# Cavatappi Hand

# Final Proposal

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# DISCLAIMER

This report was prepared by students as part of a university course requirement. While considerable effort has been put into the project, it is not the work of licensed engineers and has not undergone the extensive verification that is common in the profession. The information, data, conclusions, and content of this report should not be relied on or utilized without thorough, independent testing and verification. University faculty members may have been associated with this project as advisors, sponsors, or course instructors, but as such they are not responsible for the accuracy of results or conclusions.

# EXECUTIVE SUMMARY

Below is the proposal submitted to the team at the beginning of the semester:

> "Minimally Invasive Surgery (MIS) represents the gold standard in the majority of abdominal operations. As conventional and standard surgical tools still present fundamental limitations on dexterity and safety, this capstone will aim to address such limitations using emerging robotic solutions. This project will involve the design and fabrication of a tiny robotic hand (1 cm ×1 cm or even smaller) actuated with artificial muscles (cavatappi) used to increase the dexterity within the body for surgeons. The main idea is based on the exploitation of soft materials or artificial muscles to be intrinsically flexible and safe and enable high dexterity and selective stiffness variability. Such a system will be fully actuated using a hydraulically wearable glove consisting of syringes to generate internal pressurization in the artificial muscles, and in turn, actuation. Each syringe in the glove will allow to individually actuate each finger in the robotic hand. As a result, surgeons will be able to translate their fingers motion into the motion of the tiny hand surgical tool, leading to an increment of the safety level during surgeries"

The muscles, so named for a type of pasta of a similar shape, start out as a straight length of polymer tubing and then must be both twisted and coiled to achieve their signature shape and actuation. Most of this semester has been centered around developing mechanisms and processes to produce actuators both more consistently and more efficiently than previous methods. The prototype system is still undergoing modification, but it delivers on consistency and reduction of human interaction in the process itself. Prior to this system, the twisting and coiling would all be done by hand, with the operator drawing the tubing, twisting it and then coiling the twisted tubing around a mandrel (stiffer solid length of clear polymer). Now the pre twisted material is spun off a spool and coiled around a mandrel through the use of some new 3D printed clamps. The coiling in this new system is accomplished using a simple motorized hand drill, allowing for more consistent coils and force application. This prevents damage to the muscle at this stage previously caused by operator handling. After the individual muscles are twisted and coiled, they must be annealed at 170°F for 30 minutes. The team found that this was one of the single largest points of failure and set about finding a more consistent system of heating. The original method used a cheaper toaster oven to heat the muscles to the correct temperature for heat treatment. Since controls don't allow for precise timing and it lacks any sort of convection fan, the temperature gradient in the oven would lead to inconsistent results and often multiple failures in a batch of actuators. Ultimately design discussions led to the team electing to use a water bath or sous vide commonly found in kitchens to deliver consistent even heat. This so far has eliminated all failures in the annealing process. Images and further design discussion can be found in later parts of the report.

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# 1 BACKGROUND

## 1.1 Introduction

The Cavatappi Muscle Project focuses on the research of Diego Higueras Ruiz. His research is focused on the field of soft robotics, specifically soft muscle like actuators that unlike most of the comparable existing actuators deliver linear force with little to no radial expansion. Pictured below are the "Cavatappi" actuators, so named after the pasta of the same shape.

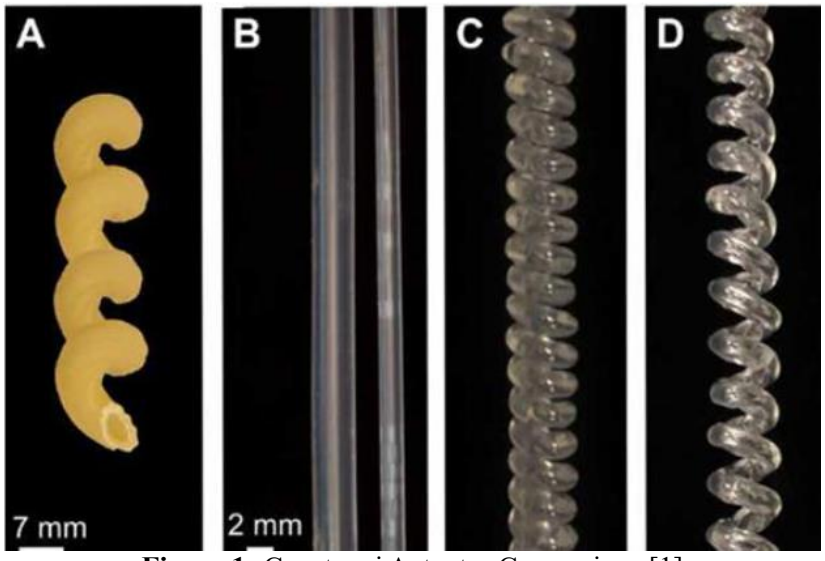



**Figure 1:** Cavatappi Actuator Comparison [1]

This project is focused mainly on two major points concerning the actuators themselves. Firstly, updating the manufacturing process to better produce actuators both in terms of efficiency and quality. Secondly, once better production is achieved, demonstrating that the base size of the tubing can be scaled down and the actuators set up to run in parallel in order to actuate a hand-like device (1cm x 1cm x 1cm in size) to demonstrate that these actuators can be utilized to perform a more dexterous/delicate task such as picking up a coin off a flat surface.

Soft robotics are going to be a key technology in the future in a variety of sectors, these being robotic systems that directly interface with humans. Soft actuators in that field are going to be critical to making functional objects that be safely used directly with humans. To increase interest in actuators like these for further research and development practical demonstrations to be done to showcase that they have potential. This project may not revolutionize the field or actually directly build a functioning prosthetic limb for an amputee, but it may attract the attention of those with the ability to move the technology forward in a meaningful way so that those things may one day be a reality. Progress is slow but steps like these are necessary to "move the ball down the field".

## 1.2 Project Description

Below is the original project description given to us by our client Dr. Michael Shafer:
Minimally Invasive Surgery (MIS) represents the gold standard in the majority of abdominal operations. As conventional and standard surgical tools still present fundamental limitations on dexterity and safety, this capstone will aim to address such limitations using emerging robotic solutions. This project will involve the design and fabrication of a tiny robotic hand (1 cm ×1 cm or even smaller) actuated with artificial muscles (cavatappi) used to increase the dexterity within the body for surgeons. The main idea is based on the exploitation of soft materials or artificial muscles to be intrinsically flexible and safe and enable high dexterity and selective stiffness variability. Such a system will be fully actuated using a

hydraulically wearable glove consisting of syringes to generate internal pressurization in the artificial muscles, and in turn, actuation. Each syringe in the glove will allow to individually actuate each finger in the robotic hand. As a result, surgeons will be able to translate their fingers motion into the motion of the tiny hand surgical tool, leading to an increment of the safety level during surgeries

### 1.2.1 Original System Structure

While no original system exists for the hand itself, this project also encompasses the general manufacture of the actuators themselves and there does exist a system for that already. Using hooks mounted to wooden blocks (hereafter called towers). The hook's center axis is parallel to the work surface and can still rotate freely, secured to the tower by their threads with a nut.

