Wire Bonding Mechanism for Microsystem Assembly

Project Team 23

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ABSTRACT

With rising usage of in vitro diagnostics, there is a need for a less invasive solution for typical endomicroscopy. We are working on a laser endomicroscopy solution that integrates the microscope into the endoscope to conduct in vivo microscopic testing. Precise and robust electrical wire connections between the Micro-electromechanical systems (MEMS) and external devices are needed to control the piezoelectric actuators that support the miniaturized laser scanner. This project focuses on a time-saving solution to precisely bond wires and MEMS bond pads together. The solution focuses on the development of an epoxy dispenser for accurate bonding. These combined will make an efficient solution for wire bonding with epoxy. The validation and verification of this solution led to reflections on weaknesses of our design and potential solutions following more iterations.

EXECUTIVE SUMMARY

The design problem is that, in order to create solid electrical connections between wire (50.8 µm - 101.6 µm) and bond pads (as small as 144 µm x 144 µm) on MEMS devices, a microscale epoxy dispenser with minimum dispensing capacity of 4 nL is required to be integrated with a wire holder on a high precision positioning system and allows for wire bending and bonding. Based on the requirements from the sponsors and our engineering understanding, we have divided the system into two parts, which are the bonding system and manufacturing process. Due to the scale of the system we are working with, we have identified a set of possible challenges that we may encounter when designing the wire bonding system. Specifically, we are highly concerned about the impact of different epoxies in the dispensing system, the precision placement of bent wires, and the weak adhesion between MEMS device layers. Some of these challenges were identified by our stakeholders who had encountered them previously while others are challenges we foresee in the development of our device. Based on our current understanding, we acknowledge that we are working on a wire bonding system that has high requirements for precision and fine control over epoxy dispensing. We understand that our system is to be composed of the following subsystems: a positioning system, an epoxy dispenser, and a wire bending and holding mechanism. We understand that our microsystem assembly may be built upon a current positioning system and we have identified a set of requirements and specifications that our system will have to meet. We are planning on exploring designs on integration of mechanism with positioning system, wire extrusion and bending mechanism, analysis of fluid properties and liquid dispenser mechanism, and wire bonding process design and analysis. We used different concept generation methods like design heuristics and functional decomposition to develop a diverse set of potential solutions. The alpha design was developed using these concept generation methods and working alongside our sponsors. They gave useful input into our design which led to its final form. The final alpha solution includes a motor activated epoxy dispenser that can switch between the two epoxies required. It is able to move in the Z direction and also have its pitch and yaw customized for each use. We have decided to use the current positioning system as the basis for our design. Analysis has been completed to better inform our design and its limitations. We also designed a verification and validation plan to ensure our design could meet the requirements and specifications we developed. The outcome of the first iteration of design led to a need for iteration that we did not have time for. This led us to develop many strengths and weaknesses of our design and also reflect on the process we had completed. We reflect on both our relationships with stakeholders and within the team itself and also the design space we explored. We also have future recommendations of designing additional aspects of the wire bonding system like the wire bender, wire holder, and positioning system. We also would aim to make a device that could make multiple bonds at once.

INTRODUCTION

This semester, our team is tasked with creating a manufacturing process and mechanism that is to be used to carry out wire bonding for a MEMS that utilizes electrical components on the scale of tens to hundreds of microns. This MEMS device was developed by Joonyoung Yu, a Ph.D. student researching under Dr. Kenn Oldham, to be used in an endomicroscopy scanning device.

The process that currently exists for bonding wires to these devices consists of our Ph.D. student, Joonyoung, using an existing positioning system from a much older wire bonder and manually applying an adhesive epoxy to the wire and bond pads with syringes[5]. This has proved to be a very time consuming and laborious process and has yielded little to no success. Furthermore, traditional wire bonding methods such as ball and stitch bonding have shown to cause the aluminum-platinum layers that make up the bond pads to delaminate[12]. Therefore, it is necessary to create a wire bonding mechanism that can effectively bond wires on this small scale in a timely and repeatable manner that does not damage the bond pads. A successful wire bonding mechanism will be able to repeatedly dispense an amount of epoxy small enough to accommodate the size of the bond pad and be able to configure many aspects of these bonds including bond angle, position, and amount of wires bonded at a time. The MEMS device and a manual wire bonding attempt are shown in Figure 1.

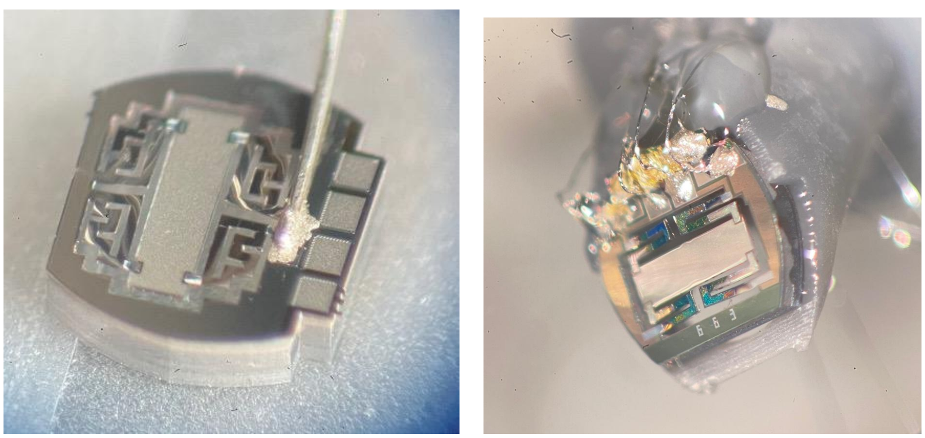


Figure 1. MEMS devices with a solder ball bond (left) [5] and manual epoxy bonding (right) [21]. Both pictures are taken from the lens of an optical microscope with 1000 times magnification.

In our approach to defining this problem, we first engaged with our stakeholders, in this case Dr. Oldham and Joonyoung, to understand the contextual factors and background information surrounding this problem, as well as the specific details that our design needed to consider in terms of materials to accommodate and specifications of the MEMS device. These engagements took the form of interviews and meetings that consisted of open discussions as well as organized presentations. As a primary information source, our stakeholders gave us direction to investigate secondary sources of information, including ASTM standards governing endomicroscopy devices and literature discussing microfluidics and other physical phenomena that are crucial to the success of the wire bonding process.

Background Information

The MEMS device we are working with is to be used in a novel endomicroscopy device. Endomicroscopy devices are minimally invasive surgical tools that typically consist of an optical microscope and biopsy end effector. These devices are used to search internal organs such as the intestines for polyps, tumors, and other indicators of cancer and disease. Once one of these indicators is identified, the physician will use the biopsy end effector to remove the suspect tissue in vivo to analyze in a lab [5]. An example of an endomicroscopy device is shown in Figure 2.

Figure 2. *Olympus medical endomicroscope with biopsy end effector [3].*

This biopsy process can be uncomfortable and painful for the patient as well as time consuming. Joonyoung and Dr. Oldham intend to solve this problem by creating an endomicroscopy device that can directly observe these tissues in vivo with a miniaturized laser scanning confocal microscope[4,11]. This solution would also increase the fault tolerance of testing the wrong tissue sample. The laser scanning mechanism will include the MEMS device that will change the position of a mirror to carry out different scanning patterns utilizing its four piezoelectric actuators[11]. A diagram that illustrates the working principle of the device can be seen in Figure 3.

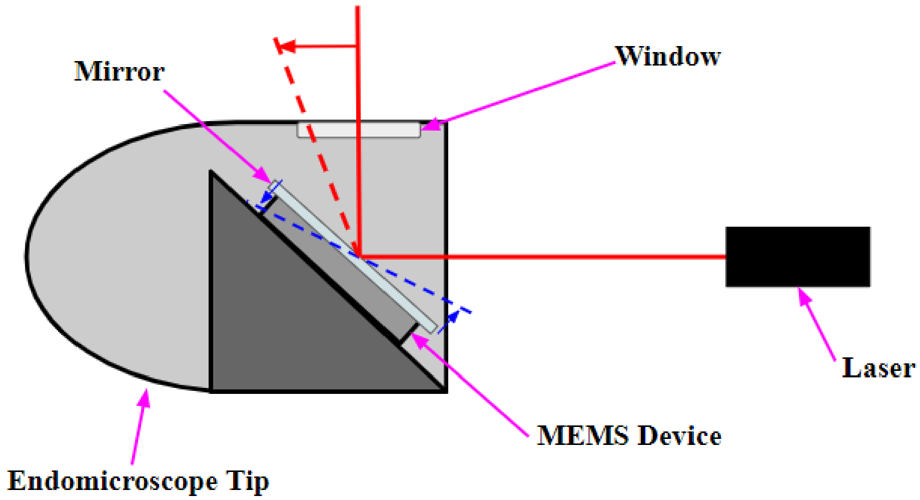


Figure 3. *The working principle of the MEMS device.* The device uses its four piezoelectric actuators to change the angle of the laser allowing it to scan a specimen.

