

Plot 1.1: Vertical holding force (Newton) versus Initial distance between finger & scale(mm)



Theoretically, the holding force for 0mm initial distance can be justified by considering the free-body diagram of element D (figure 1.4) of the finger

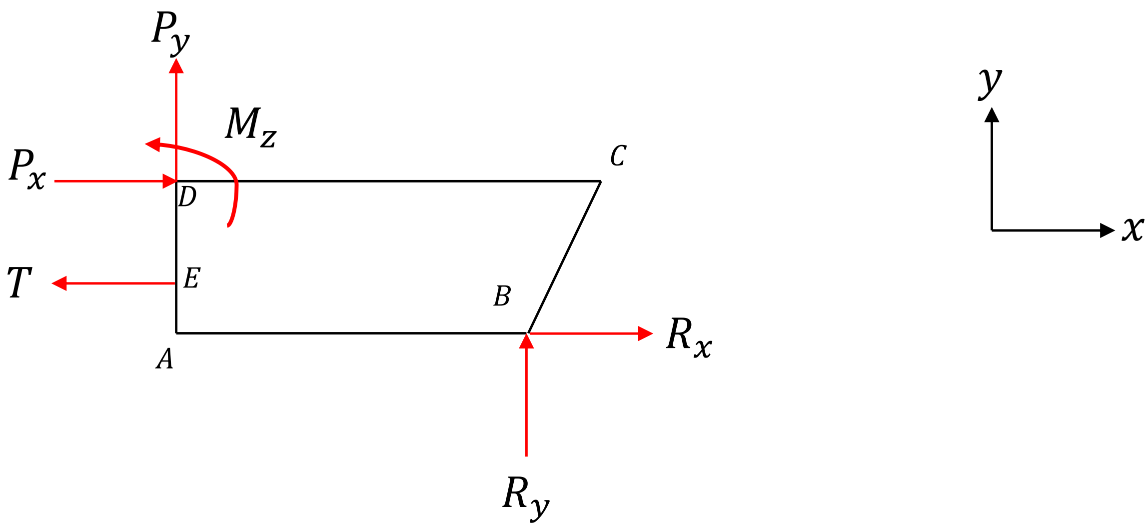


Figure 1.9: Free body diagram of element D. B is the point of contact on the scale, E is point of contact between actuator and string. D is the pivot point.

Assuming,

- $M_z \approx 0$ for initial 0mm distance between the finger and scale
- $R_x \approx 0$ assuming the scale only as exerts a vertical force

Moment balance about D :

$$-\overrightarrow{r_{DE}} \times \overline{T} + \overrightarrow{r_{DB}} \times \overline{R_y} = 0$$

At stall, the servo delivers 30.1N to both the strings. Taking $T = 15.0\ N$ and using geometric properties from the finger, we get the estimate for $\overline{R_y} = 8.4\ N$. Experimentally, we have $\overline{R_y} \approx 2.5N$ for a distance of 1mm between the finger and the scale. The difference can be explained by the fact that $M_z \neq 0$ when distance is 1mm. Further, $R_X \neq 0$ since the contact between finger and the scale does not remain normal as the finger actuates. Lastly, the tension in the string would be less than 15.0 N since the servo does not necessarily get stalled.

Chapter 20

Robotic Gardening

2.1 Introduction

The 3D printed Ninjaflex® fingers qualify for excellent choice of actuators for robotic garden application. The requirement here is to have a soft material which can is complaint to pick squishy vegetables like tomatoes; is robust and cheap to manufacture. Additionally, the fingers have an advantage over pneumatic based systems that it can operate in thorny environments, has a lower consumption and is well suited for untethered applications. The next section described the assembly, results and conclusions for the robotic gardening application.

This work was done as a part of MAE207 during Spring 2016. The project was advised by Professor Michael Tolley. The work is a joint effort by four Master's students - Xiao Cui, Chufan Kong, Mingkun Lin, Kishan Sachdeva.

2.2 Assembly

The motors and NinaFlex fingers are attached to a laser-cut fiber glass board using zip-ties. Two 99:1 metal gearmotor with 1 N-m torque and 2.8A stall current at 6V were used to pull two fingers each. Open-loop control was used to control motion of motors with a user controlling motion using a switch to prevent stalling. The details of circuit board are specified in the appendix.