### 1.2.2 Original System Operation

Both tubing (silicone or pvc) and mandrel (stiff solid plastic round stock of similar size to the tubing) are secured into a small copper clamp at one end. The mandrel is clamped at the other end and both clamps are secured to the hooks. One hook has a slightly loosened nut and can rotate, as it rotates the tubing is twisted along its own center axis and simultaneously coiled around the mandrel. The operator does their best to maintain consistent and uniform coils. Once the coiled length reaches its desired amount, the operator holds the excess material taught so as not to allow the muscle to uncoil or untwist as both are vital to function. The excess tubing is clamped with the mandrel so that both ends of the mandrel and the actuator are clamped. This entire assembly is clamped into a metal rack and placed into a small toaster oven at 170 °F for 30 minutes to anneal. This annealing process allows the actuator to maintain its coiled length without the need for clamps.

### 1.2.3 Original System Performance

The system as it exists now was designed purely for research purposes. It's not built for producing consistent muscles in larger amounts quickly. While it can produce good muscles, overall, with unpracticed operator the failure rate was around 60% due to various issues within the process. A good actuator takes about 15-20 minutes to twist and coil another 30 minutes to anneal.

### 1.2.4 Original System Deficiencies

The largest deficiencies in the current process lie in the amount of hands-on interaction with the muscle by the operator. Various inconsistencies in the process lead to introductions of excess force that can cause plastic deformation in the material at different points in the actuator itself. This also means that in limiting the final quality of the muscle that it also increases failures before the actuators themselves can even be tested, causing waste of material and time. Beside the inherent inconsistencies with the operator interaction the process itself is inconsistent in timing even for successful actuators.

# 2 REQUIREMENTS

The main requirement of the Cavatappi Capstone is to use Cavatappi artificial actuators to produce a laparoscopic surgical tool intended for minimally invasive surgical procedures (MIS). Team Cavatappi is to design and fabricate a small robotic hand that is both dexterous and flexible to make MIS procedures safer and easier. Intended manipulation of the device is to use a glove-like control system with syringes to translate user input into actuation of the hand. Individual "finger" actuation using multiple muscles in parallel is also a necessary design feature. [2] Customer Requirements are developed by Team Cavatappi with the clients. Engineering Requirements are developed by Team Cavatappi based on CRs. Both CRs and ERs used to make a House of Quality to compare CRs and ERs.

## *2.1 Customer Requirements (CRs)*

Team Cavatappi developed customer requirements after meeting with clients Dr. Michael Shafer and Diego Higueras-Ruiz. All CRs were weighted on a scale from one to five, five being the most important. The three most important CRs are minimizing the cross-sectional area of the final design, a glove-like control system, and operation safety. These three have the highest weights because they drive a majority of the final design geometry, with safety being self-explanatory. Controlling the final design with simple inputs like syringes allows for intuitive actuation. A small cross section requirement is because of the intended use in MIS.

The next highest requirements are designing a muscle manufacturing process, ensuring the muscles are scalable, and utilizing muscle systems in parallel. The current manufacturing system is not ideal for smaller muscles, so this needs to be addressed and developed early on in the project. The Cavatappi muscles need to be smaller than they have been in the past, since a small cross-section is required. To build on this, a selling point of the Cavatappi muscle design is their ability to be used in parallel with one another, which saves space compared to other soft robotics actuators. [1]

The less-pertinent requirements are minimizing muscle leaks, staying under budget, and ensuring the design is reliable and durable. While design durability and reliability is important, the other requirements above were deemed top priority by the clients. Because a lot of materials were pre-purchased, staying under budget is also less of a concern. Finally, the current methods of mounting and using Cavatappi muscles can cause leaks, so some testing regarding this issue will be a point of testing along the way.

## *2.2 Engineering Requirements (ERs)*

Based on the CRs, Team Cavatappi developed the following Engineering Requirements (Note: Metrics included below were pulled from supplied literature or come directly from clients): [1] [2]

- Maximize Force Output ( >=0.38kJ/kg)
- Minimize Muscle diameter (d<=1.5mm)
- Minimize Manufacturing Cost (Cost < $200.00 USD)
- Mech Input to Hydraulic Output (Wout/Win ~ 0.45)
- Minimize "Hand" Size (<= 1.0 $cm^2$)
- High Factor Of Safety (1.25 < FS < 3.25)
- Minimize # Muscles per Bundle (2 < N < 4)
- Minimize Muscle Length (L < 90 mm)
- Minimize Pressure Input (100 psi < P < 150 psi)
- Maximize Muscle Efficiency (Efficiency > 20%)

The most notable metrics above are the cost, pressure input, hand size, and the factor of safety. The total budget of the project is $200.00 USD. Despite a large portion of the supplies being pre-purchased, Team Cavatappi should not exceed this amount for new materials, manufacturing, or any other potential charges. [2] Cavatappi muscles are rated to withstand up to 150 psi, so the system cannot apply more than this pressure. [1] The hand size is directly from the client. [1] Finally, the system must be safe to use, so it is the job of Team Cavatappi to prove that the muscles will not fail and cause injury to the user or the patient. Safety factor calculations will need to take place after a manufacturing process is developed.

The force output of a Cavatappi muscle has been measured to be around 0.38 kJ/kg. [1] The muscles created for the final design must be able to output a similar force. The diameter of the muscle depends on the manufacturing process, with a coil diameter of 1.5 mm being average for small Cavatappi. This number must be maintained. When actuated in a system, the Cavatappi muscles exhibit an input-output ratio of around 45%. This metric is based on the mechanical input by the fluid on the muscle and the output work of the muscle. [1] The number of muscles per bundle and maximum muscle length target values were suggested by the client. [2] Finally, human muscle has an efficiency of around 20%. [1] Because of this, clients suggested that ensuring that these muscles are similarly efficient on their own is a good benchmark for future testing.

## *2.3 Functional Decomposition*

### 2.3.1 Black Box Model

A black box model is a design tool used to determine the overall function of a device and express it in verb-object form. Black box models are also used to determine the input and output flows of a device. The team identified that a black box model would simplify the task of identifying which design aspects of the project to target.

The team began by identifying the overall function as being muscle actuation and the input flows for the materials, energy, and signal. It was determined that a signal was not necessary for the design of the project and that input/output flow was omitted for the model. Next, the team identified that the materials that would be input were hand and fluid, these materials were taken from simulations done with test muscles produced in the lab. The team noted that input from a human hand and an incompressible fluid were key to producing muscle actuation. The coincident energy inputs were identified as mechanical energy and human energy, which were also necessary to produce muscle actuation. The team then identified the remaining material and energy flows as outputs for the system. That output for the material flow was the incompressible fluid, which remained after muscle actuation, and kinetic energy for the energy flow. The team utilized kinetic energy for this flow because the client proposed utilizing water for the incompressible fluid.

Utilizing the black box model, the team was able to identify that manufacturing reliable muscles was a key aspect to success for the project. Reliable muscles will ensure proper delivery of fluid to the system and maximize the energy output of the system. The black box model can be found in Appendix A.

### 2.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

A functional model visually describes the methods used to transform input flows to desired output flows. Functional models can be utilized to emphasize what needs to accomplish to achieve a desired output rather than how to achieve a desired output, which the team used to determine what subfunctions proposed designs needed to achieve.

The team determined that the material inputs were primarily used to input, store, and guide the fluid through the muscle. This was achieved by inputting and converting mechanical energy into kinetic energy that could be transferred to the fluid. The fluid was then guided through the muscle and exported from the system, expelling both kinetic energy and fluid. This model was helpful in determining that the team

should focus on the energy output as that was one of the functional requirements that was determined to be of high importance in the house of quality. In addition, the team determined that other important design aspects that should be kept in mind are consistent production quality, reduction of leaks in muscle, muscle diameter, and the mechanical input to hydraulic output ratio that were also identified in the house of quality. The functional model can be found in Appendix B.