BENCHMARKING

Following this initial investigation, benchmarking was carried out to learn more about existing solutions and to understand why they fail to meet stakeholder needs. This will help us conceptualize new solutions and identify their potential pitfalls and foreseeable problems.

Table 1 shows current solutions for liquid dispensing devices. The devices have been quantified by four different factors within our scope. The first is whether or not the dispenser contains its own positioning system. This was important to analyze because our potential solution can either use an existing positioning system or have its own. The next factor is if the device is compatible with epoxy. The usage of epoxy in the system is a requirement given by our primary stakeholders [5]. We wanted to survey how current devices are able to dispense epoxy at such a low volume. The next factor is the minimum dispensing volume. From an interview with Joonyoung, we were able to quantify that each bond would need a maximum of 4nL of epoxy [5]. We judged each existing solution on whether it had the capacity to dispense 4nL or less. The last factor we used to judge the devices was cost. Our budget was set to $1000 and we want to respect our stakeholders by maintaining that value [6].

The outcome of this analysis highlighted areas which would be more difficult to solve. It is interesting to note that every device that includes a positioning system is able to dispense the minimum amount of liquid necessary. We are keeping an open mind, but it might be telling in the concept generation phase. Cost is also a major factor in all of these existing solutions; the price seems to drastically increase with more precision. We also noticed that the capability to dispense epoxy required some kind of syringe tip on the device.

Table 1. *Benchmarking Table to show capabilities of various existing products*. The * represents an estimated cost because of the customization involved with those products.

Device	Includes positioning system?	Compatible with Epoxy?	Minimum Dispensing Volume (nL)	Cost
Micro-Dot™ Manual Syringe Dispenser [7]	No	Yes	300 nL	$730
Preeflow Eco Pen [8]	No	Yes	1000 nL	$2524
SuperJet Dispenser [9]	Yes	Yes	0.5 nL	$10,000*
PipeJet Nanodispenser Kit [10]	Yes	No	2 nL	$7,600*

DESIGN PROCESS

Team 23 has varied our design process as we have gone deeper into our problem. We find both the Decomposition and Recombination Design Process and the Socially Engaged Design Process Model important for our problem but our most used design process is the Dynamics of Divergence and Convergence. Our design problem required a wide scope to fully understand the problem we had been presented with. To understand our problem, we needed to diverge away from the initial problem to ensure we had a proper scope. All three of these design processes focus on being problem oriented rather than a simple iteration on an existing solution. This gives us a better chance to explore the problem given to us and be more creative in our pursuit for a solution.

We began with the Dynamics of Divergence and Convergence design process, as reported by Dubberly [1]. This design process is shown below in Figure 4. This process emphasizes divergent and convergent thinking, which is something we have been doing throughout our process. We began analyzing our problem with a very loose understanding of what we are required to do. This led to expansive research in an attempt to understand and find an area where this problem was deeply rooted. As we look forward into design, we see convergence to a set problem statement to then come up with more solidified solutions.

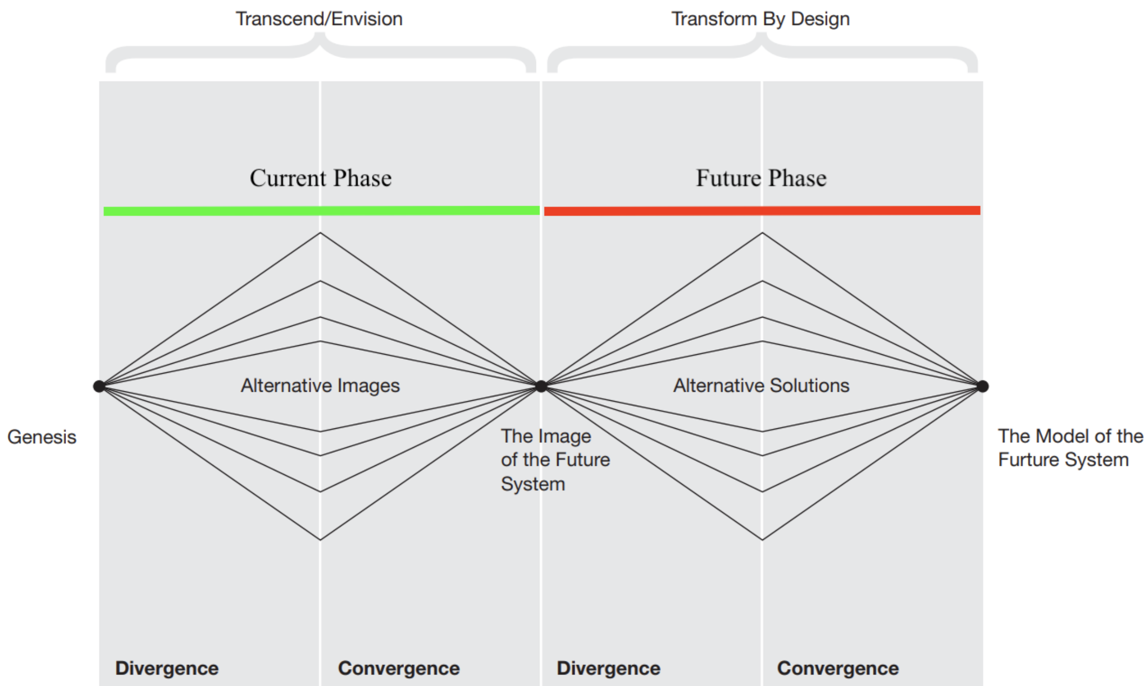


Figure 4. *The Dynamics of Divergence and Convergence design process [1].* The green label shows where we are now in the process and the red where we will be going in the future.

Another design process used was Decomposition and Recombination [1]. This process highlights breaking down the problem into smaller more manageable sub-problems. This is applicable for us because we see our problem in two different parts: one is the process of making the bond and the other is the manufacturing process as a whole. In Figure 5, it is shown how the problem gets systematically broken down and then put back together for a final solution.

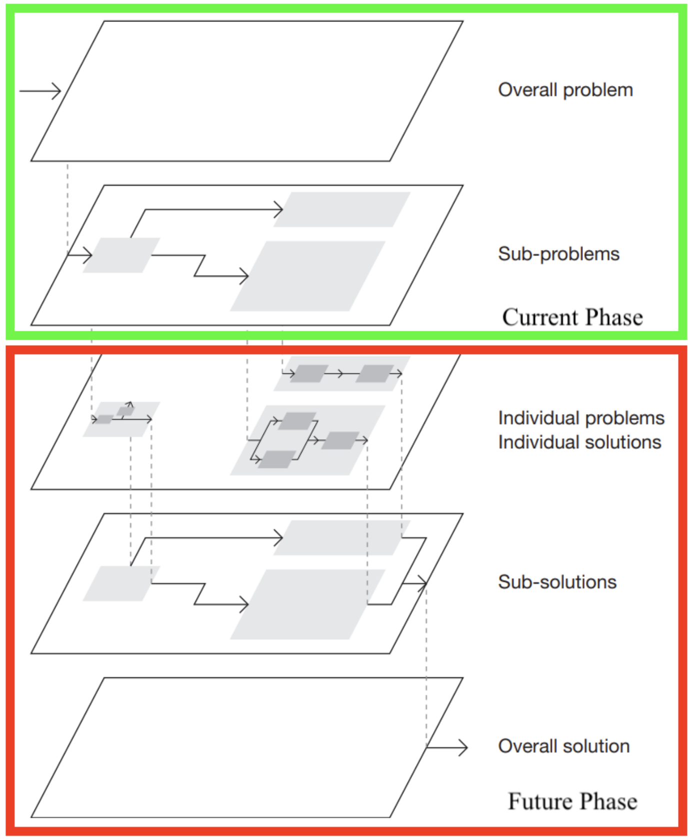


Figure 5. *The Decomposition and Recombination Design Process [1].* The green box shows the phase being reported on in this report and the red shows where we will explore in the future.

