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3D Printed Soft Robotic Hand

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Department of Mechanical Engineering

I HEREBY RECOMMEND THAT THE THESIS PREPARED
UNDER MY SUPERVISION BY

Zack Kisner, Chris Szigeti, David Leonardo

ENTITLED

3D Printed Soft Robotic Hand

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

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IN
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3D Printed Soft Robotic Hand

By

Zack Kisner, Chris Szigeti, David Leonardo

SENIOR DESIGN PROJECT REPORT

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the Department of Mechanical Engineering

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Abstract

Soft robotics is an emerging industry, largely dominated by companies which hand mold their actuators. Our team set out to design an entirely 3D printed soft robotic hand, powered by a pneumatic control system which will prove both the capabilities of soft robots and those of 3D printing. Through research, computer aided design, finite element analysis, and experimental testing, a functioning actuator was created capable of a deflection of 2.17” at a maximum pressure input of 15 psi. The single actuator was expanded into a 4 finger gripper and the design was printed and assembled. The created prototype was ultimately able to lift both a 100-gram apple and a 4-gram pill, proving its functionality in two prominent industries: pharmaceutical and food packing.

Keywords: Soft Robot, Soft Robotics, Mechatronics, 3D Printing, Pneumatic, Actuators, Human Robot Interaction, Safety, Hand, Robotic Hand, Gripper, Control System, Arduino

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Chapter 1 - Introduction

Soft robotics is an emerging sector of robotics, gaining momentum through its use of soft, flexible materials in replacement of currently deployed hard, rigid metals. Soft robotics aims at eliminating a number of issues related to the use of current robotics in industry. First and foremost, soft robots are much safer than current robots due to their lighter weight and softer materials. Soft robots allow for greater human-robot interaction and eliminate the need for robots to be contained inside of safety cages. Additionally, soft robots are substantially cheaper than current rigid bots. Current robot arms generally cost upwards of $50,000 for the arm alone and often finish in the $100,000 range once tools and programs have been created [1]. Soft robots are substantially cheaper, with the company Soft Robotics typically selling their starter kit for $12,999 [2]. Finally, soft robots are ideal for their scalability. Any alteration in the size or shape of a soft robot can be accomplished much more rapidly and cheaply in comparison to rigid robots. Rigid robots require the outsourcing of materials and require the purchase of expensive metals which may create large lead times. Soft robots require the creation of a simple cast molding and the purchase of cheaper materials such as silicone.

Soft robotics is a young industry and because it is so new, only one major university has a laboratory to study soft robotics (Harvard University) and only two companies exist that focus on creating soft robots for industrial settings (Soft Robotics, Pneubotics). Examples of current soft robotic designs can be found in Figures 1a and 1b. The images highlight a gripper design, with the fingers possessing pockets for pressurized air to be stored to create actuation. These robots largely function in the food packaging industries, utilizing anywhere from 2 to 6 fingers to pick and place objects such as tomatoes, donuts, and even retail products.

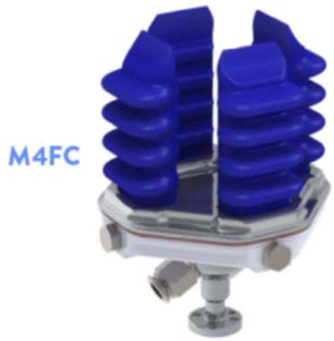


Figure 1a and 1b: Images of currently utilized soft robotic grippers in the industry [Soft Robotics; Shen, Helen]

Both the university laboratories and companies studying soft robotics have accomplished groundbreaking work (most of which can be attributed to Dr. Whiteside and his collaborators at Harvard University). The primary issue facing soft robotics is the great deal of limitations created by the current materials being deployed. Most functional robots are primarily silicone molded, with only a single published paper highlighting a 3D printed soft robot [3]. Utilizing silicone molding techniques, a number of limitations are created in the design of many soft robots. Hand molding creates limitations in the potential geometry, is often time consuming, and can lead to inconsistent manufacturing quality. As our team researched the issues with hand molding, we noticed the potential for 3D printing in the soft robotics industry.

Silicone is primarily the material used in soft robotics namely due to the material properties that it is capable of providing. Silicone is strong, but offers great flexibility required of a material that is required to bend from a pressurized input. Many 3D printing materials are unable to match the properties of silicone, mostly eliminating the potential for 3D printing of soft robots. With our established goal of 3D printing our own soft robot, it was evident that we would need to find a material capable of being 3D printed and rivaling the properties of silicone. This goal was largely accomplished due to our partnership with Molecule Corp., a startup based in Concord, CA. Molecule has agreed to supply us with all the needed resins to 3D print soft robots along with access to their lab and 3D printers. These materials have not been released on market yet and are the only materials that we could find with cured properties strong and flexible enough to fully print robots for an industrial setting.

Chapter 2 - Literature Review

Soft Robotics toolkit [4]

Soft robotics toolkit is an open sourced website that releases information on all aspects of soft robotics. Most of the information on the website is from research labs at Harvard and MIT. This site has a number of control system designs that are used for a number of applications. The design shown below illustrates the control system that utilizes pressure sensors, valves, a microcontroller as well as other components to power a soft robotic actuator. The pressure in the system is controlled by pulse width modulation (PMW) and these modulations control the opening and closing of the valves. This board and the modulations are controlled by an Arduino microcontroller.

This system allowed us to design and begin simulation of a control system. Although our system is a bit more complex, it gave us a great basis, and a good idea of how soft robotic actuators are being controlled today.

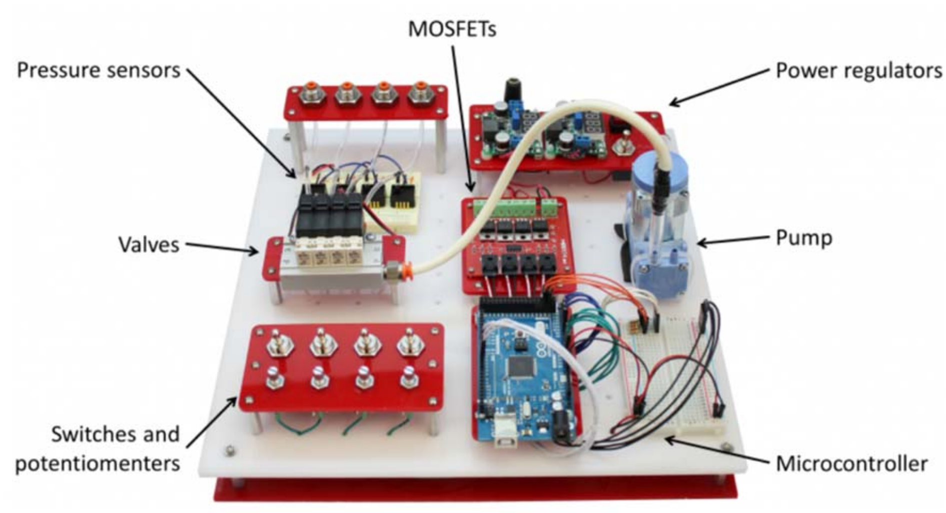
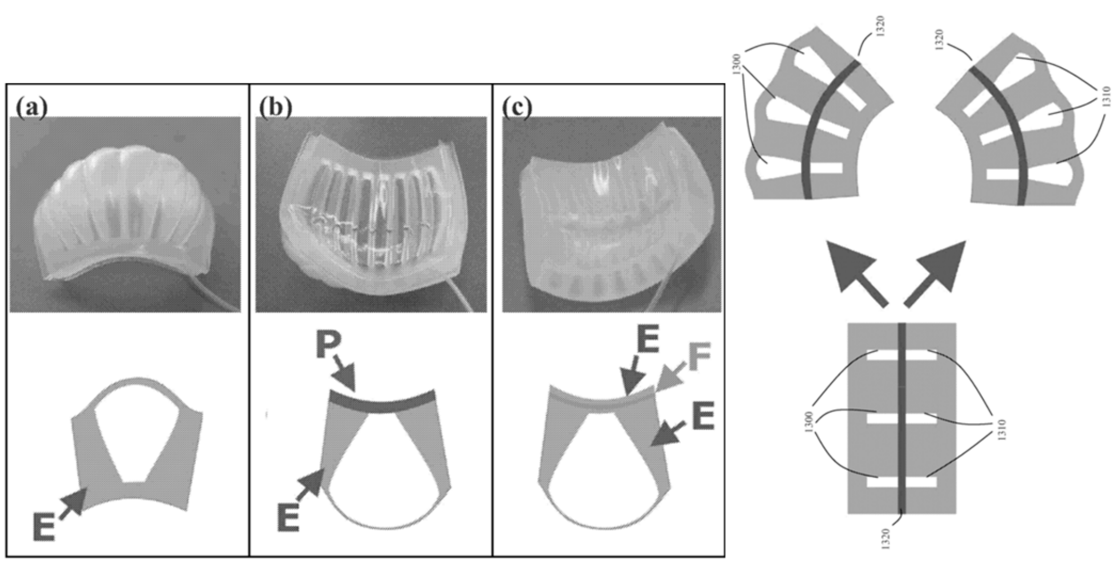


Figure 2: Open sourced pneumatic control system used for soft robotic actuators [4]

U.S. Patent WO2012148472A2: Soft Robotic Actuators [5]

This patent was one of the first filed patents pertaining to soft robotics and is perhaps the most relevant to our patent claim. The main claim of this patent is a soft robotic actuator containing a molded body and pressurized inlet which when pressurized will cause a bending motion (claim 1). This is important to our patent claim (3D printed soft robotic actuators) since this patent is specific to molded bodies. The patent also discusses the process of using a single strain limiting surface on the bottom of the actuator and an expanding top layer on the top in order to cause the desired bending motion. This is the same process by which our soft robots actuate, however the patent continually refers that the soft robot must be molded in order to classify as a “soft robotic actuator” (claims 1-35). Since our major difference is through the 3D printing process by which we create our actuators this prior art does not conflict with the patentability of our product.



Figures 3a and 3b: Images of patented soft robotic actuators [5]

U.S. Patent US20160114482A1: Soft robotic actuators utilizing asymmetric surfaces [6]

The main claim of this patent is that a soft robotic actuator be composed of two major sections, a bottom portion of constant profile and an upper section of varying profile. This is referred to as an asymmetrical geometry and is what allows for the bending motion of the soft robotic actuators to occur. This asymmetric geometry as well as pressurizing the upper section is the same method by which our product actuates. However, this patent cites and refers to U.S. Patent WO2012148472A2 discussed above which claims that soft robotic actuators are once again composed of two separate molded components. Although our product may have both a section that is of constant profile and another that is asymmetric, the 3D printing process (our main patentable claim) separates us from the claim that soft robots must be molded and also allows for seamless transition between these two sections unlike in the molded counterparts.

U.S. Patent WO2013110086A1: Flexible Robotic Actuators [7]

This patent claims intellectual property over flexible robotic actuators where bending is achieved using a stiffer base layer adhered to an inflatable upper portion. This uses the same property mentioned in the above two patents where this stiffer base layer constricts motion as the top inflates and thus finger-like bending is achieved. However, as seen in claims 1-3 of this patent the flexible robotic actuator described is composed of laminated films which are adhered together using various adhesives. Although the achieved motion is similar to our product, the 3D printing process we hope to patent is drastically different than anything used in this patent, setting our intellectual property apart.

U.S. Patent WO2012150551A1: Robot Having Soft Arms for Locomotion and Grip Purposes [8]

The main claim of this patent is the creation of a gripper that uses soft fingers that can be individually controlled to grip objects and produce motion. Similar to our product, soft fingers are mounted radially around a central point. However, the soft fingers discussed in claim 1 are simply rigid robots with a soft elastomer added on top. This is very different from our 3D soft robot in that cables and rigid parts are used to produce motion compared to geometries and pressures. Although both robots produce similar motion and have "soft components", the robot patented here is much more so a rigid robot with added soft material and is in no way 3D printed differentiating our product from interfering with this patent.

US Patent 20170095925 A1: Soft Body Robot for Physical Interaction with Humans [9]

Walt Disney has recently applied for a patent based on the application of soft robots. Although Disney's robot is not fully soft, it is composed of a rigid interior that is inside of a soft, pneumatically powered exterior. Disney's main focus of the patent is human robot interaction.

> "In this regard, it is desirable to provide soft skin and/or a soft body. Above all other design requirements is the requirement for safety. To this end, the robot may include 3D printed, soft skin modules or segments (or body parts), and these modules may include a flexible, contact-sensing, air-filled cavity (or void/interior space). The module helps to absorb unexpected impacts, reducing the likelihood of human injury and actuator damage. Further, the module provides contact force feedback via a pressure sensor connected to the air-filled cavity. When distributed over the body of the humanoid robot, these modules give the robot the ability to sense contact forces on its various links. Full body sensing allows for the implementation of engaging physical interactions. The independent sensing areas

> of the body allow a human to communicate with the robot through touch, drawing attention to certain links or guiding the motions of the robot.” [9]

The overall goal of this Disney project is to create soft robotic characters for their parks that can safely interact with guests. These ambitious goals that Disney proposes show there are many applications for soft robots in the near future, many of which expand past the agricultural and pharmaceutical industries which this project is designed for.

Chapter 3 - Soft Robotic Hand – System Level Chapter

3.1. Customer Needs

Currently, robots are largely used in a variety of industry settings. Due to their ability to automate a large variety of mundane and repetitive tasks, robots have made a large footprint in manufacturing, packaging, and processing plants. The impact and use of robots is expected to continue to rise over the next few decades, with robots allowing for a greater growth in both workplace efficiency and labor-cost savings. Soft robotics is expected to garner a chunk of this market growth, largely in the food packaging and pharmaceutical industries where their "soft" touch is useful.

Our project focused on both the food-packaging and pharmaceutical industries for deployment of our designed hand. We believe these industries are important benchmarks for ourselves, largely because in these industries soft robotics are already beginning to be deployed. Soft robotics in food packaging are necessary primarily due to the soft nature of fruits and vegetables. A soft robot should be capable of picking and placing the fruit/vegetables into packages while lowering the chance of damaging or bruising the product.

Our team interviewed Dr. Gregory Baker in the Department of Management of Santa Clara University about the possibility of using soft robots in agriculture. Dr. Baker has a PhD in Agricultural Economics from Purdue and has been researching the agricultural industry for years. He expressed the great potential for soft robots in the packaging industry noting that current packaging involves humans and robotic automation. Due to dangers of humans and robotics working side-by-side, Dr. Baker noted that soft robots could increase the overall efficiency throughout a factory and allow for a factory to process riper fruit and vegetables.

Research into the pharmaceutical industry indicated that robots currently have and will continue to play a large role in packaging. It is estimated that robots will be a part of 34% of primary pharmaceutical packaging operations in North America by 2018 [10]. Robots in pharmaceutical offer increased efficiency when compared to humans, but require great precision in their abilities to pick up small items such as pills. Similar to food packaging, robots in the pharmaceutical industry should be capable of working side-by-side with humans while supplying a touch that won't damage the object being lifted.

From our market research, it was determined that the deployment of soft robots in both the pharmaceutical and food packaging industries will continue to rise. The capabilities of soft robots to improve functionality when working alongside humans as well as add a softer touch in gripping items make them optimal for industries such as food packaging and pharmaceuticals. Additionally, soft robots allow for a lower price point in comparison to current rigid robots. By expanding the overall availability, soft robotics will become a focal point in these two industries for both small and large corporations.

3.2. System Level Requirements

The overall system goals were geared towards revolutionizing the soft robotic industry and focusing on the two industries mentioned earlier: food-packaging and pharmaceutical. The soft robotic hand should be capable of lifting both an apple and a pill with little to no human involvement. The standard weight for a small apple is around 100 grams and the standard weight of a large pill is 4 grams. These values were used as the benchmark for the objects. These two items were specifically chosen for both their differences in size, shape, and weight proving the functionality and precision of the hand. The two items will highlight the overall capabilities of the hand and will provide a proof of concept for the design.

The hand is to be controlled via a pneumatic control system. Pneumatically controlled soft robots is the current standard of the industry and utilizing pressurized air will ensure greater safety of the device. The pressurized air should be capable of creating enough actuation and force for the hand to lift both an apple and a pill. Additionally, the control system should be compatible with a user interface that is capable of controlling the overall pressure input of the actuators. Ideally, this user interface should be a computer program that allows for rapid control of the pressure and feedback.

To differentiate the project from current soft robotics, the hand (namely the "fingers") are to be 3D printed. As discussed, current soft robotics relies on hand molding which can lead to a number of limitations in the overall design of the robots. Our goal is to highlight the capabilities of 3D printing in soft robotics which we believe will be able to eliminate a number of the problems associated with hand molding. Additionally, the final printed material should have properties which rivals or exceeds that of silicone. Silicone was chosen as the benchmark due to it being the primary material which is deployed in soft robotics.

Finally, the overall design of the soft robotic hand should be safe for use by and around humans. As mentioned, current robotics limits the amount of human-robot interaction that is possible in industry settings due to safety concerns. Although the design of the robotic arm is out of the scope of this project, the hand design and pneumatic control system should serve as a proof of concept of the overall safety of soft robotics.

3.3. Physical Sketch

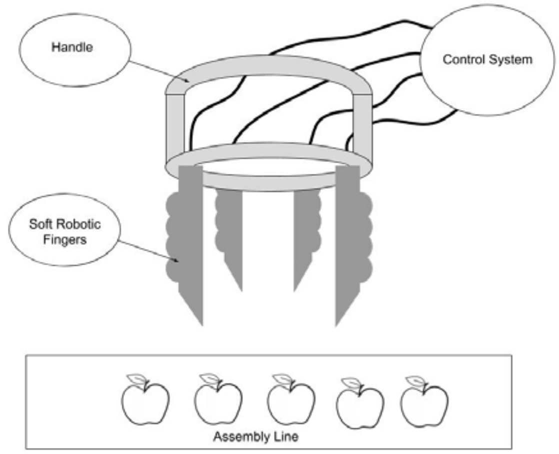


Figure 4: System level sketch showing 3D printed gripper concept for use in agricultural packing house

Figure 4 is an example sketch of the overall system design. The sketch highlights the overall project goal of creating a 3D printed, soft robotic hand that is capable of lifting a 100-gram apple and a 4-gram pill. Additionally, the sketch shows the primary subsystem components: the fingers/actuators, a holder connecting all the actuators, and the pneumatic control system.

3.4. Functional Analysis

The overall functional use of the soft robotic hand is to be able to both lift and place objects of various sizes with little to no human interaction. The purpose is to prove the functionality of the device in various industries such as food packaging and pharmaceutical. It is ideal that the device will eventually be paired with software allowing the hand to them be fully automated to create greater efficiency within these industries. By being created out of soft materials, the robot will allow for side-by-side human interaction eliminating the fear of accidents typical to current robotics. In this manner, the soft robot has the potential to replace many current robotic designs while possessing a lower price point to enhance accessibility.

The soft robot hand is to made up of four subsystems: the actuators, the control system, the handle, and the user interface. Each component is pertinent to the overall success of the hand and each has various requirements and functions. The most prominent of the subsystems is to be the soft robotic actuators. The actuators are essentially the fingers of the hand, providing the grip and subsequent force on the objects to be lifted. Each finger will have an input of pressurized air which will create the bending action of the finger. The resultant outputs will include stresses in the finger, bending of the finger, and a force when the fingers are actuated against an item to be lifted.

The control system is the component which allows the actuation of each finger. The primary function of the control system is to properly monitor and control how much air is input into each finger. By being capable of successfully managing the pressure within each actuator, the control system will allow for greater control and manipulation of the entire hand. The control system is to be powered by a standard battery with a microcontroller sending a signal to the system to manipulate how much air is allowed to each finger. The resulting output of the control system will be a direct current voltage sent to a pressure regulator attached to each finger.

The functionality of the handle is to provide a manner of attaching and arranging the fingers to the control system. The handle has points of attachment for all the fingers and locations for the tubing to be connected individually. The handle is pertinent to allowing all the subsystems to interact and successfully operate in gripping and lifting objects.

The user interface is the final subsystem component of the soft robotic hand. The user interface is the computer programming/code that is capable of interfacing with the control system to vary the input signals sent to each regulator. The user interface is capable of rapidly controlling each signal, with little to no lag between changing the input and the output by the finger. Additionally, the user interface is capable of interacting with anywhere from 2 to 8 pressure regulators.

3.5. Benchmarking Results

Table 1: Benchmark table analyzing current use of soft robotics by two companies (Soft Robotics and Pneubotics) and research labs (namely Harvard) [2], [11], [12]

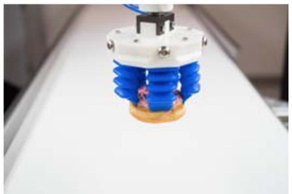
Company Name	Current Soft Robotic Design	Summary of product and uses	Key Features
Soft Robotics		- Primarily used for food packaging - Extension of Harvard Lab - Mostly a proof of concept - Developing largest market share of soft robotics in food packaging	-Number of fingers can be varied from 3-8 -Established control software for adjustment of strength and level of actuation -Software allows for storing up to 8 grip profiles - Hand molded
Pneubotics		-Minimal industry use -Have been working on proof of concept to master design of the arm -NASA has shown interest in the company and their designs	-1:2 weight to payload ratio -Controlled strictly through pressurized air -Rapid assembly and setup -Utilizes fabric as primary material
University Laboratories (Harvard)		-Proof of concept/research work to understand soft robotics -Goal to create a better predictive model to enhance use of soft robots in industry	-Harvard has created soft actuators that are embedded with flexible materials such as cloth and paper -Most designs rely on multi-step molding techniques -Created fully soft sensors for monitoring the kinematics of the robots

Table 1 analyzes the key features and current design of soft robotics being utilized by two companies (Soft Robotics and Pneubotics) and the research performed by university laboratories (namely Harvard). The table is utilized to establish a benchmark for the soft robotics sector as a whole to set a standard for our robot while analyzing the overall trends of soft robotics. The key highlights of the benchmarking results are that all current soft robotics rely on hand molding, that Soft Robotics specifically can vary the number of fingers of their grippers from 3-8, and that Pneubotics creates robots with a strength to weight ratio of 2:1.

Table 2: Range of various material properties of silicone, used as a benchmark for the chosen material due to wide use of silicone in soft robotics [13]

Material	Yield Strength (psi)	Ultimate Tensile Strength (psi)	Elastic Modulus (psi)	Percent Elongation (%)	Static Coefficient of Friction
Silicone	350-800	350-800	145-7250	200-500	0.3-0.8

Table 2 highlights various material properties of silicone, the commonly used material for soft robotics. The table is included because silicone served as the benchmark for our material selection in our design [13]. The material chosen for 3D printing should rival or exceed this established benchmark to serve as a viable option for the robotic hand.

3.6. Issues, Options, Tradeoff, and Rationale

Material Selection

After establishing our overall goals and benchmarks for the project, the team had to overcome a number of issues and tradeoffs regarding the project. First and foremost, our group had to decide what material would be used for our prototype. Because it was determined that the hand should be 3D printed versus molded, our team needed to find a material that was capable of being printed while reaching benchmark material properties. Our team was partnered with

Molecule Corp. which provided us with access to their 3D printing materials and to their labs. In return, our project was to serve as a proof of concept of the capability of their materials. To determine our ideal fluid, a number of tensile tests and experimental testing was performed on two of Molecule's materials: Molecule XS and Molecule RH. Ultimately, Molecule XS was chosen as the ideal material due to its higher material properties for Elastic Modulus and Percent Elongation. Additionally, Molecule RH had consistent failures when basic experimental testing was performed on simple pocket iterations.

