Poba Medical

Preliminary Proposal

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1 BACKGROUND

1.1 Introduction

Our team has been tasked with designing and building a radial expansion tester, with controlled temperature and axial load, for the extruded plastic tubes used by Poba Medical in the manufacture of their medical balloons. The device must be able to inflate the tubes to bursting, pull the tubes with 150 lbs of force, heat a section of the tubes to 250ºF, and measure the diameter of the tubes as they inflate. Poba Medical is a company that manufactures balloons and catheters for a variety of medical purposes. Currently, to determine whether or not it is possible to manufacture a balloon design with a tube of a specific size and material, Poba needs to actually attempt to make the balloon. This requires new tooling to be purchased and time to be spent making the balloon. Our device will allow Poba to measure the properties of their tube stock and decide in advance if a balloon design is feasible based on their findings. This will save them a significant amount of time and money.

1.2 Project Description

The following is the original project description from the project proposal as we received it from Poba Medical:

> To design and build a radial expansion tester for thermoplastic extrusions. The extrusion profile required for testing is a circular cross-sectional tube. The extrusions are made from different thermoplastic materials and are used to form medical balloons through a blow molding process. The machine needs to be capable of measuring the radial expansion of thermoplastic tubes at controlled temperature under a constant axial load.
>
> Design inputs:
>
> - Constant axial force applied during testing with the ability to pull up to 150 lbs
> - Test extrusion diameters from .02-.625
> - Test expanded extrusion diameter up to 2.5”
> - Material temperatures control, including temperatures up to 250F
> - Continuous diameter measurements during radial expansion of tubing
>
> Project completion goal:
>
> Once the project is complete Poba wants to use this machine during its incoming extrusion inspections. Poba wants to have the ability to record radial expansion data. This will help Poba improve its extrusion designs.

2 REQUIREMENTS

The requirements section will review the customer requirements, the engineering requirements, and a QFD for the Radial Expansion Tester. The Radial Expansion Tester will need to pressurize plastic extrusions, apply up to 150 lbf of axial force, heat a section of the extrusion up to 250℉, measure temperature, force, and radial expansion of the extrusion, and output all of these measurements. The customer requirements were generated through reverse engineering the project description, as well as multiple meetings with engineers at Poba. The engineering requirements were given in the project description, as well as meetings with engineers at Poba. The QFD was created to see how these requirements relate to each other, as well as benchmark other similar devices to get an idea of what does and doesn't work.

2.1 Customer Requirements (CRs)

Customer requirements are important for a design project because they help define what the design needs to do. While vague, they are an important stepping stone to creating a clear set of expectations for the machine. For the Radial Expansion Tester, the team was given a list of technical requirements. These were then reverse engineered into customer requirements by making them less technical for use in a QFD. Along with this, multiple meetings with the engineers at Poba Medical resulted in extra customer requirements. The customer requirements are as follows:

1. Actuate axial load
2. Continuously measure axial load
3. Pressurize balloons
4. Test unexpanded diameters
5. Test expanded diameters
6. Continuously measure diameters during expansion
7. Temperature control for extrusion
8. Continuously measure temperature
9. Durable and robust design
10. Reliable design
11. Safe to operate
12. Stay within budget

These needs all relate to the successful completion of the Radial Expansion Tester. This is because the purpose of the Radial Expansion Tester is to test how medical balloons created from plastic extrusions react while being pressurized while under the influence of axial force and high temperatures. Therefore, actuating an axial load is necessary as Poba wants to test balloons under the influence of and axial load, controlling the temperature of the extrusion is important because Poba wants to test under the influence of high temperatures, and taking measurements of everything going on is important because it will create quantifiable data about how the balloon is reacting.

The customer needs were grouped into 6 different groups to further organize them and begin breaking the machine into subsystems. The groups decided upon were Pulling, Heating, Diameter Measurement, Pressurization, and General. The pulling group included Actuate axial load, and continuously measure axial load. The heating group included Temperature control for extrusion, and Continuously measure temperature. Diameter Measurement includes Test unexpanded diameters, Test expanded diameters, and continuously measure diameters during expansion. Finally, general includes Durable and robust design, reliable design, safe to operate, and stay within budget.

As stated before, this grouping allows the group to break up the device into multiple different subsystems that can be prototyped individually. This allows the team to focus on one topic at a time and not get overwhelmed. The group also made a Discord with a group for each of these groups in order to easily share any ideas the members may come up with.

2.2 Engineering Requirements (ERs)

Engineering requirements help translate customer requirements into actual technical requirements that the team can aim for. This moves the team closer to the prototyping stage, as it allows them to clearly define goals and specify what the machine needs to do. For the Poba Medical team, a list of technical requirements was given. This made defining the engineering requirements for this project fairly straightforward. However, after a few meetings with engineers at Poba, extra customer requirements were added which had to be translated into engineering requirements. During these meetings the engineers from Poba also specified tolerances for each of these requirements. The requirements are as follows:

1. Apply up to 150 lbf of axial load
2. Measure Axial force within .005 lbf
3. Control Temperature of Extrusion up to 250℉
4. Measure Temperature of Extrusion within 1-2℉
5. Pressurize Balloons up to 300psi
6. Change Test diameter from .2-2.5”
7. Measure Test diameter within .005 in
8. Output measurements
9. Costs between $5,000-10,000

A Radial Expansion tester that meets all of these requirements would accomplish everything that the client required. This is because the machine would be able to pressurize the balloons, apply an axial load, control the temperature of the extrusion, measure all of the changes that are happening, and output those measurements giving quantifiable data. The measurement constraints were added during meetings with engineers at Poba, and they exist to give the team an idea of how accurate the Radial Expansion Tester must be.

These specific requirements are based on the upper limits of the balloons being created at Poba Medical. The balloons that are defining the engineering requirements are created from hard nylon, and need much more force than other types of balloons that Poba is creating. For instance, applying 150 lbf of axial load is needed for the nylon material, as most balloons will need much less force, especially when the balloons are being heated. Another example of the upper limit relating to the hard nylon is the balloons needing to be heated up to 250℉. This is enough to melt most of the balloons that Poba is creating, but it is only enough to soften the nylon.

The accuracy for the measurements is required due to the accuracy that is needed in the medical device field. Balloons that are being tested with the team's machine will be going into people, and the surgeon using them will want to have a high level of confidence in the balloons. The measurements then need to be output so that engineers can read them and gain knowledge about how the balloons react under certain conditions. The budget relates to how much devices in this field can cost, and it was hinted that if the team is obviously trying and doing good work they could be given slightly more money, as buying a device off the shelf is much more than $10,000.

This list of requirements relates directly to the customer requirements, with each engineering requirement being relevant to at least one customer requirement. An example of this is “Apply up to 150 lbf of axial load” relating to “actuate axial load.” A less obvious example of this is “change diameters from .2-2.5” relating to “test unexpanded diameters,” and “test expanded diameters.” A QFD was created to track all of these relationships, as well as to benchmark similar products and has been included in section 2.3.

2.3 House of Quality (HoQ)

In order to summarize the customer and engineering requirements for this project, a house of quality has been created. This house of quality was created by taking the engineering requirements created through the project description and meetings with engineers at Poba and reverse engineering them to create customer requirements. Additional customer requirements were then added in order to meet the requirements for ME 476c. The team then examined how these requirements were related, with a 3 representing the requirements being slightly related, a 6 representing the requirements being fairly related, and a 9 representing the requirements being strongly related. Because the customer requirements were reverse engineered for this project, most customer requirements only relate to 1 or 2 engineering requirements. Along with this, they are either fairly related or strongly related. An example of this is "apply up to 150 lbf of axial load," only relating to "actuate axial force," and "continuously measure axial load."

The team then created the top of the QFD, where engineering requirements are related to each other to see how accomplishing one will affect accomplishing another. For this project, most engineering requirements were positively correlated with a few notable exceptions. Continuously measuring the diameter and heating the extrusion up to 250℉ are at odds because all of the ideas for heating the team has would directly get in the way of a digital micrometer, which is the main way that medical balloon machines measure diameter. Along with this, pressurizing the balloon up to and heating the balloon up to 250℉ are also at odds due to the pressurization changing a fluid property, which will make accurate heating harder to do.