Lastly, we have also been using the Socially Engaged Design Process Model [2]. This is important for our design process because it highlights designers' own power, privilege, and identity to encourage reflection. This ensures we are considering the problem from all angles and everyone on the team's perspective. This design process helps us cover every aspect of our design and the impact that each of us has on the design. We also have used the decision points to help guide us as it can be difficult to know when to move on from a certain area with our limited timeline. This design process is shown below in Figure 6.

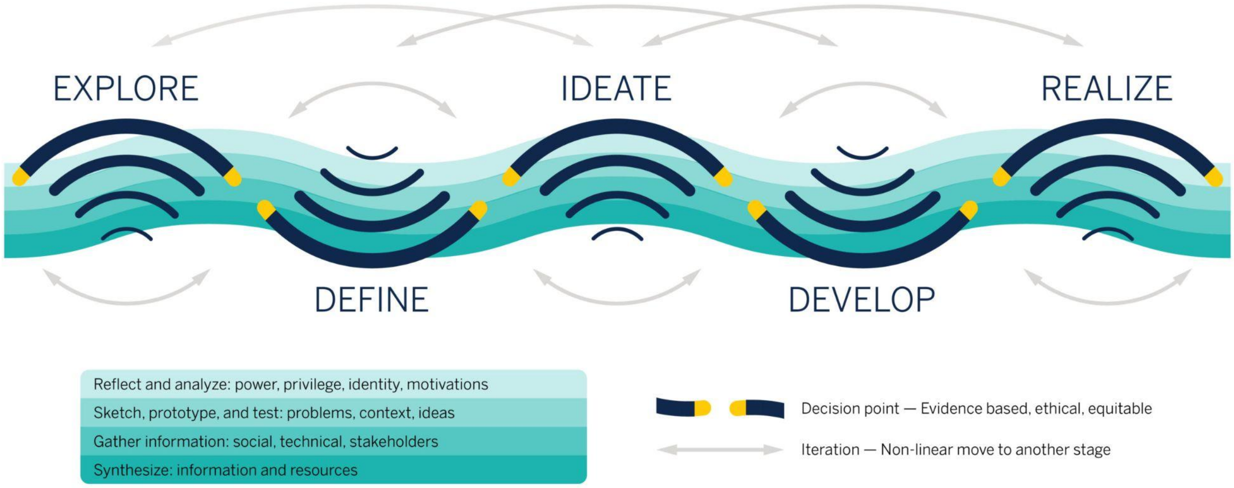


Figure 6. *The Socially Engaged Design Process Model [2]*. This design process is iterative so it is difficult to mark where we currently land on the figure. We have moved from explore to define and are creeping into ideate. There is still space for problem definition iteration though.

Our design process is a combination of others to make it best suited for our project. It focuses on diverging and converging our problem statement and will be the same for our concept development and selection. It is different to the 450 design process because it includes more elements and has a deeper consideration of our own designer biases and identities. It has similar aspects of iteration and redefining our problem statement. We think it is vital for our problem to use our unique combination of design processes because it needs a broad understanding to develop a specific solution.

DESIGN CONTEXT

When considering the broader context that will influence this design including but not limited to public health and safety as well as global, cultural, social, environmental impacts, we are in quite the unique position given the scope of our project. Our project is mostly intended to be a one-off design to benefit Dr. Oldham's Vibration and Acoustics Laboratory in Microsystems by enabling the prototyping of a specific design with the hopes of the mechanism and process being applicable into the future. With that being said, the context of our design has changed as we have investigated it more. In our discussion with the Nanofabrication lab, we have learned that this is a common issue among researchers making MEMS chips [22]. This context and stakeholders involved also broadens when considering the effect this process has on the success of the endomicroscopy device as seen in the stakeholder map shown in Figure 7.

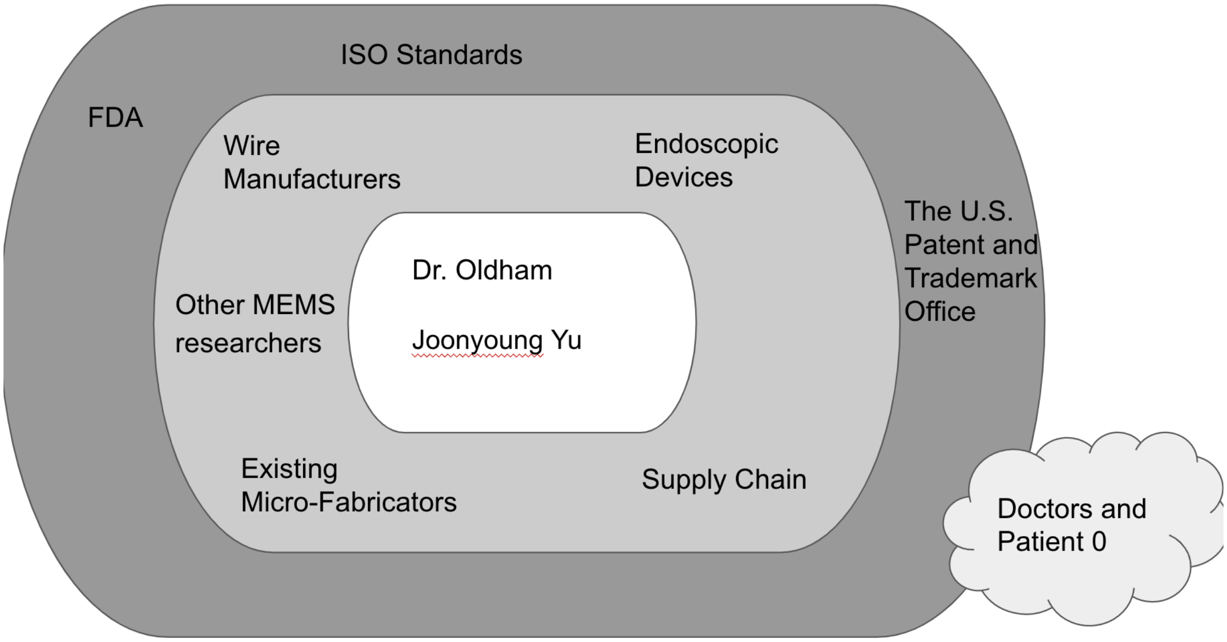


Figure 7. *The project's stakeholder map with primary stakeholders located at the center with secondary and tertiary stakeholders moving outward*. Doctors and patient 0 are considered in the scope of this project, but may not be necessarily stakeholders.

When observing our project as an enabler for a larger overarching problem being solved, we can touch on a variety of these contexts. For instance, the better our design works, the more likely part of it will be replicated in a large-scale manufacturing environment for these devices. This will impact suppliers of system components as well as tooling used by manufacturers. Therefore, it is important to be cognisant of current industry fabrication techniques so that our process can be easily translated into higher volume supply chains. Another factor of our design in a broader scope is the scientific community and standards involved with endomicroscopy devices. We must consider the outcome of our system as it could impact the reliability of the device as a whole. It will make it difficult to show the effectiveness of the design and get approval if our system can not properly do its job. Therefore, we need to ensure that our process is repeatable and precise.

Furthermore, in regards to nanofabricators in general, this process of bonding with epoxy to such devices is a common issue in academia and research applications due to the expensive nature of automated epoxy dispensers [22]. Therefore, if we can make the bonding mechanism and process accommodating to a larger set of users and intended devices, there is potential for significant impact on the approach to microfabrication in research as a whole.

We predict all stakeholders will be impacted positively or neutrally with the introduction of our design. Our design will save time and materials for the users of the device like Joonyoung Yu and other MEMS researchers. Our primary sponsor aims to use our device to better his device both for educational and innovational reasons. It will also positively impact the development of new endoscopic devices and further the need for wire manufacturers. Existing Micro-Fabricators will be neutrally impacted by the introduction of our device. The specific bond pads used in our problem are specifically bonded using epoxy so typical bonding methods will still prosper for their specific uses. The supply chain will also not be impacted by the introduction of our device.

A more narrow impact that this process will have is that it will enable faster prototyping. Faster prototyping will facilitate more iterations of system components affiliated with the MEMS device and the entire endomicroscopy system itself. This effectively could lead to an overall better design of the device. Subsequently, this will benefit the physicians and patients interacting with this technology.

The aim for the device is to be environmentally conscious from manufacturing to use to disposal. The device will be manufactured using as many existing parts as possible from the lab. This will save both money and carbon emissions by using what is already present. The use of the device will not create any emissions. The device is intended for long term usage and aspects of the design like the wire holder could be used for other tasks. This results in a minimal environmental impact.

In terms of the intellectual property associated with our project, any designs will be the team's intellectual property. Therefore, it is important to keep accurate records of design concepts, analysis, and other parts of the design process. Furthermore, if there is a novel idea that arises from this project, proper IP protection will be utilized in the form of patents and copyrights.