## 2.4 House of Quality (HoQ)

For Team Cavatappi, the House of Quality is used to determine which engineering requirements should be the main focus of the prototype development process. By directly comparing the CRs and the ERs with weighted correlations, the most important engineering requirements influence the customer needs. If an ER correlates highly with a CR, it receives a weight of 9. A moderate correlation is a 3 and a low correlation is 1. The sum of these correlations determine which ERs are most important with respect to CRs. A House of Quality based on these CRs and ERs is in Appendix C.

The five highest-rated ERs based on weighted relationships are minimizing muscle diameter, the factor of safety, the number of muscles used in parallel, length of the Cavatappi muscles, and ensuring that the pressure stays within the aforementioned maximum. Essentially, the House of Quality proves that muscle geometry and safety are the most important metrics compared to the CRs. For how these are analyzed for testing, see Section 3.

## 2.5 Standards, Codes, and Regulations

**Table 1:** Standards of Practice as Applied to this Project

| Standard Number or Code | Title of Standard | How it applies to Project |
|---|---|---|
| ASNI/AAMI HE 74:2001 | Human Factors Design Process for Medical Devices | Helps in the design of how the device will interface with the user in a safe manner. |
| AAMI TIR30:2001 (AAMI TIR 30:2011) | A Compendium Of Processes, Materials, Test Methods, And Acceptance Criteria For Cleaning Reusable Medical Devices | Compilation of information available on acceptable cleaning processes for reusable medical devices. Applicable to the project because the device would be reused in a clinical setting. |
| AAMI TIR12:2010 (AAMI TIR 12:2010) | Designing, Testing And Labeling Reusable Medical Devices For Reprocessing In Health Care Facilities: A Guide For Medical Device Manufacturers | Includes information of design and testing for medical devices. |
| ANSI/AAMI HE74 HE75 HUMAN FACTOR SET | Human Factor Set | Focuses on design and development of medical devices to develop safe and usable medical devices that are easy to use. |
| ISO/TC 299 Robotics | Robotics | Includes information on the standardization of the robotics field. |
| IEC 80601-2-77:2019 | Medical electrical equipment — Part 2-77: Particular requirements for the basic safety/ essential performance of robotically assisted surgical equipment | Potentially helpful for future developments in Cavatappi muscles. |
| ISO 18646-3:2021 | Robotics — Performance criteria and related test methods for service robots — Part 3: Manipulation | Information of robotic manipulation such as grasp size, grasp strength, slip resistance, etc. that could be applicable to hand design. |

# 3 Testing Procedures (TPs)

The two main testing procedures planned are hand testing for next semester and Cavatappi tube testing to be completed in the next week as of delivery. The objectives of each are outlined below, as well as resources required.

## *3.1 Testing Procedure 1: Perspective "Hand" Testing*

Since this semester was focused on the development of the muscle fabrication system, next semester will be focused on the development and deployment of bundled actuators as well as the hand itself. The primary goal being delivering the optimal amount of force to the "digits" of the end effector in order to accomplish the tasks set by the client.

### 3.1.1 Testing Procedure 1: Objective

After the development of the bundled muscles and research around the required force to perform the task required, bundles will be tested by displacing the required weight a given distance so as to replicate not just the force necessary to grasp a coin or sewing needle on a flat surface, but also articulate the fingers the needed to distance.

### 3.1.2 Testing Procedure 1: Resources Required

The test is relatively resource low, in that it only requires a way to suspend the muscle bundle and the requisite weight to replicate the conditions needed, both of which are available to the team in the Dr. Shafer's Lab.

### 3.1.3 Testing Procedure 1: Schedule

As soon as a satisfactory manifold is developed and applied in order to run the muscles in parallel with each other using single force input and the research around the needed force parameters is complete the team will be able to begin the testing procedure to better understand the length, coil diameter, and number of muscles/ bundle needed to accomplish the task set by the client.

## *3.2 Testing Procedure 2: Muscle Testing*

### 3.2.1 Testing Procedure 2: Objective

The objective of running actuation tests on the Cavatappi muscles is to ensure that the newly manufactured muscles will perform as intended when applied as actuators for MIS laparoscopic surgical tools. The force and deflection of the muscles will help determine how many of them are necessary to perform a desired task.

In order to make a Cavatappi muscle, the drawing and twisting process helps align the polymers in the Tygon tubing in a way that allows for linear actuation once pressurized. To see how much twisting and how much drawing is ideal to produce a functional muscle.

The Engineering requirements focused on by this testing procedure are as follows:

- Increase Force Output ( >=0.38kJ/kg)
- Mech Input to Hydraulic Output (Wout/Win ~ 0.45)
- Minimize # Muscles per Bundle (2 < N < 4)
- Decrease Muscle Length (L < 90 mm)
- Decrease Pressure Input (100 psi < P < 150 psi)
- Maximize Muscle Efficiency (Efficiency > 20%)

### 3.2.2 Testing Procedure 2: Resources Required

In order to test the muscles consistently and to test for these ERs, the following basic process is followed:

1. Muscles are manufactured at differing lengths and draw ratios, ranging from 60 to 120 mm starting tube length and draw ratios of 1:1 (undrawn), 1:1.5 (1.5x drawn), and 1:2 (2.0x drawn). This helps narrow down an optimal muscle geometry.
2. The muscles are connected to a controlled pressure system and suspended vertically with a known weight on one end. A device to measure weight displacement is aligned underneath the weight to measure deflection during testing. Varying the pressure input at regular intervals helps determine optimal functioning pressures. If the muscle deflects more at one pressure and less at others, it's an easy way to determine an optimal operating pressure.
3. The deflection and pressure are recorded using DAQ software. These values can be used to determine work output versus work input. An efficiency is easy to calculate from there.

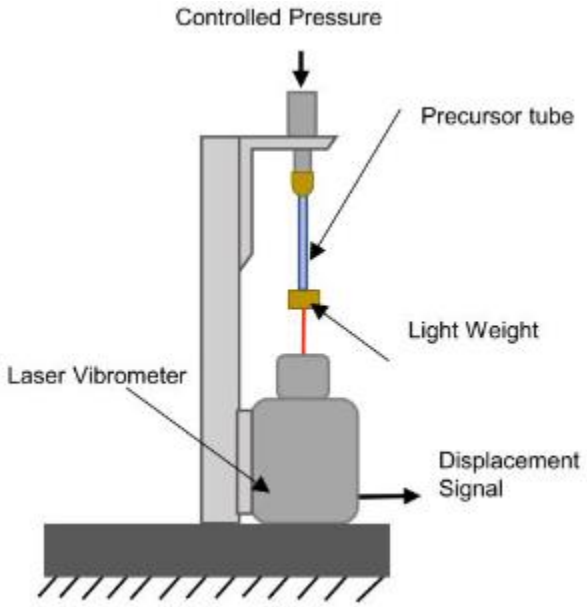



**Figure 2:** Cavatappi Deflection Testing setup [3]

Thankfully, the necessary testing instrumentation and software is available through the DAS Lab in the Engineering building and should be readily available for use.

### 3.2.3 Testing Procedure 2: Schedule

Muscle testing begins on the week of Nov. 21st, 2021. The manufacture of the muscles is likely to take but a day or two, with the full experiment conducted the following day. Calculations are expected to be done by Sunday, Nov. 28th, with a verdict on optimal muscle geometry and actuation forces the same day.