Creating a QFD helped the team in the design process by forcing the team to break the technical requirements in the project description into more manageable customer needs. This allowed the team to better understand what the machine was supposed to actually do, as that was a point of confusion when the team first started. The QFD highlighted a couple of upcoming challenges, such as the continuous measurement of the diameter and the heating of the extrusion being at odds with each other. The QFD also gave the team the ability to start brainstorming and generating concepts for all of the engineering requirements, as it gave the team actual goals to shoot for. Along with this, the QFD also showed the team that the Radial Expansion Device is not a device that is already on market, as all devices benchmarked met some of the requirements, but none of them met all of the requirements. A small amount of the QFD has been included below, with the rest being in appendix A.

		Engineering Requirem							
Customer Needs (What)	**Customer Weights**	Apply Axial Force up to 150 lbs	Change Test Diameter .2-2.5"	Control Temperature Up to 250F	Measure Axial Force up to 150 lbs	Measure Test Diameter .2-2.5"	Measure Temperature up to 250F	Pressurize Balloons	Output Measurements (Force, Pressure Diameter, T
Actuate Axial Force	5	9			3				
Continously Measure Axial Force	3.5	3			9				9
Test Unexpanded Extrusion Diameters	5		9			3		1	3
Test Expanded Extrusion Diameters	5		9			3		3	3
Continously Measure Diameter During Expansion	5		3			9		9	9
Temperature Control for Extrusion	5			9			3		
Continously Measure Temperature	3.5			3			9		9
Stay Within Budget	2								
Pressurize Balloons during Testing	5							9	

Figure 1: QFD

3 DESIGN SPACE RESEARCH

Design space research is done in order to better understand the problem the team is tackling. In the upcoming section, the report will review a literature review, where each team member explains five relevant sources, benchmarking, where relevant designs are compared to see how they accomplish similar tasks, a black box model, where the team breaks the problem down into inputs and outputs, and a functional model, where the "black box" of the black box model is defined. Going through this process will allow the team to create quality concepts during concept generation.

3.1.Literature Review

The next section will give an overview of the Poba Medical teams Literature Review. Since this is a fairly grounded design, the team opted to include a lot of options that will help them design the machine such as book chapters and machine handbooks. However, a few research articles are included in order to better understand how parts of the machine could work. For this literature review, Michael Bransky focused on machine design and heat transfer, Noah Keyes focused on control systems, and Vergil Sorg focused on balloon design to better understand how the balloons are actually being blown.

3.1.1 Student 1 (Michael Bransky)

Michael Bransky focused on finding sources on machine design and heat transfer for his literature review. This involved finding sources related to SOLIDWORKS, gear design, heat transfer, lead screw design, and motor torques. This knowledge will help the team by allowing them to understand exactly how their design is working, and if it is within safe operating conditions. A strong knowledge of heat transfer will also help as it will give an idea on what could and couldn't work for controlling the temperature of the extrusion. These sources also help boost the creativity of the team, as they will have a larger abundance of machine parts to pull from for their design.

1. *Fundamentals of Heat and Mass Transfer, 7th Edition, Chapters 3-4.*

These chapters of the Fundamentals of Heat and Mass transfer focus on conduction. Specifically, they focus on 1 dimensional and 2 dimensional conduction using the finite difference method. They also mention that if a fluid is stationary you can treat it as a solid for conduction. This will be extremely useful for the project, as it will allow us to model heat transfer systems if we decide to go with a water bath.

2. *SOLIDWORKS 2019 for Designers, 17th Edition*

SOLIDWORKS 2019 for Designers 17th Edition is a book that includes everything you may need to know for SOLIDWORKS. Topics range from creating a sketch, properly defining drawings, creating weldments, and many more. This has been included in the literature review because the engineers at Poba have requested that we make SOLIDWORKS drawings of each of the designs, so they may review them before they order parts.

3. *Shigley's Mechanical Engineering Design, 10th Edition, Chapters 13-15*

These chapters in Shigley's Mechanical Engineering Design relate to gear design. These chapters give a variety of topics including info on gear ratios, ASME gear design, proper force analysis for spur, bevel, and helical gearing, as well as information on worm gears. This will be extremely helpful for the project because the team will need to understand gearing no matter which axial force actuation option they choose to go with.

4. "Kinematic Design Optimization of The Variable Lead Screw Mechanism With One Cone Meshing Element," *Mechanism and Machine Theory, Volume 31, Issue 8 Pgs 1081-1093*

This article describes how lead screws work, and how they supply the large amount of force that they do. It then goes on to prove that lead screws can be improved by optimizing the pressure angle and the coefficient of screw theory. While not entirely relevant to the project due to the team not developing their own lead screw, it does give a good idea of how lead screws actually work, and how they can be improved. This is important for the project, as it allows the team to choose the best possible lead screw for their application.

5. "A General Design For Electric Motors" *IEEE International Electric Machines and Drives Conference*

This source gives an overview on designing an electric motor. It provides useful diagrams that depict the process and questions you should ask on your way to designing a motor suitable for your project. It then provides a step by step guide on what you should do in order to design your motor. This will be helpful to the team because the team is most likely going to create a lead screw/motor combo in order to actuate axial force.

3.1.2 Student 2 (Noah Keyes)

Noah Keyes focused his literature review on control systems to automatically regulate the processes performed by the team's device. To this end, sources containing information on the theory behind automatic control, different types of controllers, and programming the specific controller available to the team were found. There were also a couple sources on methods to accomplish the heating, pulling, and inflating processes required for the project. With this knowledge, the team will have a far easier time developing the controls necessary for the different processes that must be performed by the device.

1. "Silicone-rubber heaters stretch product utility" *Machine Design Vol. 70 Issue 17 p166.*

This is a short article describing the utility of silicone-rubber heaters in the design of new products. It describes how, due to their flexible nature, silicone-rubber heaters can be made to fit into pre-existing design parameters which simplifies the design process. Based on the contents of this article, silicone-rubber heaters seem like a convenient option for our team to use during prototyping since they can be reformed to fit our changing designs. They also pose as a convenient, dry alternative to the water/oil bath method of heating suggested by Poba.

2. *Fundamentals of Modern Manufacturing: Materials, Processes, and Systems 7th Ed. Chapter 13*

This chapter of the textbook focuses on plastic shaping processes. It specifically includes information on the same sort of blow molding and extruding processes used by Poba in the manufacturing of their balloons. Understanding these processes is important for the team because these processes perform actions similar to what our device needs to do. Both processes involve heating, the extrusion process involves pulling, and the blow molding process involves inflating.

3. *Marks' Standard Handbook for Mechanical Engineers 12th Ed. Section 10*

This section from the handbook goes into great detail about automatically controlling processes, including logic and circuit diagrams for different types of controllers. Also includes in depth mathematics for controlling processes, such as damping. It is imperative that our team understands how to automatically control the processes used by our device because Poba has given us tight tolerances that the device must work within.

4. *Control Systems Chapter 7*

This chapter focuses on different types of controllers used to control processes. In particular, it includes detailed information on using digital controllers and programmable logic controllers (PLC). Our team has been provided a Watlow F4T PLC by Poba for use in our project, so it is important that we understand how to use it. The chapter also includes a ladder diagram of a heating system that will be useful to reference when we program our PLC.

5. *F4T Controller Setup and Operations User's Guide*

This is a user manual for the Watlow F4T PLC. It contains information about the software necessary to program the F4T, how to navigate the user interface, and how to create control loops with examples of a heating and cooling control loop. This resource will prove invaluable to the team when programming the F4T to control the different processes that our device will have to perform.