As briefly mentioned earlier, the direct focus of this project is to design a wire bonding process and mechanism for Joonyoung and Dr. Oldham. Given that Dr. Oldham and Joonyoung are primary stakeholders with in-depth knowledge and experience regarding our project; the power dynamics are very much like an employer-employee relationship. Although there is less oversight than a traditional work relationship, we answer directly to Joonyoung and Dr. Oldham regarding technical details and specifications they expect from the design. Furthermore, their expertise also makes them a primary information source, as well as consultants when weighing in on design decisions.

REQUIREMENTS AND ENGINEERING SPECIFICATIONS

Based upon the design context and interviews with our stakeholders, we were able to propose a list of requirements and specifications for our wire bonding mechanism. We were able to group our requirements and specifications into two large categories: wire bonding system and manufacturing process. The wire bonding system particularly highlights the use of epoxies, the time of the bending process, and the thermal, mechanical and electrical properties that the bond has to satisfy. The manufacturing process highlights the placement of the wires through a high-precision positioning system, the bending process of the wires, the thickness of the wires, and the number of the wires held.

We have sorted our requirements from high to low priority. We assign the high priority to requirements that critically determine the performance of the design. This means, if the design does not meet requirements with high priority, the project will not be able to perform basic tasks. We assign the medium priority to requirements that have the potential to cause failure if not met. These requirements do not directly affect the basic performance of the design, but certainly affect the optimal performance. We assign the lowest priority to requirements that either do not greatly affect the design or are nice-to-have features. We believe that we have stated all requirements and specifications for the proposed system. The specifications and requirements were drafted referencing ASTM and ISO standards, interviews with our stakeholders, and existing literature. Table 2 includes the requirements and specifications for the wire bonding system and Table 3 includes the requirements and specifications for the entire manufacturing system.

Table 2. *Requirements and engineering specifications for wire bonding system*

Priority	**Requirements**	**Engineering Specifications**
High	Bond shall be made with high precision with epoxy [15]	Epoxy droplet's volume 0.5nL - 4nL [5]
High	Bond connection shall be able to be made in a reasonable time	Precision placement time < 10 minutes; Curing Time < 5 minutes [5,13]
High	Bond shall require two different types of epoxies	Conductive Epoxy: NCA 130 [5,14] Biocompatible UV Epoxy: NOA 63 [5, 13]
Medium	Bond shall withstand sterilization temperatures	121°C - 134°C for 3-15 minutes [16]
Medium	Bond shall not impact the bond pad's connection to the MEMS device	0 N applied by wire connections [12]
Low	Bond shall have a rated electrical resistance	< 100 Ω [5]

For the wire bonding system, it is required that the epoxy dispenser shall have high volume precision and the epoxy shall be alterable. The bonding process shall be quick without impacting the bond pad layer. Also, the process shall withstand sterilization temperature and have a rated electrical resistance.

Based on our engineering understanding and research, we specify that the minimum epoxy dispensing volume shall be as low as 0.5 nL - 4 nL. As the average side length of a bond pad on the MEMS device is about 200 μm, after calculating the volume of a microscale semi sphere that would fit on the bond pad, we determined that the volume of the epoxy droplet needs to be 0.5 nL to 4 nL.

For the operating time of the process, we want the precision placement time to be less than 10 minutes and curing time to be less than 5 minutes. During our interviews with Dr. Oldham and Joonyoung, we were told that the current manual attempt takes roughly 8 hours, and the curing time for the previous epoxy was about 1 hour [5]. Therefore, we want the positioning process to be less than 10 minutes with our solution and the curing time to be less than 5 minutes with right epoxy treatments.

Since the bonding solely by conductive epoxy is weak, another non-conductive epoxy will be applied on top of the conductive epoxy bondings to solidify the connections. As a result, we need the bonding system to accommodate interchangeable epoxy types of NCA 130 conductive epoxy and NOA 63 biocompatible UV epoxy.

From interviews with Dr. Oldham and Joonyoung, the bond pad layers are made of PZT, platinum, and aluminum. As the adhesion between PZT and platinum layers is so weak that very minimum force would damage the bond pad[20]. Therefore, we want the process to not apply any force to the bond pad layer to ensure a successful bonding process.
From the ISO for sterilization of medical devices, the bond pad will withstand a temperature of 121°C - 134°C for 3 - 15 minutes. The MEMS chip will be used in an endoscopic device and therefore must meet the standard for medical device sterilization before usage.
Every electrical connection has electrical resistance. To not affect the electrical connection between the MEMS device and external devices, we want the epoxy bond to have an electrical resistance less than 100 Ω.

Table 3. *Requirements and engineering specifications for manufacturing process*

Priority	**Requirements**	**Engineering Specifications**
High	Platform shall be able to move from bond pad to bond pad OR Manufacturing process shall interact with existing positioning mechanism (K&S Model 4123 Wire Bonder) [17]	Positioning system with minimum distance of 300 μm OR must accommodate existing precision of 380 μm [17]
Medium	Manufacturing process shall bend wires at different angles	Bend 38-40 gauge wires from 10°- 90° range [5]

Medium	Manufacturing process shall bend wires at a specified length	Bends at lengths ≤ 50 µm from the end of the wire [6]
Medium	Manufacturing process shall accommodate a range of wire thicknesses	38-44 gauge (55.8 µm - 101.6 µm) [18]
Medium	Manufacturing process shall use current materials and stay within budget	$1000 budget (subject to change) [6]
Low	Manufacturing process shall bond more than one wire at a time	2+ wires spanning MEMS devices with dimensions: 1000µm x 1400µm [19] Spacing between tips: 300 µm

For the manufacturing process system, the requirement of the highest priority is separated into two parts depending on different cases as shown in Table 2. As aforementioned, there is an existing wire bonder available to us. While the wire bonder does not have the feature of creating wire bonding with epoxy, it has a functional positioning system that we may be able to take advantage of. Therefore, in the case of we using the positioning system of the wire bonder, a epoxy dispenser is needed to be attached to the wire bonder, so that while the wire bonder holds the wire and MEMS device in place, the user can bring the attached epoxy dispenser to the bonding location and dispense the epoxy from it. As we would only use a part of the wire bonder in this case, we have to design the dimension of the epoxy dispenser to accommodate the overall dimensions of the wire bonder. However, as adding the epoxy dispenser on the current wire bonder limits the freedom of adding additional features and may potentially bring problems, we also consider the case of developing the positioning system, wire holder, and epoxy dispenser in one setup without the existing wire bonder. To ensure the new positioning system moves the wire holder and epoxy dispenser from one bond pad to another, which has side dimensions from 144 µm to 679 µm, we require the new positioning system to move at a minimum distance of 300 µm.

The highest priority requirement is followed by four medium priority requirements.
Firstly, due to the strict space limitation, the wire is required to be fed toward the MEMS device at an angle. With an angle less than 90°, the wire will be more likely to fit within the miniature space. Due to the locations of the bond pads on the MEMS device, the angle is required to be more than 0° so that the wire will not touch other bond pads, and more than 10° so that the wire will not touch conductive epoxy that may result in a short circuit. We keep the consideration of 90° and the reason will be discussed in the next requirement.

Next, as the angle between the wire and the bond pad is not 0°, bending at the wire tip is required. Determined from the CAD model of the MEMS device support that we received from

Joonyoung, the longest length from the tip of the wire to the bending location is 50 µm. With this bending close to the tip, we are able to arrange the position of the wire to make it fit into the enclosure.

Thirdly, as different sizes of wires will be used, the design also needs to accommodate various sizing of the wire. As discussed with Dr. Oldham and Joonyoung, the 38 gauge wire and 44 gauge wire are currently in use. Therefore, our wire holder should be able to hold wires with diameters ranging from 55.8 µm to 101.6 µm.

Additionally, as our design will include current materials and off-the-shelf components to save time and support the quality of the project, while we do not have infinite financial support from Dr. Oldham, we specify that our project has a budget limitation of $1000. However, the budget is subject to change as we talked to Dr. Oldham afterwards.

Finally, we have a low priority requirement. It is a nice-to-have feature that would reduce the operating time and potentially improve the user experience. Dr. Oldham and Joonyoung had expressed in the interview that it is helpful if the system can operate multiple wire bonding processes at the same time. Since the bonding process involves waiting time for epoxy curing, adding additional wire bonding systems will shorten the operating time. Therefore, we would add additional wire bonding systems with the spacing between each tip to be about 300 µm, which is approximately the side dimension of a bond pad. We consider this to be a low priority requirement as one functioning bonding system is sufficient to complete the bonding process on one MEMS device with current time limit. Plus, an additional setup can be easily added once we have developed a functioning design.