Pressure Input

As briefly discussed, a pneumatic control system was chosen as the subsystem capable of varying pressure input to create actuation of each finger. The team was deciding between 15 psi valves and 30 psi valves for the control system (the valves affect how much pressure is sent to each finger). Ultimately, the team determined that a maximum pressure input of the control system would be 15 psi. This decision was made for two reasons: 1) 15 psi valves were cheaper and 2) 15 psi would make for a safer robot in comparison to 30 psi. Moving forward, the geometry of the fingers was designed for actuation at pressure inputs ranging from 0-15 psi.

One Print versus Multiple Prints

An important design decision for the overall system was whether the hand would be made up of one print versus multiple prints with an assembly. Ideally, the hand would be completed in one print - all the necessary fingers and palms eliminating the need for assembly. Our team believed this would create for a more functional hand design and serve as a better proof of concept for the capabilities of 3D printing. For the process of printing the hand, our team was greatly limited due to the design area of the printers. The printers used had a build area with the length of approximately 2.5 inches. This created a large constraint on the overall design with the only possibility of a full hand being printed requiring a complex layout and support system for the hand.

Ultimately, it was decided that the hand would be created through a multi-part assembly. Each finger would be printed separately and the palm/handle would be a separate print as well. This is how current soft robots are molded and assembled and the process of printing everything separately resulted in more rapid, simpler prints.

Thumb versus Gripper

An additional issue with the project was the initial reach goal of creating a robotic hand with four fingers and one thumb. Initially, the team believed that the design of a thumb would be the ideal route of design which would enhance the overall functionality and capabilities of the robotic hand. A thumb would allow our design to expand beyond simply serving in food-packaging and the pharmaceutical industry, having great potential for the eventual design of a prosthetic limb. During the early design phases, our group began early research into the potential thumb design. A prototype is shown in Figure 5. The design was based off research into soft robotics, replicating an elephant’s trunk. With three channels for air to be stored, it was believed that varying pressure inputs in the channels could ultimately result in the desired actuation.

Figure 5: Printed thumb prototype utilizing 3 channel design

Ultimately, the thumb was eliminated for consideration as the design moved forward. There were a number of difficulties involving both the design of the thumb, printing, and experimental testing. Due to this, the focus could then be placed exclusively on the fingers.

3.7. System Layout

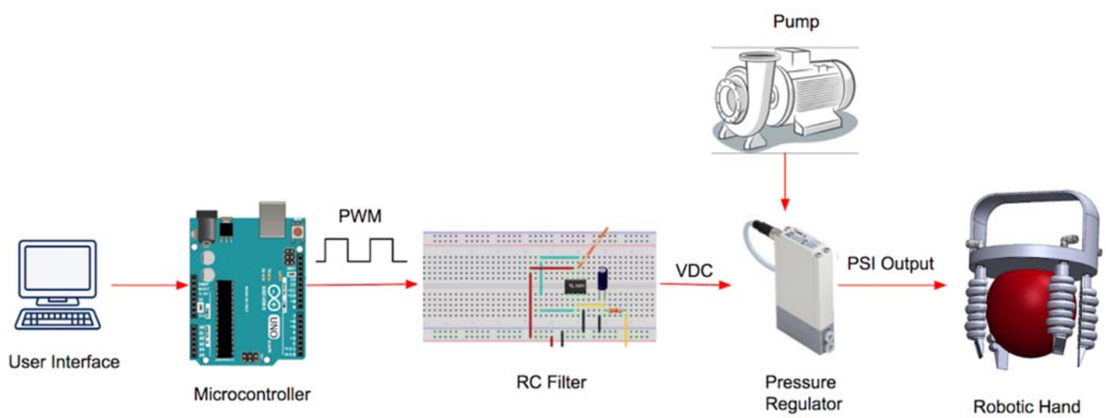


Figure 6: Overall system layout of the 4 finger, robotic gripper utilizing a user interface, a microcontroller, an RC filter, a pump, and a pressure regulator to create actuation of the fingers [14], [15], [16], [17]

Figure 6 provides a system layout of the entire robotic hand system. The system utilizes a user interface paired with a microcontroller to send various PWM (Pulse Width Modulation) signals to an RC filter. The RC filter works to convert the PWM signal to a DC voltage, with this voltage value determined by the width of the PWM signal. Depending on the value of this voltage (0-5 V), the pressure regulator then varies the amount of pressure input from the pump that is output into each actuator.

3.8. Team and Project Management

It is important in all projects to have a clear idea of team management prior to starting the design process. For our project, all of us had different experience in engineering design whether it be coding, 3D modeling, project management, etc. Although we were all involved in every part of the design process, different group members spearheaded individual parts of the project such as control system design and part sourcing (Chris), FEA and printing mechanics (Zack), and mechatronics system and mathematical design (David). With this in mind, we aimed to make sure that every member was aware of what was going on during all phases of the project. We also focused on using a top down design process where the design of all subsystems was completed with the top-level system and goals in mind.

Over the course of this project it was assumed that various problems and challenges would arise. This is expected of any engineering task, however overcoming these obstacles can be the difference between a successful project and a failed one. Our team scheduled weekly meetings with our advisors, Dr. Panthea Sepehrband and Dr. Michael Taylor, which allowed us to use their expertise to stay on track with the project, set goals, and overcome any obstacles. Additionally, our team met regularly with all group members to brainstorm solutions and work on any problems that would arise. Due to the complex nature of our project, specifically with the mathematical simulation portion, we assumed a large amount of problems would arise. Some technical issues that occurred included: FEA analysis (namely licensing restrictions), actuator printing, component lead times, and access to certain facilities.

Another complex part of this project was dealing with the overall budget. Luckily, our partnership with Molecule Corp. provided us with all of the needed printing resins free of cost, greatly reducing our budget. However, almost all of the remaining budget was devoted to the creation of our pneumatic control system and can be viewed in the Bill of Materials in the Appendix F. Outside of our partnership, all of our funding has been raised independently of the University totaling at $4,600. Although we had such a large budget, we only needed around $3,000 and saved the additional amount for backup and potential project expansion in the future.

Some of these expansions include sensors for the fingertips, PCB printing, and creation of the thumb subsystem.

Our main project timeline consisted of design and planning in the fall, control system assembly and overall prototyping in the winter, and finalization and presenting in the spring. A more broken down version of the project schedule can be viewed in the Gantt chart in the Appendix.

Our group's approach for this project was to treat it as though we are engineers working for a mechatronics company. Our diverse background working for different robotics, product development, and 3D printing companies has provided us with a plethora of experience in industry as design engineers. Our general design process was to make sure all aspects of the project had been properly thought out and all simulation and mathematical verification had been properly completed prior to making large decisions. Throughout the design process we also properly documented all aspects including 3D modeling and drawings, BOM maintenance, budget updates, and thorough testing reports. Although we planned to approach the design of this project first using simulation and modeling tools to verify design choices, our access to 3D printing also allowed for rapid prototyping to take place, aiding in design updates through experimental testing.

Chapter 4 – Mechanical Subsystems

4.1. Soft Robotic Actuators

4.1.1. Role and Requirements

The overall role of the soft robotic actuators is to bend at various angles when supplied specific pressures in order to pick up objects of various sizes, namely an apple and a pill. In order for this objective to be met, a number of goals were set for the actuators and their functionality.

To successfully create a 3D printed soft robotic hand, the individual actuators must also be 3D printed. This goal helps set our hand apart from other products on the market today. As discussed, almost all current soft robots are hand molded out of silicone or other polymers, which greatly decreases the possible geometries and also increases the prototype time. By 3D printing the actuators, the range of geometry possibilities is greatly increased while allowing for more rapid iteration and design.

Secondly, the actuators must be functional for a pressure range between 0 and 15 psi. A max pressure of 15 psi was chosen for safety precautions, but the actuators must prevent failure at this maximum pressure input. Additionally, each finger must deform at upwards of 2 inches at the maximum pressure input. This goal ensures that enough deformation will occur to allow for smaller objects like a pill to be lifted while ensuring a proper resultant force. Also, in order to rival current soft robots, the static coefficient of friction of the material used must be able to rival or exceed that of current silicones used. As discussed in the Benchmarking Results section, our hand's overall functionality should be similar to current soft robotics. This requires similar pressure input requirements and similar resultant forces which is dependent on the coefficient of friction. Lastly, each individual finger must supply enough force to allow for an apple to be lifted when expanded to a 3-5 finger gripper.

In summary, there are 5 goals for these soft robotic actuators: 1) they are 3D printed, 2) they can withstand 15 psi, 3) a maximum fingertip deflection greater than 2 inches, 4) their static COF is similar to silicone, and 5) they can exert enough force to lift an apple when paired with 3-5 fingers. Through testing, the success of these actuators can be determined by analyzing their ability to meet these goals.

4.1.2. Issues, Options, Tradeoff, and Rationale

Printer Selection

Moving away from hand molding to meet the first outlined goal of our actuators, the team had to obtain access to 3D printers and printing fluids. Luckily, our team was partnered with Molecule Corp. which provided us with access to their printing labs. Our partnership was created due to the materials that Molecule owns, highlighted by Molecule's XS material which was discussed in the System Level Chapter.

Although the partnership with Molecule made 3D printing possible, there were still a number of issues encountered. To begin, an Origin DLP 3D printer was initially selected as the printer of choice. Origin's printers utilized Teflon trays which were optimal when working with Molecule XS. Teflon trays were required due to the ability to withstand that materials curing during printing. Silicone trays (those typically used) can suffer a burning failure during the curing of Molecule XS. Unfortunately, the build length of this printer was 64mm, which was smaller than that of our ideal finger size. We hoped to create a finger that was similar in length to a human finger of 3.5 inches (~90 mm). Due to the tray limitations, these fingers would have to be printed at high angles, forcing support structures to be used which can not only decrease the accuracy of the print, but also greatly increase the print time (~5 hrs. per finger). As we worked more and more with the Origin printers, our team continuously struggled with the build area limitations.

In the middle of our project, Molecule was given 2 new printers that were designed by 3D Systems, the Figure 4®. These printers had a build length of 107.52mm (~4.20 inches), allowing for fingers to be printed with no support structures. This would allow for quick and accurate prints and rapid design iterations for our team (~45 min per finger). Due to the build length of the 3D Systems printer, it was ultimately determined that these were the ideal printers for the requirements of the project.

Material and Material Curing

Once a printer was selected, the Molecule XS material was analyzed. The Molecule XS material is UV curable meaning that when applied with energy from a light (laser or projector), the material turns from a liquid to a solid. The material used is also extremely unique and unlike any 3D printing materials due to its curing capabilities. Depending on how the material is cured on the printer (how much energy is applied, thickness per layer), the mechanical properties can be greatly varied. For the use of this project, a very small percentage of the material properties that Molecule XS could meet were analyzed.

Material Testing

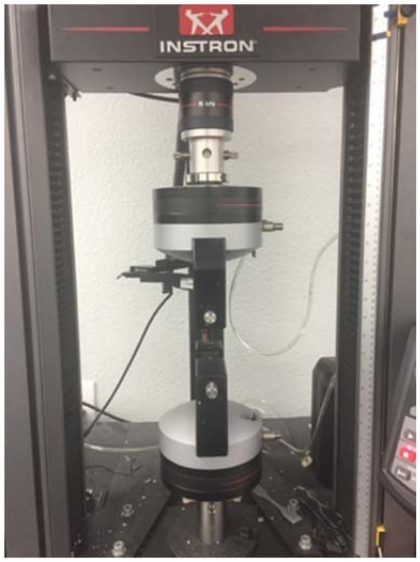


Figure 7: Instron testing apparatus for tensile testing

In order to understand the properties, tensile testing was performed using an Instron with a 5 kN load cell (Figure 7). The method of collecting data followed the ASTM standard for a rubber like material. With this, the load was displacement driven and pulled at 50 mm/min, and extensometers were used in order to follow standards, and collect the most accurate results. Figure 8 shows the small material range of the Molecule XS material that was to be analyzed for the scope of this project.

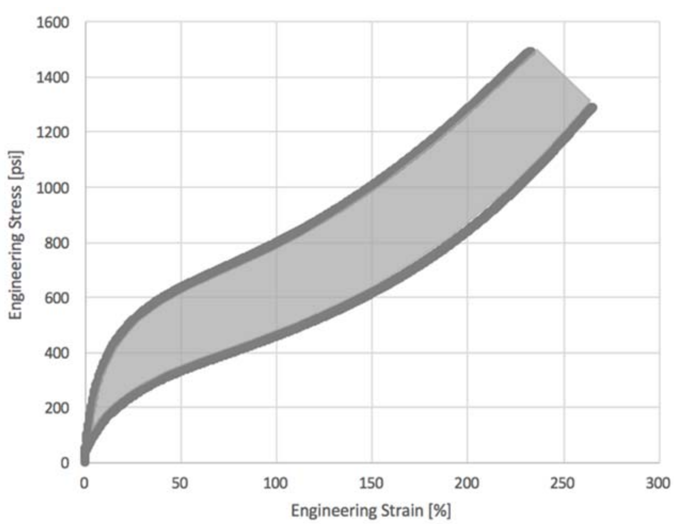


Figure 8: Range of material property capabilities of Molecule XS considered for the project

Coefficient of friction testing was also performed on the Molecule XS material using an Instron, this time with a 500 N load cell. The testing was performed on five materials (paper, cardboard, plastic, aluminum, and felt) to get a range of the coefficient of friction. To perform the test, a small sled was connected to the Instron via a nylon string with a thin layer of the Molecule XS material attached below. Pull the specimen against the Instron until it is taught, and then initialize the test by zeroing the extension. Use the "Set Displacement" option of 5 inches. Perform the test and the data will be automatically plotted by the Instron. The test was repeated 3 times for each material. The testing apparatus can be seen in Figure 9.

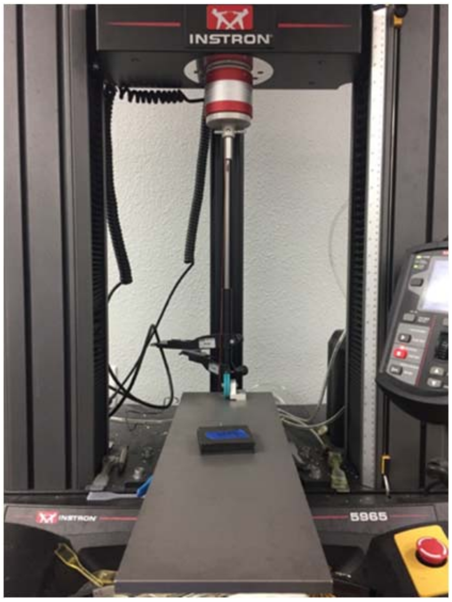


Figure 9: Instron testing apparatus for coefficient of friction testing

The static and dynamic coefficient of friction values were automatically calculated within the software, with the results outlined in Table 4. Table 3 highlights the final results for the coefficient of friction testing and includes the results from the tensile testing. Figure 10 and Table 4 show an example of the plotted data and a results table for 2 of the materials in which the Molecule XS was tested upon. Figure 10 shows the basic results of the test showing the extension of the Instron versus the supplied load. Table 4 shows the table that is automatically generated from the Instron with the test number and the subsequent static coefficient of friction and dynamic coefficient of friction. As is shown, the range of the static coefficient of friction of the Molecule XS material far exceeded that of silicone.

Table 3: Comparison of mechanical properties of Silicone and Molecule XS [13]

Material	Yield Strength (psi)	Ultimate Tensile Strength (psi)	Elastic Modulus (psi)	Percent Elongation (%)	Static Coefficient of Friction
Silicone	350-800	350-800	145-7250	200-500	0.3-0.8
Molecule XS	700-1000	1285-1555	1510-6380	230-275	1.01-3.1

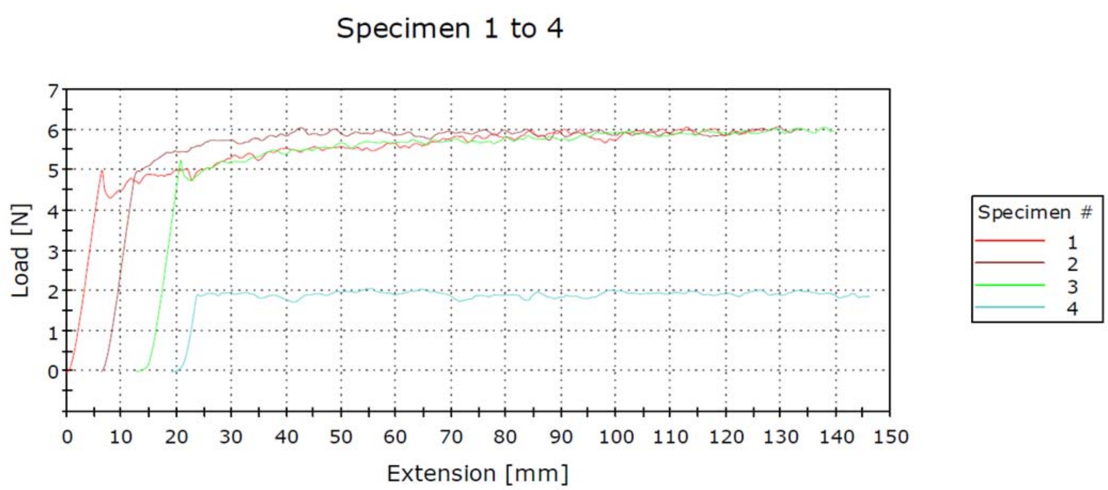


Figure 10: Plotted static coefficient of friction testing performed on the Molecule XS material

Table 4: Tabulated results of the static and dynamic coefficient of friction results for testing of the Molecule XS material

	Specimen number (included)	Static at Coefficient of friction	Dynamic at Coefficient of friction
1	1	2.49622	2.69723
2	2	3.02266	2.82835
3	3	2.62355	2.72306
4	4	0.98397	0.93566
5	5	1.04526	0.92981
6	6	1.00141	0.93069
7	7	1.66140	1.20208
8	8	1.67544	1.26096
9	9	1.79278	1.27618
10	10	3.28884	2.38610

The range of capabilities that the material is able to reach allows for a number of different geometries to be designed and tested. Each design could be tested at various print settings with each variation affecting how the actuators would ultimately function. This flexibility allowed for in depth testing for each geometry design which affected the overall understanding of the soft robotic actuators.

Analysis

As discussed in Roles and Requirements, one of the primary goals of the material is to obtain a static coefficient of friction value comparable to that of silicone. Through testing, it was confirmed that Molecule's XS material was capable of exceeding that of silicone, allowing for this goal to be met. With this, it was determined that our actuators would have to exert lower forces than common silicone actuators based on the relationship between force and friction. Equation 1 shows the relationship between the weight of an object ($W_{\frac{A}{P}}$) and the horizontal force applied by all the fingers (Fsum) with the static coefficient (μ).

$$W_{A/P} = \mu F_{sum} \qquad 1$$

In order to have a better understanding of actuator motion, FEA simulation was performed on various finger and knuckle designs. The primary simulation softwares used for analysis of the fingers were Abaqus and Solidworks with the goals of simulation being: to allow for rapid design iteration, analyze stress concentrations and deformations of actuators, and to compare simulation testing to experimental testing.

Simulations of knuckle and finger actuators were performed using the Neo-Hook nonlinear, hyperelastic model. These models were made accurate by applying the material properties found through experimental testing. In order to manipulate experimental testing, the left side of the actuator was applied a fixed boundary condition, and a pressure was applied to all inside pockets. In order to speed up simulation and decrease the number of nodes, the finger was cut in half (seen in cross sectional images Figures 11 and 12) and a symmetry boundary condition was used across the median plane.

Overall, due to student licensing restrictions, accurate simulation results were not able to be achieved. Abaqus had a nodal restriction, preventing analysis of complex actuator geometries during extreme deformation and Solidworks did not allow for the input of a material with custom properties. Although this did not allow us to compare simulation results to experimental results, comparisons of actuator stresses and deformation within the software were still utilized. Figures 11 and 12 shows one way in which a design iteration was performed. By analyzing the different stress concentrations, our team was able to choose one geometry (Figure 12) over another (Figure 11) due to the lower stresses.

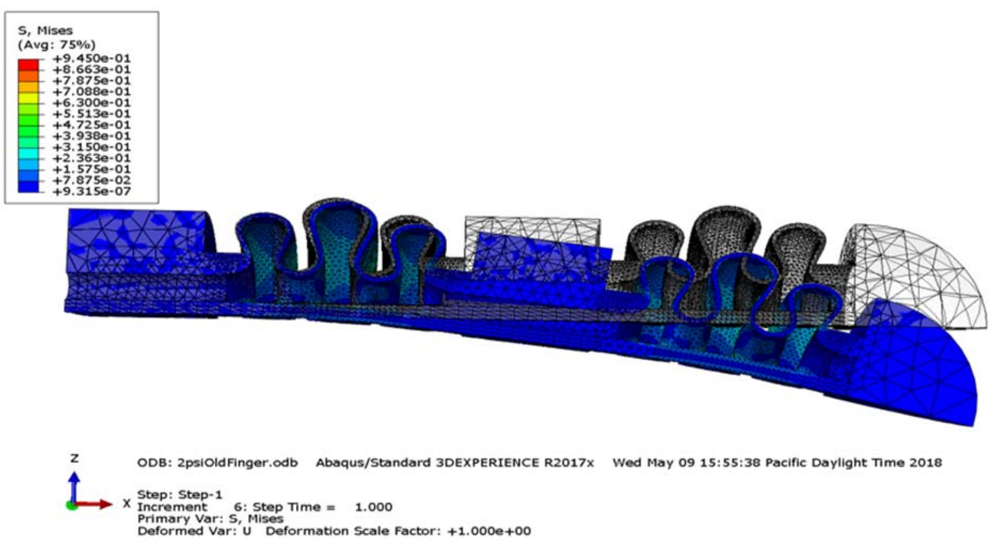


Figure 11: FEA image of a two knuckle finger with resultant stresses at 2 psi

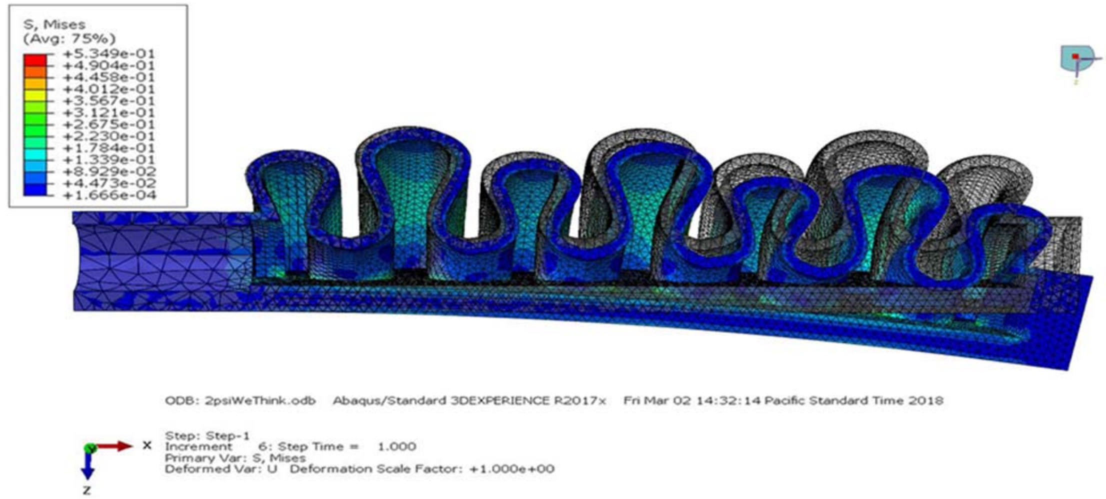


Figure 12: FEA image of a full-knuckle finger with resultant stresses at 2 psi

4.1.3. Design Description

Knuckle Design

Initial iterations of the actuators were designed as knuckles. Design began with the knuckles since they are the primary component of motion when comparing to a human finger. Since soft robotics is a new industry, our team had little experience and exposure to the dynamics of soft robotic motion. By beginning with the simpler component of a knuckle, we were able to quickly iterate the design while performing simple experimental testing.