3.1.3 Student 3 (Vergil Sorg)

1. *"Methods for manufacturing multilayer balloons for medical applications"*

This is a patent which describes a general process and possible considerations for medical balloon manufacturing. It proved to be particularly useful in establishing a baseline of how these balloons are formed. Notably, this patent details general parameters such as estimated cross sectional areas after balloon expansion as well as general forces in which the balloons are subjected to both in operation as well as during the forming process. This patent was especially useful in the very early stages of the project development when the team was less confident in their understanding of the general balloon forming process.

2.*“Comparison of the diameter consistency and dialating force of the controlled radial expansion balloon catheter to the conventional balloon dilators”*

In contrast to the patent above, the purpose of this study was to examine the variations in balloon diameters as well as the associated force required to inflate them. Various different methods are discussed and the overall results seem to indicate that the influence of heat applied during the balloon forming process will be a major contributing factor in the effectiveness and the consistency of inflation force.

3. “Pneumatic Drives: System Design, Modeling and Control”

This is a book whose main focus is educating the reader about the intricacies of designing, sourcing, and operating a wide range of pneumatic systems. Of particular interest to our group specifically is the section on “electro-mechanical converters” wherein it documents how to read pneumatic schematics as well as good practises to follow when using various equipment such as solenoids and proportioning valves in both a manually operated form as well as electrically actuated.

4. “Interface Catheter Solutions Advances Balloon Forming Process with High-Efficiency Water Jackets”

Since it was clear that the method of heating was going to be quite important for this project, finding sources which detail the current state of the art balloon heating methods ought to prove quite useful. This article describes one design solution to this problem which is a “water jacket”. During our initial visit with the client this method was brought up quite frequently for its ability to provide both a stable heating source as well as an integrated method of rapid cooling. This article details the advantages of such a system as being primarily one of repeatability and uniform heating.

5. “Foundations of Ultraprecision Mechanism Design”

This is a book which details a wide range of considerations when one is concerned with precise mechanical operation of a machine. Since accuracy of measurement was stressed by the client, chapter 7: “Actuators and Sensors for Controlled Displacements” proved to be useful in that it contained information about how one would go about calculating the estimated displacements seen by measuring devices down to even the nanometre range. Additional chapters on various topics such as force feedback loops and strain gauge calculations also were of great interest to the group and useful for their rigorous mathematical descriptions of these physical phenomena.

3.2 Benchmarking

This section will go through the benchmarking that the Poba team has gone through. It will include a brief summary of three full system designs that have been benchmarked, as well three subsystems that can be benchmarked. Along with this, it will also include three designs for each subsystem. It is important to note that not all subsystems match with the subsystems in the concept generation section. This is because the team could not find 3 subsystems that measured diameters or produced axial force. Therefore, they felt it would be better to benchmark clamping and pressurization in order to get an idea for how other machines accomplish these tasks.

3.2.1 System Level Benchmarking

This section will introduce other designs that accomplish similar tasks to what has been requested of the team. It is important to note that while all of these machines accomplish some of the tasks, even accomplishing them very well, none of them accomplish all of the tasks. The 3 full systems that will be reviewed are the BW-TEC Balloon Forming Machine, The Hydraulic Burst Leak Tester and the Vertical Load Tester.

3.2.1.1 Existing Design #1: BW-TEC Balloon Forming Machine

The BW-TEC Balloon forming machine that can heat and pressurize balloons. It can heat balloons up to 599℉ [6] and pressurize them up to 1015 psi [6]. While this more than exceeds the project requirements, the machine does not apply axial loads or measure the diameter of the balloon. It has an easy to understand GUI, allowing for easy reading of measurements. The machine also costs much more than $10,000, meaning it exceeds the project budget.

Figure 1: Balloon Blowing Machine

3.2.1.2 Existing Design #2: Hydraulic Burst Leak Tester

The Hydraulic Burst Leak Tester is a machine that is used to test medical balloons. It applies pressure of up to 5000 psi depending on which model is bought [7]. This greatly exceeds the project requirement of 300 psi. Along with this, the hydraulic burst tester can also perform fatigue testing, as well as various other modes that test the balloons in different ways. The Hydraulic Burst Tester also gives readings on a very well made GUI. However, it has no temperature control, axial load actuation, or diameter measurement ability. This means that it only meets one of the engineering requirements, and would not be a competent design for the team.

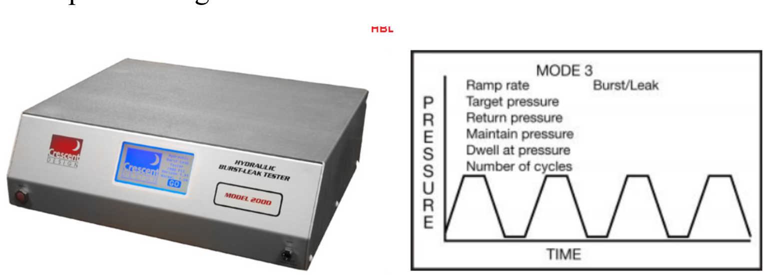

Figure 2: Hydraulic Burst Tester and Fatigue Testing

3.2.1.3 Existing Design #3: Vertical Load Tester

The vertical load tester is a machine in use at Poba Medical that applies an axial load to extrusions. It is set up vertically, which is atypical for medical balloon machines. It can apply loads up to 200 lbf, which exceeds the amount of axial force needed for the project. It actuates load through a lead screw and motor, which is a design that the engineers at Poba wanted the team to use. However, it cannot pressurize balloons, measure diameters, or control the temperature of the extrusion. It also cannot output measurements, making it a fairly incompotent design for the team.

3.2.2 Subsystem Level Benchmarking

[Use this section to discuss existing designs that address requirements relevant to your project at the subsystem level. Under each subsystem heading, list existing designs meeting similar or related requirements. There must be at least three existing designs described under each component/subsystem.]

3.2.2.1 Subsystem #1: Clamping

One function that the Radial Expansion Tester must accomplish is applying axial force up to 150 lbf without the balloon slipping. Because of this, a robust clamping system must be created. This section will discuss three different designs that already exist, the Blockwise Tube Grabber, the BW Tec Alligator Clamp, and Collets.

3.2.2.1.1 Existing Design #1: Blockwise Tube Grabber

The Blockwise Tube Grabber is a pneumatic clamp that closes radially around the extrusion. It is currently in use in a couple of the Poba machines. It can exert up to 300 psi, making it a possible choice for the side that needs to clamp and pressurize. This would help the team pressurize the extrusion, as well as actuate axial force without slippage.

3.2.2.1.2 Existing Design #2: BW Tec Alligator Clamp

Another clamp that is currently in use is an alligator clamp by BW Tec. This clamp closes with enough force to crush the extrusion, allowing it to be pressurized from the other side. It is machined out of aluminum, which makes it easy to manufacture something similar. This would help the team pressurize the extrusion, as well as actuate axial force without slippage.

3.2.2.1.3 Existing Design #3: Collets

A collet is a type of chuck commonly used in machining with a hollow cylindrical interior and slightly conical exterior. A round workpiece is placed inside the collet and the collet clamps the piece by forcing the conical exterior into a matching tapered hole. Collets are good at distributing force around the circumference of the workpiece to prevent deformation. This makes collets a good possible option for holding the plastic extrusions without crushing them.

3.2.2.2 Subsystem #2: Temperature Control

One of the engineering requirements that the machine must achieve is heating the extrusion up to 250℉. Currently, many medical balloon machines have very good control over the temperature of the extrusion. In the following section, three different temperature control subsystems are examined. These subsystems are the Water Bath from Poba Medical, the Box Heaters from BW Tec, and air heating.

3.2.2.2.1 Existing Design #1: Water Bath at Poba Medical

A temperature control solution currently being used at Poba medical is a hot water bath. This was essentially a food holding tray from Safeway filled with water that was jury rigged in order to act as a temperature controller. This was done by heating the water, and then lowering an extrusion into the heated water along with a sub assembly that held the extrusion in place. This helps the team accomplish heating the extrusion up to 250℉, and is fairly cheap which helps the team stay within budget.