# 4 Risk Analysis and Mitigation

Team Cavatappi was provided with a base design for the muscle manufacturing system at the start of the semester and focused primarily on redesigning the coiling mechanism. The team performed an FMEA on the initial coiling system to determine what components were likely to cause failures and the types of failure modes. This information was used in the initial development of the final design, where the coiling apparatus, clamps, and polymer properties were the main design updates. The initial FMEA can be

viewed below in Figure 3 and Critical Failures 1-3 correspond to this information.

**Figure 3:** Initial System FMEA

Team Cavatappi performed an additional FMEA on the redesigned manufacturing system to identify if the

| Cavatappi Hand | | Development Team | | | | | Page No 1 of 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Manufacturing System | | | | | | | FMEA 1 | | | |
| Initial Coiling Mechanism | | | | | | | 10/3/2021 | | | |
| Part # and Functions | Potential Failure Mode | Potential Effect(s) of Failure | Severity (S) | Potential Causes and Mechanisms of Failure | Occurance (O) | Current Design Controls Test | Detection (D) | RPN | Recommended Action | |
| Clamps | Stress Corrosion | Shearing of the muscle | 8 | Polymer deformation | 9 | Physical Examination | 3 | 216 | Design/manufacturing of new clamps | |
| Clamps | Stress Corrosion | Wasting of material | 8 | Polymer deformation | 9 | Physical Examination | 3 | 216 | Design/manufacturing of new clamps | |
| Clamps | Stress Corrosion | Unreliable manufacturing | 8 | Polymer deformation | 9 | Physical Examination | 3 | 216 | Design/manufacturing of new clamps | |
| Twisting/Coiling mechanism | Stress Corrosion | Shearing of the muscle | 8 | Overstressing | 9 | Physical Examination | 3 | 216 | Hand-coiling until system can be tested/redesigned | |
| Twisting/Coiling mechanism | Stress Corrosion | Wasting of material | 8 | Overstressing | 9 | Physical Examination | 3 | 216 | Hand-coiling until system can be tested/redesigned | |
| Twisting/Coiling mechanism | Wear | Unreliable manufacturing | 8 | Overstressing/assembly errors | 9 | Physical Examination | 3 | 216 | Hand-coiling until system can be tested/redesigned | |
| Polymer | Stress Corrosion | Shearing of the muscle | 8 | Size/material properties/overstressing | 9 | None | 10 | 720 | Testing with various sizes and evaluating material properties | |
| Polymer | Wear | Wasting of material | 8 | Size/material properties | 9 | None | 10 | 720 | Testing with various sizes and evaluating material properties | |
| Polymer | Fatigue/wear | Inconsistent manufacturing of muscles | 8 | Size/material properties | 9 | None | 10 | 720 | Testing with various sizes and evaluating material properties | |

new design effectively mitigated failures from the initial system. Upon analysis, the team felt confident with the updated RPN of the clamps, the coiling mechanism, and the increased rate of successful muscle production. The updated FMEA is based on the CAD package presented in section *5.2 Implementation Plan* and can viewed below in Figure 4. Note that Critical Failures 4-10 correspond to this information.

| Cavatappi Hand | | Development Team | | | | | Page No 2 of 4 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Manufacturing System | | | | | | | FMEA 1 | | | |
| Coiling Mechanism | | | | | | | 10/25/2021 | | | |
| Part # and Functions | Potential Failure Mode | Potential Effect(s) of Failure | Severity (S) | Potential Causes and Mechanisms of Failure | Occurance (O) | Current Design Controls Test | Detection (D) | RPN | Recommended Action | |
| 1-T Slot Rail | Abrasive Wear | Noise, poor appearance | 2 | Overstressing, assembly errors | 1 | Physical Examination | 1 | 2 | Good RPN, no action needed | |
| 2-T Slot Rail | Abrasive Wear | Noise, poor appearance | 2 | Overstressing, assembly errors | 1 | Physical Examination | 1 | 2 | Good RPN, no action needed | |
| 3-T Slot Bracket | Abrasive Wear | Noise, poor appearance | 2 | Overstressing, assembly errors | 1 | Physical Examination | 1 | 2 | Good RPN, no action needed | |
| 4-Tower_Spool | Brittle Fracture | Erratic operation | 4 | Overstressing, assembly errors | 3 | Physical Examination | 3 | 36 | Look into properties of printing material. Possibly making modifications based on the fill, stiffness, strength, ect. | |
| 5-Spool | Brittle Fracture | Erratic operation | 4 | Overstressing, assembly errors | 3 | Physical Examination | 3 | 36 | Look into properties of printing material. Possibly making modifications based on the fill, stiffness, strength, ect. | |
| 6-Tower Mandrel | Brittle Fracture | Erratic operation | 4 | Overstressing, assembly errors | 3 | Physical Examination | 3 | 36 | Look into properties of printing material. Possibly making modifications based on the fill, stiffness, strength, ect. | |
| 7-Clamp | Fatigue/Abrasive Wear | Inconsistent manufacturing of muscles | 6 | Overstressing, assembly errors | 4 | Examination of Muscle | 2 | 48 | Look into properties of printing material. Potentionally redesign clamps | |
| 8-Clamp | Fatigue/Abrasive Wear | Inconsistent manufacturing of muscles | 6 | Overstressing, assemply errors | 4 | Examination of Muscle | 2 | 48 | Look into properties of printing material. Potentionally redesign clamps | |
| 9-Clamp Jaw | Stress Corrosion | Inconsistent manufacturing of muscles | 6 | Overstressing, assembly errors | 4 | Examination of Muscle | 2 | 48 | Look into properties of printing material. Potentionally redesign clamps/clamp jaw. | |
| 10-Set Screw | Wear | Difficulty with assembly | 3 | Overstressing | 1 | Only hand tightening | 1 | 3 | Good RPN, no action needed | |

**Figure 4:** Redesigned System FMEA

## *4.1 Critical Failures*

### 4.1.1 Potential Critical Failure 1: Initial System Clamps

[Provide a brief description of the potential failure here, how that failure could be caused, the effect of the failure, and then discuss how the failure can be mitigated.]

### 4.1.2 Potential Critical Failure 2: Initial System Twisting Mechanism

The initial design utilized a power drill to coil the polymers onto a mandrel which created the potential for stress corrosion. The team determined that the initial coiling mechanism was caused by overstressing of the muscle fibers, which were contributing to shearing of the muscle, depletion of materials, and unreliable manufacturing of muscle. The team also determined that the severity and the number of failures observed was too high to ignore. The course of action that the team decided on was to hand coil muscle fibers until the team could redesign the coiling mechanism.

### 4.1.3 Potential Critical Failure 3: Initial System Material

The material was the greatest source of failure in the initial system with stress corrosion, wear, and fatigue being the highest observed failure modes. The potential effects of failure were muscle shearing, depletion of materials, and inconsistent manufacturing. It was determined that size and material properties were the root of failure and additional testing would need to be conducted with various sizes of muscle fibers and research into the material properties of the polymer.

### 4.1.4 Potential Critical Failure 4: Redesigned System Part #1/2 T Slot Rail Abrasive Wear

The redesign of the manufacturing mechanism greatly reduced the potential for failure. Parts #1 and #2 are the aluminum base of the assembly and would only need to be assembled once over the course of the project. The main potential failure mode identified was abrasive wear due to overstressing and assembly errors and the potential effects of this failure are noise and poor appearance. The low level of severity, low number of occurrences, and high possibility of early detection contributed to a RPN of 2 and the team determined that no additional action was necessary.