To gauge the success of these knuckles, a simple experimental test procedure was performed. Initially, the knuckles would be pressurized with air at 3 psi with the deformation analyzed and recorded. Pressure would then be gradually ramped up until failure would occur, or 15 psi was achieved. The points of failure would then be analyzed and recorded.

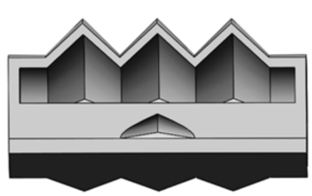
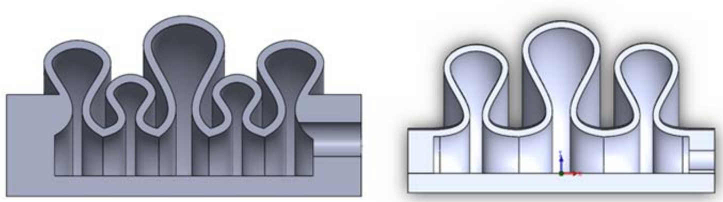


Figure 13: Original, triangular pocket knuckle design

Figure 13 shows an initial prototype design with triangular pockets. The initial belief was that when the top triangular pockets were pressurized, they would expand creating a large enough force to create bending about the bottom base layer. In practice, this design ultimately was gauged as non-successful due to the inability of the geometry to experience any bending.

Due to this design failure, the design was iterated, printed, and then retested. We decided to move towards a curved pocket design, using splines in Solidworks. This was done in hopes that the radial pressure forces would expand the pockets, creating a larger force which would ultimately cause bending about the thick base layer. When analyzing the curved pocket system, knuckles were designed with three and five pockets. Cross sectional images of these designs can be found in Figures 14a and 14b.



Figures 14a and 14b: Design iterations of knuckle with rounded pockets - finalized knuckle design is the image to the right

After pressurizing these designs with 3 psi, both were able to experience deformation, allowing for the designs to be compared to one another. Overall, it was determined that both knuckles had very similar deformations when tested at 3 psi, allowing for the 3 pocketed knuckle, (Figure 14b), to be chosen due to its simplicity. From this knuckle, the team was able to focus on expanding into the design of the finger.

Finger Design

Once the final knuckle design was achieved, finger iterations were relatively simple. The finger designs relied on scaling up from the final knuckle design Shown in Figure 15, initially a two knuckled system was analyzed.

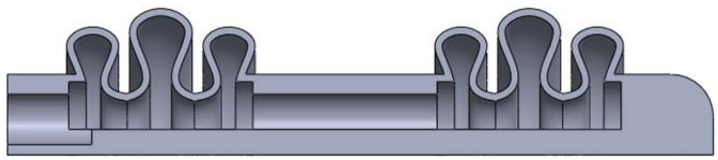


Figure 15: Original, two knuckle finger design

The initial design was chosen due to its resemblance to a human finger. It was believed that the two knuckled, actuator design should create similar bending to that of a finger allowing for comparable motions of both. A second design was also created (Figure 16) which relied on a fully knuckled finger. This was done primarily to compare to our initial design relying on only two knuckles. As briefly discussed, in Simulation under this section, our team was able to compare the stress concentrations between the two designs. In Figures 11 and 12, it is shown that the Abaqus simulations performed at 2 psi resulted in a maximum stress in the two-knuckle design which was nearly double that in the fully knuckle design. Thus, our team opted for the design with the lower stress concentration.

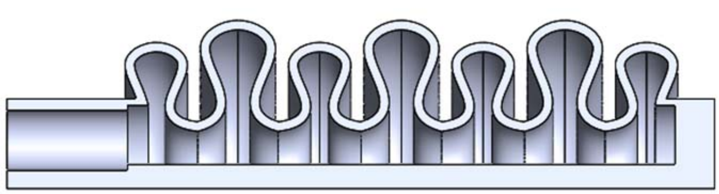


Figure 16: Full knuckle finger design

In order to increase the precision of these actuators and allow for smaller objects to be lifted (such as a pill), a fingertip was added. This fingertip was designed to function similarly to a fish fin. The fish fin design allows for an opposing force on the fingertip (the reaction force of the pill) to create some give on the fingertip which would allow for a softer touch. Figure 17 shows the final finger design.

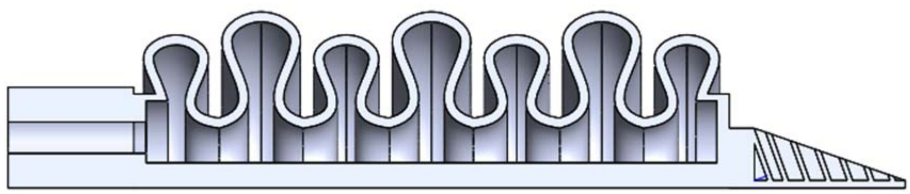


Figure 17: Finalized fully-knuckled finger design with additional fingertip

4.1.4. Supporting Evidence and Results

Once a final finger design was chosen, experimental testing was performed in order to select the ideal printed material properties of the finger. As stated above, and shown in Figure 8, the material properties of the 3D printing fluid can be changed by varying the settings of the 3D printer. Ultimately, the printer settings have a noticeable impact on the overall performance of the finger motion. Due to this, in order to select the ideal final material properties, experimental testing was performed on the finger at a variety of print settings. The testing included: force testing and displacement testing.

Force testing was done to determine whether the force goals could be met. The force was analyzed by holding the finger at a constant height above a scale and applying a variety of pressures ranging from 0-15 psi. At each pressure the force was measured 3 times and the average value was taken. It was determined that, at the chosen print settings, each actuator would exert 0.16 lbs.

Displacement testing was also done to see if the displacement goal of two inches could be met. In order to test whether this goal could be met, the finger was held constant and activated with pressures ranging from 0-15. At each pressure, a dot was drawn at the fingertip, and the displacement was measured with a ruler. Similar to force testing, the displacement was measured three times in order for an average to be calculated. It was determined that at max pressure, the finger would experience 2.17 inches of displacement.

Test results of the force and displacement testing can be found in the "Verification Data" section found on page 23.

Table 5: Table indicating the original actuator goals and the overall results of each

Goals	Results
3D Printed	✓
Functional for Pressure Range of 0-15 psi	✓
Minimum 2 inch Fingertip Displacement at Max Pressure Input	2.17 in Displacement at 15 psi ✓
Static COF Comparable to Silicone	Exceeded Silicone's COF by 3x ✓
3-5 Fingers capable of Supplying Enough Force to Lift 100 g (0.022 lb.) Apple	Single Finger Exerted 0.16 lb. ✓

Overall, it was determined that all 5 goals for the actuators were able to be met. More analysis into how these goals were met can be found in the next section, Verification Data.

4.1.5. Verification Data

Calculations

As stated above, one goal of the actuators was that each individual finger must supply enough force to allow for an apple to be lifted when expanded to a 3-5 finger gripper. In order to have an idea of what force each individual actuator would have to exert, calculations were done based on a 3 finger gripper.

Based on Equation 1 in ‘Material and Material Curing’ ($W_{A/p} = F_{sum}\mu$) and using the lowest determined static coefficient of friction (1.01), the maximum required force for a 3 finger gripper is approximately 0.08 lbs. This value was set as the standard benchmark for all our prints to ensure forces large enough for lifting an apple.

Force Testing

Once determined that each finger must exert 0.08 lbs. of force, fingers at 4 different print settings (2 settings on 2 printers) were analyzed to see whether they could exert the required force. More description of the printers can be found in the Appendix G. Figure 18 analyzes the force exerted by these 4 different fingers at a variety of pressures.

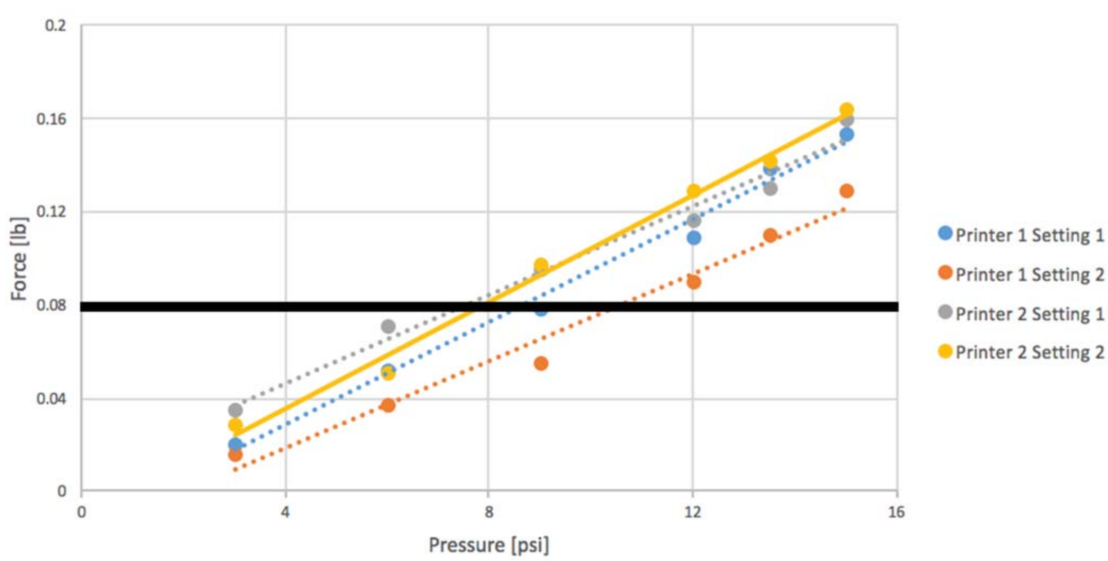


Figure 18: Force [lb.] vs. pressure input [psi] for fingers at 4 print settings

As seen in Figure 18, all 4 print settings were able to exert enough force to, in theory, lift an apple with a 3 finger gripper. Due to the similarity is exerted force, and the fact that all four fingers were able to meet the goal, further testing was done in order to determine the ideal print setting.

Displacement Testing

The next set of testing done was displacement testing. As stated as a goal above, each finger needs to deform more than 2 inches at the maximum pressure input. Figure 19 analyzes the displacement of the same four actuators that were analyzed in force testing.

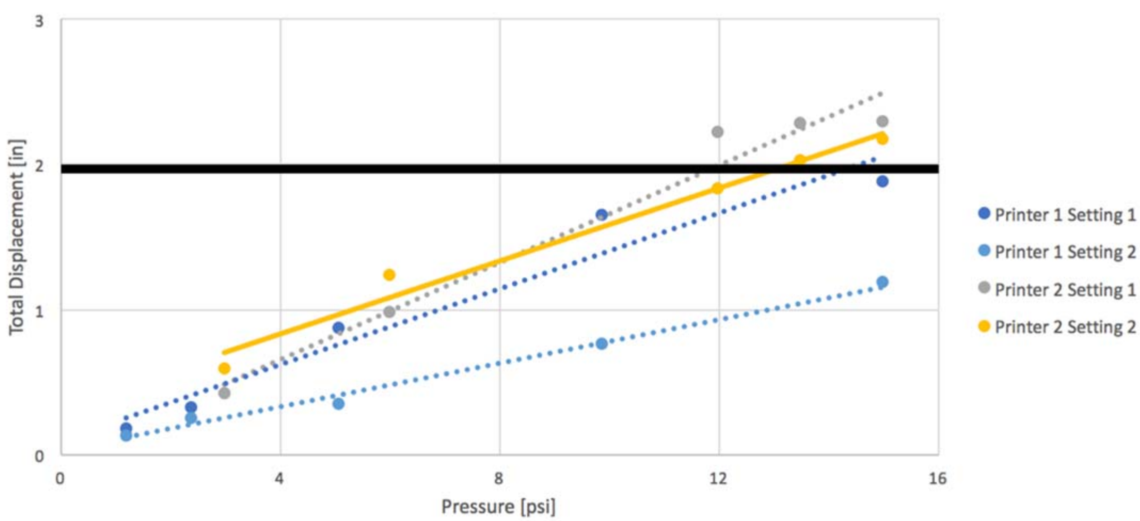


Figure 19: Fingertip Displacement [in] vs. Pressure [psi] for fingers at 4 different print settings

As seen in the displacement graph, only Printer 2 Settings 1 and 2 were capable of reaching two inches of displacement. We determined that, for the sake of this project, the maximum force exerted was more important than displacement, as long as the goals could be reached. With this, Printer 2 Setting 2 was chosen. This print setting allowed for 2.17 inches of displacement and 0.16 lbs. of force when tested at 15 psi, both of which exceeded the goals. More testing can be found in Appendix H.

Final Material Selection

Once the final material was decided upon, tensile testing was done in order to better understand its mechanical properties. Figure 20 shows the tensile data of the final material. It can be seen that the mechanical properties happened to fall right in the middle of the range that we analyzed.

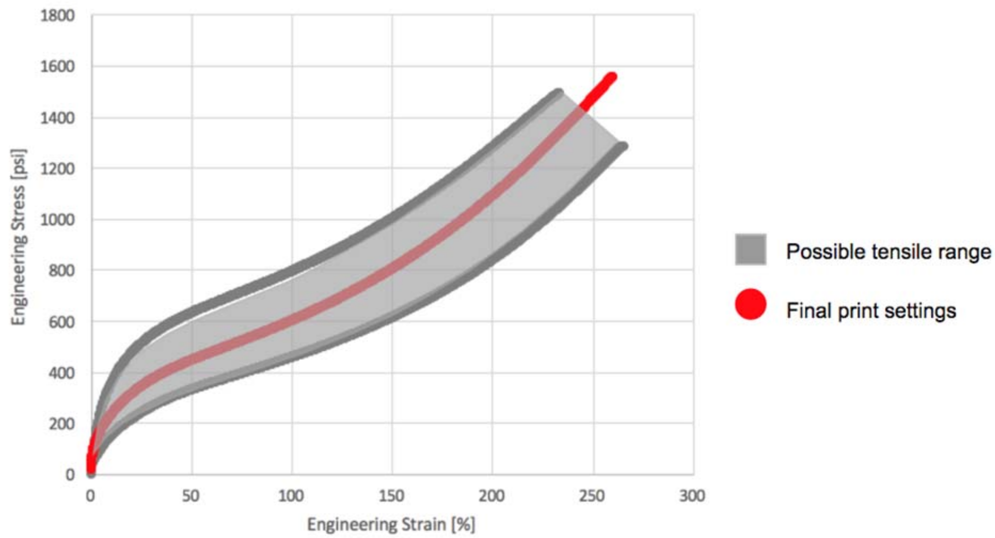


Figure 20: Plotted final print settings in comparison to the initial considered range

Cycle Time

In order to have a better idea of the actuators performance, further testing was conducted. One data point tested for was the cycle time. The cycle time determines the amount of time it takes for an actuator to be fully deflected by a pressure input of 15 psi and then return to its initial state. In practice, this would determine the time needed to wait in between lifting different objects on an assembly line. Cycle time testing was done by using a stopwatch and analyzing the time it took for the material to hit maximum deformation, and when purged, return to its initial state. Each print setting was tested 5 times to find the average cycle time. Overall, a cycle time range of 0.4 to 5 seconds was found, with the final material setting having the lowest value (0.4

seconds). This testing further validated the use of the final material properties chosen. Table 6 shows data collected for one setting that was tested in force and displacement testing (Printer 1 Setting 2). For more information on the printers and print settings, look in the Appendix.

Table 6: Cycle time testing for Printer 1 Setting 2

Trial	Pressure [psi]	Open [s]	Close [s]	Total [s]
1	15	3.93	0.20	4.13
2	15	3.95	2.16	6.11
3	15	3.2	0.21	3.41
4	15	4.5	0.28	4.78
5	15	3.36	2.12	5.48

4.2. Control System

4.2.1. Role and Requirements

The overall role of the control system is to supply the finger actuators with varied pressure inputs in order to achieve the required bending and force to lift different objects. However, to achieve this overall goal a variety of different requirements must be met. One such requirement is that the control system be capable of individually controlling up to four fingers at a time (outputting between 0-15 psi to meet our safety requirements). This is needed to pick up smaller objects such as a 4g pill where only two fingers must be supplied pressure at a time. If all four fingers are on the same control circuit then this drastically limits the capabilities of the soft robotic gripper, making it a less viable product. Another needed requirement is that the control system fit within an 18”x12”x6” space. This allows our project to be both mobile and lightweight, as well as reducing the overall footprint of our soft robotic system when compared to current industrial robots. Lastly, the control system must be able to successfully interface with a variety of different user interfaces so that design capabilities of our chose interface are not limited by the control system. This will allow us to choose the best control system for our needs as well as show application for working in a variety of industries that may have different software standards.

4.2.2. Issues, Options, Tradeoff, and Rationale

To meet the overall role and individual requirements for the control system we chose to use four major components in our design: an air pump, microcontroller, RC filter, and pressure regulators. The block diagram for the system as well as the final design are shown in Figure 21.

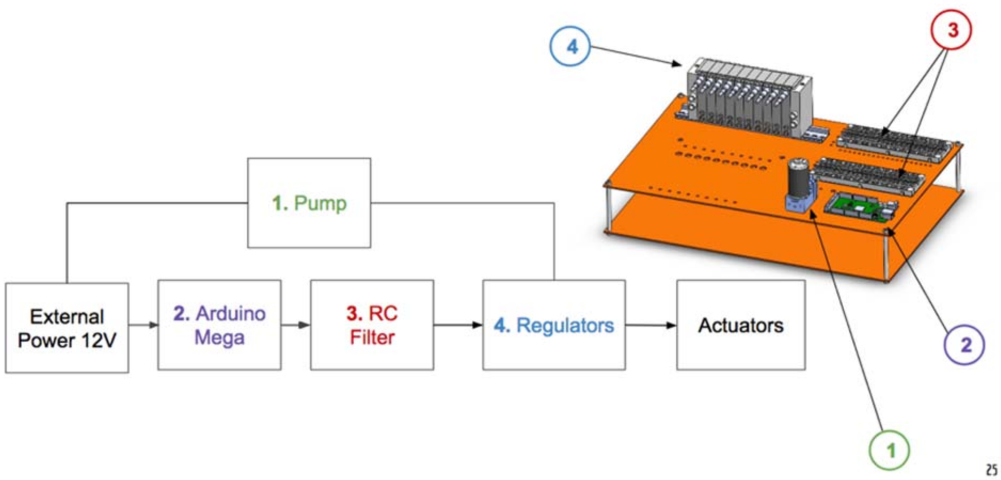


Figure 21: Basic block diagram of designed control system with components highlighted

The first component of this system, the pump, was chosen to be a Parker BIITC micro pneumatic pump capable of supplying 32 psi. This was chosen due to the ample output pressure as well as the size being much smaller than most air pumps on the market. This allows for the control system to be very small in size since air pumps typically take up more room than other control system components.

The second control system component chosen was our microcontroller. The microcontroller is responsible for controlling the regulators which require a voltage signal to vary the pressure. For this application, the two industry standards in microcontrollers are an Arduino or a raspberry pi. Since both are similar in control and output signal, we decided that the Arduino mega would be a better choice due to having more pulse width modulation (PWM) output ports than a raspberry pi. As previously mentioned, the pressure regulators require a volts of direct current signal (VDC) to be controlled. However, off the shelf microcontrollers can only output a PWM signal and do not have built in digital to analog converters which would transform this PWM wave into a voltage output. To control the outputted PWM wave a command between 0-255 is sent to the Arduino. Based on this command sent the duty cycle of the square PWM wave width is varied changing the output. This is illustrated in Figure 22.

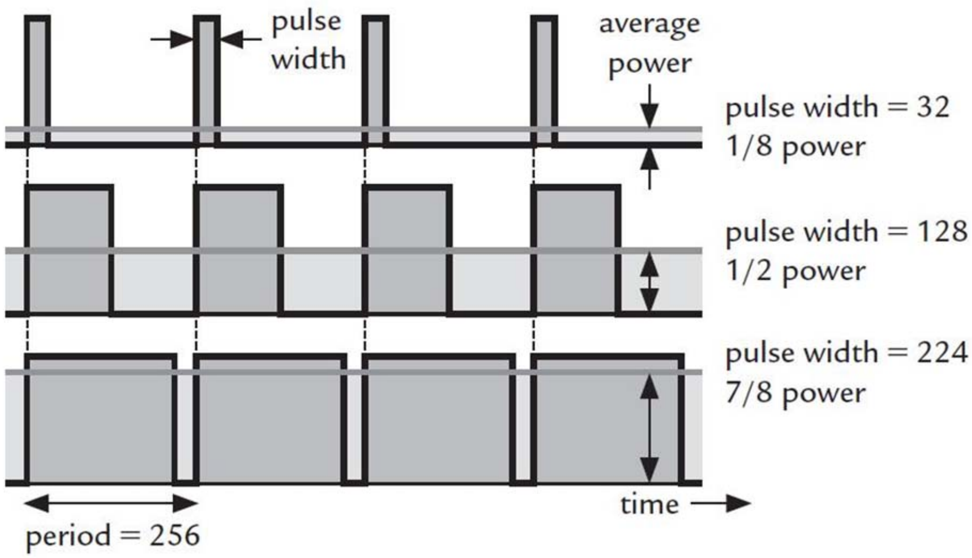


Figure 22: Pulse Width Modulation (PWM) signals with respective duty width and expected power output [18]

The third control system component is a custom RC (low pass) filter. After the width of the wave is varied, the RC filter is used to convert the 0-255 PWM wave into a proportional 0-5 V signal. To achieve this desired 0-5V conversion we used a 3.3 kOhm resistor, 22 uF capacitor, and TI2451 op amp. This combination of components was chosen using a RC filter calculator designed to quickly create RC filters for electrical systems [19]. In Figure 23 the generated wiring diagram for the filter and Arduino Mega is shown.

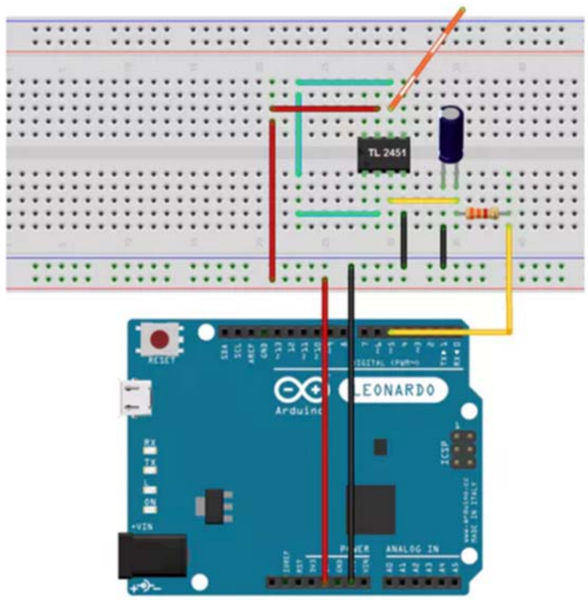


Figure 23: RC Filter for converting PWM signal to DC voltage output [15]

The final component of the control system is our pressure regulators which step down the pressure from the pump and send the desired output to the finger actuators. For this application (as well as to meet our requirements) the pressure must be stepped down from 32 psi to 0-15 psi all while individually controlling this input for each finger. To achieve this, we looked at a variety of different regulator options including solenoid valves with custom feedback loops, off the shelf digital regulators, as well as creating a custom regulator system. However, due to the ease of use and small dimensions we decided to use electronically controlled proportional pressure regulators from SMC (P/N ITV00). These regulators essentially use two internal solenoid valves, a release valve, and a custom internal PID controller to step down pressure proportional to a 0-5V command signal. As previously stated, this 0-5V signal comes from converting the Arduino’s PWM output into a VDC signal via an RC filter. This allows our control system to be very compact as well as simplifying the overall control of each regulator.