3.2.2.2.2 Existing Design #2: Box Heater at Poba Medical

Another solution currently being used at Poba medical are what they call box heaters. These are used in tandem with the BW Tec Machines, and are as expensive as one would expect from BW Tec. They work by using cartridge heaters that are filled with hot water to heat up the extrusion, and then cooled rapidly with cold water. They would help the team heat the extrusion up to 250℉, but are fabulously expensive and would cost most if not all of the teams budget.

3.2.2.2.3 Existing Design #3: Air Heating

The final solution that will be discussed is heating the air around the extrusion. This is done by creating a case around the balloon, and then heating the air inside that case. This can be done through a variety of methods, including induction coils, cartridge heaters, and flexible silicone heaters. This will help the team achieve the engineering requirement of heating the extrusion up to 250℉ without completely blowing our budget.

3.2.2.3 Subsystem #3: Pressurization

Another main sub function that the Radial Expansion Tester must accomplish is pressurizing the balloons up to 300 psi. This is currently being done very well in the medical balloon world, with some machines reaching up to 5000 psi. The subsystems talked about in this section are the BW Tec Balloon Blower, the Hydraulic Burst Tester, and the Standard Pressurization used at Poba

3.2.2.3.1 Existing Design #1: BW Tec Balloon Blower

The BW Tec Balloon Blower is currently the state of the art balloon blowing machine. It can pressurize balloons up to 1015 psi, while maintaining temperatures of up to 599℉. Unfortunately BW Tec is secretive about how they blow their balloons, so even after a visit to Poba the team was still unsure of how this was exactly accomplished. This is much more than is required for the project, but it completely blows any budget we have out of the water.

3.2.2.3.2 Existing Design #2: Hydraulic Burst Tester

The Hydraulic Burst tester can currently apply up to 5000 psi of pressurization. Along with this, it can also be used for a variety of different pressurization tests. However, these are not needed for the project, so they are not being considered a pro of this system. This machine accomplishes the engineering requirement of blowing the balloon up to 300 psi, but it is out of the budget and also unclear of how it does so.

3.2.2.3.3 Existing Design #3: Poba Standard

During the team's tours at Poba Medical, the team saw how the custom made machines pressurize their balloons. This is done through a madril that goes into the extrusion, which fills it with nitrogen, pressurizing the balloon. The standard pressure at Poba is 300 psi, which is exactly what they are requiring for the project. This will help the team pressurize the balloon while not breaking the bank.

3.3 Functional Decomposition

Functional decomposition helps the team visualize what the device needs to do. For the Radial Expansion Tester, the device must take a plastic extrusion and compressed nitrogen, and create a popped balloon and a variety of measurements. This was mapped onto a black box model, and then the black box model was expanded to create a functional model.

3.3.1 Black Box Model

Poba Medical wants the team to design a device that they can place a plastic extrusion and some nitrogen into and turn on, that will then output a popped balloon as well as a variety of measurements and some heat. By generalizing the function of the device using a black box model, the team can be far more creative when generating ideas to accomplish each individual function of the device.

Figure 3: Black Box Model

3.3.2 Functional Model/Work-Process Diagram/Hierarchical Task Analysis

The functional model expands on the black box model by defining how the inputs get used to create the outputs. This is done by essentially expanding the “black box” into a list of sub functions that the design must accomplish. All of the inputs and outputs in the black box model should be accounted for in the functional decomposition. Doing this allows the team to come up with ideas on how to do every individual task required to complete each of the overall functions.

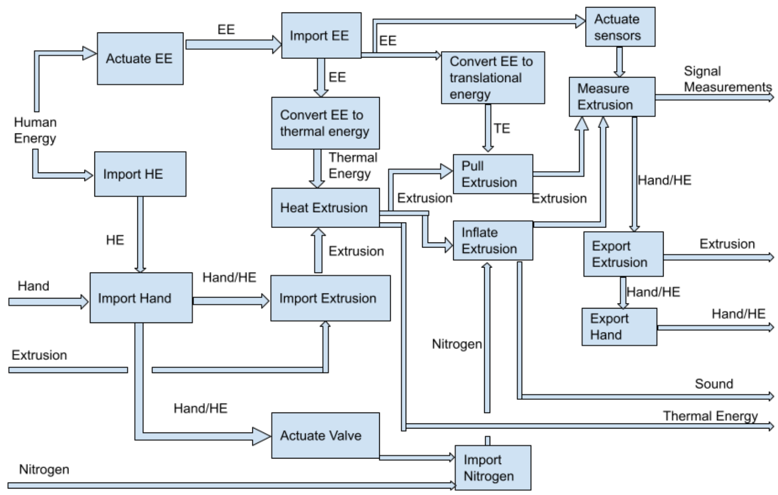

Figure 4: Functional Model

4 CONCEPT GENERATION

Concept generation is the first stage of prototyping. In this stage, the team created a multitude of concepts and concept variants that accomplished the tasks that were required from the radial expansion tester. Concepts were generated through team meetings, meetings with engineers at Poba, and through a Discord created by Vergil Sorg. In this section, three full system concepts will be discussed, as well as 4 axial load actuation subsystems, 4 temperature control subsystems, and 3 diameter measurement subsystems.

4.1 Full System Concepts

In this section, three full system designs will be described, and their pros and cons will be discussed. These are the initial design, the modified design, and the creative design. The initial design is what we would make if time and money were not objects, and it is based on what is already being made. The modified design is a modification of the initial design based on feedback from engineers at Poba medical. The creative design is a design that was created during brainstorming in order to improve the creativity of the group. A detailed discussion of each design is included below.

4.1.1 Full System Design #1: Initial Design

The first full system design that was considered was using a linear actuator to drive a guidecar with clamp holding the extrusion mounted on the guidecar. This would satisfy the requirement of actuating up to 150 lbf of axial force. The extrusion would then be heated using the box heaters currently used at poba, and the radius would be measured using a digital micrometer. The other end of the extrusion would be clamped pneumatically, allowing the extrusion to be pressurized from one side. All outputs would be read on a Watlow F2T, as that is a high end piece of equipment that Poba wants us to use. The pros of this design are that it uses a lot of pre-made assemblies allowing for easy assembly, and it uses a couple of solutions that are known to work such as the box heater. The cons are that it is extremely expensive, the parts don't all work in tandem with each other such as the digital micrometer and the box heater, and the engineers at Poba recommended not using a linear actuator. A figure has been included below.

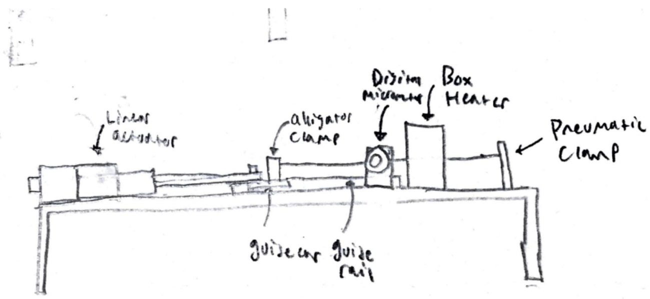

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Figure 5: Initial Design

4.1.2 Full System Design #2: Modified Design

The second full design that was considered is a modification of the first design discussed based on recommendations by engineers from Poba. Instead of a linear actuator, the axial force will be created using a lead screw and motor. A carriage will be attached to the lead screw, and a clamp that will hold one end of the extrusion will be attached to the carriage. The diameter will still be measured by a digital micrometer, but the extrusion will be heated by a fluid bath so the micrometer can see the extrusion. The other end will still be clamped with a pneumatic clamp, allowing for up to 150 lbf of axial force to be applied with no slippage. All measurements will be read on arduinos, and output onto a Watlow F2T. A figure has been included below. The pros of this system are that it is much cheaper than the first iteration, all parts work in tandem, and the noise of the balloon popping is dampened by the water it is submerged in. The cons of this design are that another sub assembly needs to be made to lower the axial load system into the water, all of the design must work around the fluid bath, and when the balloon pops it will send 250℉ fluid everywhere.