PROBLEM DOMAIN ANALYSIS AND REFLECTION

Based upon the specifications listed above, we believe that to design a wire bonding assembly that would be able to simplify and reduce the time used in the current process, engineering fundamentals from manufacturing, design, control systems, mechatronics, fluid dynamics, and mechanics may be required. Since the overall design of the assembly needs to be either integrated into a positioning system or building a new positioning system, we believe that fine control and assembly of this process would require skills from manufacturing, design and possibly control systems and mechatronics if there are plans to electronically control the position of the wire bonding. We also know that the bond should be able to withstand sterilization temperatures and external forces, hence we highlight the importance of mechanics due to the impact of thermal and mechanical strains on the bond. Fluid dynamics may also be a consideration since we are accommodating different viscosity epoxies.

Our team has a knowledge status that is quite familiar with the above fundamentals highlighted above. However, since we are dealing with micro-scale devices, none of us have prior experience working with devices of such low clearance and precision, which might be a possible difficulty when working on the design and assembly of the system. However, our stakeholders (Dr. Kenn Oldham and Joonyong Yu) have plenty of experience working in these fields and thus they will be a valuable resource to build upon. Other difficulties include the integration of electronics, coding and automatic control of the device, which could be possibly required. Our team has all had prior experience working with these fields, but none of us are particularly comfortable working with software or code, which could be a possible difficulty we may wish to avoid. Other major problems that we may encounter may include the weak adhesion between layers of the MEMS device, viscosity difference in epoxy resulting in limitation of dispensing methods, and moving a bent wire with fine control and accuracy. Highlighting the major problems above, we believe that we will be able to address these challenges by conducting first principles analysis, performing simulations, and consulting experts with prior experience in the field.

The inclusion of special equipment and more understanding of the fabrication processes of MEMS devices could be essential to solving and developing engineering solutions that meet the requirements and specifications. We understand that the inclusion of high precision equipment may be relatively expensive, so we have interviewed our stakeholders and we understand that we are working with a budget of $1000. We also understand that it is possible to obtain special equipment that is currently used in the lab, which would definitely reduce the cost of designing and building a high-precision system for wire bonding. We understand that the University of Michigan also has a MEMS nanofabrication lab, which we plan to reach out to for further benchmarking and analysis. Currently, the information gap is mainly due to our inexperience in working with micro-scale MEMS devices and high precision systems. We believe that this lacking information may be obtained through further communication with the MEMS nanofabrication lab, our stakeholders, and commercially available manufacturing solutions.

CONCEPT GENERATION

The concept generation process was conducted in two phases. The first of which was conducted on an individual basis and mainly focused on a combination of design heuristics and functional decomposition to encourage a diverse set of ideas that an exclusively group setting would not likely accomplish. Team members were encouraged to derive 20 unique concepts for each subsystem of the decomposed system. The nature of this decomposition was also left to each individual team member’s discretion as to promote a more holistic understanding of the system. In this individual phase, team members were also encouraged to utilize concept generation tools including design heuristic cards and morphological charts.

The second phase of the concept generation process consisted of an open discussion facilitating the congregation of these individual concepts that was used to initiate a brainstorming session. The general framework of this session maintained the theme of functional decomposition; a mutually agreed upon system breakdown was decided and concepts were generated for each subsystem. The final subsystem breakdown can be seen in Figure 8. The team also focused on how combinations of these subsystems could interact and was used to further generate subsystem concepts.

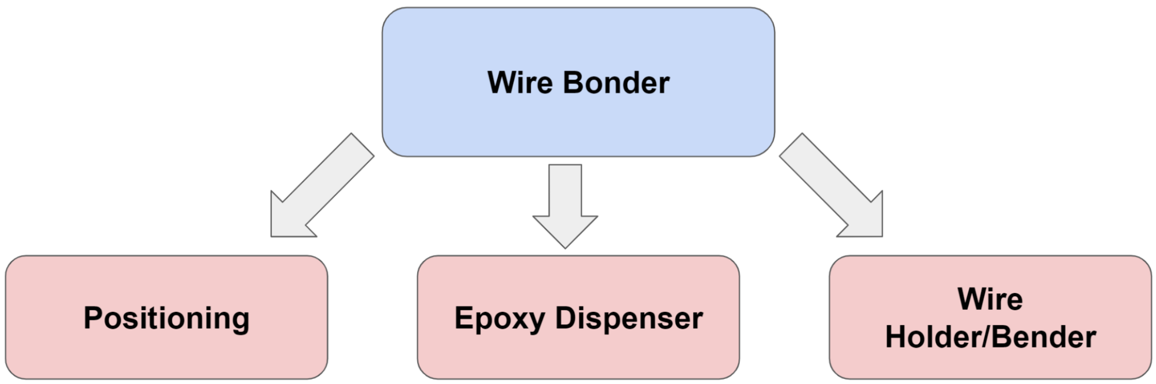


Figure 8. *Functional decomposition of wire bonding mechanism.* The wire bonder was determined to have three distinct subsystems by which concepts could be more focused on achieving specific functions: the positioning system, epoxy dispenser, and wire holder and bender.

A comprehensive list of all concepts generated can be found in Appendix 3. To illustrate the extent and diversity of our generated concepts, the most diverse and/or promising concepts will be discussed in greater detail for each subsystem mentioned above.

The first subsystem of discussion is the positioning system. This subsystem is likely to manifest itself in the mechanism with two functions: to position and orient the dispensing subsystem and to position the MEMS holder. The need to position the dispensing system is contingent on the use of certain concepts and may not be required, but for the sake of thorough concept generation it has been considered. With that said, a positioning system for the dispenser may have to orient itself in up to 6 DoF (degrees of freedom) while the MEMS holder will likely only need to carry out up to 2 DoF.

The first and most promising concept for the dispenser positioning is a micropositioning stage. This is a readily available component, and can be readily integrated into custom components to accommodate our system. A micromanipulator can actuate in up to 3 DoF, and therefore may need to be used in tandem with a second concept. A direct alternative to a micropositioning stage is a linear rack. Linear racks only actuate 1 linear DoF, however they can be easily implemented and stacked to provide up to 3 DoF. Figure 9 shows a micropositioning stage and linear rack that are representative of what would be implemented in our system.

Figure 9. *Linear rack (left) and micropositioning stage (right).* Both positioning systems can be easily integrated and will allow up to 3 DoF [24].

As the concept discussed above only actuate the three linear DoF, concepts that facilitated the 3 rotational DoF were also considered. Two concepts that came to mind that could accomplish this were spherical joints and a stack of swivel joints. The spherical joint is a singular joint that can accomplish all three rotational DoFs (yaw, pitch, and roll), while a swivel joint can only accomplish one. However, a stack of swivel joints will allow the user to isolate specific DoFs unlike a spherical joint. Both of these concepts are also readily available and can be incorporated into a custom system. A spherical joint and stack of swivel joints is shown in Figure 10.

Figure 10. *Swivel joint stack [26] (left) and locking spherical joint [25](right).*

Another, much more involved, concept is utilizing a flexure mechanism with magnetic linear actuators to achieve nanometer resolution positioning with a millimeter scale travel, as used in the HIPERNAP system [23]. Mechanisms like HIPERNAP are used for automated IC manufacturing, which has very similar if not more rigorous requirements as our project in terms of positioning performance. The HIPERNAP system is shown in Figure 11.

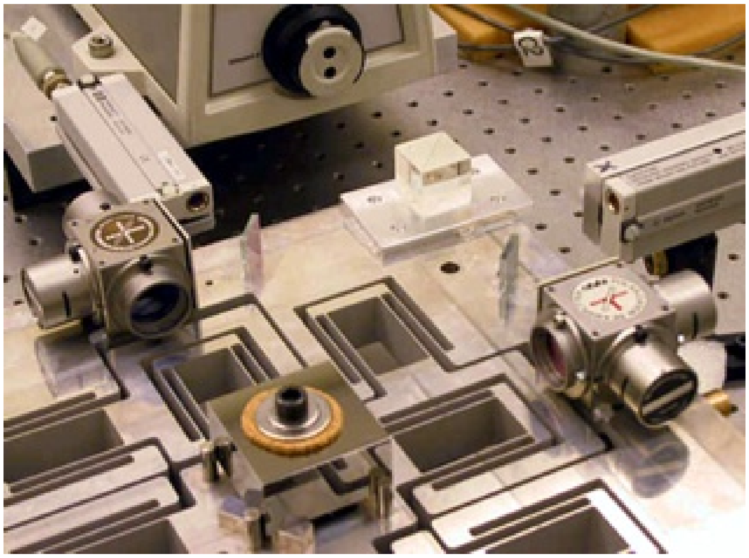


Figure 11. *HIPERNAP nanopositioning system.* This system includes four linear ferromagnetic actuators with a flexure mechanism to achieve nanometer resolution across a range of millimeters[23].