Another major benefit of these control regulators is that they can easily be arranged in a manifold so that only one supply pressure port is needed, reducing the amount of tubing needed. You can see the selected regulators in Figure 24 as well as the final design of the pneumatic control system (Figure 25).

Figure 24: SMC Proportional Pressure Regulators [17]

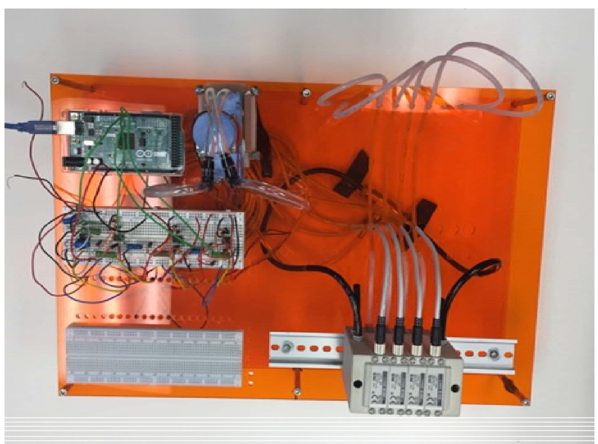


Figure 25: Finalized control system with regulators, RC filter, pump, and Arduino board

After completing the design and assembling the final control system our group noticed a few issues that could be improved upon. For starters, the system was designed to be able to control up to 10 regulators (and thus 10 fingers) at once. This was a design choice made due to not having finalized a gripper design before the components had to be ordered based on lead times. If the system was only made to control four fingers as in our final gripper design, then the overall system volume could have been drastically reduced. In addition, the scope of this project was mostly as a proof of concept however, if time had permitted making a PCB board for the RC filter would not only reduce the needed space of the control system (by eliminating the breadboards) but would make the wiring connections more reliable. Throughout the prototyping phase we frequently ran into wire connection issues due to our use of breadboards and jump wires, something that a PCB with solder connections would eliminate. In addition, the use of compact PCB circuitry would move our control system much further into a production phase when compared to the current prototype design. This would also allow us to have a more stable filter which although was plenty accurate for our needs, would decrease the lag observed in converting the PWM into VDC and allow for quicker actuation time of the soft robotic actuators.

5.2.3. Supporting Evidence and Results

The final design specifications for the control system are given in Table 7. Based on these final results, it is clear that the design was able to effectively meet all initial requirements including the individual control of four fingers, the output of pressure between 0-15 psi, as well as being compact enough to fit on top of a table (overall dimensions 18”x12”x6”).

Table 7: Table highlighting various components of the control system with their respective requirements and outputs

Component	Specification	Value
Pump	Power Requirement (V)	12
	Output Pressure (psi)	32
Regulators	Power Requirement (V)	12
	Control Signal (V)	0-5
	Output Pressure (psi)	0-15
Microcontroller	PWM Output	0-255
	Number of PWM Ports	13
	Max Voltage Output (V)	5

4.2.4. Verification Data

To verify that our system was working properly we used a combination of LabView and laboratory equipment (oscilloscope, multimeter) to test the voltage seen at different points of the control system and filter components. By sending a PWM command between 0-255 to the Arduino it was expected that a proportional response for both the converted voltage signal and pressure output would be seen. For example, sending 100 to the Arduino would give 1.275 volts out of the filter and 3.825 psi from the regulators. Completing this testing at a variety of different PWM inputs showed that we were getting the proper values which we expected, confirming that our control system worked properly. Figure 26 shows an example Arduino code used to test that the filter was converting the signal properly is shown.

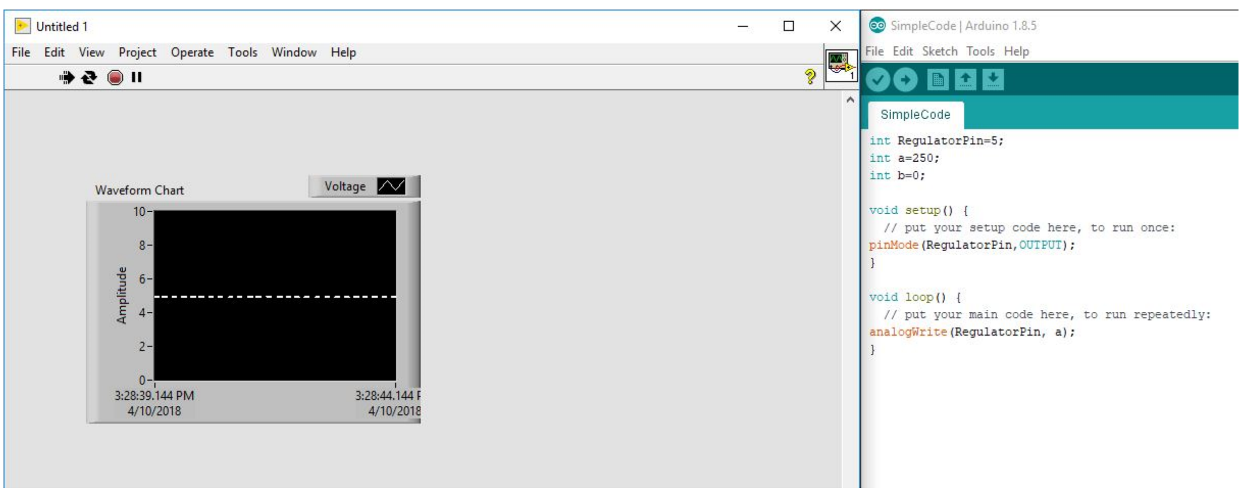


Figure 26: Verification test of the filter indicating the voltage output with the respective PWM signal sent

4.3. User Interface

4.3.1. Role and Requirements

The primary role of the user interface is to properly interact with the control system (Arduino Mega) creating an easy-to-use program allowing for control of PWM signal. The PWM signal sent from the microcontroller is in ultimate control of the pressure inputs to each actuator of the hand. The user interface must be capable of interacting with up to 10 different valves/actuators while ideally allowing for rapid, real-time control. Finally, the user interface should be capable of allowing for real time data acquisition of the resultant voltage signals.

4.3.2. Issues, Options, Tradeoff, and Rationale

The primary user interfaces analyzed for the project were the Arduino IDE, a python script code sponsored by Arduino, and LabView, a National Instruments based program. The Arduino IDE is a free download from Arduino's website [20] and a basic picture of the code is shown in Figure 27. The example image shows the process of using the Arduino IDE for control of 4 valves. Highlighted in the image is the required lines of coding for the Arduino IDE that allows for control of the pressure regulator valves. First, a line defines the pins in which the PWM signal are to be sent from. Next, the width of the signal (varies from 0-255) is defined. Finally, a line defines the signal sent as an output. Defining the signal as an output ensures that the Arduino writes the signal to be used by the control system. Every time a change is made to the script shown, the new code must be uploaded to the Arduino which can create a lag of approximately 5 seconds.

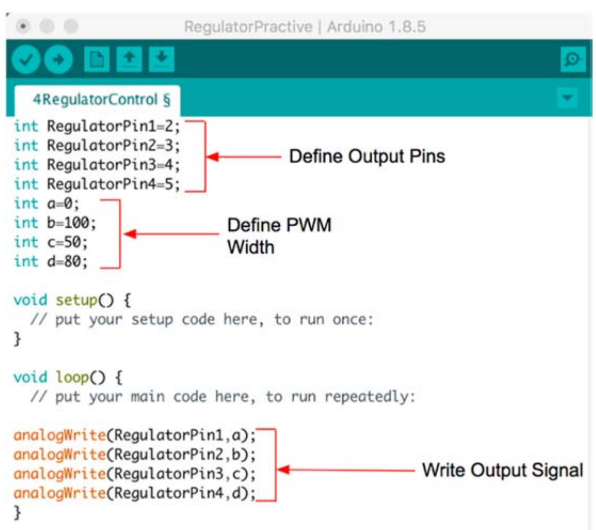


Figure 27: Arduino IDE script for control of 4 pressure regulators with lines highlighted with descriptions

The LabView program requires the downloading of a package known as LIFA (LabView Interface for Arduino) [21]. This package is required to use the Arduino with the LabView, providing the program with various blocks and controls required for proper interaction between the two components. LabView offers the package for free with a LabView license which was provided to the team by the school.

Similar to the Arduino IDE, the LabView program for controlling the pressure regulators is also quite simple. The program requires a simple while loop which allows for constant, real-time uploading of the code to the Arduino and requires 3 simple controls and a Block Diagram. Figure 28 highlights the key components of the LabView program. Controls are created to define the pin in which the signal is sent, define the signal as an output, and finally to control the width of the duty cycle sent to the control system. In comparison to the Arduino, rather than having to type in the signal width a slider control was created. This allows for rapid changing of the signal width, eliminating the delay that results from having to type in the value. Additionally, as briefly discussed, the LabView runs with a while loop which creates constant uploading of the code to the Arduino creating instant response to a change in the PWM control.

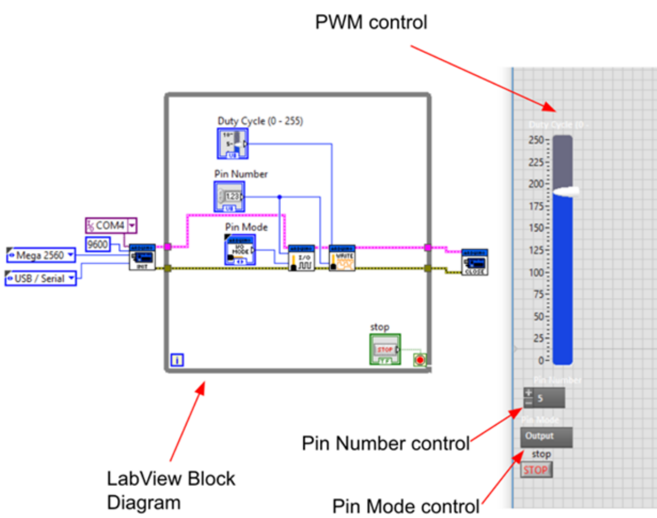


Figure 28: LabView program with defined controls and block diagram for controlling a single pressure regulator

4.3.3. Design Description

Ultimately, the final design choice utilized the LabView functionality. The LabView and LIFA package allowed for easy-to-use and easy to create programs that could be custom designed to control anywhere from 2 to 10 pressure regulators. The custom sliders deployed for controlling the PWM signal was confirmed to be faster when compared to the Arduino IDE. By constantly uploading the code to the Arduino board, there is no delay in using the LabView program as there is with the IDE. Additionally, the LabView program can allow for user feedback regarding the resultant voltage signal sent to each regulator. In order to do this, additional block diagrams were created to measure voltage and the resultant output was plotted.

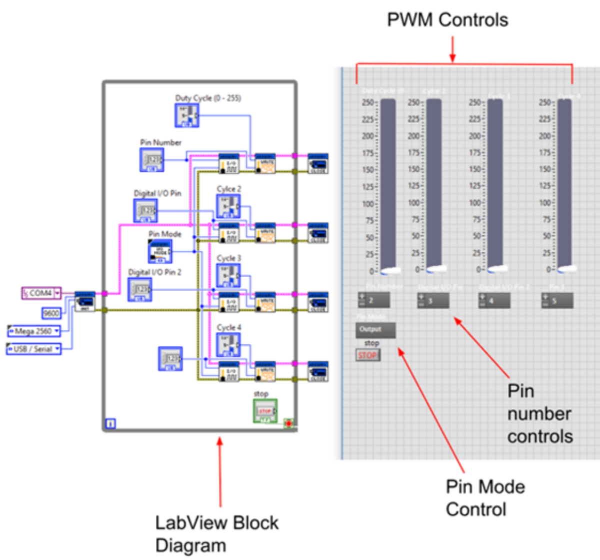


Figure 29: LabView program for controlling 4 pressure regulators individually

Figure 29 shows one of the finalized programs deployed for the gripper. This specific LabView program allows for control of 4 different pressure regulators with a slider control varying from 0-255. This program allows for each finger to be controlled separately following the Arduino's pin numbers and pin modes being defined. Additional programs designed relied on a singular control for the PWM signal meaning all 4 fingers were sent the same pressure.

4.4. Handle

4.4.1. Role and Requirements

The fourth and final subsystem in this project is the handle which connects the control system to the finger actuators. The overall role of this subsystem is to allow for quick and secure connection between the pressure hoses and the finger actuators so that the entire system can be moved/lifted to grasp objects. To fulfill this overall role a variety of requirements must be met. This includes having the system be 3D printed to meet one of our overall project goals, be capable of attaching four finger actuators in a configuration where picking up both a 100g apple and 4g pill can be achieved, and be designed in such a way that someone can easily lift the gripper to simulate the motion of a robotic assembly line arm. Through the fulfillment of these subsystem requirements the overall role of the handle can be successfully achieved.

4.4.2. Issues, Options, Tradeoff, and Rationale

In order to create a handle that could successfully meet all of our projects requirements some design options had to be taken into consideration. We began by creating a design matrix to analyze the best amount of finger connections to add to the handle. This was necessary to consider since the gripper must exert enough overall force to lift a 100g apple. In addition to this tradeoff study it was important to conduct a similar design matrix for finger spacing. In order to lift both the apple and the pill, the finger actuators must be properly spaced so that at a chosen pressure input they would bend/displace properly to lift objects. To pick up an apple and lift a pill the fingers must perfectly meet fingertip to fingertip when reaching max deflection of 2.17”. Seen in Table 8 is the design matrix used to evaluate the handle design in terms of the number of actuators needed to meet requirements.

Table 8: Comparison table for 3 Finger gripper vs. 4 Finger gripper

Gripper Type	Required Force per Finger [lb.]	Pros	Cons	Manufacturability
3 Finger	0.08	-Force to lift an apple	-Spacing for lifting small objects -Restricted application range	✓
4 Finger	0.06	-Force to lift an apple -Diagonal fingers for lifting a pill	-Restricted application range	✓

Once proper rationale was decided upon a number of issues with the subsystem could be evaluated and improved upon. One such issue was that due to the nature of 3D printing it was going to be difficult to properly connect both the actuators and the pressure hoses to the handle without using non-3D printed components. We evaluated this issue and decided that the use of off the shelf hardware was not only necessary to allow for solid component connections but that it would allow for quick disconnect of both the hoses and the fingers. Another issue that we expected was the print quality of the handle. Although it was our goal to 3D print this subsystem (which was achieved) it was obvious that the quality and consistency of the print was lower than that of a machined handle. Although we were able to print the handle, a machined counterpart would have been much easier to interface with the off the shelf hardware and had time permitted would have been a better overall design.

4.4.3. Design Description

After considering the issues and options associated with the handle subsystem and creating design matrices to determine the best design, 3D modeling and printing began. This led us to our final design which is shown in Figure 30. As seen, we designed and prototyped a 4 finger gripper that was 3D printed. From here we used press fit 10-32 threaded inserts on both sides which allowed for quick connect hose connectors to be screwed in on the top of the handle and Eldon James couplers to be screwed into the bottom for actuator connection. After the entire system is assembled the handle allows for objects to be picked up and manipulated in a variety of ways to simulate the attachment of our soft robotic gripper to an industrial robotic arm.

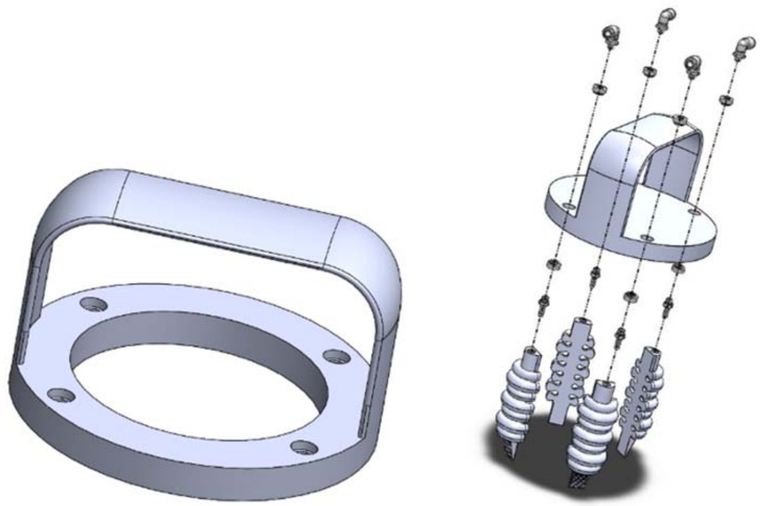


Figure 30: CAD image of fully assembled gripper

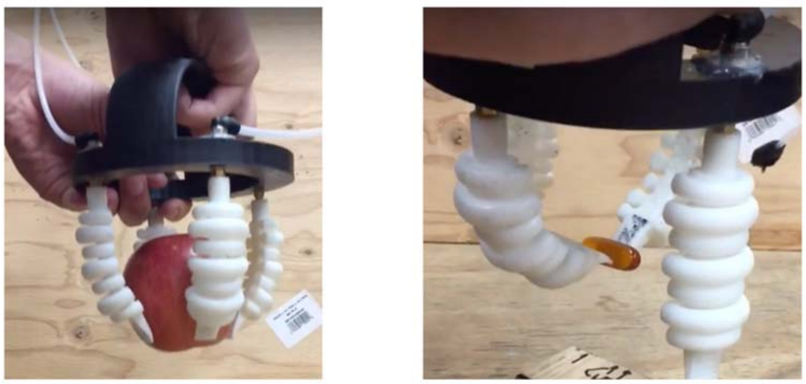
4.4.4. Supporting Evidence and Results

Upon finalizing the design of the handle, we were able to successfully assemble the gripper and test to determine how successful our design would be. We were able to not only meet both overall project goals by picking up both a 100g apple and a 4g pill, but were capable of lifting a variety of other objects and a weight of over 1.6 lbs. The completion of these goals allowed us to determine that both the amount of finger actuators chosen (4) and the spacing between them (3.75” diagonal) was the proper design choice for our requirements.

Chapter 5 - Test and Results

Testing of the entire system was performed by analyzing what objects could be lifted by the finalized four finger gripper, mainly an apple and a pill. In order to test the ability of our gripper to lift these objects, we used the LabView interface which contained the pressure sliders to slowly increase pressure sent to the fingers and grip the various objects. Testing began with the apple where multiple apples were used ranging from 100g-170g to ensure that our gripper could lift a variety of different apple sizes which may be used in the agricultural industry. Each apple was tested multiple times to maintain the ability of the gripper to consistently lift each apple. To maintain consistency, each test the gripper was held unpressurized over each apple and pressure was slowly increased from 0psi up to maximum pressure at 15psi per finger. From here the gripper was manually raised up and down a minimum of 3 times to ensure that the apple was securely held and would not fall out as the gripper completed a range of motions. After testing it was conclusive for all different sized apples that the gripper could successfully hold the apple and would: 1) not drop it and 2) not bruise or damage the fruit. For the pill, the same testing procedure took place however only the two diagonal fingers were sent pressure so that they would meet at the pill and lift the object. Once again, after testing a variety of fish oil pills (chosen for their 4g weight standard) the gripper was able successfully grip the pill through a variety of motions. Each of these successful tests proves that our soft robotic gripper could properly lift a variety of objects, specifically those highlighting the use in agricultural and pharmaceutical packing.

Although the gripper was able to lift both a 100g apple and a 4g pill which was our teams target goal, we determined that the maximum weight our gripper could lift would be a useful data point to measure the success of our project. To measure this, we used an empty coffee cup due to its capabilities to hold an increasing amount of weight and followed the same testing procedure as the apple. Our gripper was able to lift up to 800g (~1.76lbs) before a finger connection failed and a press fit insert pulled out of the handle. For the max weight testing our limiting factor was not the fingers or the amount of pressure we could send but was due to the cap being 3D printed. To improve upon this design using a machined aluminum cap would eliminate the need for press fit inserts and allow for a much higher weight to be picked up. Although our gripper eventually failed, it successfully met all project goals and was a great proof of concept for adding soft robots into both the agricultural and pharmaceutical industries.



Figures 31a and 31b: Images taken during successful testing of the gripper for a 100g apple and 4g pill

Table 9: Final specifications for the 4 finger 3D printed soft robotic gripper

Specification	Value
Max Gripper Force [lbs.]	0.66
Max Fingertip Displacement [in]	2.17
Max Lifting Weight [lbs.]	~1.60
Cycle Time [s]	0.40
Finger Actuator Weight [lbs.]	0.03
Gripper Weight [lbs.]	0.48
Strength to Weight Ratio	4.48
Actuator Print Time [min]	~45

Chapter 6 - Cost Analysis

Funding

The current budget of the project is $4,569. This budget was raised from a $1,000 prize awarded to our team in the Donald L. Lucas Pitch Competition and the remaining $3,569 was raised from the team's Kickstarter campaign.

Spending

The overall cost of the prototype will be associated to two primary factors: the cost of 3D printing fluids and the control system. Fortunately, the 3D printing fluids are provided to our group for free from Molecule Corp. Other costs will come from some off the shelf components necessary to perform testing and finalize the handle design.

Initially, we believed that 10 actuators were required. This forced us to spend $2,080 on 10 proportional regulator valves, which made up the majority of our spending. Excess control system spending added up to $637. This was made up of circuit boards, wires, an Arduino, and other small costs. Lastly, small costs to perform testing (scale and other components) came out to about $250 dollars. A pie chart of the total costs can be found in Figure 32.

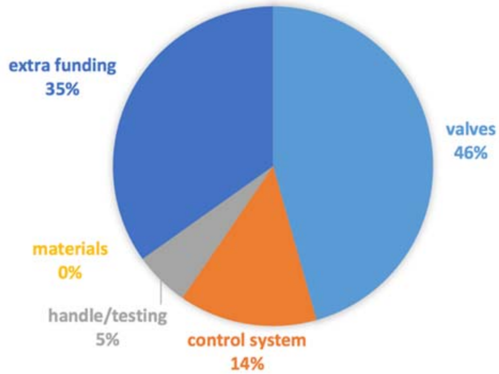


Figure 32: Spending breakdown

Thanks to the support and material donations from Molecule, we were able to have about $1,600 (~35%) of excess funding.

System Price

Overall, it was determined that a gripper with 10 valves or actuators is not necessary. In order to match industry standards (soft robotics starter pack) a system with 6 valves and actuators will be used. This would allow for the system to power grippers ranging from 2-6 actuators. A 6 valve control system would cost about $1,800. Further costs would come from the 3D printing materials, as it cannot be assumed they will continue to be free. The material used (Molecule XS) costs $249 a liter. Each finger uses about 40 mL of fluid, meaning that a liter of fluid can print 25 fingers, making each finger cost about $10. Also, the production of a handle will cost about the same when including off the shelf components. This would make the handle and fingers to cost $70 when supplying the user with 6 actuators. Although only a 4 finger gripper will be sold in the starter kit, CAD designs of 2, 3, 5, and 6 finger handles can be bought at low prices.

Overall, our starter kit would have a raw cost of about $1,900. Rather than using cost-based pricing in order to determine our final cost, we will use price-based pricing. This will allow us to compare our starter kit to Soft Robotics Inc. which is $12,999 [2]. We determined that our starter kit would sell for a price between $8,000 and $10,000. This would allow us to have very high margins (400-500%), while also undercutting the market price, allowing us to gain market share in the growing soft robotics industry.