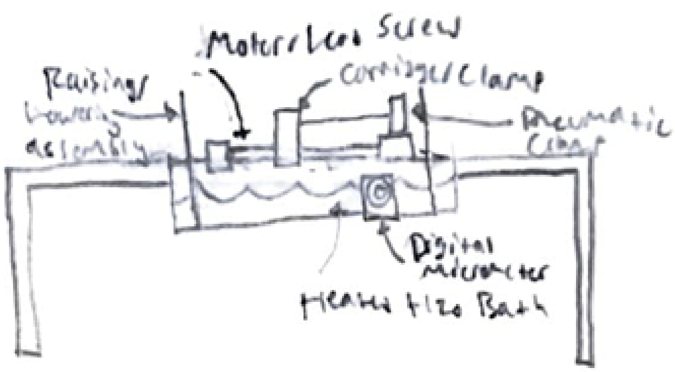

Figure 6: Modified Design

4.1.3 Full System Design #3: Creative Design

The final design considered was the team's "creative design." This design was created to improve creativity during brainstorming, and will not be made. This design used a pulley system combined with free weights to pull a guidecar holding a clamp holding the extrusion to actuate axial force. the extrusion is then heated and the diameter is measured using the sub assembly discussed in section 3.2.2.4. The other end of the extrusion is clamped using a pneumatic clamp, which will allow the balloon to be pressurized while having 150 lbf of axial force applied with no slippage. The pros of this system are that it includes an extremely cheap way to actuate linear force, it has a custom subsystem in it, and it improves the teams creativity during brainstorming. The cons are that there is a catastrophic failure waiting to happen once a balloon pops, the creation of the custom sub assembly would cost a lot of time and money, and Poba would need to find somewhere to store free weights. A figure has been included below.

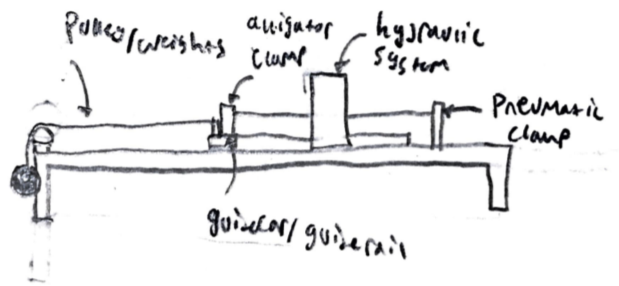

Figure 7: Creative Design

4.2 Subsystem Concepts

For this section, three separate subsystems will be discussed. These are the axial load actuation subsystem, which is required to actuate 150 lbf of axial load with an accuracy of ± 1 lbf, the temperature control subsystem, which is required to heat the extrusion up to 250℉ with an accuracy of ± 2℉, and the diameter measurement system, which is required to measure the radius of the extrusion with an accuracy of .005”. Four concept variants have been created for the axial load actuation and temperature control subsystems, while three have been created for the radial measurement system.

4.2.1 Subsystem #1: Axial Load Actuation

The first subsystem described is the Axial Load Actuation. This subsystem involves applying up to 150lbf of axial force to the extrusion, so that Poba can test the extrusions under significant axial loads. Four concept variants have been created for this subsystem: a linear actuator that drives a guide rail, a pneumatic actuator that drives a guide rail, a lead screw and motor, and a ball screw and motor. Detailed descriptions of each subsystem as well as their pros and cons have been listed below.

4.2.1.1 Design #1: Linear Actuator

A design solution that was considered was combining a linear actuator with a guiderail to actuate linear load. The actuator would be attached to the guidecar, which would be attached to a clamp holding the extrusion. The pros of this design are that it is relatively cheap, easy to design, intuitive, and it uses pre existing hardware. The cons are that it is hard to control the exact amount of force, the guide rail/ guide car can break, and the device would require a custom made controller for proper use. A figure has been included below.

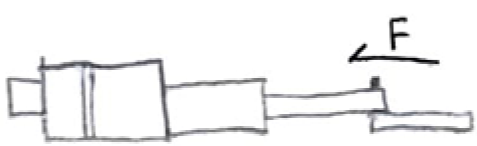

Figure 8: Linear Actuator Driving a Guide Rail

4.2.1.2 Design #2: Pneumatic Actuator

Another design solution that was created was using a Pneumatic Actuator instead of a linear actuator to drive the guardrail. This subsystem would work the same as the one above, but it would run off of compressed nitrogen which is in abundance at Poba Medical. This system has the pros of running off a readily available resource, being fairly cheap, being an original design idea, and . The two main cons of this system are that it is very hard to control, and the system would completely fail if the guide rail breaks. A figure has been included below.

Figure 9: Pneumatic Actuator Driving a Guide Rail

4.2.1.3 Design #3: Lead Screw/Motor

A design solution that was recommended by the Engineers at Poba was to use a lead screw that is being driven by a motor. The lead screw would have a carriage attached to it, which would have a clamp attached that would hold the extrusion. The carriage would travel down the lead screw as the motor turns, creating axial load in the extrusion. The pros of this design are that it can be made very cheaply, it takes up very little space, it converts motor torque directly into axial load, and it would be easier to find a controller for the motor. The cons are that it would be a very involved assembly, additional components would need to be bought in order to control it, and pre-bought lead screw assemblies can be very expensive.. A figure has been included below.

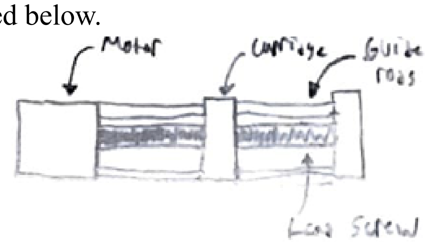

Figure 10: Lead Screw and Motor

4.2.1.4 Design #4: Ball Screw/Motor

This is another design solution that was recommended by the Engineers at Poba, and it works in a very similar way to the last design solution. The main difference between the two is that this design uses a ball screw instead of a lead screw. This would allow the process to move more quietly and smoothly, but would cost slightly more money. The pros of this design are that it would require less torque, it would be quieter, and it would run smoother than the lead screw. The cons are that it will be more expensive, ball screws do not auto lock, and the ball screw would generate less heat than the lead screw. A figure has been included below.

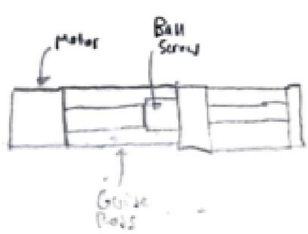

Figure 11: Ball Screw and Motor

4.2.2 Subsystem #2: Temperature Control

In order to meet all of the engineering requirements, the Radial Expansion Tester must be able to heat the extrusion up to 250℉. This means that the design must have some kind of subsystem that controls the temperature of the extrusion. 4 concept variants have been created for this purpose. The concept variants include cartridge heaters, a fluid bath, silicon heaters, and induction coils. These variants are described in detail below.

4.2.2.1 Design #1: Cartridge Heaters

One design concept that came directly from tours at the Poba facility was to line cartridge heaters radially around the extrusion for uniform heating. The cartridge heaters would be attached to a cube with a circular hole in it, so the extrusion can run through the heater. The pros of this design are that it is similar to what is being used in industry which works well, and there are known controllers for cartridge heaters. The cons of this design are that it is extremely expensive, the diameter of the hole cannot be changed, a digital micrometer cannot see inside of it, and if it breaks it is expensive to repair.

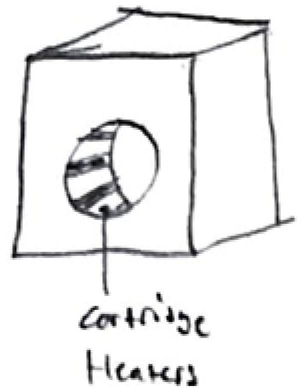

Figure 12: Cartridge Heater

4.2.2.2 Design #2: Water/Oil Bath

Another idea that was pulled from touring the Poba facility was using a bath of some kind of fluid to heat the extrusion. The fluid that is used currently is water, but this design may need some kind of oil to reach temperatures up to 250℉. This would also involve creating another subassembly that lowers the axial expansion subsystem into the fluid, and all wiring would need to be able to handle that. The pros of this assembly are that it's cheaper than the cartridge heaters, it's another known solution, and it is the only proposed design that can make use of a digital micrometer without the use of a separate subassembly. The cons are that it creates another separate subsystem, all circuitry being used would need to be built around it, and it takes upwards of an hour to heat the fluid up to 250℉.