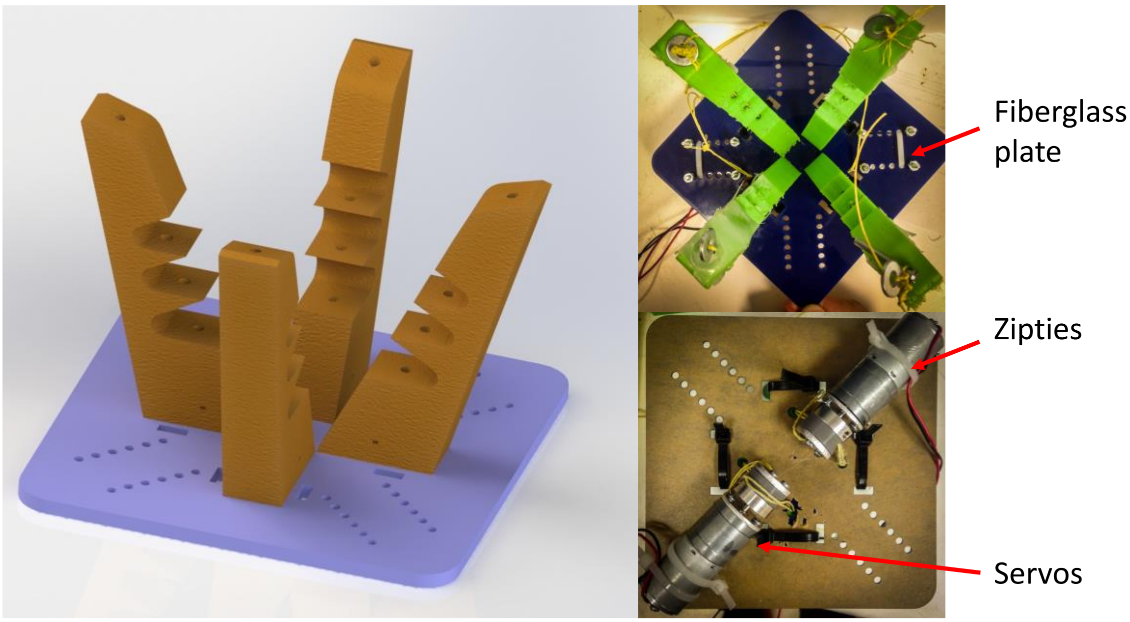


Figure 2.1 : (Left) Assembly CAD demonstrating orientation and placement of finger on the board. The zip-ties, motors, and motor-mounts are omitted from the CAD. (Right-Top) Top view of assembled gripper. (Right-Bottom) Bottom view of assembled gripper

2.3 Results

For the purpose of testing, a user holds the fiber glass plate in his/her hands with fingers pointed downwards. Objects are placed on the reference origin of the supporting surface and griped from the top. Actuation is achieved by manual open loop control using the potentiometer.

While our target use case was tomatoes, the mechanism can was successful in picking up objects various other vegetables and fruits. The design seems to be robust and capable of picking objects as heavy as a banana (~260g) to as light as fishing lines. The mechanism fails to pick up objects which are either too thin or too short such as smartphone, green onions etc.