These types of margins would allow us to quickly purchase 3D printers and do all manufacturing in house. To begin, print farms could be used in order to save large spending on printers. This would allow us to get our feet on the ground before bringing manufacturing in house.

Chapter 7 - Engineering Standards and Constraints

Health and Safety

The design of a soft robotic hand can be seen as vastly safer in comparison to current rigid robotics. As briefly discussed, many rigid robotics, when utilized in large scale factories operate at rapid speeds to maximize efficiency. This poses a large threat to workplace safety limiting the ability for humans to work side-by-side with robots. Rather, companies opt for creating containment cages for their robots or humans are forced to operate in entirely different rooms then the automated bots.

By deploying soft robots, workplace accidents involving humans and robots can be almost entirely eliminated. The fear of bumping or hitting a soft robot is almost non-existent. Due to the 3D printed, soft plastic nature of the robot, getting hit with the robot at the speeds required for operation is more comparable to getting hit with a balloon rather than a car. In doing so, the need for cages and the separation of humans can be eliminated, resulting in workplace efficiency and almost the entire elimination of workplace accidents involving robots. We believe that some precautions will be required for proper human-robot interaction seeing as accidents involving pinch points may still occur if workers aren’t entirely careful.

The primary safety concern of the 3D printed soft robot is the type of material being used. The current material being used has passed cytotoxicity and is currently being tested to become an FDA approved material. In order for the material to meet these safety standards, the material must be cured properly. Currently, Molecule is accepting printed parts to test the percent that the material is cured in order to analyze the cure and validate a “print-post cure” process. Once any “print-post cure” method is validated, it can be confirmed that the material will meet the safety requirements stated.

Manufacturability

A key feature of our groups soft robotic gripper is that 3D printing is the main form of manufacturing. Unlike current soft robots or rigid robots currently deployed in industry, our gripper can be completely 3D printed cutting down on manufacturing cost, time, and accuracy. As previously mentioned, manufacturing silicon parts can be a costly, time consuming process [22]. Our ability to 3D print our silicon-based parts not only reduces time and cost, but allows for quick replacement of broken parts in an industrial setting. All that is needed to create replacement parts is an on-site 3D printer and a bottle of fluid. This streamlines repair time, cost, and efficiency allowing for a better manufacturing method of the gripper components.

When taking our project from the research phase into a commercialized product it is important to recognize that some components will need to be added to the 3D printed design such as metal connectors, push-fits, etc… Although this means the commercialized product could not be 100% 3D printed, it is simple to incorporate these add-ons into the printed design to allow for quick and easy system integration. This is much easier to accomplish via 3D printing since holes, threads, and slots can more easily be added into the 3D model and printed when compared to machining or die casting a similar part.

Ethical

The utilization of automation in manufacturing and packaging plants can receive complaints of being unethical due to the elimination of lower-skilled positions. As discussed in the Background, this elimination of lower-skilled jobs does occur, but it has been argued that robotics and automation result in major growth of the number of skilled jobs. Our robotic design is similar to current automation systems - the robot performs mundane tasks largely required of humans. But, our design is limited in comparison to current designs as well. Our robotic design cannot perform as many tasks as current automation systems due to the inability of automatically changing its tool (the hand/gripper design) and limitations due to the current programming. Due to this, there will be a requirement for more low-skilled workers assisting the processing operation with our robot.

Additionally, less than 10% of jobs performed can be fully automatable meaning there is always a requirement for human assistance with robotics [23]. Our soft robotic design allows humans to work directly alongside the robots (with some precautions), meaning more efficient operation and the possibility for more human employment. Through our soft robotic design, we believe that the implementation of our robots in food packaging would cut in half the amount of lower-skilled jobs typically lost when new automation systems are created while maintaining the same number of newly created higher-skilled positions.

Economic

One of the great positives of current robotic systems in manufacturing and packaging plants is the enhanced efficiency paired with fewer human employees resulting in labor-cost savings. As discussed in the Ethical subsection of our design, the deployment of our soft robot would result in greater human employment due to the simpler nature of the design and the enhanced capabilities of human-robot interaction. In doing so, a factory or plant deploying our robot will see larger wage payments paired with a lower efficiency than current automation designs (humans are generally less efficient than fully automated robots). As a result, the plant output may slightly decrease in comparison to a fully automated factory utilizing rigid robots while the operating costs increase. From our estimates, we perceive that the labor-cost savings of a plant using our robotic design will be cut in half in comparison to an automated rigid robotic plant.

Sustainability

Currently, our soft robot is being designed for a few specific applications, none of which will severely help the sustainability of the environment. Although the applications of this robot may not be sustainable, the energy use, and ability to work 24 hours a day are considered sustainable. Similar to current rigid robot technologies, by balancing the energy use over a 24-hour span, the electrical efficiency is much higher, and can lead to large energy savings. Currently, power is generated at a constant value that matches the peak hours, leading to large waste in energy when during certain parts of the day. By using automation, the efficiency is much higher, due to the balance in energy use over the day.

Also, due to the simplicity and lightweight of our soft robotic design, the predicted energy use is much lower than that of rigid robots. By helping balance the energy use, and decreasing energy when compared to other robots, it is believed that if commercialized, our soft robot would dramatically increase the electrical sustainability of the companies that use our bot.

Furthermore, the materials being used in our project are considered to be OXO-degradable. OXO-biodegradation is defined as "degradation resulting from oxidative and cell-mediated phenomena, either simultaneously or successively.” By using these material, the waste can be degraded, allowing for these bots to be considered sustainable.

Chapter 8 - Conclusion

After researching the robotics industry, it became apparent to our group that there are various flaws with rigid robots. Some of these flaws include safety issues, size, weight, and cost. After analysis of these issues our group realized that there was a large market for a new type of industrial robot which prompted our research into soft robotics. We then secured a partnership with Molecule Corp., a leader in the 3D printing resins industry, who agreed to sponsor our project and supply us with materials and resins to create a fully 3D printed, soft robotic gripper. Our project goal was to design this gripper so that it could be 3D printed and capable of picking up both a 100g apple and 4g pill.

In order to achieve our project goals, our group began by designing four main subsystems: the soft robotic actuators, the control system, the user interface, and the handle. Over the course of a year we were able to use our engineering knowledge, as well as CAD, and FEA to successfully design each subsystem and create a gripper capable of picking up both a 100g apple and 4g pill. The pneumatic control system was created to output 0-15psi and control up to 10 individual actuators, all while fitting within an 18”x12”x6” container. A LabView VI was created which successfully interfaced with the pneumatic control system and allowed for real time control of 10 individual actuators at a time. The final handle design utilized four 3D printed soft robotic actuators (similar to fingers) that would achieve a maximum deformation of 2.17” at 15 psi. The combination of these subsystems resulted in a product which met and exceeded all of the initial goals, successfully picking up both of the goal objects as well as lifting a maximum weight of 800g (~1.76lbs) and a variety of other objects. The scope of this project was to create a proof of concept for introducing soft robots into various industries which after completion of this research project was successfully accomplished.

Many hypotheses that the future of industrial robots lays with technology that will allow humans and robots to work side by side. Soft robots allow for this form of interaction to take place and provide many other benefits such as being lightweight, cost efficient, and easily customizable for any industry. This project has successfully shown the capabilities of soft robots to break into traditional mechanized industries such as agriculture and pharmaceuticals, but also shows the possibility to add mechatronics into untouched industries where rigid robots could not safely be implemented. As rapid advancements in material sciences and mechatronics continue to occur, the use of soft robots will simultaneously increase allowing for these new robots to break into industry in the near future.

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Appendix A: Gantt Chart

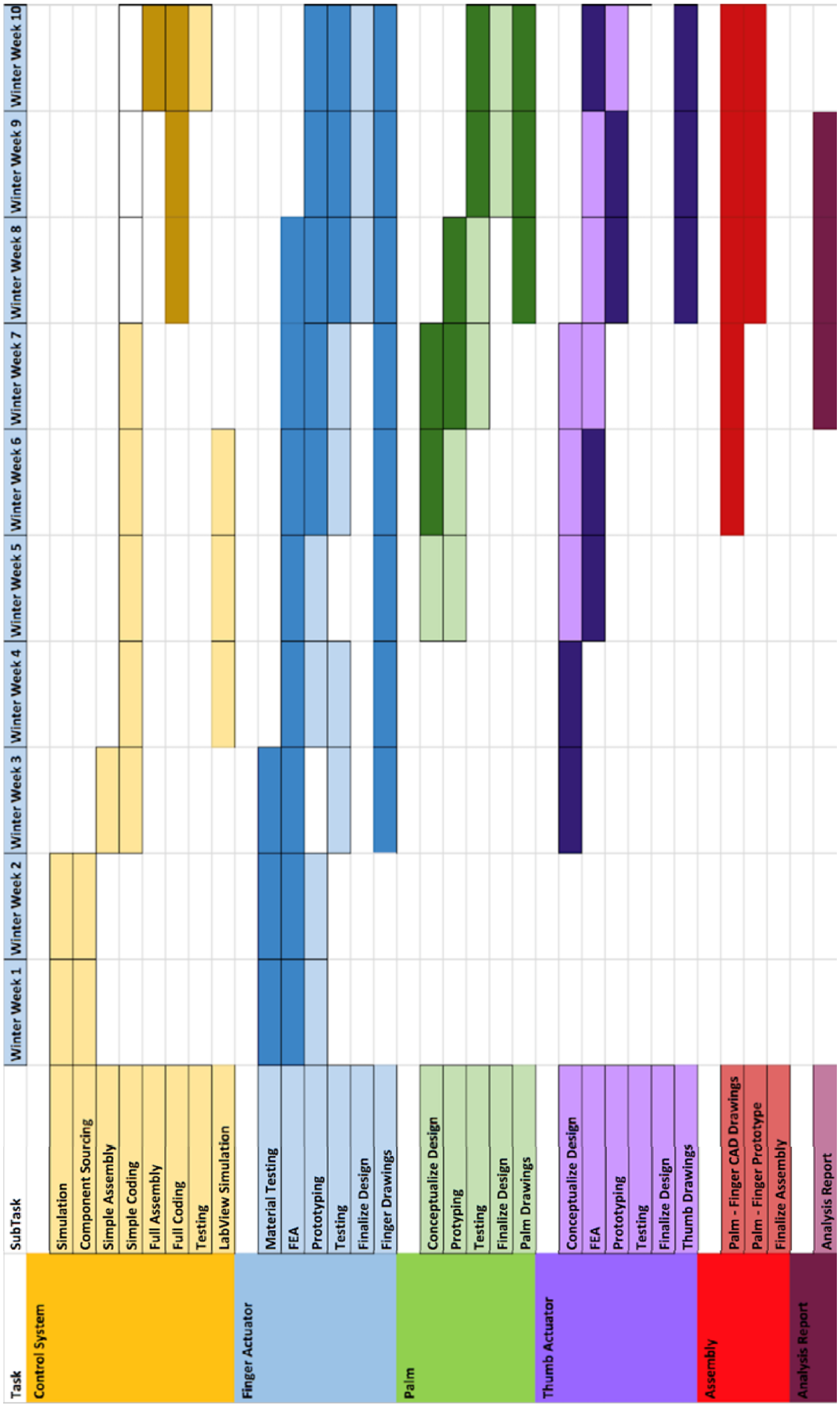


Figure 33: Gantt chart for Winter quarter

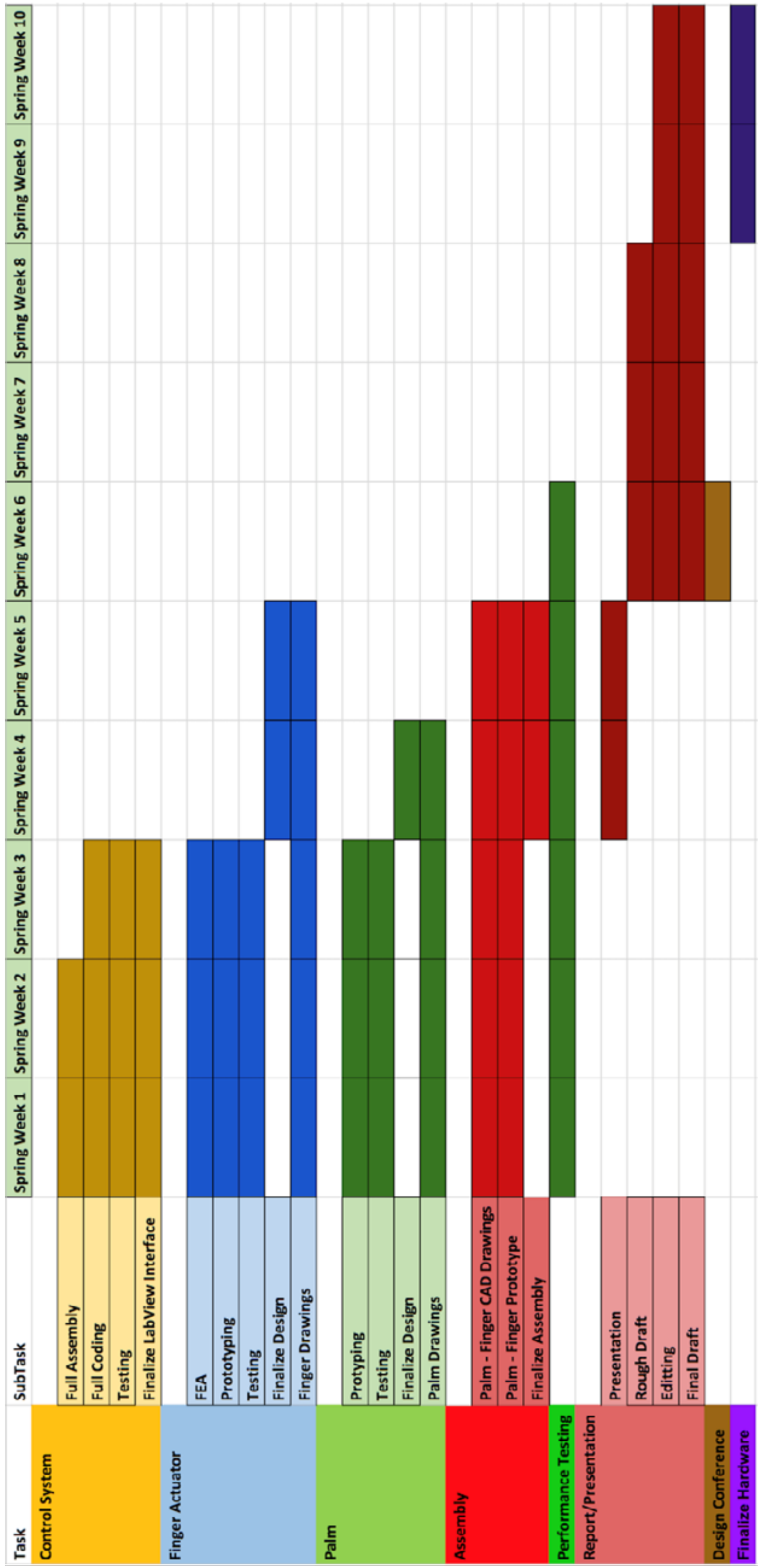


Figure 34: Gantt chart for Spring quarter

Appendix B: Printer Settings

Printer 1: Origin prototype printer

Setting 1: 0.7 seconds of cure per layer

Setting 2: 1 second of cure per layer

By changing the cure time per layer, the material hardness could be affected. Other than the cure time per layer, all other print settings were held constant.

Printer 2: 3D Systems Figure 4

Setting 1: 50 micron layer thickness

Setting 2: 100 micron layer thickness

Due to different “triggers” when changing cure settings between the Origin and 3D systems printer, different values were changed. By changing the layer thickness, the material hardness was changed in a very similar way that cure time changed the settings on the Origin printer.

Appendix C: Health and Safety

Uncured 3D Printing Resins

The Molecule XS material is harmful if not properly cured. The material can cause skin irritation, and during the cure process, a respirator must be worn. In order to avoid any safety concerns of this material, certain steps must be made. First off, the post cure procedure of this material must ensure that the material has a very high cure conversion. In Molecule's lab, a D Bulb with a belt is used. The material is passed under the light 8 times when travelling at 25 ft/min. Other post cure procedures can be used, but test pieces must be sent to Molecule in order for them to check the cure conversion. Depending on the percent cure, they can approve your post cure procedure.

If being used for medical purposes or in contact with food, further post processing methods must be used. The material must be soaked in IPA (isopropyl alcohol) for 24 hours, and then placed in a 60 C oven until all IPA is evaporated. This will not hurt the material properties of the part, but will ensure that ALL uncured resins are removed from the part. This is referred to as an extraction method.

Also, when working with the resins, gloves and safety goggles must be worn to avoid any skin irritation. There are a number of hazards that could be caused by direct contact with this fluid (skin irritation/rash, severity varies from person to person), so wearing gloves and safety glasses is mandatory.

3D Printing

For this project, there are a few different printers being used, but there are some hazards that remain constant for all stereolithography printers. First, due to the use of high power lasers or projectors, users must be sure to not look at these lights. Although these lasers or projectors are normally covered by the tray of resin, and have UV protected covers, extra precaution must still be taken. Also, when handling any part of the printer, make sure that gloves and safety goggles are worn due to the uncured resin (more information on this can be found in the Uncured 3D Printing Resins section). Lastly, when removing a part from the build platform, it must be done carefully. In some cases, when a large cross section is attached to the build platform, the piece will be very difficult to remove with a scraping tool. When this occurs, make sure to remove carefully, as in some cases you will accelerate through the piece and can cut your hand on the build platform. This can cause 3D printing resins to get into the bloodstream which may cause skin irritation.

Control System

To prevent injury many precautions have been taken within the control system to isolate all electrical components. A custom acrylic component holder will be made to separate all components and have specific routes for all the wires to run. This will prevent unwanted electrical connections and shorts from occurring. In addition, pressure blow out (purge) valves have been incorporated into the system so that no backpressure buildup can occur. Mechatronics industry standards will be maintained on all components and connections to ensure that the highest level of safety is met. The pressures used in this system will be no greater than 30 PSI (however the working range is closer to 0-15 PSI) limiting the danger that can occur from pressure build ups and leaks. The fluid used will be air to limit danger compared to using different inert gases. Lastly, to prevent any other electrical hazards the control system will be isolated (acrylic shield) to prevent any contact with the outside environment (water, dust, etc…).

Test/Operation

Testing of the full assembly relies on the control system, the printed hand, a LabView program and a voltage source.

To begin testing, ensure that the control system is properly attached to the hand. Make sure that there are no holes in the hand or tubes as these could be points for air to leak. Connect the power source to the control system. The full assembly should have tubes and cords short enough that they will not run on the ground thus tripping shouldn't be an issue. To test the hand, vary the set point voltage on the LabView program with the pump on. The set point voltage will vary how open or closed the transducers are for each finger to allow air to enter.

To lift an item, have one user grip the printed hand. Hold the hand over the item of interest and have another team member change the set point voltage for the LabView. Hold the hand through the entirety of the operation, allow it to close around the item. Slowly lift the item a short distance upwards and then set it back down. Have the other team member disengage the gripping of the hand. Once the test is completed, disconnect the power source from the control system.

The final hand assembly should be light (under 5 lbs.) so lifting by a user shouldn't be a concern. Take note of any points on the assembly that may be sharp or possess pinch points. If there are noticeable locations, take extra precaution during operation or find a means to eliminate the dangers.

Material Storage

When these materials are not being used, they must be stored properly. Avoid leaving these materials in high temperature places, and make sure they are in UV proof containers to avoid premature curing. The max storage temperature of the printed material and the fluids should not exceed 85° F. These materials have a shelf life of about a year, so the manufacturing date should be known. Although old resins will not have new safety hazards, material properties may be effected.

All materials are stored in the Molecule chemical room that is kept at a proper temperature for these chemicals. We must make sure that we put the materials in the room after use.

Part Storage

When a soft robotic hand is not in use, the part must be properly stored. The only concern when storing the part is temperature. With this, one must be certain to avoid leaving a soft robotic hand at very high temperatures as is may affect the material properties.

As of now most prototypes are tested and are normally analyzed and thrown away. As we begin to have longer lasting prototypes, the parts will be stored for the mean time at Molecule, Corp. To create greater access to the parts, a location on campus should be found for storage such as the Machining Lab. Our team must get approval from Dan MacCubbin and obtain a designated space or find an alternative location on campus if we are unable to do so.

Disposal

The resins being used must also be disposed of properly. Due to the waste hazards that this resin has, there are two potential disposal methods that must be used. First, the resin can be disposed of as a chemical waste. This has some restrictions as it can be difficult to get permits to dispose chemicals. The second and better option is to use Molecule’s Eco Cure product. This product solidifies the resin and allows for it to be disposed with normal trash.

Since all printing is being done at Molecule, disposal will be very simple. Molecule can use their Eco Cure product, but is also approved to dispose chemicals legally. This makes our disposal process very simple. If any liquid materials (not using EcoCure) need to be disposed of, make sure to pour them into the chemical waste bins located in the hoods.

Appendix D: Patent Search

Title: 3D Printed, Soft Robotic Actuators

Description: Soft robotics is an emerging industry within robotics, focused on replacing rigid materials currently deployed with soft, flexible materials. Commonly, soft robotics deploy materials such as polymers and fabrics, capable of being designed and manipulated in a manner that enhance the overall capabilities of robotics. Many soft robotics act similarly to a balloon, being inflated and deflated in various manners to create motions such as twisting, flexing, and straightening. This creates a wide range of capabilities for soft robots. Where rigid robots cannot be used (i.e. situations where a "soft" touch is required or operation is on non-rigid surfaces) soft robots can now be deployed.

The deployment of polymer based soft robotic actuators has largely been attributed to growth in the last 2-4 years. During this time, soft robotics has been limited to actuator design via hand-molding and silicone based polymers. In doing so, current actuators suffer from a number of issues limiting their overall use and functionality. Namely, hand-molding vastly limits the overall geometry deployed. Almost all patented soft robots are forced to be created in multi-part assemblies, delaying how quickly they can be manufactured as well as creating issues with repeatability and quality. Additionally, hand-molding limits scalability of designs. With high costs and large lead times, rapid design iterations of soft robotics are basically non-existent.

The primary feature of the discussed design is its capability of being entirely 3D printed. A partnership with Molecule Corp. provided us with exclusive access to their 3D printing fluid: Molecule XS. This material has the potential of rivaling or exceeding material properties of silicone - the most widely used polymer for soft robotics. By 3D printing the actuators, issues with hand molding are entirely eliminated while creating a print in a single, simple process. 3D printing allows for the design of actuators with no limitation on their potential geometry. Rather than requiring multiple molds and an assembly, the actuator is ready almost immediately after the print is finished. With the expanding technology in 3D printing, an actuator can be printed in a little under an hour.

The design of the actuator includes three distinct features: an inflatable upper layer, a thick base layer, and a fingertip. The inflatable upper layer is made up of a series of pockets, extending along the entire finger. The pockets will alternate in size with a smaller pocket followed by a subsequent larger pocket. The design was completed through the use of splines, with the small pockets reaching a height of 0.51 in and the larger pockets reaching a height of 0.6 in. There is a singular pressure inlet in each actuator where air of various pressure values can be pumped into the finger. When this occurs, the pressurized air is capable of expanding the pockets of the upper layer. This outward expansion can create the bending required.

The thick base layer is 0.1 in thick and 3.5 in long. The design of the thick base layer is meant to create a reactionary force for the actuator. Due to its thickness and constant length, as the top layer expands due to the input the constant length of the base layer forces the top layer to bend. This bending is dependent on the amount of air pressure pumped into the finger - more pressure equals greater bending and vice versa.