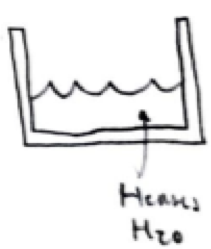

Figure 13: Heated H20

4.2.2.3 Design #3:Flexible Silicone Heaters

Another design that was discussed was a radial application of flexible silicone heaters. The silicon heaters would be mounted in a similar way to the cartridge heaters, and the extrusion would run through the center of the block. If these heaters were mounted on something flexible, it is possible that the diameter of the hole in the mount could be changed without having to have multiple different mounts. The pros of this design are that if designed right only one mount would be needed, they could work with a Watlow controller that the team has access to, and the design could be kept completely dry. The cons of this design is that it is on par with the cartridge heaters price wise, assembly would be difficult, and additional circuitry would need to be done.

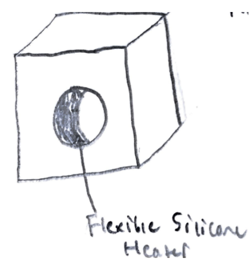

Figure 14: Flexible Silicone Heaters

4.2.2.4 Design #4: Induction Coils

The final design that was being considered uses induction coils. The extrusion would run through the induction coil, and be warmed by the heat radiating off of the hot metal.(add) The pros of this system are that it is very cheap, it heats up very quickly, and . The cons of this system are that it will require a separate controller, it may be hard to accurately control the heat coming off of the induction coil and a digital micrometer cannot see inside the induction coil.

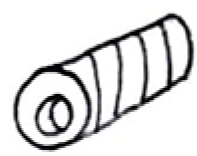

Figure 15 Induction Coil

4.2.3 Subsystem #3: Diameter Measurement

Another requirement from the Radial Expansion Tester is that it must be able to measure radius expansion from .2-2.5”. The measurement must be accurate up to .005”, meaning that top of the line technology must be used. This is where the team is expecting to spend most of their budget. Three possible solutions have been included and discussed below: A digital micrometer, callipers, and a custom hydraulic system.

4.2.3.1 Design #1: Digital Micrometer

The digital micrometer was another solution that was recommended by the engineers at Poba. It is a device that optically measures things, and can be used for very small measurements. It also is very accurate, making it ideal for this design’s applications. The pros of this design are that it is accurate, can measure a variety of diameters, and takes measurements very fast allowing for the capture of the diameter right before the extrusion pops. The cons are that it needs to be able to see the extrusion, it cannot operate under temperatures of up to 250℉, and digital micrometers are often very expensive.

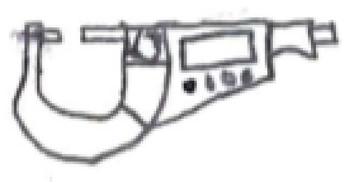

Figure 16: Digital Micrometer

4.2.3.2 Design #2: Callipers

Callipers could be employed in the Radial Expansion Tester. The would be set up inside of the heating element and would be set so the callipers will expand with the extrusion. This would allow engineers to read the measurement after the extrusion pops, allowing them to get a diameter measurement of when the extrusion popped. The pros of this design are that it is very cheap, it can withstand high heats, and it would eliminate the need for extra controllers. The cons of this system are that there is possible interference in the measurement when the balloon pops, it may not be possible to find a way in which the callipers can extend easily one way but not the other, and it would be hard to get the measurement within .005”.

Figure 16: Callipers

4.2.3.3 Design #3: Hydraulic System

The final subsystem that will be discussed for diameter measurement is a custom hydraulic system. This system will include a mesh that is being supplied with enough water pressure to be flush with the extrusion. As the extrusion expands, the mesh will also expand. The mesh will retain its shape after the extrusion pops, which will allow the change in diameter to be measured. The pros of this system are that it is a completely original design, if the water was heated it would allow us to combine two subsystems into one, and . The cons of this design is that it would be extremely hard to design causing the team to lose a lot of valuable time designing one subsystem, along with this it would also likely be very expensive.

Figure 17: Hydraulic Subsystem

5 DESIGNS SELECTED – First Semester

The following chapter details and quantifies the current form of the chosen design. Below is a technical selection criteria where the justification for narrowing down all of the possible solutions to each individual subsystem discussed above. After having narrowed down these alternatives to the top two, a rationale for choosing the winning one is presented for each system with all of the relevant calculations and considerations.

5.1 Technical Selection Criteria

In order to establish a clear and precise definition of what will constitute a successful machine, the team has quantified their choice of design by using the customer requirements to formulate a Pugh Chart in which the top five design solutions were narrowed down to two of the best iterations. Since this project involves so many different subsystems which all work collectively, three separate pugh charts were made in order to narrow down each available option.

5.1.1 Axial Loading

To start, the group determined it would be necessary to establish a method of extrusion axial loading. The available options being one which is operated manually with a pulley and weights, one operated with a pneumatic cylinder, one with a linear actuator, an electric motor attached to a leadscrew, and a belt- driven actuator. For this pugh chart the "baseline" use would be a manually operated vertical force tester. This is a machine used at the customer facility which measures the axial load that is placed on a piece of equipment.

The technical criteria chosen to evaluate these choices were safety, the ability to hit the target weight of 150lbs, the manufacturing and/or shipping time, the simplicity of the design, the accuracy it could be operated with, it's ability to be controlled easily, the cost, and the ease of data output. These are all very important criteria to consider as they affect the teams ability to use the design solutions in a safe, effective, and practical way while also staying within the budget as well as the timeframe given. The three leading designs would be the electric motor-driven ball screw, the linear actuator, and the belt-driven actuator. Clearly, we can see below that a system with the ability to pull a large load, be safe and easy to operate while being relatively simple tended to be the deciding factors to a systems success.

		Alternatives						
Criteria	Baseline	Electric Motor with Leadscrew	Linear Actuator	Belt- driven Actuator	Pneumatic Cylinder	Pulley / Weights	Totals	Rank
Saftey	0	+	+	+	0	0	3	1
Hit Target Weight (150lbs)	0	+	+	−	−	+	1	2
Manufacture/ Shipping Time	0	+	+	0	+	−	2	3
Simplicity	0	+	−	+	+	+	3	4
Accuracy	0	−	+	0	−	−	-2	5
Controllability	0	+	+	+	0	+	4	6
Cost	0	+	−	−	+	+	1	7
Easy Data Output	0	−	0	+	0	−	-1	8
	Totals	4	3	2	1	1		
	Rank	1	2	3	4	5		

Figure 19: Axial Loading Pugh Chart

5.1.2 Temperature Control

Next, a pugh chart for determining the best possible solution for a heating method was created. Since the success of the balloon expansion would be directly tied to the way in which the extrusion is heated, establishing this subsystem would be of the utmost importance. Similar to the axial loading devices, the relevant criteria would also be the safety, time to manufacture/ ship, simplicity, accuracy, controllability, and cost. However for heating obviously consideration should be given to the systems ability to hit the target temperature and do so in a reasonable timeframe.

As a "baseline" heating method an oven type configuration was chosen wherein an enclosed space would be heated around the products. For these criteria, the ability to hit the target temperature as well as be a safe and easily controllable system tended to determine which designs would end up succeeding. Below we can see that the prevailing solutions would be the induction coil heaters, flexible silicone heaters and Cartridge heaters heating flowing water would end up as the top choices.