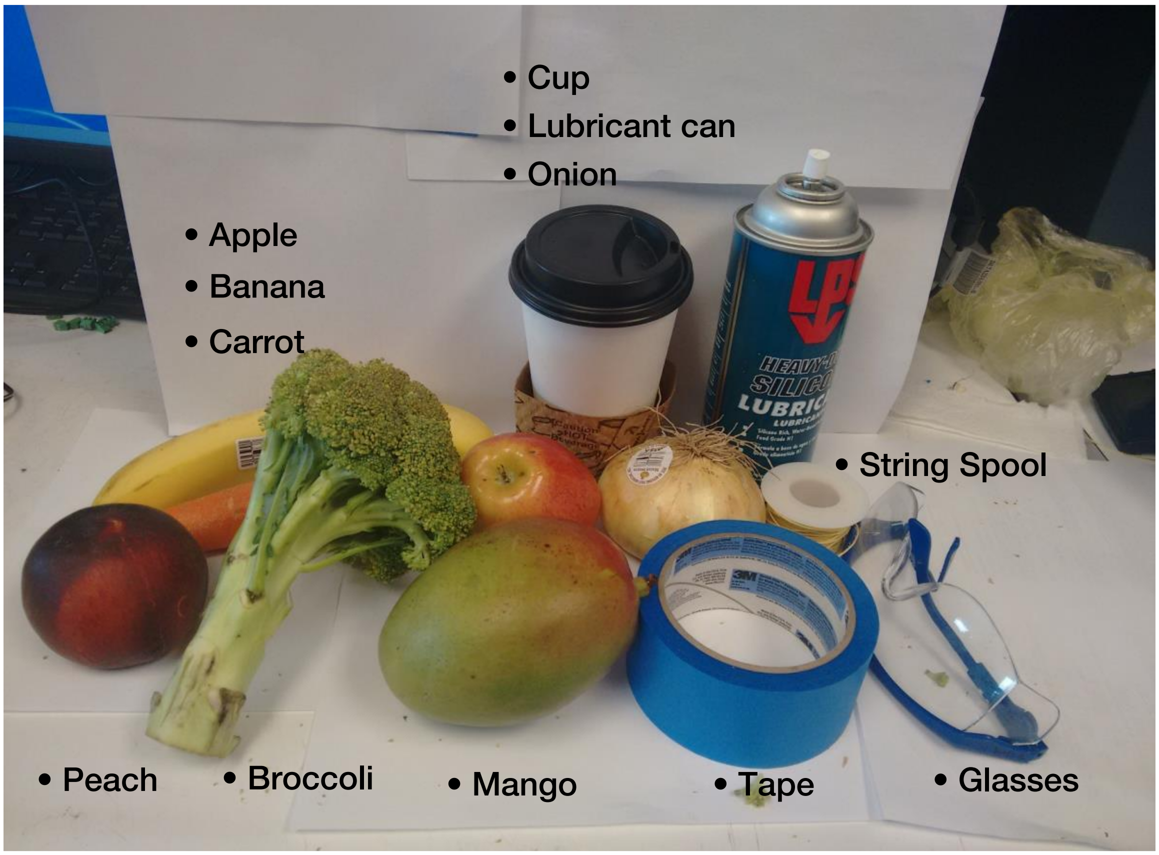


Figure 2.2: Objects successfully gripped

We observed buckling and twisting in fingers for elongated objects. While the fingers weren't designed to exhibit such properties, they are advantages since they enable a 'curling' like motion to conform to target object's geometry.

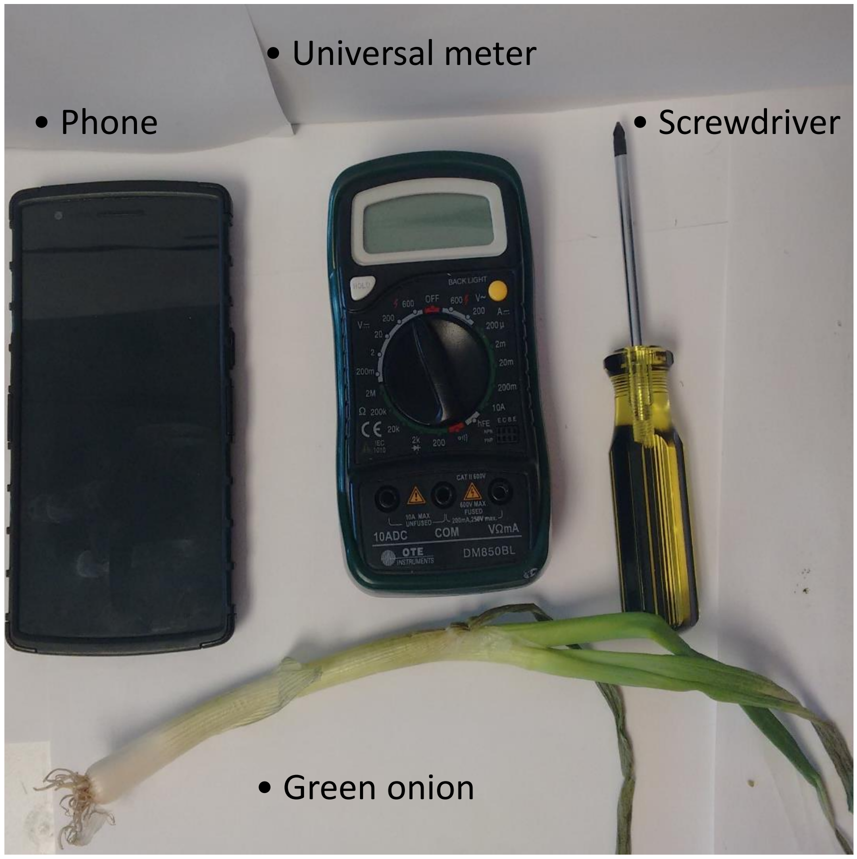


Figure 2.3: Gripper fails to pick up these objects. Too thin or too flat objects cannot be picked

The mechanism achieved a sub-second actuation (~0.8s) when being driven by a 12V DC power supply and 5A motor driver.