The final characteristic of the actuator is the fingertip. The fingertip relies on a ‘finned’ design similar to the design of fish fin. The fingertip allows for a soft touch for the actuator. When it presses against an object such as a pill, the fingertip has a certain amount of give allowing the surface of the fingertip to form around the object. This produces a greater surface area in contact with the object which will ultimately assist in lifting the object.

The variants analyzed for design of the full actuator considered either two knuckles of the full knuckle design. The two knuckle design was meant to mimic human fingers, attempting to create an actuator which can match the motions of an actual hand. Each variant had the three characteristics discussed above: a pocketed top layer, a thick base layer, and a fingertip. An initial iteration of the finger was printed and experimental testing for the finger was performed. The testing resulted in a finger with a very limited range of motion barely comparable to an actual human finger. As a result, this design was eliminated for contention. The next variant considered was the full knuckle design which was ultimately chosen for the final design. The primary reasoning for choosing this design was due to its capabilities of mimicking the motion of a finger. The full knuckle design was capable of meeting full actuation at the maximum pressure input (15 psi) while hitting various deflection points for lower inputs.

Currently, there are two distinct companies working on soft robotic hands: Soft Robotics and Pneubotics. The two companies utilize hand molding for the creation of their full actuators, but their designs are deployed in a number of industries. The two companies have actuators with similar designs to the proposed design. A base layer with a pocketed top layer allowing for bending of the finger. Because the companies rely on hand molding, each actuator is made up of a multi-part assembly. Multiple molds are created for each finger which can create long assembly processes.

One unique aspect of these current hands is there ability to vary the number of fingers utilized. Soft Robotics' hands have magnetic connects for their fingers and palms to interact. These allows users to be able to vary the fingers used from 2 fingers up to 6 fingers. This creates a hand with a wide range of lifting capabilities with a user-friendly assembly process.

Overall, the design of the soft robotic actuators have great capabilities for mass commercialization. The 3D printing process expands the availability of the actuators and hands to smaller companies and industries, generally unable to pay the large up front costs for expensive robots. Additionally, because the actuators are made of soft polymers, the cost of materials goes way down. Molecule Corp. currently sells a liter of their fluid for approximately $249, which is capable of printing about 25 actuators. The largest overall front end cost of the actuators is the required purchase of a 3D printer which is roughly around $5,000. Comparatively, this cost is much lower than that of molding and the 3D printing process allows for rapid iterations and the ability to scale the design of the actuator easily without the requirement of a new mold. Due to the low cost and the overall success of a 4 finger gripper in lifting objects such as an apple and a pill, it is believed that the design would have great commercialization success in both the food packaging and pharmaceutical industries.

Sketch:

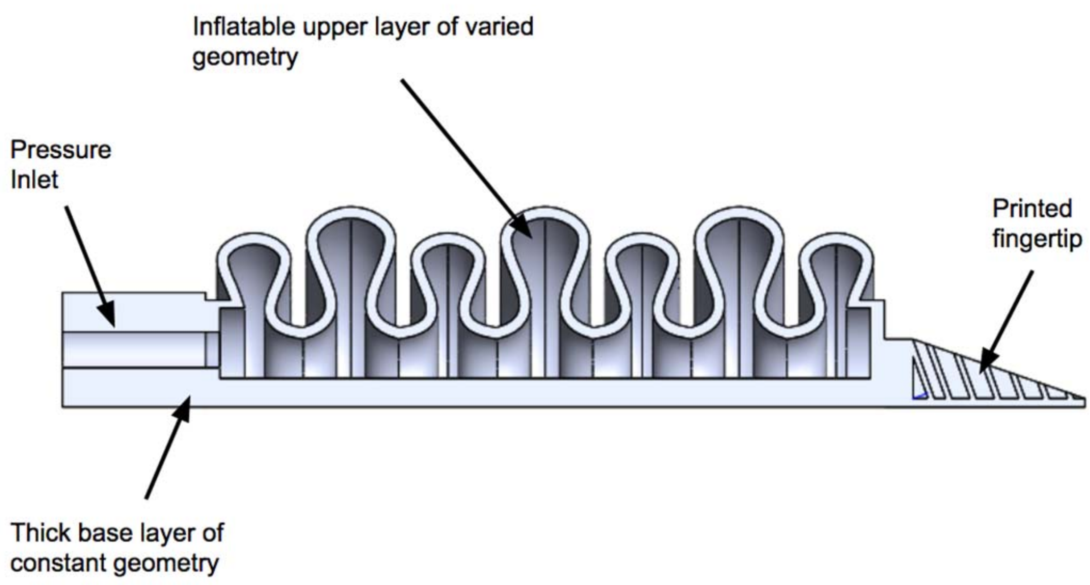


Figure 35: Cross-sectional CAD image of soft robotic actuator with highlighted components

Patent Classifications:

F mechanical engineering; lighting; heating; weapons; blasting

F15 fluid-pressure actuators; hydraulics or pneumatics in general

F15B systems acting by means of fluids in general; fluid-pressure actuators, e.g. servo-motors; details of fluid-pressure systems, not otherwise provided for

F15B15/00 Fluid-actuated devices for displacing a member from one position to another; Gearing associated therewith

F15B15/08 Fluid-actuated devices for displacing a member from one position to another; Gearing associated therewith characterized by the construction of the motor unit

F15B15/10 Fluid-actuated devices for displacing a member from one position to another; Gearing associated therewith characterized by the construction of the motor unit the motor being of diaphragm type

B performing operations; transporting

B25 hand tools; portable power-driven tools; manipulators

B25J manipulators; chambers provided with manipulation devices

B25J11/00 Manipulators not otherwise provided for

B performing operations; transporting

B25 hand tools; portable power-driven tools; manipulators

B25J manipulators; chambers provided with manipulation devices

B25J9/00 Programme-controlled manipulators

B25J9/10 Programme-controlled manipulators characterized by positioning means for manipulator elements

B25J9/1075 Programme-controlled manipulators characterized by positioning means for manipulator elements with muscles or tendons

F mechanical engineering; lighting; heating; weapons; blasting

F15 fluid-pressure actuators; hydraulics or pneumatics in general

F15B systems acting by means of fluids in general; fluid-pressure actuators, e.g. servo-motors; details of fluid-pressure systems, not otherwise provided for

F15B7/00 Systems in which the movement produced is definitely related to the output of a volumetric pump; Telemotors

F15B7/06 Details

B performing operations; transporting

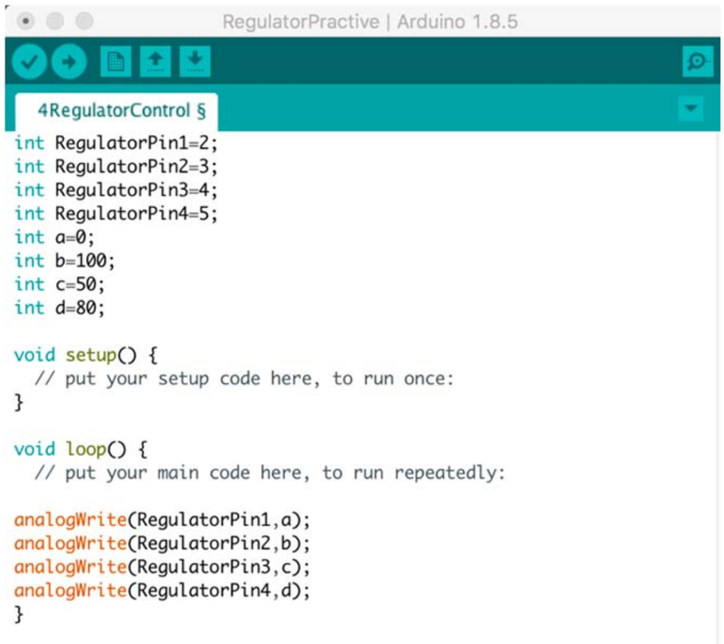
B33 additive manufacturing technology

B33Y additive manufacturing, i.e. manufacturing of three-dimensional [3-d] objects by additive deposition, additive agglomeration or additive layering, e.g. by 3-d printing, stereolithography or selective laser sintering

B33Y10/00 processes of additive manufacturing

Appendix E: Arduino IDE Raw Codes

The following images display the basic code structure of the Arduino IDE program. The code structure was briefly discussed in the User Interface subsection and the images are included to provide greater clarification.




```
int RegulatorPin1=2;
int RegulatorPin2=3;
int RegulatorPin3=4;
int RegulatorPin4=5;
int a=0;
int b=100;
int c=50;
int d=80;

void setup() {
  // put your setup code here, to run once:
}

void loop() {
  // put your main code here, to run repeatedly:

analogWrite(RegulatorPin1,a);
analogWrite(RegulatorPin2,b);
analogWrite(RegulatorPin3,c);
analogWrite(RegulatorPin4,d);
}
```

Figure 36: Arduino raw code for controlling 4 regulators


```
int RegulatorPin=5;
int a=250;
int b=0;

void setup() {
  // put your setup code here, to run once:

pinMode(RegulatorPin,OUTPUT);

}

void loop() {
  // put your main code here, to run repeatedly:

analogWrite(RegulatorPin,a);

}
```

Figure 37: Arduino raw code for controlling1 regulator

Appendix F: Design Tables and Sketches

Table 10: Bill of Materials for the soft robotic gripper

Top Level	Sub Level 1	Sub Level 2	Description	Qty.	B/M/O	Vendor	Vendor Number	Price Per Unit	Total Cost	Responsible Person	Order Date	Received Date
			Soft Robotic Hand	1	M	-	-	-	-	Team	-	-
			Soft Robotic Fingers	4	M	-	-	-	-	Team	-	-
			3D Printed Handle	1	M	-	-	-	-	Team	-	-
			3D Printing Resin - Custom	-	O	-	-	-	-	Team	-	-
			Control System	1	B	-	-	-	-	Team	-	-
			Baomain Silicone Tubing - Vacuum Hose Line 6mm (1/4 Inch) 9.8 Foot 3M	1	B	Amazon	B01IB9BL3Q	11	11	Chris	12/15/18	12/19/18
			ARDUINO A000067 DEV BRD, ATMEGA2560, ARDUINO MEGA 2560 R3	1	B	Amazon	B0046AMGW0	43	43	Chris	12/15/18	12/20/18
			BTC IIS and TTC IIS Mineature Diafram Pump	1	B	Parker	D737-23-01	288	288	Chris	12/15/18	12/21/18
			Compact Electro-Pneumatic Regulator	10	B	SMC USA	ITV0011-2UMS	208	2080	Chris	12/22/18	-
			Regulator Manifold	1	B	SMC USA	IITV20-N02-2	69	69	Chris	12/22/18	-
			Acrylic Control System Container	1	M	-	-	-	-	Team	-	-
			1/8" tubing	1	B	-	-	-	-	Chris	-	-
			1/4" tubing	1	B	-	-	-	-	Chris	-	-
			5/32" tubing	1	B	-	-	-	-	Chris	-	-
Page Totals									2491			

Table 11: Design matrix used to determine gripper configuration

CRITERIA	TARGET or FACTOR	1 = Baseline		3 Finger Claw		4 Finger Claw		5 Finger Claw		5 Finger Hand (w/ aposable thumb)		5 Finger Hand (no thumb)	
										DESIGN IDEAS			
Time – Design	1	1		2		3		4		5		5	
Time – Build	1	1		3		3		4		4		4	
Time – Test	1	1		2		2		3		3		3	
Time weighting	5		5		11.67		13.33		18.33		20.00		20.00
Cost – Prototype	$ 1.00	$ 1.00		$ 3.00		$ 5.00		$ 2.00		$ 4.00		$ 4.00	
Cost – Production	$ 1.00	$ 1.00		$ 3.00		$ 5.00		$ 2.00		$ 4.00		$ 4.00	
Cost weighting	15		15		45.00		75.00		30.00		60.00		60.00
Range of Motion	20	3	60	3	60	3	60	3	60	4	80	4	80
Pressure Input	5	3	15	4	20	4	20	4	20	4	20	4	20
Size	5	3	15	3	15	3	15	3	15	3	15	3	15
Aesthetics	5	3	15	3	15	3	15	3	15	5	25	4	20
Strength	20	3	60	3	60	3	60	3	60	3	60	3	60
Precision	15	3	45	4	60	4	60	4	60	5	75	4	60
Usability	10	3	30	3	30	3	30	3	30	5	50	4	40
0	0	3	0		0		0		0		0		0
0	0	3	0		0		0		0		0		0
0	0	3	0		0		0		0		0		0
0	0	3	0		0		0		0		0		0
0	0	3	0		0		0		0		0		0
	TOTAL		240.0		223.3		191.7		231.7		265.0		235.0
	RANK												
	% MAX		90.6%		84.3%		72.3%		87.4%		100.0%		88.7%
	MAX	265.0											

NOTE: User fills in Purple areas, gold areas are calculated or fixed

Light blue areas filled from prioritizing matrix

BASELINE = Soft Robotics Gripper

Design Idea Descriptions

- 3 Finger Claw
- 4 Finger Claw
- 5 Finger Claw
- 5 Finger Hand w/ thumb
- 5 Finger Hand no thumb

Timescore(i)=Timescore(B)*(TD(i)/TD(B) + TB(i)/TB(

Costscore(i)=Costscore(B)*(Cprot(i)/Cprot(B) + Cprod(

Total(i) = SUM(Factor(j)*Comparison(i,j)) + (Timescor

Comparison(i,j) = 5 if idea "i" is much better than baseli

Comparison(i,j) = 4 if idea "i" is better than baseline for

Comparison(i,j) = 3 if idea "i" is same as

Comparison(i,j) = 2 if idea "i" is worse than baseline for

Comparison(i,j) = 1 if idea "i" is much worse than basel

Table 12: Scoring system used in design matrix

Project:	3D Printed Robotic Hand	
System:	Finger Prototypes	
Date:	5-Nov-17	
	Criterion	FACTOR
1	Range of Motion	20
2	Required Pressure Input	5
3	Size	5
4	Aesthetics	5
5	Strength (weight capable of being lifted	20
6	Precision	15
7	Usability	10
8		
9		
10		
11		
12		
Time		5
Cost		15
SUM		**100**
Target		**100**
difference		**0**

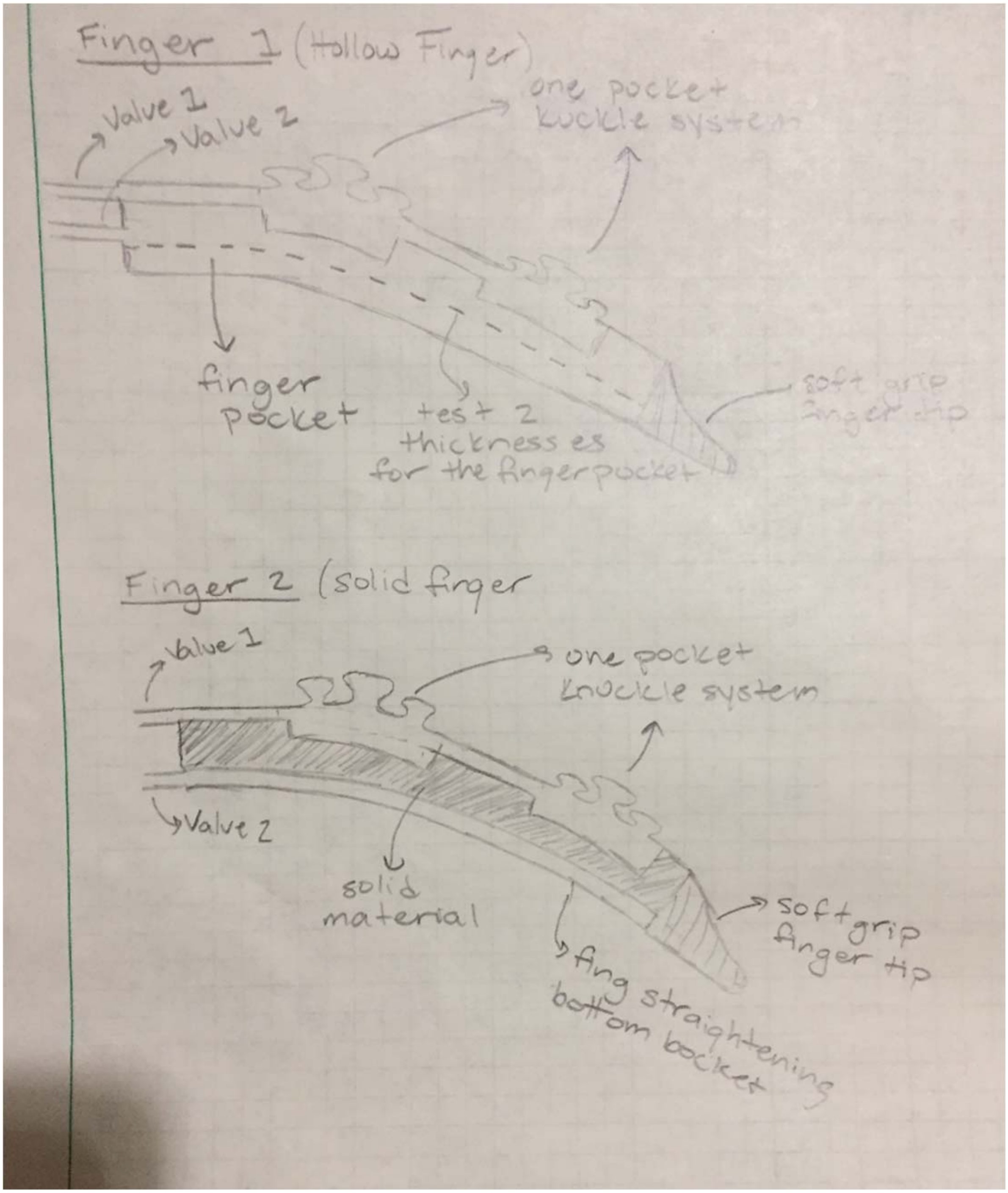


Figure 38: Early concept sketches for finger prototypes

Table 13: Product design specification (PDS) table

Constraints	Parameters		
	Units	**Datum**	**Target**
Maximum Temperature	°C	65	65
Coefficient of Friction	N/a	0.9	0.9
Percent Elongation	%	100	300
Required Pressure	psi.	0-12	0-15
Range of lifting weights	g	0-100	0-100
Weight	g	1,000	1,000
Size	m2	0.016	0.010
Lifespan	years	2	2.5
Time to Produce	hours	12-24	3-5
Cost	$	10,000+	3,000

Appendix G: Finger Force Testing Raw Data

Table 14: Force testing raw data of the 0.7 s cure time with the Origin printer

Voltage (V)	Pressure (psi)	PWM Output	Force (g)	Average Force (g)	Average Force (lb.)
1	3	50	10	9.333333333	0.02057645333
			8		
			10		
2	6	100	21	23.66666667	0.05217600667
			24		
			26		
3	9	150	36	35.33333333	0.07789657333
			33		
			37		
4	12	200	50	49.33333333	0.1087612533
			49		
			49		
4.5	13.5	225	62	62.66666667	0.1381561867
			66		
			60		
5	15	250	73	69.66666667	0.1535885267
			69		
			67		

Table 15: Force testing raw data of the 1 s cure time with the Origin printer

Voltage (V)	Pressure (psi)	PWM Output	Force (g)	Average Force (g)	Average Force (lb)
1	3	50	4	7	0.01543234
			7		
			10		
2	6	100	18	17	0.03747854
			16		
			17		
3	9	150	24	25	0.0551155
			25		
			26		
4	12	200	40	40.66666667	0.08965454667
			41		
			41		
4.5	13.5	225	49	49.66666667	0.1094961267
			46		
			54		
5	15	250	54	58.66666667	0.1293377067
			61		
			61		

Table 16: Cure setting 1 on the Figure 4 printer

Voltage (V)	Pressure (psi)	PWM Output	Force (g)	Average Force (g)	Average Force (lb)
1	3	50	19	20	0.0440924
			20		
			21		
2	6	100	29	30	0.0661386
			29		
			32		
3	9	150	53	49	0.10802638
			45		
			49		
4	12	200	51	51	0.11243562
			51		
			51		
4.5	13.5	225	61	58.33333333	0.1286028333
			57		
			57		
5	15	250	57	59.66666667	0.1315423267
			60		
			62		

Table 17: Finalized cure setting for the Figure 4 printer

Voltage (V)	Pressure (psi)	PWM Output	Force (g)	Average Force (g)	Average Force (lb.)
1	3	50	13	13	0.02866006
			10		
			16		
2	6	100	23	23	0.05070626
			21		
			25		
3	9	150	46	44	0.09700328
			43		
			43		
4	12	200	56	58.33333333	0.1286028333
			59		
			60		
4.5	13.5	225	68	64.33333333	0.1418305533
			62		
			63		
5	15	250	74	74.33333333	0.1638767533
			73		
			76		

Appendix H: Finger Displacement Testing Raw Data

Table 18: Finger Displacement results for the 0.7 sec cure Origin prints

0.7 sec cure										
Voltage [V]	Pressure [psi]	X Deformation [cm]			Y Deformation [cm]			Average X [cm]	Average Y [cm]	Total Disp.
5	15	4.8	4.8	4.7	5.5	5.7	5.9	4.77	-5.70	7.43
3.3	9.9	4.1	4.1	4.3	2.3	2.3	2.5	4.17	-2.37	4.79
1.7	5.1	2.1	2.3	2.2	0.5	0.5	0.4	2.20	-0.47	2.25
0.8	2.4	0.8	0.9	0.7	-0.25	-0.2	-0.2	0.80	0.22	0.83
0.4	1.2	0.5	0.5	0.3	-0.1	-0.1	-0.1	0.43	0.10	0.44

Table 19: Finger Displacement results for the 1 sec cure Origin prints

1 sec cure										
Voltage [V]	Pressure [psi]	X Deformation [cm]			Y Deformation [cm]			Average X [cm]	Average Y [cm]	Total Disp.
5	15	2.9	3	3.1	1.1	1.3	1.3	3.00	-1.23	3.24
3.3	9.9	1.8	2	2	0.7	0.6	0.7	1.93	-0.67	2.05
1.7	5.1	0.8	0.9	0.9	0.2	0.3	0.3	0.87	-0.27	0.91
0.8	2.4	0.6	0.7	0.6	0.1	-0.1	0	0.63	0.00	0.63
0.4	1.2	0.3	0.3	0.4	-0.1	0	0	0.33	0.03	0.33

Appendix I: Finger Cycle Time Raw Data

Table 20: Cycle time of 0.7 second cure on Origin printer

Trial	Pressure [psi]	Open [s]	Close [s]	Total [s]
1	15	3.3	0.4	3.7
2	15	3.46	0.3	3.76
3	15	3.1	2.18	5.28
4	15	3.73	0.4	4.13
5	15	3.26	2.33	5.59

Table 21: Cycle time of the Figure 4 printer Angel

Trial	Pressure [psi]	Open [s]	Close [s]	Total [s]
1	15	0.5	0.23	0.73
2	15	0.4	0.3	0.7
3	15	0.3	0.3	0.6
4	15	0.5	0.45	0.95
5	15	0.3	0.45	0.75

Table 22: Cycle time for the Figure 4 printer Braves

Trial	Pressure [psi]	Open [s]	Close [s]	Total [s]
1	15	0.25	0.21	0.45
2	15	0.30	0.22	0.52
3	15	0.21	0.20	0.41
4	15	0.15	0.23	0.38
5	15	0.18	0.26	0.44