### 4.1.5 Potential Critical Failure 5: Redesigned System Part # 4 Tower Spool Brittle Fracture

The redesigned manufacturing system is comprised primarily of low-cost 3D printed parts that can be replaced and redesigned efficiently. The drawback of this design is that the parts are made of a brittle material that has the potential to fracture when overstressed or assembled incorrectly. Fracturing of the material has the potential to cause erratic operation but the low rate of failure combined with the high detention rate have the design an acceptable RPN of 36. The team determined that additional research on the printing material was the only action needed.

### 4.1.6 Potential Critical Failure 6: Redesigned System Part #5 Spool Brittle Fracture

Part #5 shared the same failure modes, failure effects, severity, failure causes, occurrences, and RPN as Part #4. The team determined that additional research on the printing material was the only action needed.

### 4.1.7 Potential Critical Failure 7: Redesigned System Part #6 Tower Mandrel Brittle Fracture

Part #6 shared the same failure modes, failure effects, severity, failure causes, occurrences, and RPN as Part #4. The team determined that additional research on the printing material was the only action needed.

### 4.1.8 Potential Critical Failure 8: Redesigned System Part #7/8 Clamp

### Fatigue/Abrasive Wear

The redesign of the clamps changed the method of securing the muscle fibers from kinking the polymer in one place to applying pressure to the polymer over two different places without bending the muscle. This change has greatly reduced the effects of the failure to inconsistent manufacturing alone. The muscles no longer shear, and the inconsistent muscles still produce viable actuation, so no material is being wasted during production. These updates have reduced the RPN from 216 in the initial design to 48 in the redesign. The team has determined that the RPN is acceptable, and the only recommended action is to investigate the properties of the materials utilized in the updated design.

#### 4.1.9 Potential Critical Failure 9: Redesigned System Part #9 Clamp Jaw Stress Corrosion

Part #9 works in conjunction with Parts #7/#8 and share the same failure effects, severity, failure causes, occurrences, and RPN as Parts #7/#8. The team determined that additional research on the printing material was the only action needed.

#### 4.1.10 Potential Critical Failure 10: Redesigned System Part #10 Set Screw

Part #10 has the potential to fail due to wear from overstressing of the set screws during the assembly process. The team determined that this failure was not severe because the set screws will only be utilized at the start of assembly, would not need to be removed, and would only need to be tightened on rare occasions. The RPN was determined to have a value of 3 and would not need any additional action.

## *4.2 Risks and Trade-offs Analysis*

The final design that team Cavatappi chose to move forward with was a redesigned manufacturing system comprised primarily of low-cost 3D printed parts. Each of the parts were designed such that they can be replaced and updated efficiently to fit the needs of the project. The team did not experience trade-offs and the team was able to mitigate the main failure modes without having to increase risk in any areas of the design.

# 5 Design Selected

Included below are the final manufacturing design and prototype information. Current design geometry, changes, and cost analysis are included as well.

## *5.1 Design Description*

The design selected for Cavatappi muscle manufacture was named the Spooling Method. A mandrel is mounted horizontally between two bearing surfaces with freely rotating clamps. Cavatappi tube material is spooled perpendicularly to the mandrel, which can rotate via the clamps to spool material around it. Once coiled, the clamps can take the Cavatappi tube as well as the mandrel. The clamp and mandrel setup can be heated to thermoset the muscle into shape.

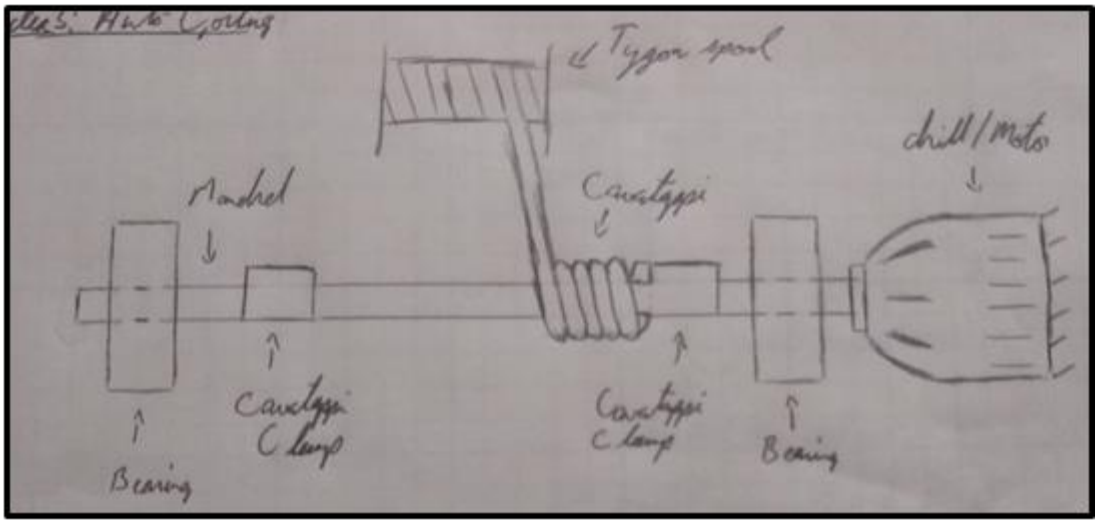



**Figure 5:** Drawing of Spooling Method

Not much if anything needed to be calculated to develop the design itself, as we were just adding mechanisms that removed human interaction from the process or further stabilized previously inconsistent processes. The spooling method allows the clamp and spool in combination with the motor (a simple electric hand drill in this case) to take the place of the operator that was previously simultaneously twisting and coiling raw material onto the mandrel by hand. This manual method introduced inconsistent force concentrations within the material that have now been removed. The current version of the manufacturing system is shown below:

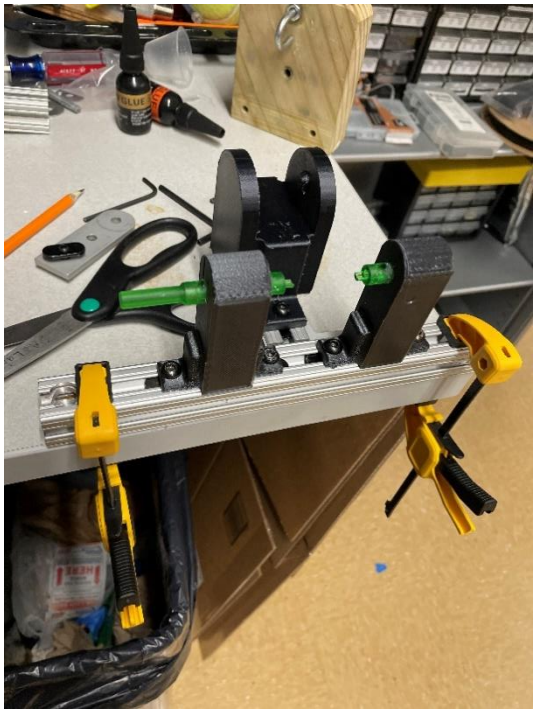


**Figure 6**: Current Manufacturing System

Along those same lines, the heating method that was used to anneal the actuators was a significant point of failure due to the heat source being a toaster oven with very simplistic controls and no internal convections fans to distribute heat more consistently across the actuators. Instead heat concentrations would happen unpredictably within the oven leading to actuator failure and scrap due to deformations in coils. To avoid this the heating method was replaced with a water bath or sous vide, commonly found in kitchens to cook food at low fixed consistent temperatures. Now while also maintaining the needed 170°F for 30 minutes, the actuator being submerged in water that is constantly moving means that it is getting a consistent heat distribution across the entire surface, almost eliminating the issues the team experienced prior in the toaster oven.