The second subsystem that was focused on in concept generation was the wire holder and bender. This subsystem can arguably be further decomposed into holding and bending subsystems. However, given that these systems directly interact with one another or can be integrated into the same mechanism, they are considered a singular subsystem in this report.

The first wire holding and bending subsystem concept is a roller mechanism that utilizes a tube track and lever arm to apply bends. A sketch of this concept is shown in Figure 12.

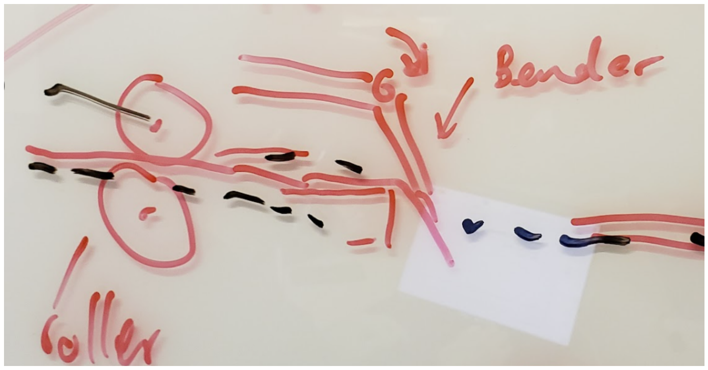


Figure 12. *Roller feeder with tube holder and lever arm bender.* The rollers will clamp around the wire allowing the user to feed the wire through a small tube and into a pre-positioned lever arm track.

As mentioned in Figure 12, the rollers will secure the wire and allow the user to feed the wire by turning these rollers. The wire will then be fed into a tube like track and be bent by an adjustable lever arm. This will allow the user to change the bend angle and finely adjust the length of wire being bent via the rollers.

The second concept is a hinged wire clamp. This concept mainly consists of a tweezer-like clamp with a joint that will allow half the clamp to pivot, creating a bend in the wire. The bender will also have a moveable stopper, allowing the user to adjust the length of wire bent. Once the bend is made, the pivot end can be disengaged, leaving the bent wire exposed. An initial concept sketch is shown in Figure 13.

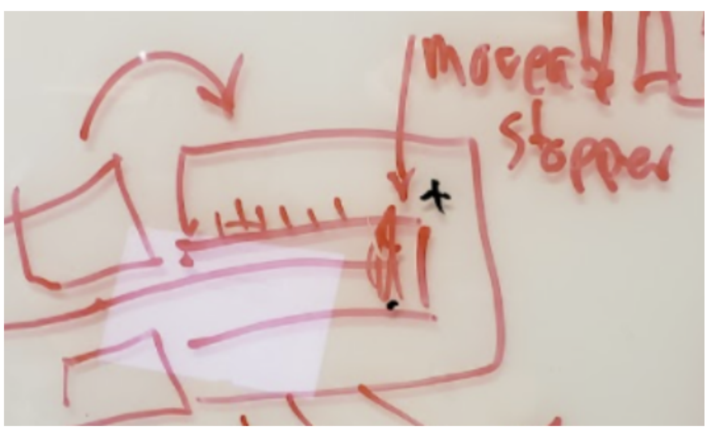


Figure 13. *Hinged wire clamp concept.* This combined wire holder and bender allows the user to make fine adjustments in bend length and angle by utilizing a stopper and adjustable hinge.

A third, quite outlandish concept is to use magnetic levitation to levitate the wire as opposed to holding it. This would require a series of magnets that would utilize feedback control to suspend a wire in the air and allow for movement to fine tune the position. A sketch of the concept is shown in Figure 14.

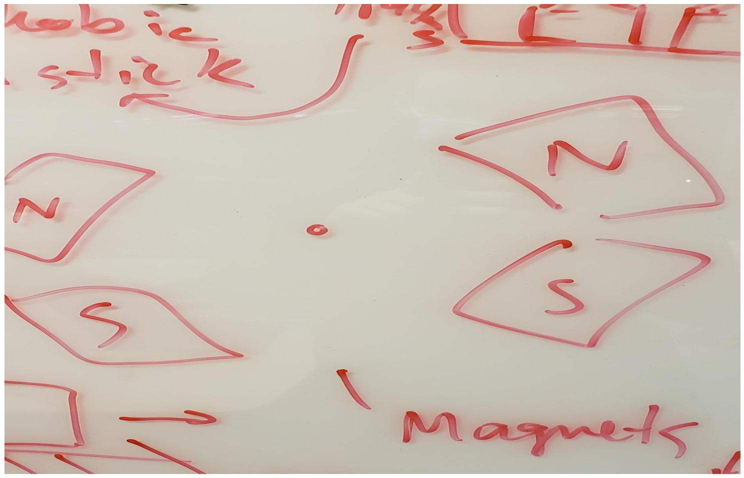


Figure 14. *MagLev wire holder.* This holder consists of a series of magnets that will be used to control the position of the wire. The view shown has the wire coming out of the page.

This design is likely not feasible and was mostly conceptualized to help with the ideation process.

The last and arguably most critical subsystem is the epoxy dispensing system. As the major focus of our brainstorming session, this subsystem had the most concepts as well as the most diverse. Furthermore, given that this was the main subsystem that was benchmarked, it was imperative to have as many different ideas as possible to avoid defaulting to an existing solution.

The first concept presented here is most influenced by benchmarking; it is a syringe mechanism that uses a ball/leadscrew for actuation. The novelty of this concept is that it includes a revolver mechanism that can make two epoxies readily available to the user. An initial sketch is shown in Figure 15.

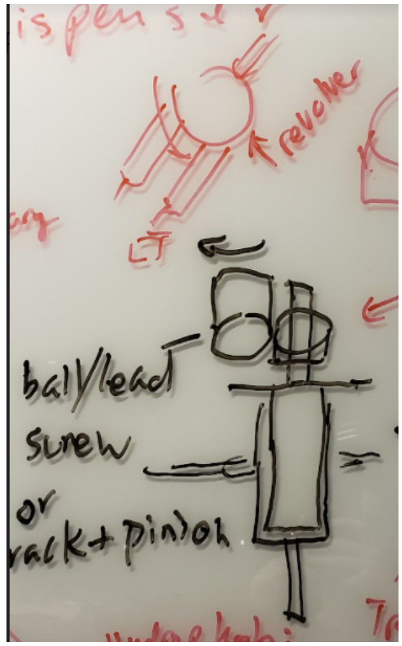


Figure 15. *Syringe with ball screw actuator and revolver mechanism.* The ball screw will allow for high mechanical advantage and thrust loads when using highly viscous epoxy and small needles while the revolving mechanism facilitates toggling between the two epoxies.

Another concept inspired by other nanofabrication methods is using a blade coater. A blade coater is traditionally used to apply thin films of material on the scale of microns to substrates. In our application, we would use the blade coater to apply a very thin layer of epoxy to the tip of the wire to be placed on the bond pad. This coating process could either be done when the wire is in the holding fixture or done before the wire is placed in the holder. A sketch of the blade coating mechanism is shown in Figure 16.

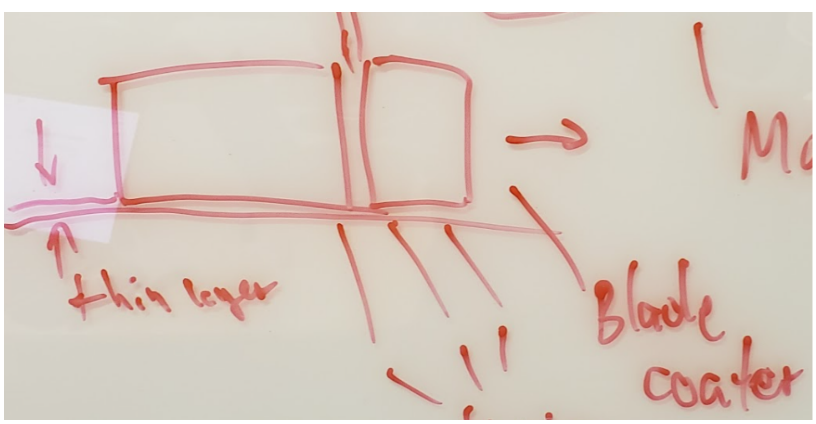


Figure 16. *Blade coating dispenser.* The blade coater coats a thin film of epoxy over the wires as shown. This process would allow multiple wires to be prepared at once.