Criteria	Baseline	Cartige heaters heating ambient air	Cartige heaters heating flowing water	"Water Bath" mineral oil submersion	Flexible Silicone Heaters	Induction Coils heating ambient air	Totals	Rank
		Alternatives						
Saftey	0	0	+	+	0	−	1	1
Hit Target Temperature	0	+	+	0	+	+	4	2
Manufacture/ Shipping Time	0	+	+	−	0	+	2	3
Simplicity	0	+	−	+	+	+	3	4
Accuracy	0	−	+	−	+	0	0	5
Controllability	0	−	−	−	0	0	-3	6
Cost	0	+	0	+	0	+	3	7
Easy Data Output	0	0	+	−	0	+	1	8
	Totals	2	3	-1	3	4		
	Rank	4	3	5	2	1		

Figure 20: Heating Pugh Chart

5.1.3 Diameter Measurement

Lastly, since the goal of this project focused largely on the ability to measure the expanded balloon diameters, determining which system or devices would accomplish this task would be of obvious importance. Of note would be that almost no existing systems were found that would give the machine the precision required to measure the expanded balloon diameters in a way that would not interfere with the measurement. As such most design options took a hit on accuracy besides the optical micrometer, which has the downside of being quite expensive.

Understanding this, one of the main criteria when choosing a system here would be the accuracy of measurement. Also of high importance would be the ability to accommodate a range of different diameters up to the largest estimated diameter of 2.5inches. Like all other systems discussed the shipping lead times for these pieces of equipment would be considered as well as their simplicity, reliability, controllability, cost, and ease of which we can extract data. Below we can see that the top three choices for diameter measurement given all the these relevant criteria would be the optical micrometer, the visual system, and the drop-test dial indicator.

		Alternatives						
Criteria	Baseline	Optical Micrometer	Drop-Test Dial Indicator	Visual System with grid backround	Hydraulic System	Calipers	Totals	Rank
Accuracy	0	+	-	-	-	-	-3	1
Accomidate range of dia	0	-	+	+	+	+	3	2
Manufacture/ Shipping Time	0	0	0	+	0	+	2	3
Simplicity	0	+	+	+	0	+	4	4
Reliability	0	+	0	-	+	-	0	5
Controllability	0	+	-	-	-	-	-3	6
Cost	0	-	0	+	+	+	2	7
Easy Data Output	0	+	+	+	-	-	1	8
	Totals	3	1	2	0	0		
	Rank	1	3	2	4	5		

Figure 21: Diameter Measurement Pugh Chart

5.2. Rationale for Design Selection

After knowing the top scoring design alternatives, the decision to choose a specific one was done by performing an assortment of "back of the envelope" calculations, and a comparison of various spec sheets and performance characteristics. The subsequent results were weighed against each other in a decision matrix to provide a clear and concise winner. The following section details the rationale for why a specific design decision was made and how exactly each relevant criteria plays a role in establishing the winner amongst the top two finalists from the pugh charts created for each.

5.2.1 Motor & Lead screw vs Linear Actuator

Since the motor and leadscrew combination would require deciding on a stepper motor size that would achieve the required force output, as shown in the graph below, a "nema 34" stepper motor would generate, depending on the "stack length" (the length or how many rotors are "stacked" on one another), on average around 8 Nm of torque.

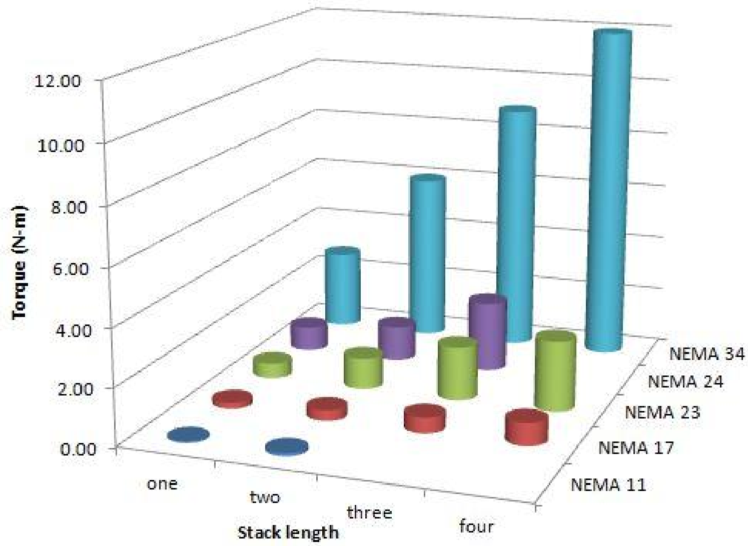

Figure 22: Nema Stepper Motor Size Chart

If we take a look a the three stack nema 34 stepper motor from "stepper online" we can see that the spec sheet for this specific model gives us a holding torque of 1841 oz.in

Electrical Specification	
Inductance(mH)	11
Phase Resistance(ohm)	1
Rated Current(A)	5
Step Angle(deg.)	1.8
Bipolar/Unipolar	Bipolar
Holding Torque(Ncm)	1300
Holding Torque(oz.in)	1841

Figure 23: Nema Motor Spec Sheet

Dividing this value by 16 gives us an estimated holding torque of around 115 lb.in. However, if we incorporate a pinion gear fixed to the end of the shaft of the motor with a diameter of 0.5in, meshing with a subsequent gear affixed to the ball screw with a diameter of 1.0in. Since the output torque would be

$$Tb = F * Lb$$

we could potentially see a torque value double that of the motor output at around 230lb.in

Conversely, for the linear actuator, a "Firgelliauto FA-150-S" gives an estimated pulling force or “dynamic force” shown below of 150lbs, however this will come at a const increase of over 100%.

Specifications

Model	FA-35-S-12-XX	FA-150-S-12-XX
Dynamic Force	35 lb	150 lb
Static Force	70 lb	300 lb
Speed ("/S)	2"	.5
Gear Ratio	5:1	20:1

Figure 24: Linear Actuator Spec Sheet

In order to decide between these two design alternatives a decision matrix weighting these two options was created, below we can see the various decision parameters used which include an assortment of relevant customer requirements as well as some device specific considerations. For these options we will weigh 4 different criteria; “ability to pull 150lbs”, “cost”, “safety” and “practicality”. As with the pugh chart, these metrics were extrapolated from the customer. Each of the two design solutions were given a score ranging from 0-10. The results of this decision matrix are shown below.

	Criteria 1	Criteria 2	Criteria 3	Criteria 4	
CRITERIA DESCRIPTION	Ability to Pull 150 lbs	Cost	Saftey	Practicallity	
OPTIONS	Criteria 1 SCORES	Criteria 2 SCORES	Criteria 3 SCORES	Criteria 4 SCORES	TOTAL SCORE
Stepper Motor/ Lead Screw	7	10	8	8	33
Linear Actuator	10	5	9	5	29

Figure 25: Axial Loading Decision Matrix

We can see that the stepper motor and lead screw combination does score slightly higher. This is a result of it being much cheaper to buy and operate than the linear actuator as well as being much more practical to use since the linear actuator will take up a large amount of space when compared to the small form factor of the lead screw. While the stepper motor and lead screw combination does take a significant hit from its requiring us to incorporate a secondary gear reduction, this does not prove to be as big of an obstacle to overcome when weighed against the fact that we will be saving so much money to be spent at a later time. At the moment of this document's publication, the Stepper motor and lead screw combination is the winner for the axial load system.

5.2.2 Induction Coils vs Silicone Heaters

The induction coils slightly won out over the silicone heaters in the pugh chart so as such we will look at some available configurations for both and compare these results. Instead of hand-calculating the required electrical conditions to achieve a certain temperature, a more reliable and accurate method would be to buy off the shelf components. As such, below is a decision matrix which compares the use of an already made heating system utilizing induction coils and one which utilizes silicone heating elements. The criteria for comparison includes: "Ability to reach desired temperature", "Cost", "Safety" and "Usage".