## *5.2 Implementation Plan*

**Table 1:** Bill of Materials

| ITEM NO. | PART NUMBER | PRICE | manual explode/QTY. | COST ($) |
|---|---|---|---|---|
| 1 | T_Slot Rail | $1.96/in | 1 | 23.52 |
| 2 | T_Slot Rail | $1.96/in | 1 | 23.52 |
| 3 | T_Slot Bracket | $0.89/item | 2 | 1.78 |
| 4 | Tower_Spool | $0.05/mL | 1 | >0.20 |
| 5 | Spool | $0.05/mL | 1 | >0.20 |
| 6 | Tower_Mandrel | $0.05/mL | 2 | >0.20 |
| 7 | Clamp | $0.12/g | 1 | >5.00 |
| 8 | Clamp | $0.12/g | 1 | >5.00 |
| 9 | Clamp Jaw | $0.12/g | 2 | >5.00 |
| 10 | Threaded Insert | $0.30/insert | 4 | 1.20 |
| 11 | B18.3.1M - 3 x 0.5 x 5 Hex SHCS -- 5NHX | $0.14/screw | 4 | 0.56 |

The design itself has already been implemented to a significant degree, and while some changes do need to be made the Towers, Spool, Clamps, and Clamp Jaws have all been 3D printed. The heat set threaded inserts were already in the lab as were any associated fasteners and other necessary hardware. While the costs listed in the Bill of Materials (shown above) would be the given prices if the parts were not available to the team in the lab, no money in the budget has been spent on this prototype. Further implementation is going to involve adjusting fits and tolerances to make the system more efficient. Hopefully by the end of week 15 these changes will have been made and could be tested in the first week of next semester. With the idea being that the focus for next semester should be the hand the first week of next semester should mark the end of the development cycle for the manufacturing system barring any unforeseen issues. Below is the current iteration of the manufacturing system and associated assemblies:

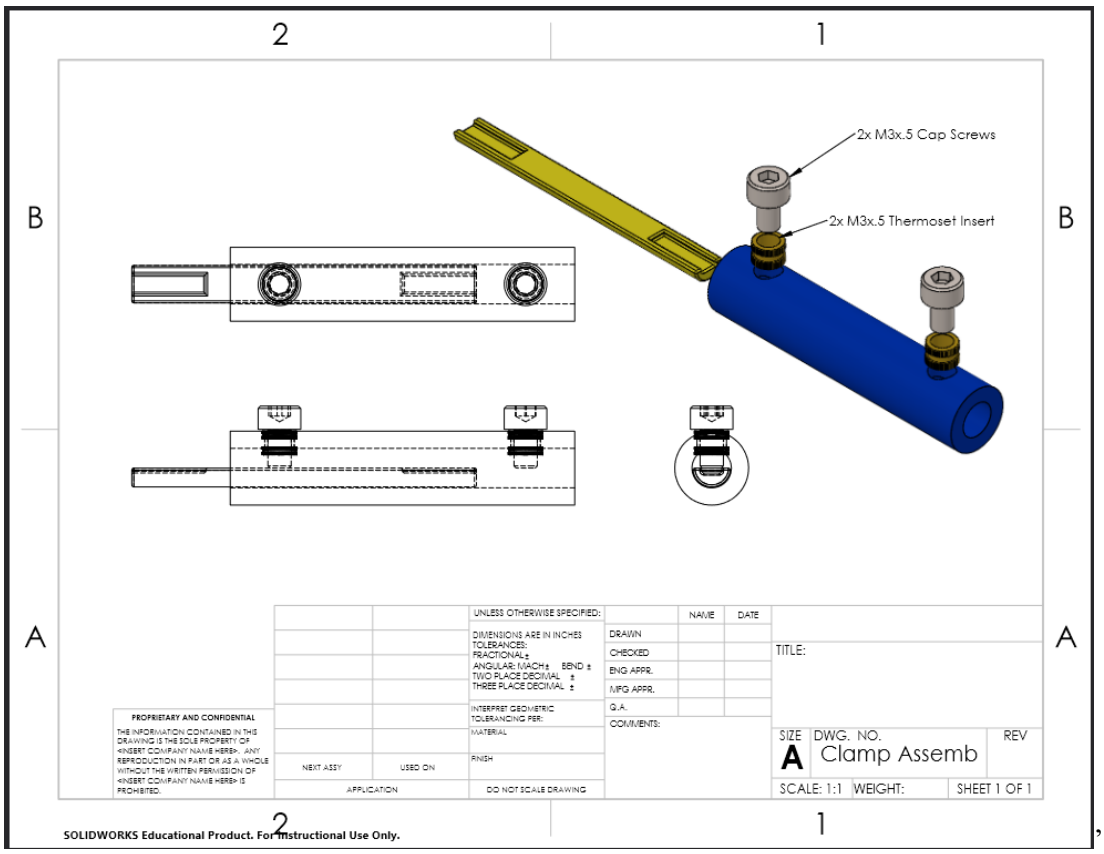



**Figure 7:** Clamp Assembly w/ Exploded View

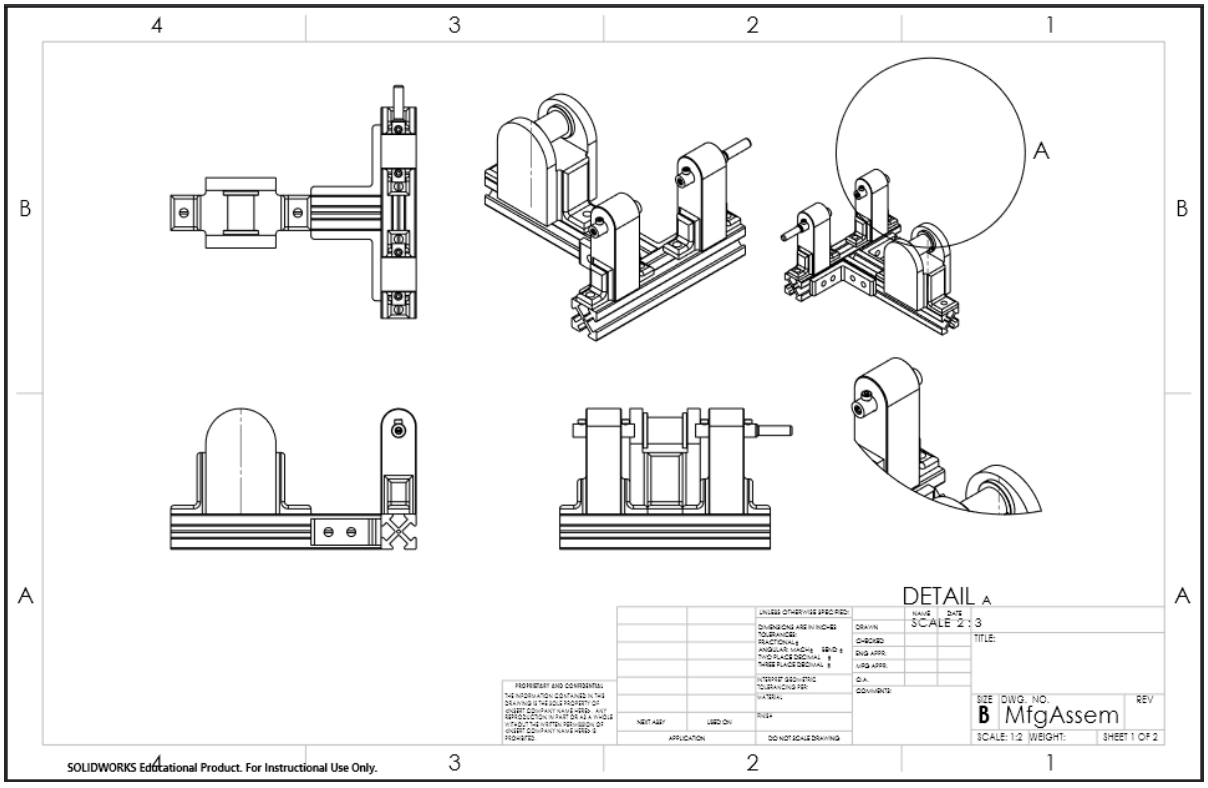



**Figure 8:** Manufacturing System Main Print

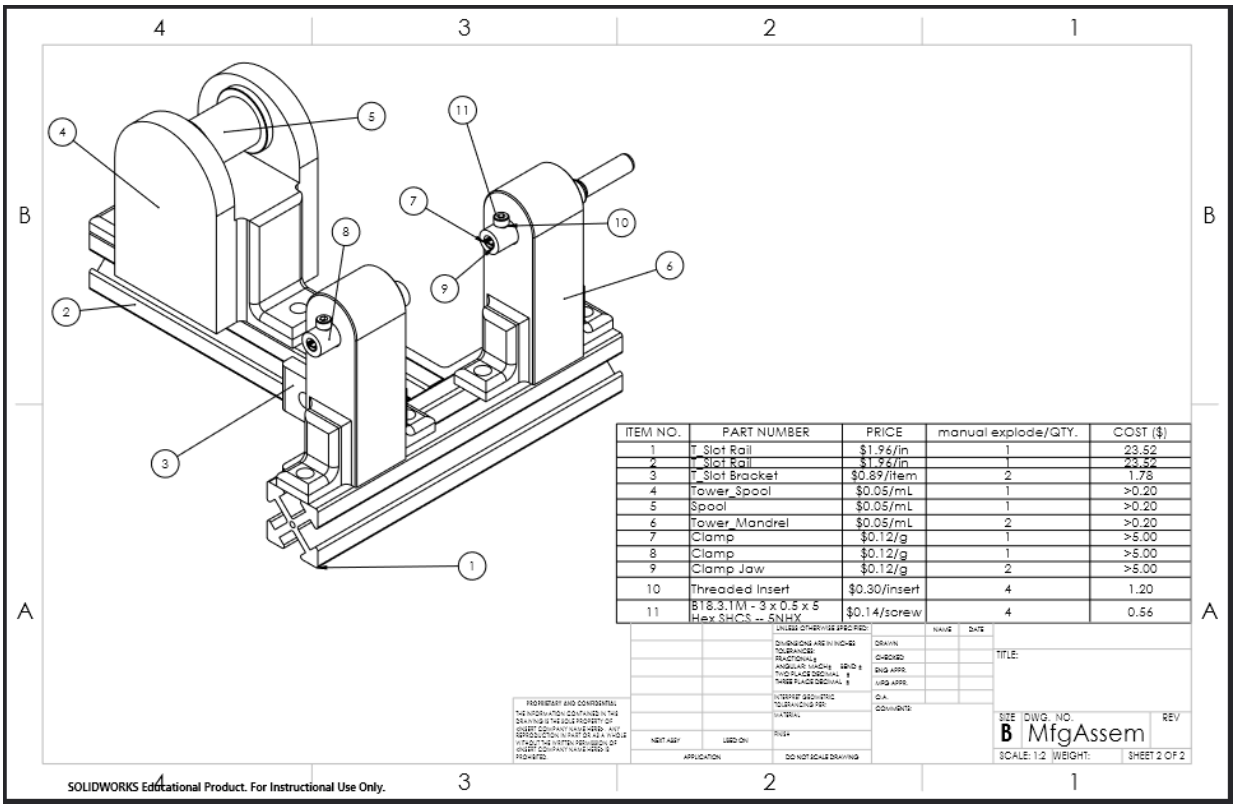



**Figure 9:** Manufacturing System w/ BOM

As the project continues into next semester after week 1 and the final tests of the manufacturing setup the teams focus will be set on developing muscle bundles capable of delivering the force necessary for accomplishing the task set by our client. The initial manifold tests will be run with what are known as “cable glands”, these are used for waterproof pass-through for wiring going into an enclosure that is going to be partially or fully submerged in a liquid. The are comprised of two plastic threaded components that when tightened squeeze down on a rubber gasket with holes in it that the straight uncoiled ends of a given actuator would be fed into. In the current design a syringe is directly interfaced with a single actuator, in this design the syringe would be interfaced with the cable gland where it could use pressure to drive the actuation of not just one muscle but multiple. In weeks 2 and 3 tests will be run to interface a syringe with the cable gland and some of the cavatappi actuators to find out how the cable glands and parallel muscles effect the overall work output.

# 6 CONCLUSIONS

The main goal of this semester was to design a manufacturing process for Cavatappi artificial muscles. Critical requirements of the project include making the muscles as small as possible to facilitate using them in parallel. The muscles should be actuated using hydraulics (syringes) to articulate an artificial hand-like laparoscopic tool. Minimizing its cross-section is a requirement to make a device that's as non-invasive as possible.

The current final design (The Spooling Method) utilizes a rotating mandrel with perpendicular Tygon fed in to create the muscles. Clamps can be removed from the setup to automatically be heated, setting the muscle and making it ready for application. Aside from previously mentioned analysis regarding design generation, the FMEA conducted for the manufacturing process recommends moving away from 3-D printed parts towards different materials to prevent inconsistencies in manufacturing. The parts would also wear less, preventing device failures. Testing procedures include future hand actuation and testing the muscles for work output and necessary pressure inputs. The focus of next semester will be to use these Cavatappi muscles in a laparoscopic tool for minimally invasive surgical procedures, as well as refining the new process for manufacture further.

# 7 REFERENCES


[1] D. R. Higueras-Ruiz, M. W. Shafer, and H. P. Feigenbaum, “Cavatappi artificial muscles from drawing, twisting, and coiling polymer tubes,” Science Robotics, p. 1 to 12, April 2021. Available: ScienceRobotics, https://www.science.org/doi/10.1126/scirobotics.abd5383. [Accessed: 01, Sep. 2021].

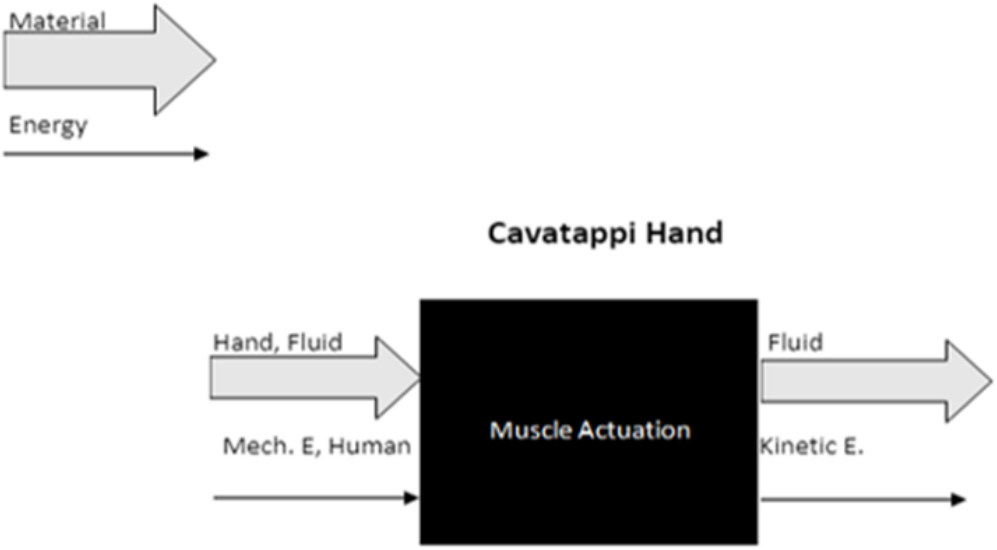
[2] D. R. Higueras-Ruiz, M. W. Shafer, “Highly Dexterous Surgical Hand using Cavatappi Artificial Muscles,” p. 1 to 2, August 2021. [Online].