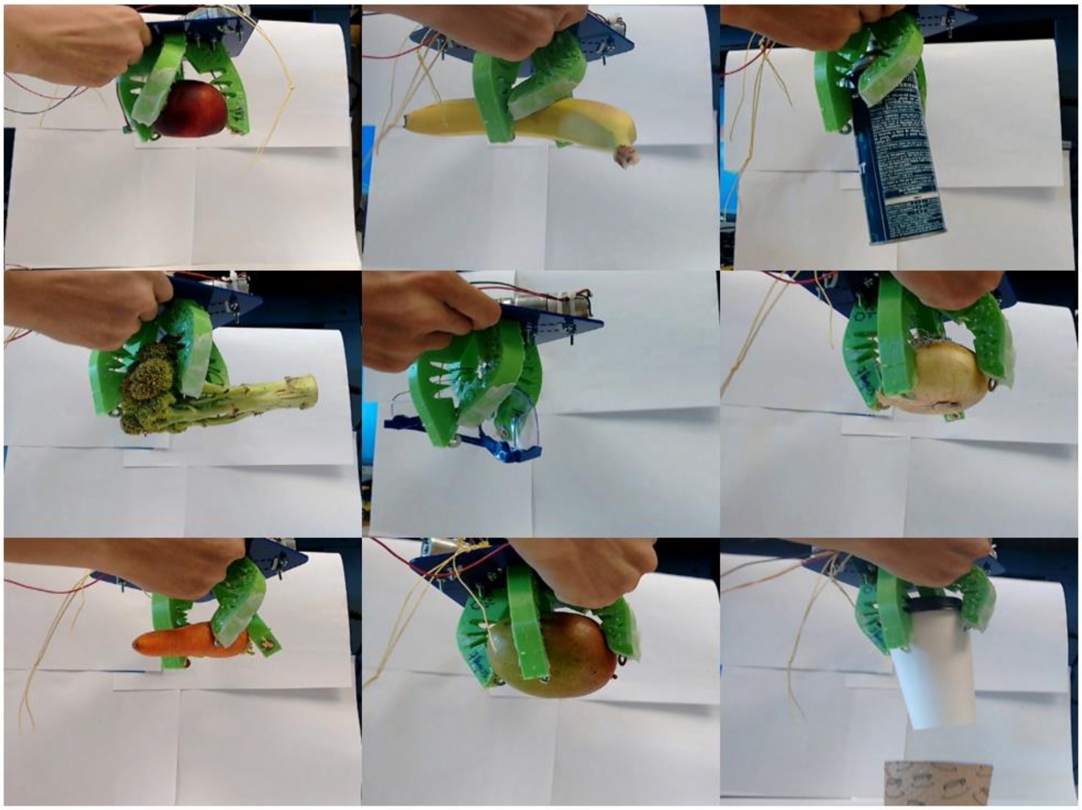


Figure 2.4: (From left to right, top to bottom): Peach, Banana, Empty Lubricant Spray, Broccoli, Glasses, Onion, Carrot, Mango, Empty Styrofoam Cup

2.4 Conclusion

This work presents a novel approach at designing, fabrication and operating a 3D-printed complaint gripper. While system was designed for tomatoes, it was successfully able to pick a broad variety of objects - both soft and rigid. The gripper achieved faster actuation speeds than any other previously existing work. Going forward, there lies scope in optimizing the design for a wider range of objects, improve energy consumption, test for repeated actuation cycles and implement state feedback control.

Chapter 3

Perching UAV

3.1 Introduction

As mentioned previously, there is a need for low-weight robust perching mechanisms for quadcopters. The expectations from this system was four-fold. First, it was expected to be mechanically robustness which translates to ability to perch on a range of surfaces. Second, system was supposed to be repeatable - defined as the ability to repeat perches and predict system behavior. Third, the mechanism needs to work well in untethered setting i.e. ideally with a 2S lipo pack. Last, it needs to be easy to manufacture, preferably on a desktop 3D printer.

The intention was to design mechanism compatible with the hexcopter UAV platform being developed in the Coordinated Robotics lab at UCSD. This translated into two design constraints – (1) compatibility with BeagleBone Black (2) total weight to be less than 100 grams. The weight constraint was calculated as $1/3^{rd}$ of total available upward thrust on the UAV platform.