The last epoxy dispenser concept utilizes capillary action. This dispenser would utilize the viscosity of the cohesive and adhesive properties of the epoxy to extract epoxy from a reservoir to be dispensed onto the bond pad. The design consists of a small tube that the epoxy would 'climb' into using capillary action and then be released onto the bond pad once the epoxy makes contact with the device. This concept could be alternatively used in a similar way as a water reservoir for pets like hamsters. These concepts are shown in Figure 17.

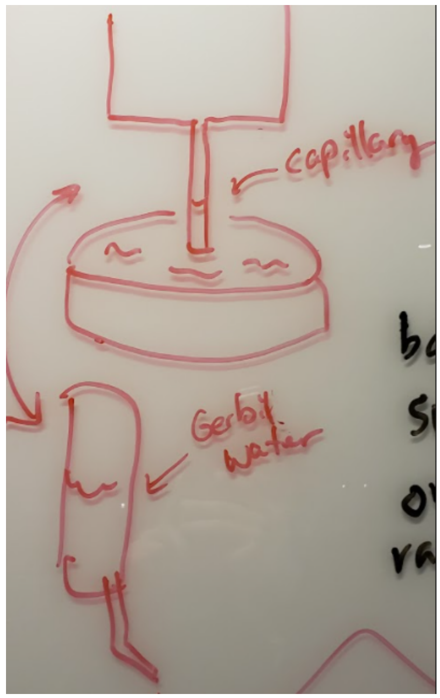


Figure 17. *Capillary Action Dispenser*. This dispenser utilizes capillary action to extract epoxy from a reservoir for dispensing.

These concepts are by no means the end of the concept generation process, and we will be constantly reiterating on related ideas and our selected concept throughout the process.

CONCEPT SELECTION PROCESS

After our concept selection process, we had to identify a design which would best meet our stakeholder requirements. Our concept selection process primarily consisted of two large phases: inside and outside the group. Inside the group, our group primarily focused on concept selection through technology readiness assessment, Pugh Chart, and simplicity checks. Outside of the group, our concept selection process primarily focused on active communication with our stakeholders and receiving professional feedback on our proposed design strategy.

For the wire holder subsystem and the positioning subsystem, we identified these two subsystems as being relatively simple to tackle with a good foundation of current resources to work off of. Specifically, our stakeholders are currently satisfied with the current condition of the wire holder and positioning system and believe that they currently meet their requirements. However, this does not mean that these two subsystems are not open to further development and improvements. After evaluation of these two subsystems through our accessibility to current resources, time and budget, we highlighted and selected concepts for the wire holder and positioning system.

The epoxy dispenser subsystem was the main challenge in terms of concept selection processes as we generated the most amount of unique ideas and this subsystem had to meet the most amount of specifications and requirements. Thus, after our regular simplicity check and accessibility check which was previously conducted on other subsystems, a decent amount of possible designs remained that could meet our specifications. Thus, to highlight the importance of different weighting factors and influences on our concept selection process, we used a Pugh Chart to compare and contrast the advantages and disadvantages of multiple design solutions proposed for the epoxy dispenser, as shown in Table 4.

Table 4. *Pugh Chart for concept selection of epoxy dispenser subsystem*. This dispenser utilizes capillary action to extract epoxy from a reservoir for dispensing.

Criteria	**Weight**	**Ball/Lead Screw + Syringe + Revolver**	**Capillary Method**	**Blade Coaster**	**Current Hand Bonding Method**
Bond shall require two different types of epoxies	3	3	2	2	0
Reliability	3	3	1	2	0
Precision	3	2	2	2	0
Time	2	2	1	3	0
Manufacturability	2	2	1	1	0
Total	N/A	32	19	26	0

Among the criteria for our Pugh Chart, we highlighted the targeted functional requirements for the epoxy dispenser subsystem: the bond shall require two different types of epoxies. We also recognized that the reliability and the precision of the epoxy dispenser subsystem were inherent from our functional requirements as our proposed solution should allow for consistent performance while improving over the current bonding method, which was not precise enough to dispense small amounts of epoxy. Thus, reliability and precision also contained a weight of 3, as they were identified to be equally important to being able to dispense two different kinds of epoxies. Other criterions we evaluated were time and manufacturability. We believed that these would be equally important, as they would impact the experience of the wire bonding process and the difficulty of producing a viable solution, but we considered them to be lower in priority than the previous factors. This is due to the fact that although time is an essential factor during the bonding process, we believe that any proposed solution would be a significant improvement over the 10 hour hand bonding process. We also recognized that any proposed solution, to its high requirement for dispensing small amounts of epoxy, would be difficult to manufacture. Thus, time and manufacturability were both considered to contain a weight of 2.

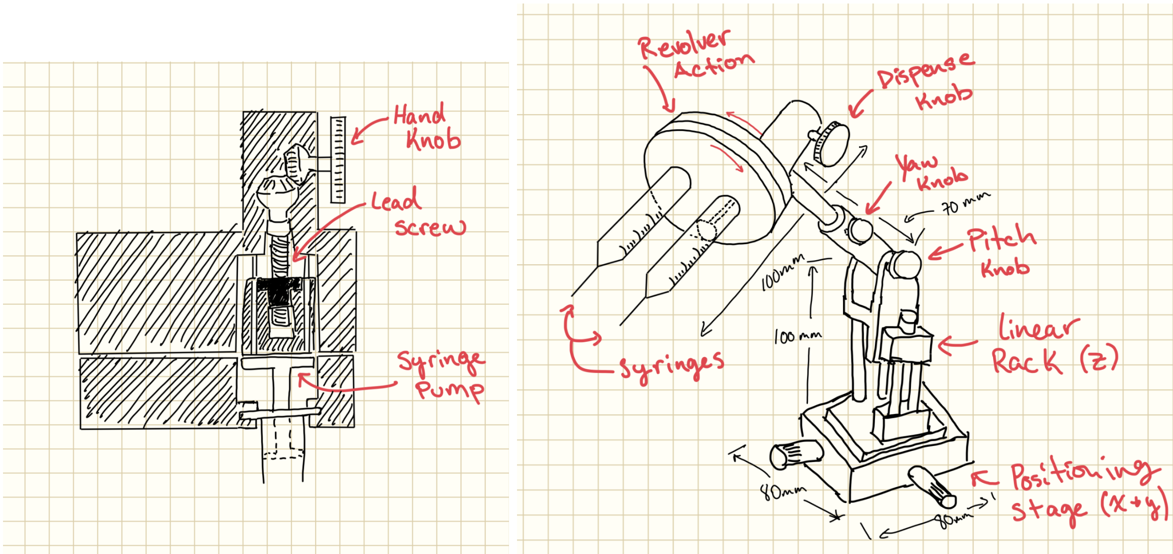
For a baseline concept to compare against, we chose the current hand bonding method of wire bonding. We recognized that this process had low precision, took a long time, could not swap easily between epoxies, and did not propose a viable manufacturing solution. Thus, this baseline concept had a zero for all criteria.

We then evaluated our most viable proposed designs for the epoxy dispenser subsystem (ball/lead screw + syringe + revolver, capillary method, blade coater) in comparison to our baseline concept. After evaluation and weighting on the factors proposed above, we summed up the relative weights and concluded that the ball/lead screw + syringe + revolver method was our primary concept for the epoxy dispenser subsystem due to its unique advantage in reliability and swapping between two different kinds of epoxies.

SELECTED CONCEPT

Based on the concept selection strategies proposed above, we were able to select a concept that we evaluated would best meet our functional requirements and specifications. Our initial selected design consists of a dual positioning system – the Mouse System for MEMS and the linear rack for the epoxy dispenser. For the epoxy dispenser subsystem, we selected a combination of a syringe, a ball screw, and a revolver. For the wire holder subsystem, we chose a clamping mechanism with a rotating bender.

For the epoxy dispenser subsystem, we elected for a design that contains a syringe pump, a lead screw, a hand knob, and a revolver. When the hand knob is actuated via rotation, it drives the lead screw through a set of bevel gears, which applies force on the syringe pump. Revolver action in the subsystem occurs through a turret mechanism which allows the dispensing of another kind of epoxy, as shown in drawing (a). In drawing (b), the subsystem is mounted upon a positioning system. An x-y positioning stage and a linear rack to allow the whole subsystem to move in x, y, and z directions. There are two knobs that will be used to adjust the yaw and pitch angle of the system. Then the dispensing mechanism will be attached to the positioning base. As two types of epoxy will be used for the wire bonding process, we implemented a revolver so that users can easily change the epoxy types by rotating the revolver and having the desired syringe locked against the dispense knob.