[3] H. P. Feigenbaum , D. R. Higueras-Ruiz, and M. W. Shafer, “Supplemental Material for Cavatappi artificial muscles from drawing, twisting, and coiling polymer tubes,” Science Robotics, p. 1 to 10, April 2021. [Online]. Available: https://www.robotics.sciencemag.org/cgi/content/full/6/53/eabd5383/DC1

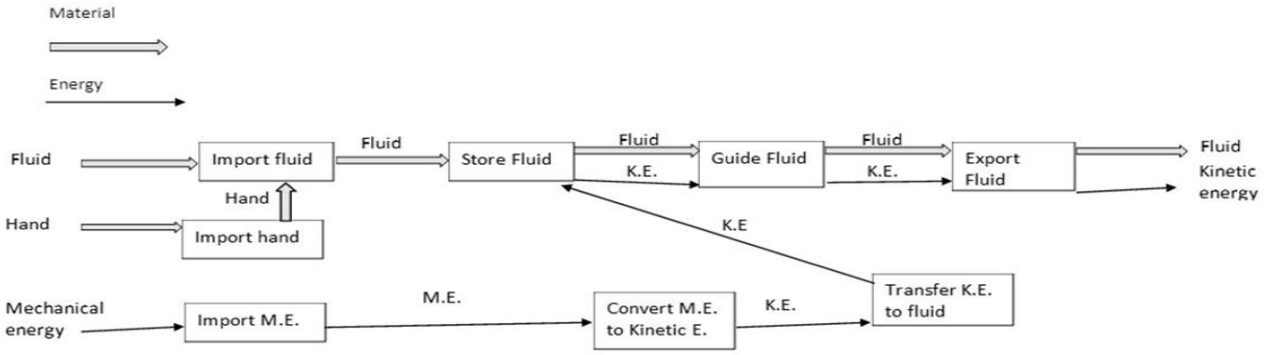
# 8 APPENDICES

[Use Appendices to include lengthy technical details or other content that would otherwise break up the text of the main body of the report. These can contain engineering calculations, engineering drawings, bills of materials, current system analyses, and surveys or questionnaires. Letter the Appendices and provide descriptive titles. For example: Appendix A-House of Quality, Appendix B- Budget Analysis, etc.]

## *8.1 Appendix A: Black Box Model*




## *8.2 Appendix B: Functional Model*

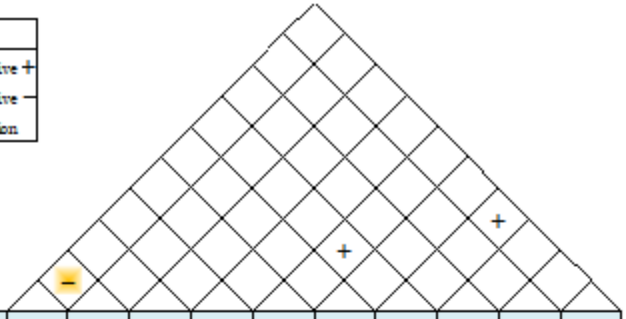


## 8.3 Appendix C: House of Quality

| Relationships | |
|---|---|
| Strong | ● |
| Moderate | ○ |
| Weak | ▽ |

| Correlations | |
|---|---|
| Positive | + |
| Negative | − |
| No Correlation | |

| Direction of Improvement | |
|---|---|
| Maximize | ▲ |
| Target | ◇ |
| Minimize | ▼ |




| Row # | Weight Chart | Relative Weight | Customer Importance (rating 1 - 5) | Maximum Relationship | Customer Requirements (Explicit and Implicit) \ Functional Requirements | 1 Maximize Force Output | 2 Minimize Muscle diameter (d) | 3 Minimize Manufacturing Cost (USD) | 4 Mech Input to Hydraulic Output (ratio) | 5 Minimize "Hand" Size | 6 High Factor Of Safety (FS) | 7 Minimize # Muscles per Bundle (N) | 8 Minimize Muscle Length (L) | 9 Minimize Pressure Input (P) | 10 Maximize Muscle Efficiency (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Column # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| | | | | | Direction of Improvement | ▲ | ▼ | ◇ | ◇ | ▼ | ▲ | ▼ | ▼ | ▼ | ▲ |
| 1 | | 11% | 4 | 9 | Design System For Muscle Fabrication | ○ | ○ | ● | ○ | ○ | ● | ▽ | ○ | ▽ | ▽ |
| 2 | | 11% | 4 | 9 | Muscle Scalability | ● | ○ | ○ | ● | ● | ▽ | ● | ○ | ○ | ○ |
| 3 | | 8% | 3 | 9 | Reliable | ▽ | ▽ | ○ | ▽ | ○ | ● | ○ | ▽ | ○ | ● |
| 4 | | 14% | 5 | 9 | Safe to Operate | ▽ | ▽ | ▽ | ○ | ▽ | ● | ▽ | ▽ | ○ | ▽ |
| 5 | | 14% | 5 | 9 | Acuated in a "glove-like" mechansim | ▽ | ● | ▽ | ○ | ○ | ▽ | ▽ | ● | ● | ○ |
| 6 | | 11% | 4 | 9 | Utilize bundled muscles in paralell | ● | ● | ○ | ● | ▽ | ▽ | ● | ● | ○ | ● |
| 7 | | 14% | 5 | 9 | 1cm x 1cm maximum size of "hand" | ○ | ● | ▽ | ▽ | ● | ▽ | ● | ● | ● | ○ |
| 8 | | 8% | 3 | 9 | Flexible/ Durable | ○ | ▽ | ▽ | ○ | ▽ | ▽ | ● | ▽ | ○ | ● |
| 9 | | 8% | 3 | 9 | Reduce leaks in muscle | ○ | ▽ | ▽ | ○ | ▽ | ● | ▽ | ▽ | ○ | ○ |
| 10 | | 3% | 1 | 9 | Cost Within Budget | ▽ | ▽ | ● | ▽ | ○ | ▽ | ▽ | ○ | ▽ | ▽ |
| | | | | | Target | >=0.38kJ/kg | d<=1.5mm | Cost < $200.00 USD | Win/Wout = 1 | <=1cm^3 | 1.25 < FS < 3.25 | 3 < N < 4 | L < 50 mm | 120 psi < P < 150 psi | Efficiency = ~ 20% |
| | | | | | Max Relationship | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 | 9 |
| | | | | | Technical Importance Rating | 361.11 | 455.56 | 250 | 388.89 | 366.67 | 433.33 | 472.22 | 455.56 | 444.44 | 416.67 |
| | | | | | Relative Weight | 9% | 11% | 6% | 10% | 9% | 11% | 12% | 11% | 11% | 10% |