3.2 Assembly

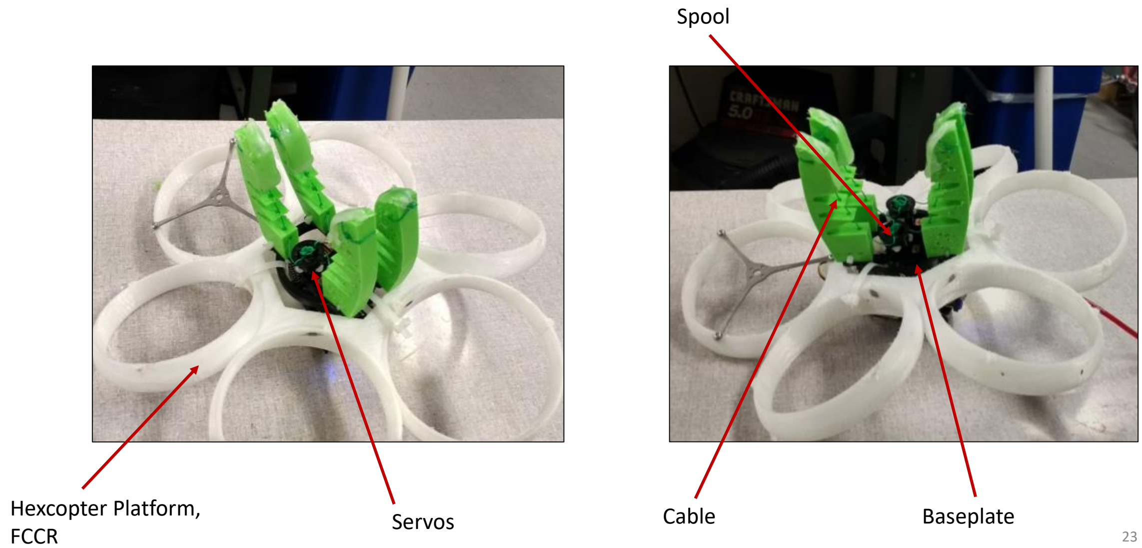


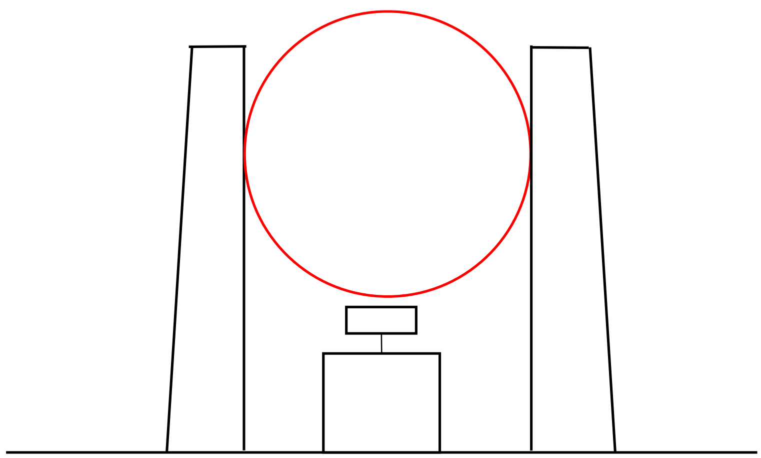
Figure 3.1: Assembled perching UAV

Table 3.1 : Perching UAV component details

Description	Count	Details	Weight/count	Sub-total Weight
NinajFlex ® Fingers	4	3D printed, See Appendix	10g	40g
Servos	2	Hitech HS5070MH	12g	24g
PLA Baseplate	1	3D printed, See Appendix	10g	18g
PLA Spool	2	3D printed, See Appendix	2g	4g
Zip-ties/ Fixtures	-	-	-	4g
Total				90g

The total weight of assembly was 90grams. The detailed designs of the main components is listed in the appendix. The servos were chosen to have a high torque/weight ratio for requirement of 2N to pull each finger. The spool dimension were chosen to have a 30mm pull to actuate the actuator 90º in half a turn of the servo. The servos were controlled with two separate 6.0V PWM output pins from the robotics-cape for the BeagleBone Black.

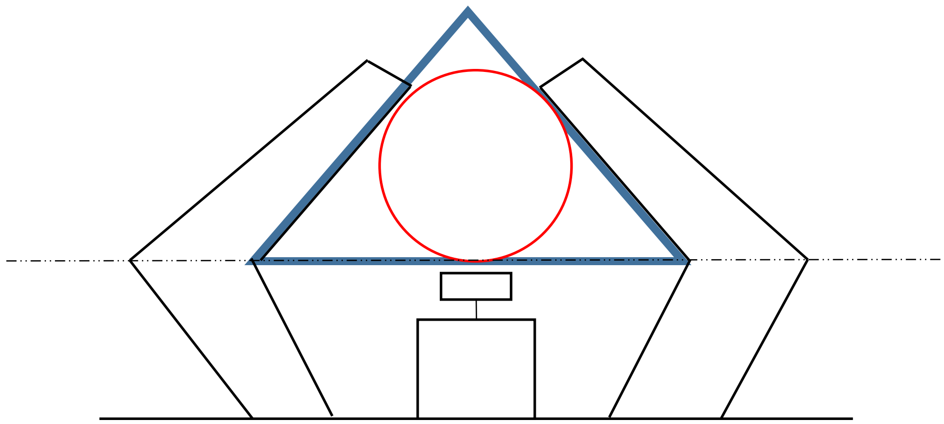
The maximum radius of curvature of the assembly is constrained by the finger geometry and base-plate dimensions. The biggest sphere which the hexcopter can hold onto from below corresponds to the situation when internal surface of the fingers is vertical (Figure 3.2). Any sphere larger than this would cause an under-pinch hold which would not be stable.



$$r_{max} = \frac{1}{2} * d_{fingers,vertical} \approx 45mm$$

Figure 3.2 : Maximum radius for perching from below

Similarly, the minimum radius of curvature corresponds to the radius of the in-circle of the triangle bounded by fingers' internal surface at maximum actuation and the top surface of the spool (Figure 3.3).