	Criteria 1	Criteria 2	Criteria 3	Criteria 4	
CRITERIA DESCRIPTION	Ability to Reach desired temperature	Cost	Saftey	Usage	
OPTIONS	Criteria 1 SCORES	Criteria 2 SCORES	Criteria 3 SCORES	Criteria 4 SCORES	TOTAL SCORE
Induction Coils	10	8	5	6	29
Silicone Heater	10	7	9	7	33

Figure 26: Heating Method Decision Matrix

We can see here that the induction coil design solution wins out in this category. This is less so a result of them being a very safe alternative (silicone heaters are notorious for being used in applications where safety is a major factor) and more so a result of them being the more generally applicable method of heating objects rapidly. This is shown in the "Usage" criteria where, since there seems to exist a comparatively much larger amount of data for applications utilizing a basic induction coil design, these present as having a distinct advantage over their silicone counterpart as usage characteristics such as controlling, regulating, and feedback sensing would be harder to find data for.

5.2.3 Optical Micrometer vs Visual System

Since both of these measurement systems have a non-contact method of measurement, one of the main deciding factors determining their successful operation is the accuracy of the measurements. Starting with the optical micrometer, a "Keyence TM-X5006" whose spec sheet is shown below, has a measurement position accuracy of 0.2 micrometers which is well below the +/- 0.005" tolerance range specified by the customer. This very impressive level of accuracy also comes at the slight drawback of having a 2.36" throat distance, which comes in at just slightly under the engineering requirement of measuring up to 2.5"

Sensor head

Model			TM-X5006	TM-X5040	TM-X5065
Transmitter/receiver distance			60 mm 2.36"	180 mm 7.09"	270 mm 10.63"
Measuring range	Field of view	High-accuracy measurement area	ø4 mm ø0.16"	ø26 mm ø1.02"	ø40 mm ø1.57"
		Measurement area	ø6 mm ø0.24"	ø40 mm ø1.57"	ø65 mm ø2.56"
	Depth of field	High-accuracy measurement area	2 mm 0.08"	10 mm 0.39"	20 mm 0.79"
		Measurement area	4 mm 0.16"	20 mm 0.79"	30 mm 1.18"
Exposure time			25/50/100 μs (Adjustable 3-stage)		
Imaging time (Trigger interval)			Approx. 24 ms (at "Full" vertical/horizontal measurement range sizes) Approx. 3 ms (at "4/16" vertical/horizontal measurement range sizes)		
Light source			InGaN green LED		
Measurement position accuracy*1		High-accuracy measurement area	±0.2 μm ±0.000008"	±1 μm ±0.000039"	±1.2 μm ±0.000047"
		Measurement area	±0.3 μm ±0.000012"	±2 μm ±0.000079"	±2.2 μm ±0.000087"
Repeatability*2			±0.03 μm ±0.000001"	±0.08 μm ±0.000003"	±0.1 μm ±0.000004"
Pixel resolution			Approx. 3.5 μm 0.000138"	Approx. 21 μm 0.000827"	Approx. 37 μm 0.001457"
Environmental resistance		Enclosure rating*3	IP64		
		Operating ambient temperature	0 to +45°C 32 to 113°F		
		Operating ambient humidity	20 to 85% RH (No condensation)		
Material			Aluminum		
Weight		Transmitter	Approx. 160 g 5.65 oz	Approx. 620 g 21.89 oz	Approx. 1300 g 2.87 lb
		Receiver	Approx. 480 g 16.94 oz	Approx. 890 g 31.42 oz	Approx. 1900 g 4.19 lb
		Base	Approx. 210 g 7.41 oz	Approx. 670 g 23.65 oz	Approx. 1500 g 3.31 lb

Figure 27: Optical Micrometer Spec Sheet

To accurately compare a vision system to the optical micrometer above, a type of camera purpose made for measurement ought to be chosen. Below is the specification of an optical microscope commonly used in the tool and die industry titled an "OM2300s-B-GX4". Here, we can see an advantage over the optical micrometer in that we can achieve a wider range of view, however the accuracy of measurement would be determined by the gauge by which it would be compared against during the reading.

	GM2300S-B-GX4 Binocular Stereo Microscope System
Head	
Head Type	Binocular
Optical Design	Greenough Converged
Magnification Type	Zoom
Ocular Angle	45°
Ocular Tube Diameter	30.5 mm
Barlow Mount Diameter	47 mm
Diopter Adjustment	Dual
Interpupillary Adjustment	Arc (Seidentopf)
Interpupillary Adjustment Range	55-75 mm
Trinocular Tube Focusable?	No
Head Rotation	360 Degrees
Trinocular Type	-
Trinocular Standard	-
Optics	
Minimum Objective (X)	0.7
Maximum Objective (X)	4.5

Figure 28: Vision System Spec Sheet

Constructing a decision matrix from this data below we can see that the optical micrometer has a very clear and distinct advantage over the vision system although the results end up being quite close due to the vision systems ability to adjust to a wider range of available areas. Overall the optical micrometer wins out even though it also takes a significant hit for being quite costly. However, after discussing the matter with our clients, money saved on products and devices used to build other aspects of the machine would be happily spent on a higher quality system of measurement so the cost criteria weight here ought not to be weighted as heavily as the accuracy.

	Criteria 1	Criteria 2	Criteria 3	Criteria 4	
CRITERIA DESCRIPTION	Accuracy	Cost	Reliability	Range	
OPTIONS	Criteria 1 SCORES	Criteria 2 SCORES	Criteria 3 SCORES	Criteria 4 SCORES	TOTAL SCORE
Optical Micrometer	10	4	10	5	29
Vision System	3	8	7	10	28

Figure 29: Diameter Measurement Decision Matrix

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7 APPENDICES

Appendix A: QFD For Radial Expansion Tester

Roof Matrix

NO INPUT IN THIS AREA

	Apply Axial Force Up to 150 lbs	Change Test Diameter .2-2.5"	Control Temerpature up to 250F	Measure Axial Force Up to 150 lbs	Measure Test Diameter .2-2.5"	Measure Temperature Up to 250F	Pressurize Balloons	Output Measurements (Force, Pressure, Diameter, T
Apply Axial Force Up to 150 lbs	+							
Change Test Diameter .2-2.5"		+						
Control Temerpature up to 250F		-	+					
Measure Axial Force Up to 150 lbs	+							
Measure Test Diameter .2-2.5"		+			+			
Measure Temperature Up to 250F			+			+		
Pressurize Baloons		+	-		+		+	
Output Measurements (Force, Pressure, Diameter, Temperature)				+	+	+		+

PHASE I QFD

Preferred (up or down)

Engineering Requirements (How)

Customer Needs (What)	Customer Weights	Apply Axial Force up to 150 lbs	Change Test Diameter .2-2.5"	Control Temperature Up to 250F	Measure Axial Force up to 150 lbs	Measure Test Diameter .2-2.5"	Measure Temperature up to 250F	Pressurize Balloons	Output Measurements (Force, Pressure Diameter, T										1 Poor	2	3 Acceptable	4	5 Excellent
Actuate Axial Force	5	9			3														ABC				
Continously Measure Axial Force	3.5	3			9				9										AB			C	
Test Unexpanded Extrusion Diameters	5		9			3		1	3										AC				B
Test Expanded Extrusion Diameters	5		9			3		3	3										AC				B
Continously Measure Diameter During Expansion	5		3			9		9	9										A			C	B
Temperature Control for Extrusion	5			9			3												AC	B			
Continously Measure Temperature	3.5			3			9		9										A			B	C
Stay Within Budget	2																		A	BC			
Pressurize Balloons during Testing	5							9											C				AB
Absolute Technical Im		55.5	105	55.5	46.5	75	46.5	110	138	0	0	0	0	0	0	0	0	0					
Relative Technical Im		9%	17%	9%	7%	12%	7%	17%	22%	0%	0%	0%	0%	0%	0%	0%	0%	0%					
Unit of Measure		lbf	in	DegF	lbf	in	DegI	lbf/in^3															
Techical Target		150	.2-2.	250	150	.2-2.5	250																

Now vs Now What

Benchmarked Products

A	Crescent Design HBLT
B	BW Tech 2349 1UP Insepction Device
C	Watlow F4T