Appendix J: Tensile Data

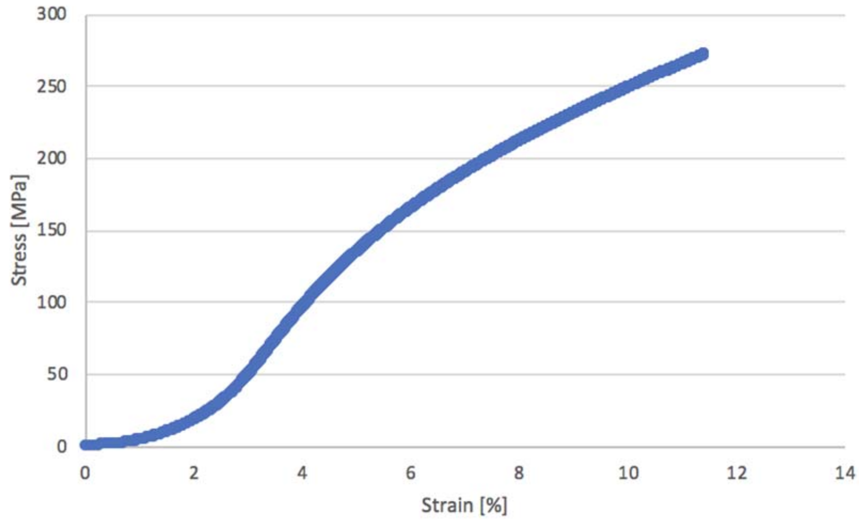


Figure 39: Tensile test of finalized material settings on Figure 4 printer

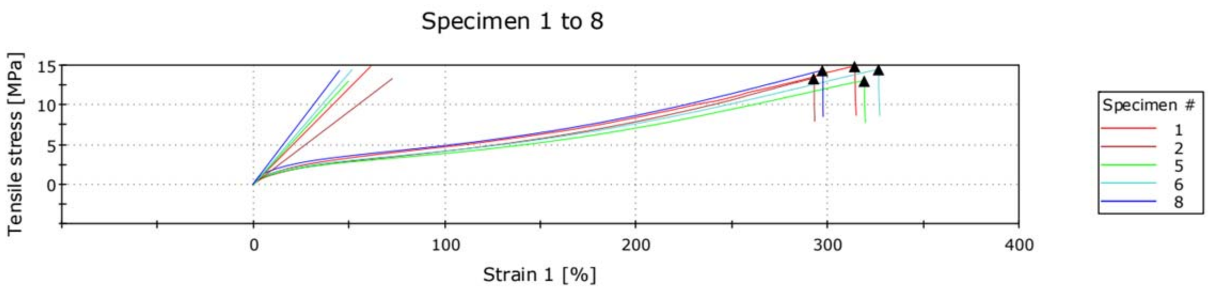


Figure 40: Tensile data output from Instron for Origin 1 second cure

Appendix K: Coefficient of Friction Data

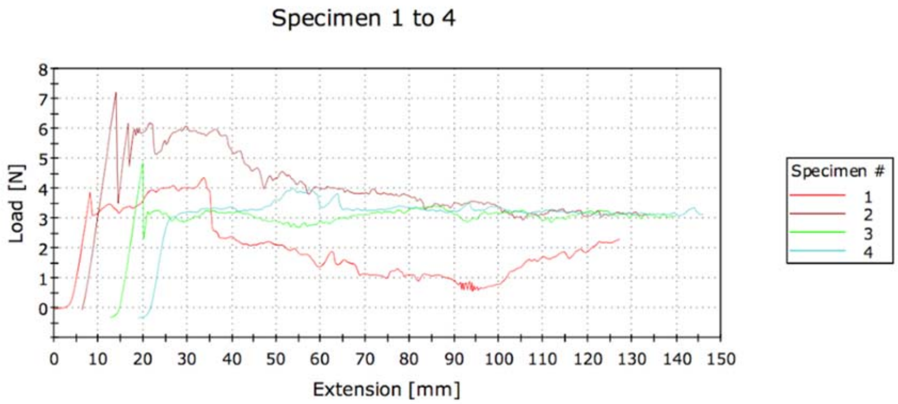


Figure 41: Trials performed on felt (1-3) and paper (4) for determining coefficients of friction

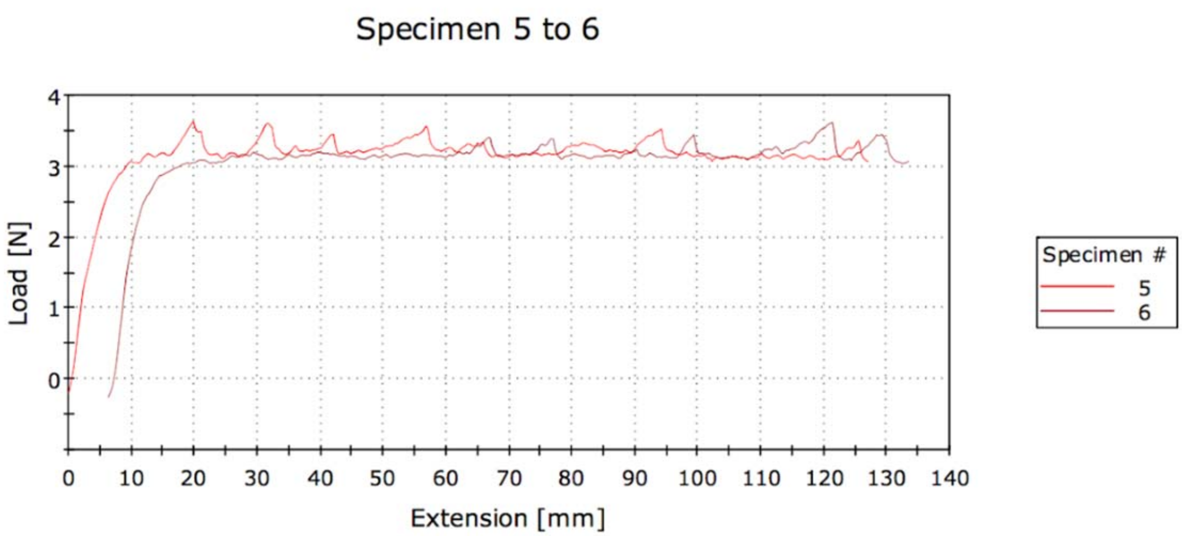


Figure 42: Trials 5 & 6 performed on paper for determining coefficients of friction

Table 23: Subsequent coefficients of friction determined from testing on felt (1-3) and paper (4-6)

	Specimen number (included)	Static at Coefficient of friction	Dynamic at Coefficient of friction
1	1	1.93304	0.99180
2	2	3.59843	2.02719
3	3	2.42128	1.50558
4	4	2.00039	1.58876
5	5	1.81355	1.56356
6	6	1.70355	1.53840

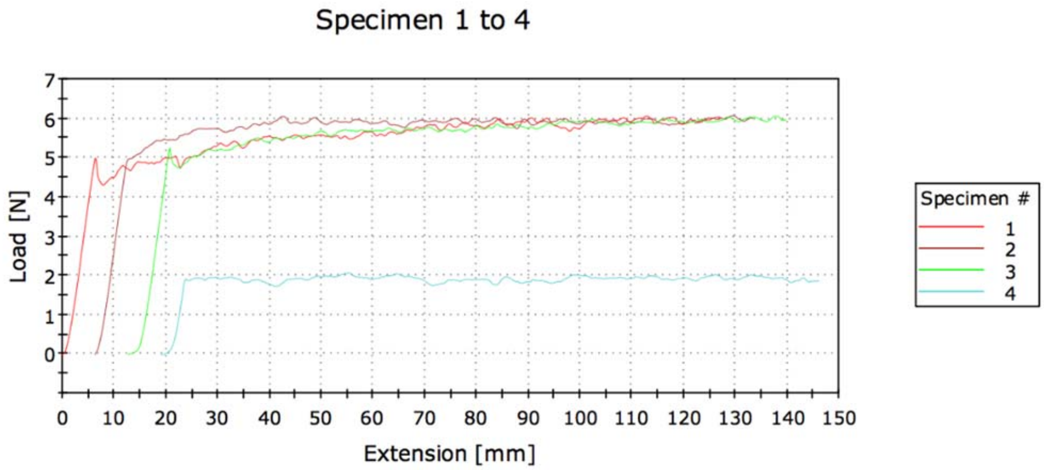


Figure 43: Trials of tests performed on aluminum (1-3) and cardboard (4) for determining coefficients of friction

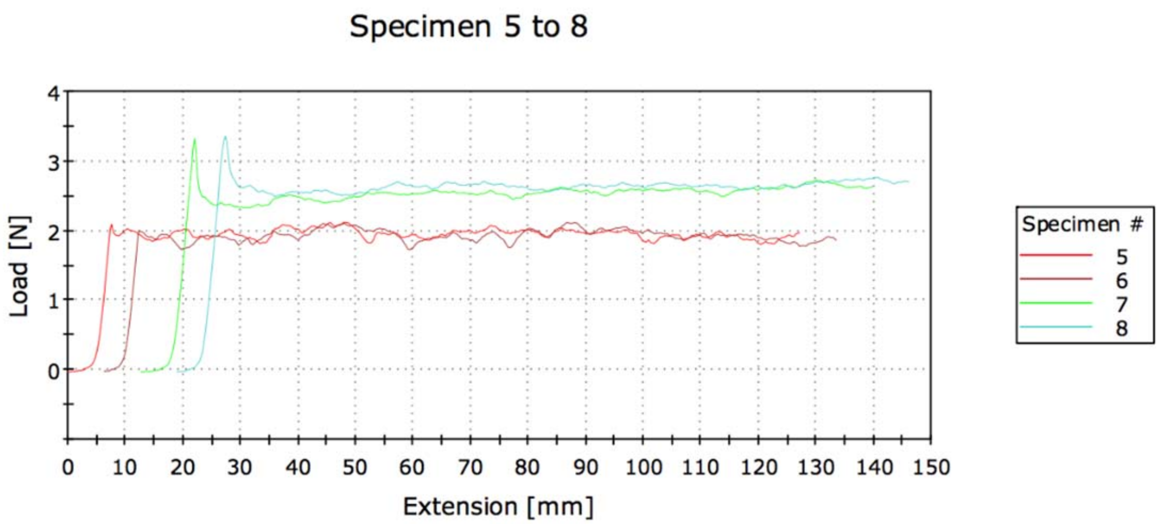


Figure 44: Trials performed on cardboard (5-6) and acrylic (7 & 8) for determining coefficients of friction

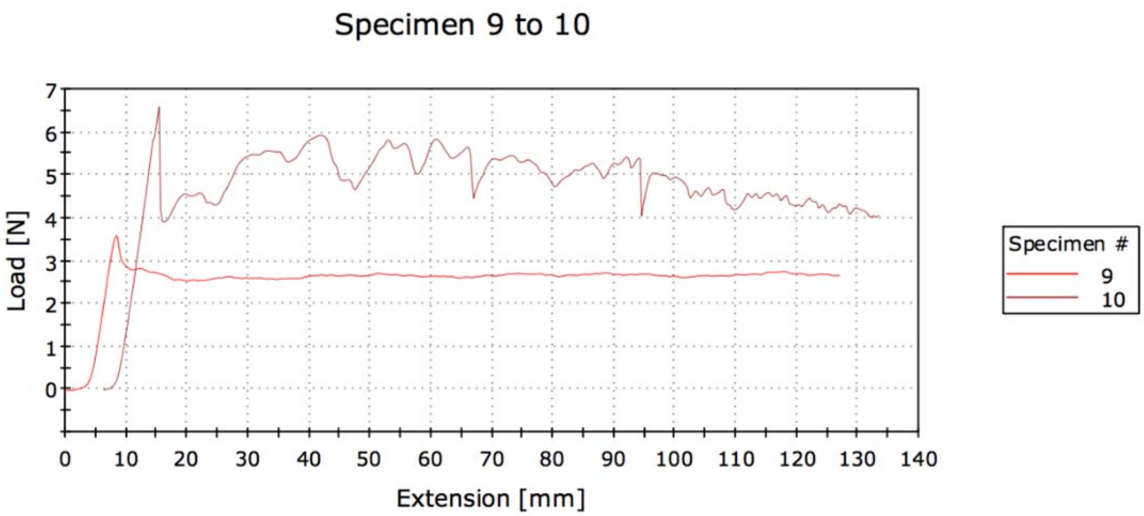


Figure 45: Final testing performed on acrylic (9 & 10) for determining coefficients of friction

Table 24: Coefficients of friction determined for testing on aluminum (1-3), cardboard (4-6), and acrylic (7-10)

	Specimen number (included)	Static at Coefficient of friction	Dynamic at Coefficient of friction
1	1	2.49622	2.69723
2	2	3.02266	2.82835
3	3	2.62355	2.72306
4	4	0.98397	0.93566
5	5	1.04526	0.92981
6	6	1.00141	0.93069
7	7	1.66140	1.20208
8	8	1.67544	1.26096
9	9	1.79278	1.27618
10	10	3.28884	2.38610

Appendix L: Hand Calculations

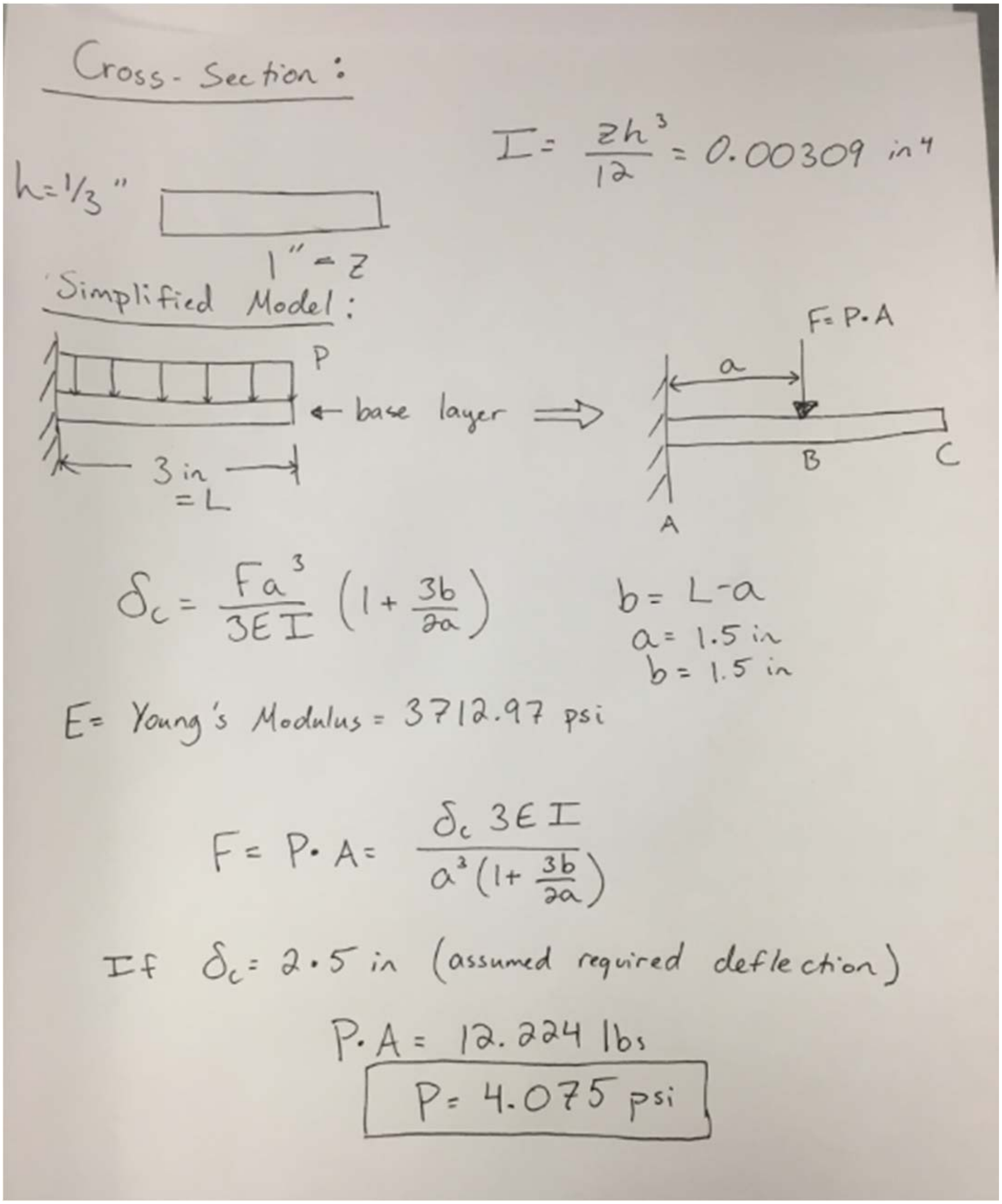


Figure 46: Hand calculations of required pressure input for max desired deflection

Appendix M: Simulation

The Neo-Hookean model was deemed appropriate because it represents good modeling accuracy for strains under 20%. The Neo-Hookean model utilizes the approximation equation:

$$W = C_1(I_1 - 2) + D_1(J - 1)2 \#(1A)$$

where W is the strain energy density of the model, C_1 is a material constant equal to μ /2, I_1 is the first invariant of the right Cauchy-Green deformation tensor, D_1 is a material constant equal to τ /2, and J is equal to the product of the three principal stresses of the material (123). Additionally, μ is the shear modulus of the material and τ is first Lame parameter.

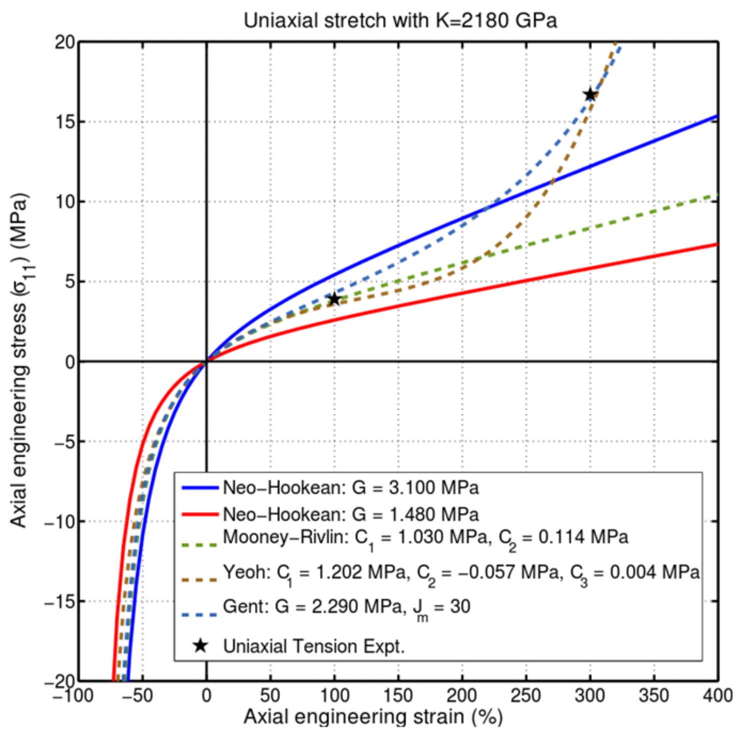
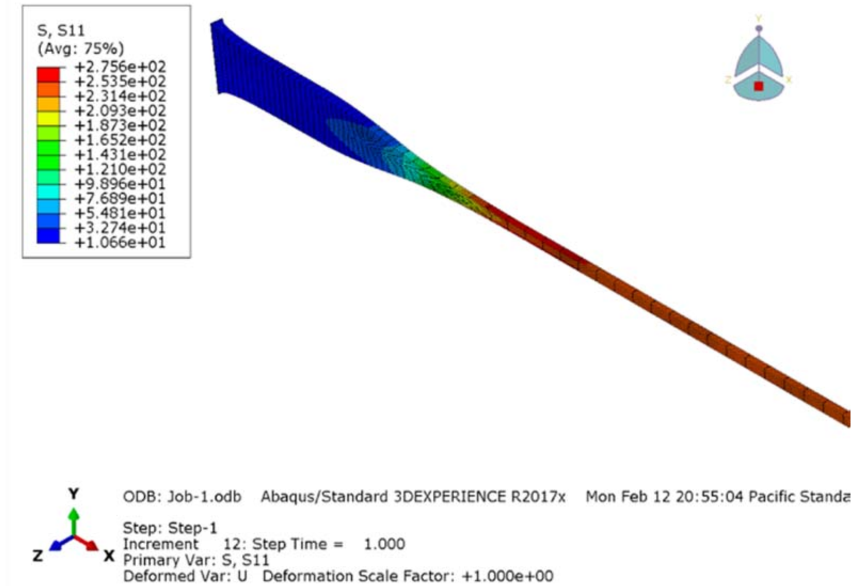
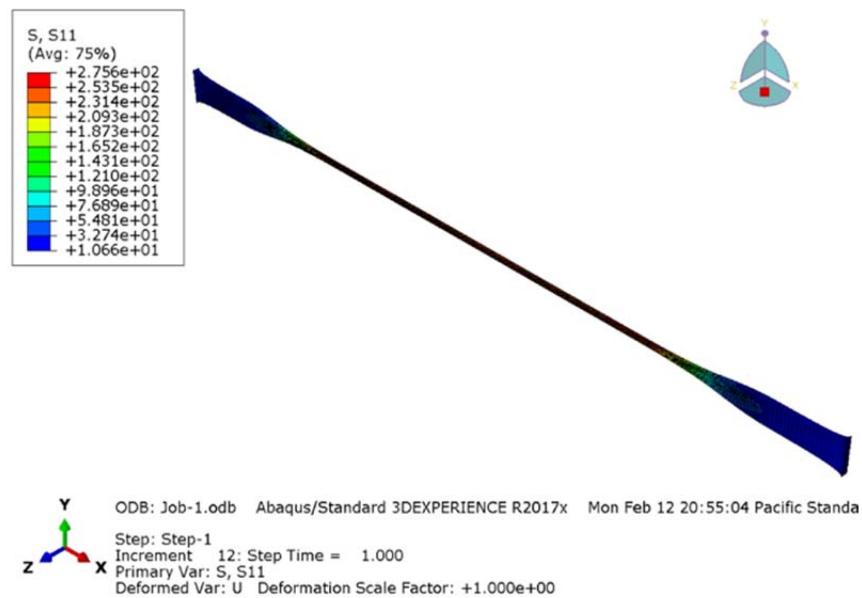


Figure 47: Plotted modeling fits for stress-strain of hyperelastic materials [“Hyperelastic Material”]



Figures 48: Tensile simulation of a Type 4 test piece in Abaqus, an FEA simulation tool



Figures 49: Tensile simulation of a Type 4 test piece in Abaqus, an FEA simulation tool