$$r_{min} = r_{incircle} \approx 8mm$$

Figure 3.3: Minimum radius for perching from below

3.3 Results

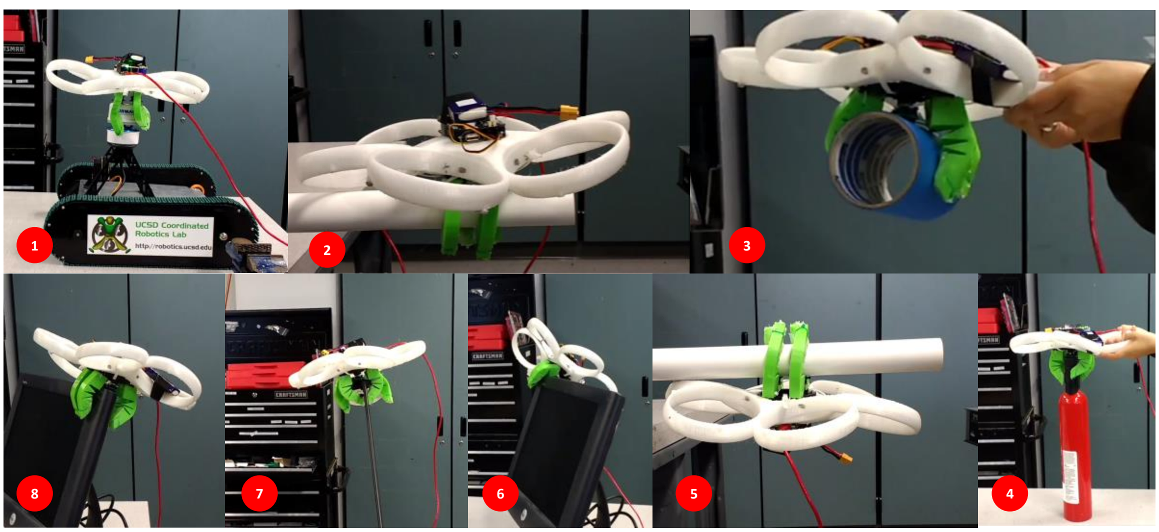


Figure 3.4: Successful perches (Clockwise from top-left) – Perching on (1) a LIDAR unit (2) PVC pipe, radius 21mm (3) Scotch tape roll (4) Top of fire extinguisher (5) PVC pipe, radius 21mm , upside down (6) Vertex of a monitor (7) Top of a table lamp (8) Top-edge of a monitor

For this experiment, the hexcopter was held in hand and slowly lowered the fingers of the mechanism. Once fingers achieved sufficient depth around the object, the

PWM was sent to BeagleBone and the gripper was actuated. The hold was considered successful only if the experiment was repeatable at least three times.

3.4 Conclusions

This Chapter demonstrates the robustness of the tendon driven actuators. Through careful design considerations, the mechanism meets the strict requirements of weight, robustness and ease of manufacturing.

While the work meets all the original objective, there is scope for improvement. First, there lies value in making the mechanism passive – so that servos need not be stalled for extended duration of time. This can be achieved by starting in fully actuated position in pre-tension and then doing work against using servos to grab the geometry. Other possibility is to either use worm gears or breaks to mechanically hold the tension in the string.

Chapter 4

Conclusions: Tendon-driven Actuators

This work demonstrated favorable properties of tendon-driven soft actuators. These properties include robustness, fast actuation speeds, ability to work with sharp objects, low power-consumption and low-weight. This makes them a great choice for untethered robotics manipulation applications.

This work opens possibilities and opportunities to other possible soft-robotic applications. For future work, there is a potential to explore infill and microstructure properties and their effects on the actuator. Additionally, the work stands to benefit from dynamic and kinematic modelling of the actuators.

Appendix

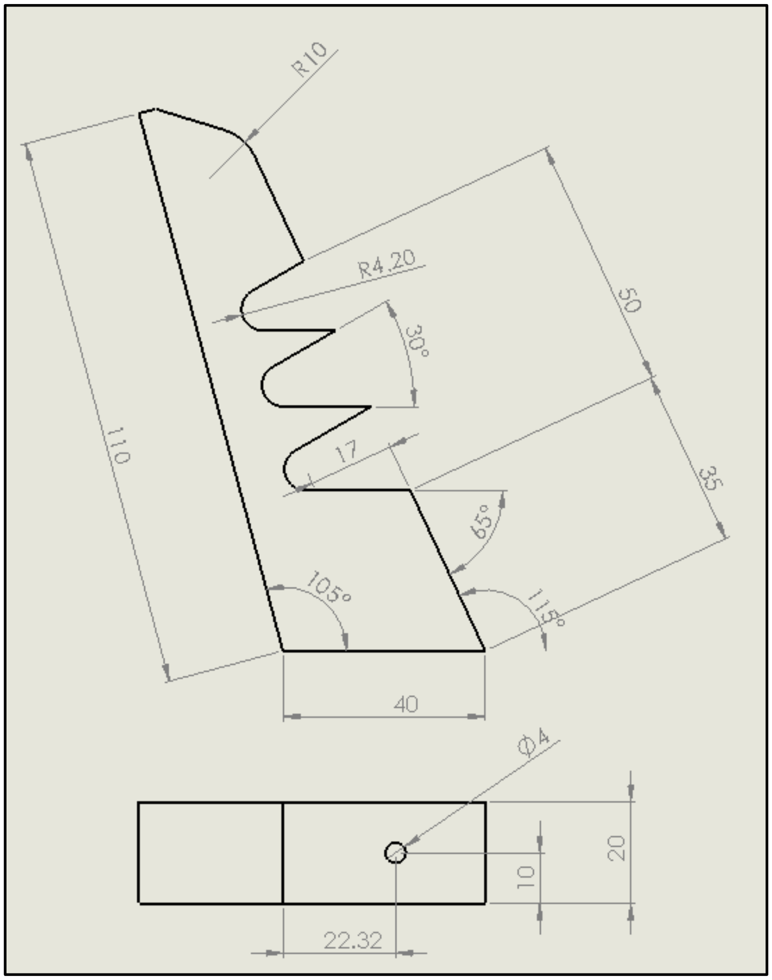


Figure A1: Dimensions for finger for robotic garden

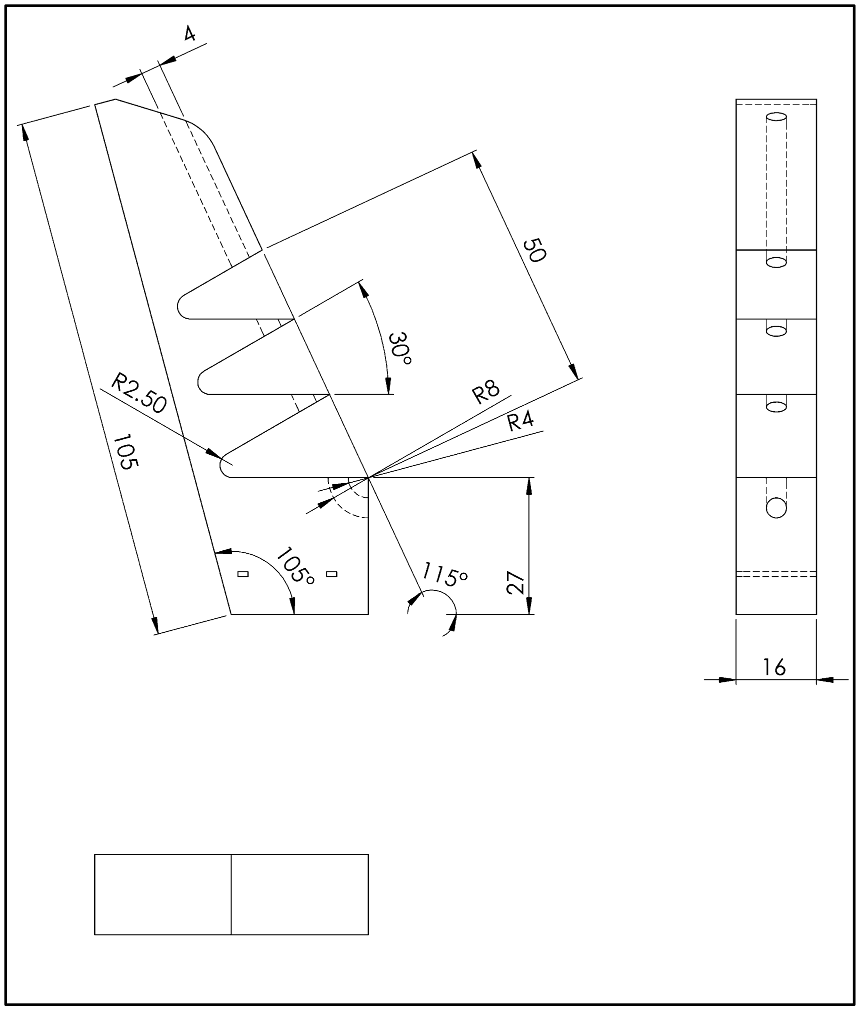


Figure A2: Dimensions for finger for perching UAV

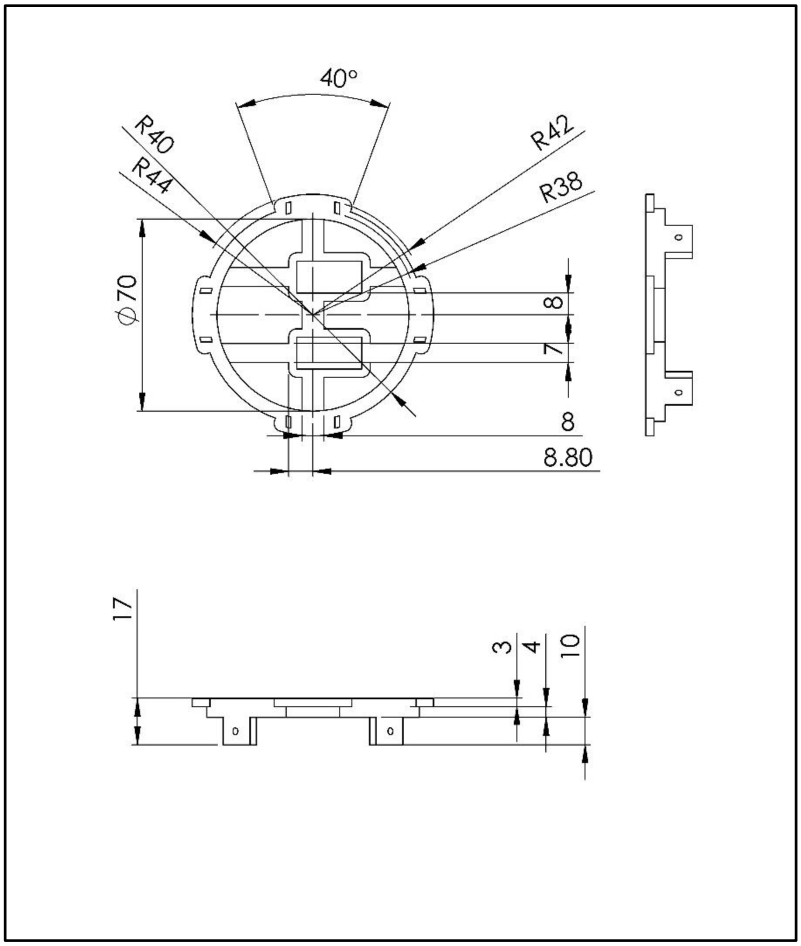


Figure A3: Dimensions for baseplate for perching UAV