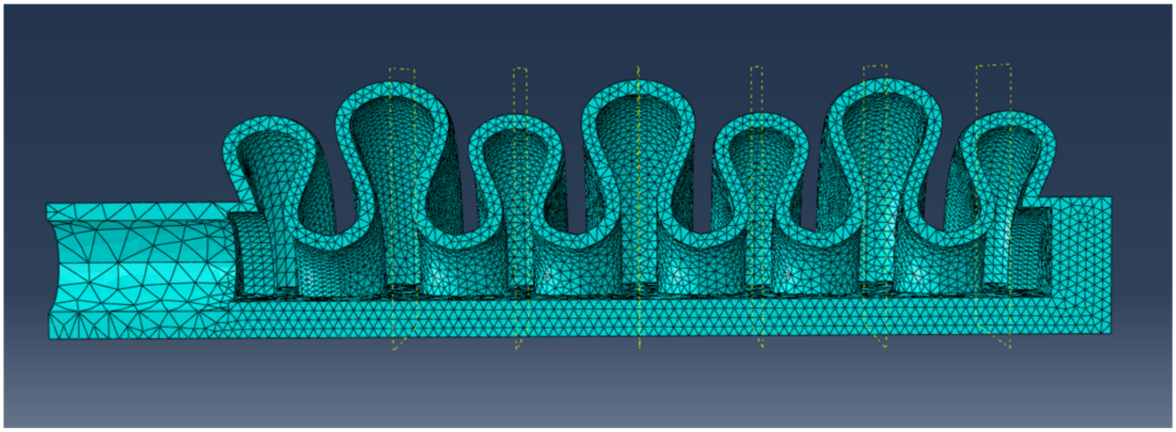


Figure 50: Mesh of full finger design for FEA simulation on Abaqus

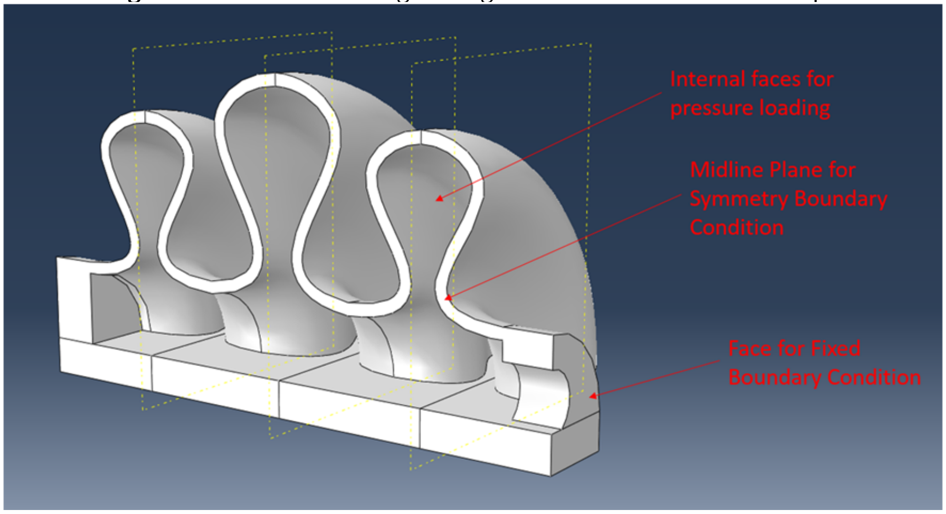


Figure 51: Indicated faces for boundary conditions and loading on a knuckle prototype uploaded in Abaqus

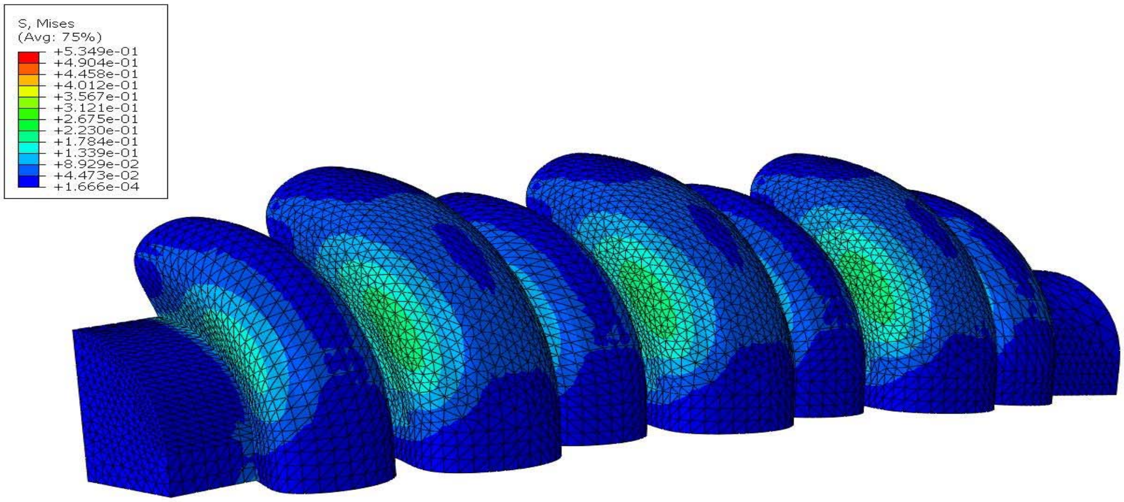


Figure 52: Stress concentration on back of finger at 2 psi

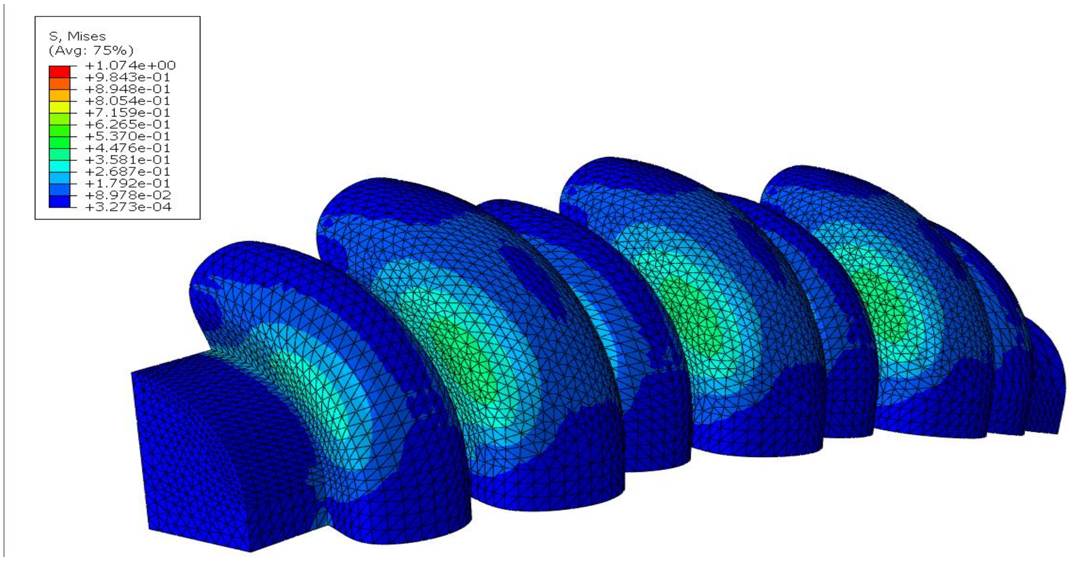


Figure 53: Stress concentration on back of finger at 4 psi

Appendix N: Final Design Images

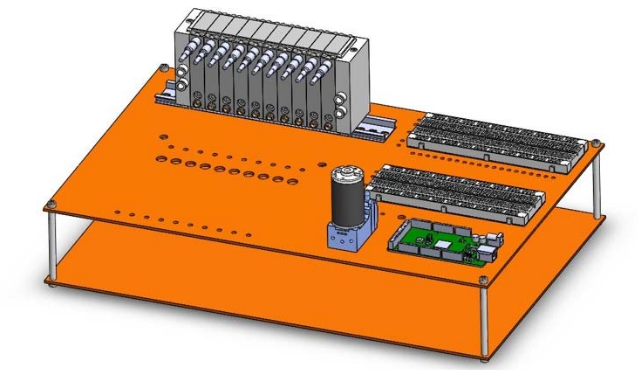


Figure 54: CAD image of finalized control system design

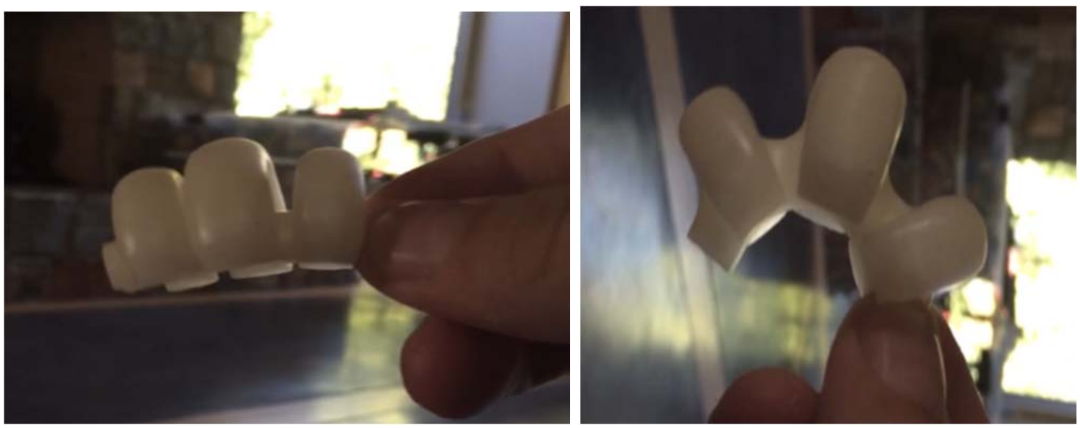


Figure 55a and 55b: Current knuckle prototype comparing pre and post input of pressurized air showing subsequent bending

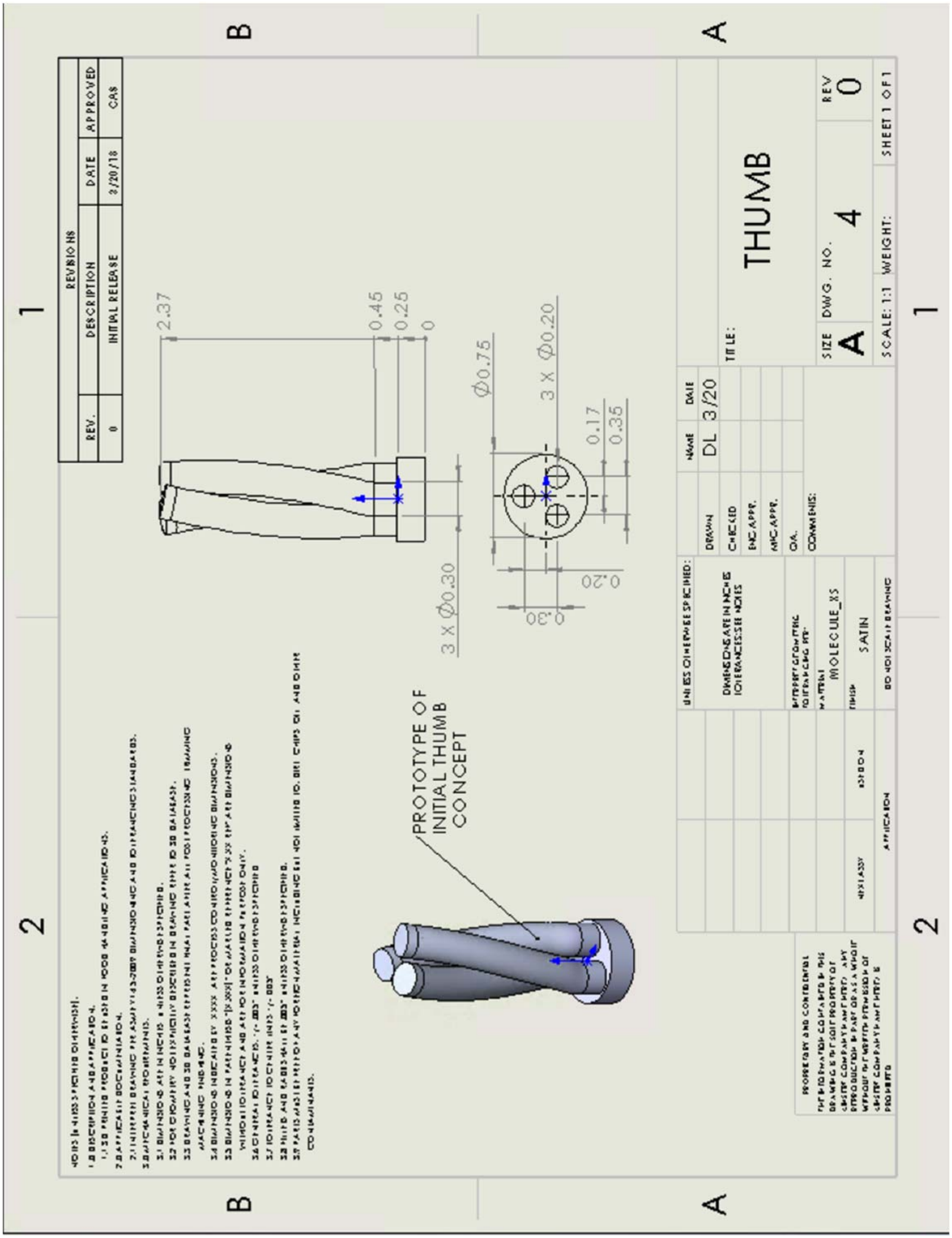


Figure 56: Design drawing of thumb prototype

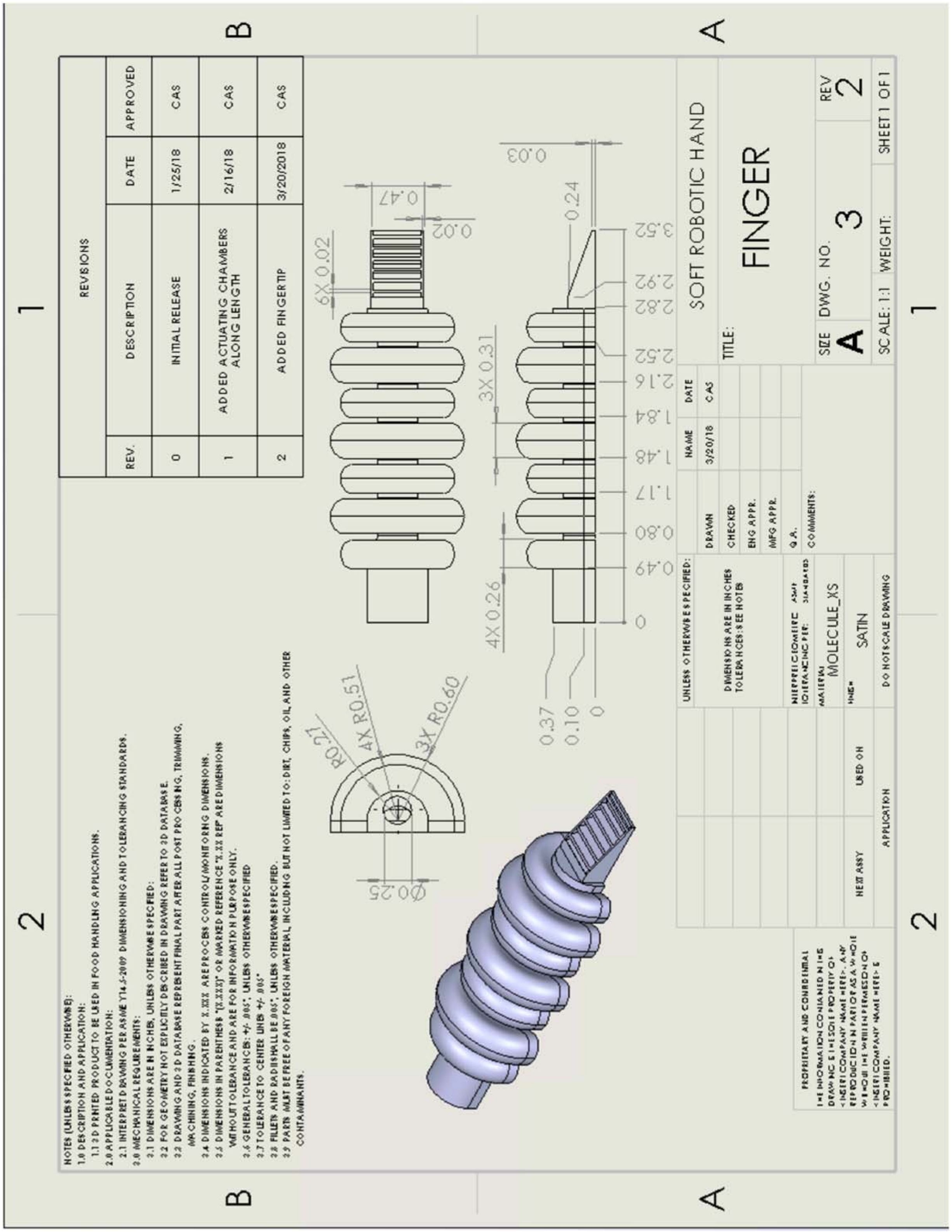


Figure 57: Solidworks drawing for soft robotic finger actuator

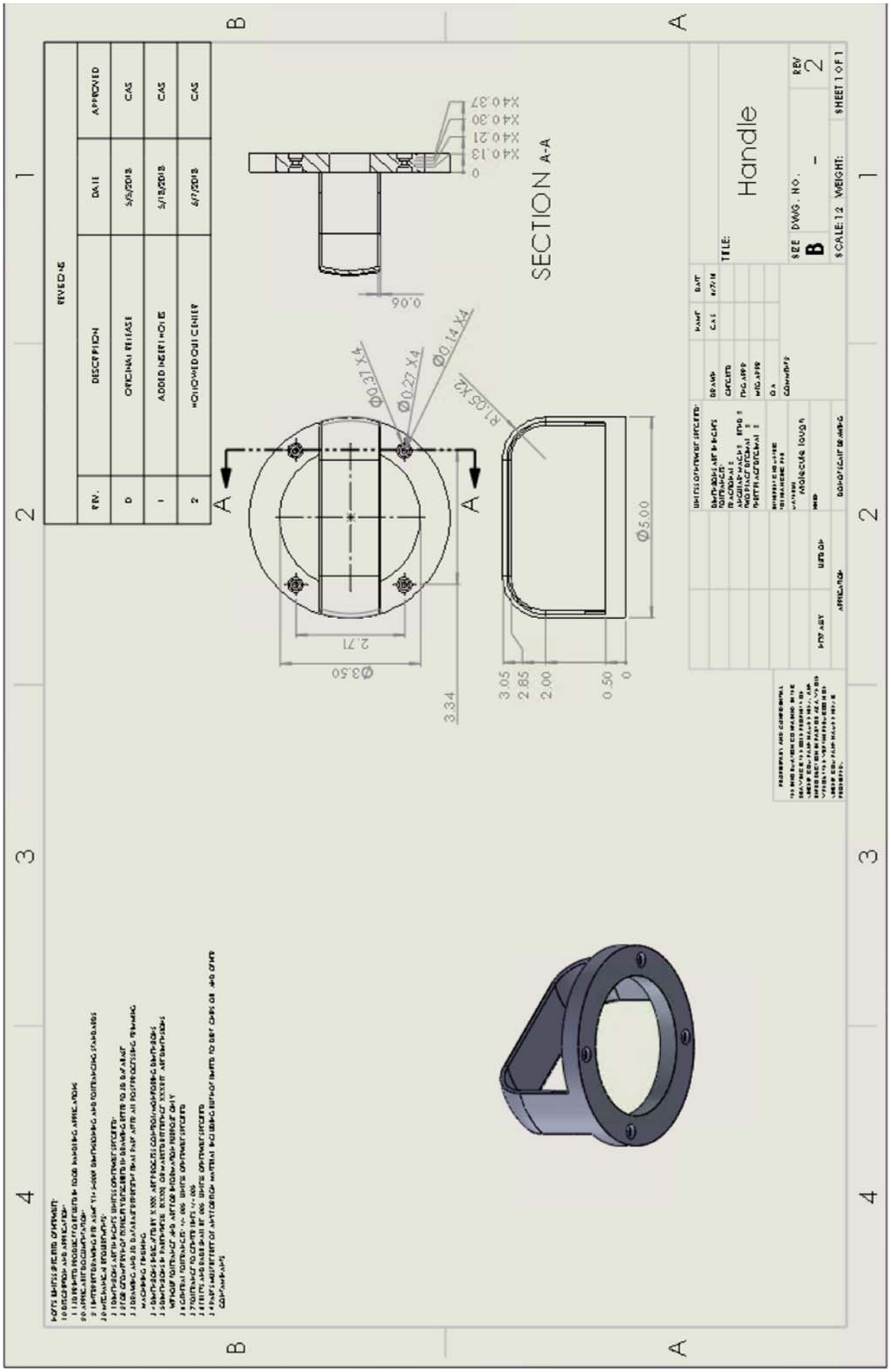


Figure 58: Design drawing for 3D printed handle

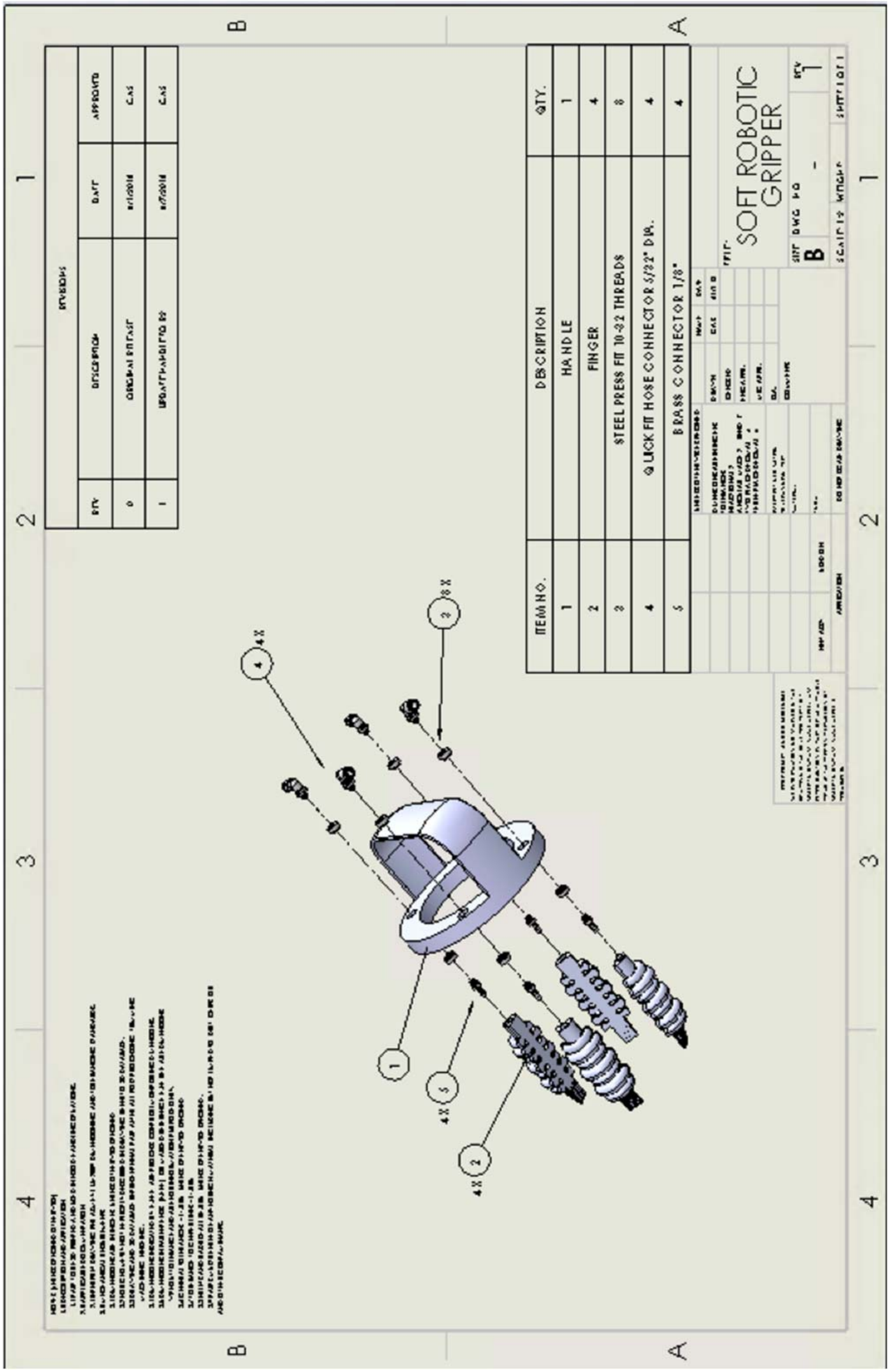


Figure 59: Solidworks assembly drawing for the complete soft robotic gripper system