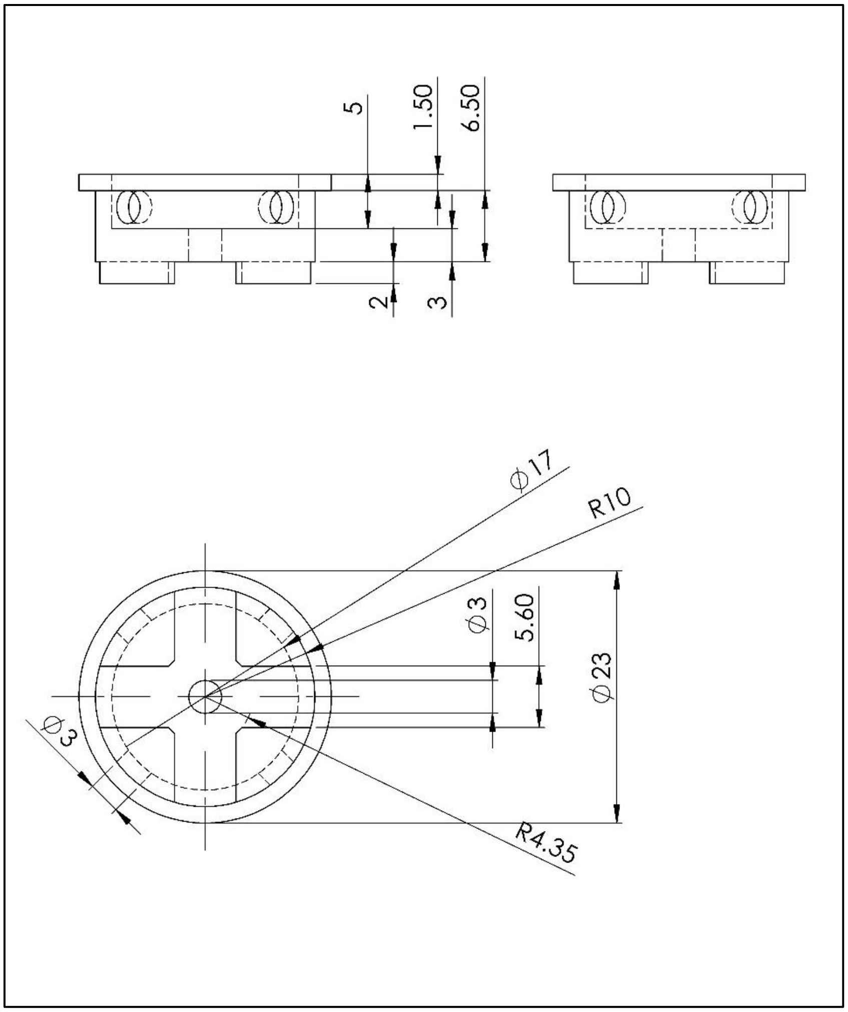


Figure A4: Dimensions for spool for perching UAV

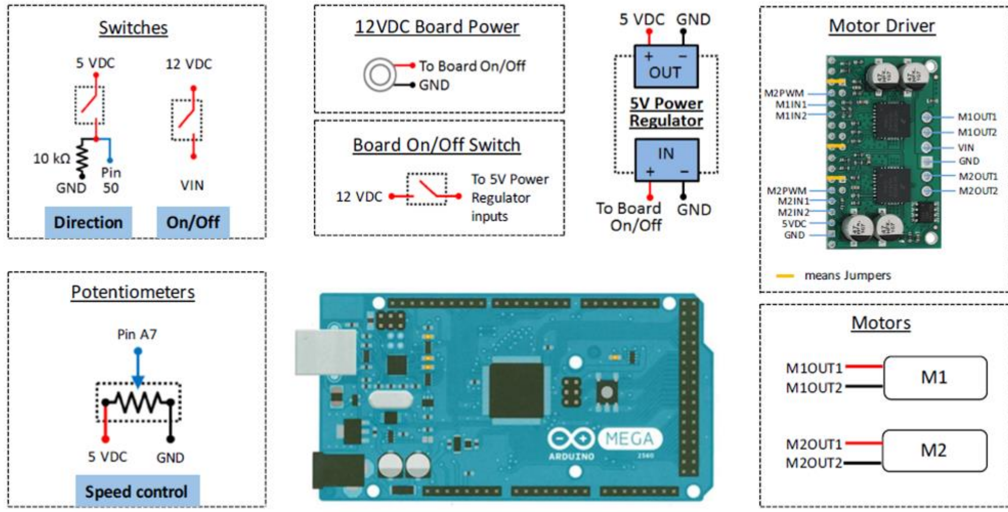


Figure A5: Circuit board and open loop control schematic

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