(a) **(b)**

Figure 18. *Drawings for the top cross-section view of the dispensing mechanism (a) and the epoxy dispensing subsystem (b).*

For the wire holder subsystem, we have once again a positioning subsystem that allows for not only change in x-y coordinates, but also change in pitch and yaw through a swivel joint. The wire is threaded through a clamp and held on using tweezers. A bender is mounted at the end of the wire holder which allows for wire bending at different locations and angles.

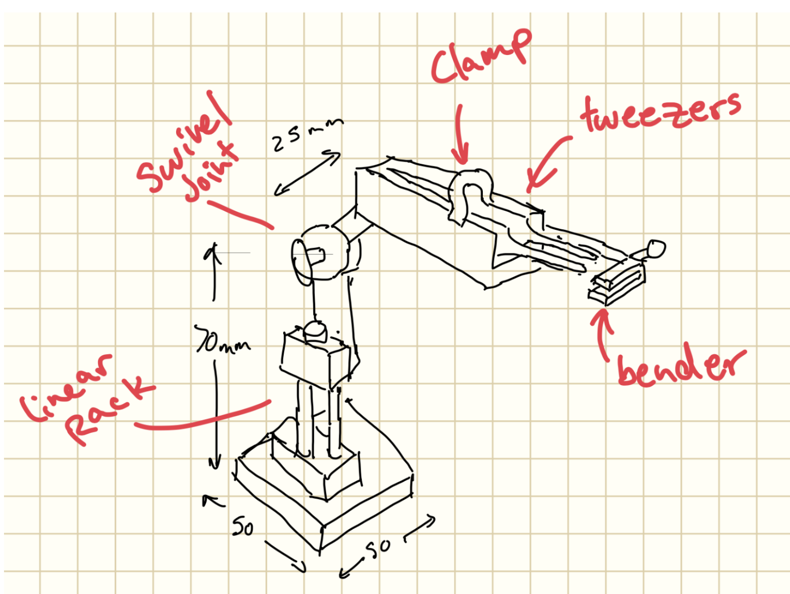


Figure 19. *Drawings for the isometric view of the wire holder subsystem*

Based on the selected subsystem ideas, we then have proposed a specific concept design for each individual subsystem. In our selected concept, we have defined a positioning system for the wire holder subsystem and the epoxy dispenser subsystem individually. Thus, we know that these two subsystems will move independently to each other. More detailed integration for the specific integration of the wire holder subsystem and the epoxy dispenser subsystem with their positioning subsystems should be custom designed using 3D printed PLA / ABS parts. We believe that the selected concept design will best meet our functional requirements and specifications defined previously.

ENGINEERING ANALYSIS

When we first started the engineering analysis, our primary goal was to be able to dispense epoxy with certain viscosity through a 28 gauge needle. We first conducted a physical testing that we equip the needle to a syringe and attempted to dispense the epoxy. It turned out that the procedure required a great amount of force. Therefore, we conducted first principle analysis to estimate the force required to better understand the system. Meanwhile, the high force requirement made the procedure highly unstable, leading us to move forward with controlling the subsystem with a motor. To do so, we also looked into the property of the motor and the pressure it can provide through the lead screw.

When conducting engineering analysis, we focused on the design drivers most pertinent to ensuring a functional system. Specifically, we wanted to ensure that the dispenser would be able to dispense a high enough resolution of epoxy per unit increment, in this case encoder counts of the motor, to ensure that the user could achieve the precision of epoxy volume required for a bond. To determine the relationship between the volume resolution (nL/encoder count) and various properties of the system, the following formula was derived:

$$\rho = \frac{1\cdot 10^{12}\cdot L\cdot \pi\cdot R^{2}}{C} \tag{1}$$

Where ρ is the volume resolution in nL/count, *L* is the lead pitch of the lead screw in m/rev, *R* is the plunger radius in meters, and *C* is the encoder count at the output shaft of the gearbox in counts/rev. Figure X shows the relationship between volume resolution and these parameters.

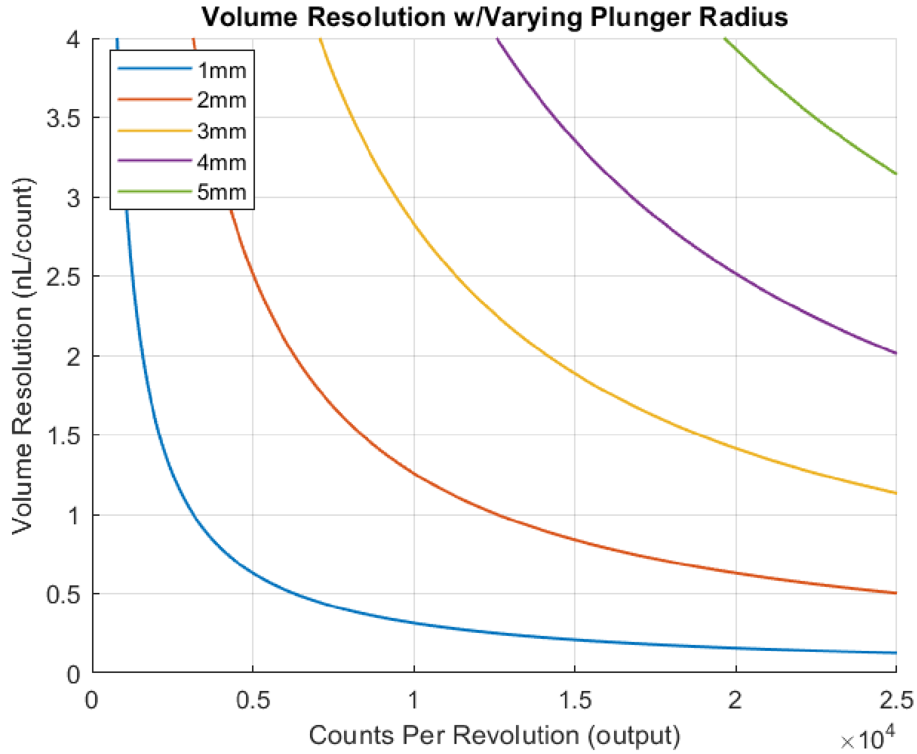


Figure 20. Relationship between volume resolution of epoxy dispensed and encoder CPR with varying plunger radius. Lead pitch for all curves = 1mm/rev.

It can be seen from Equation 1 and Figure 20 that the radius of the syringe plunger as well as CPR (counts per revolution) has a significant effect on the volume resolution. Given that we are dispensing a maximum volume of 4 nL per bond, a plunger radius of less than 1mm and the highest encoder CPR available are desired to give a reasonable total encoder count per bond. By maximizing this resolution, we can improve the precision and minimize error of volume dispensed.

It should be noted that with this analysis that there were a series of assumptions made for simplification. The first of which is that there is no mechanical play between the lead screw and lead nut. The presence of mechanical play will lower the actual volume dispensed for a given encoder count for the lead nut will initially rotate with the leadscrew if the guide rail and nut are not in contact. Since the actual volume will be less than expected. This is a safe assumption to make, for mechanical play will not cause the mechanism to over dispense. The second assumption made is that there is no slip in the system. For the same reason of lowered actual volume dispensed, this assumption is also safe to make to simplify the analysis. This approach was chosen because this relationship was needed in order to source components including the syringe and motor encoder and therefore physical testing was not a viable option. The math is also very straightforward and does not require too many assumptions to confidently carry out.

The second analysis performed was to determine the pressure drop across the length of the dispensing needle for a given flow rate. The need for this analysis rose after testing the 34 gauge needles with our stakeholder Joonyoung. We noticed that the flowrate was extremely slow and that a large amount of force was required to dispense the more viscous epoxy. This concerned us in regard to the required capabilities of the motor and leadscrew to dispense the epoxy as well as the time required to deposit the epoxy, which has a direct impact on our time requirement.

To model the relationship between flow rate and pressure drop across the needle, a variation of Hagen-Poiseuille flow was used as seen in Equation 2:

$$\Delta p = \frac{8\mu l Q}{\pi R^4} \tag{2}$$ [28]

Where Δp is the pressure drop in Pa, R is the needle inner radius in meters, l is the needle length in meters, μ is the dynamic viscosity in Pa-s, and Q is the flow rate. The relationship between pressure drop and flow rate is illustrated in Figure 21.

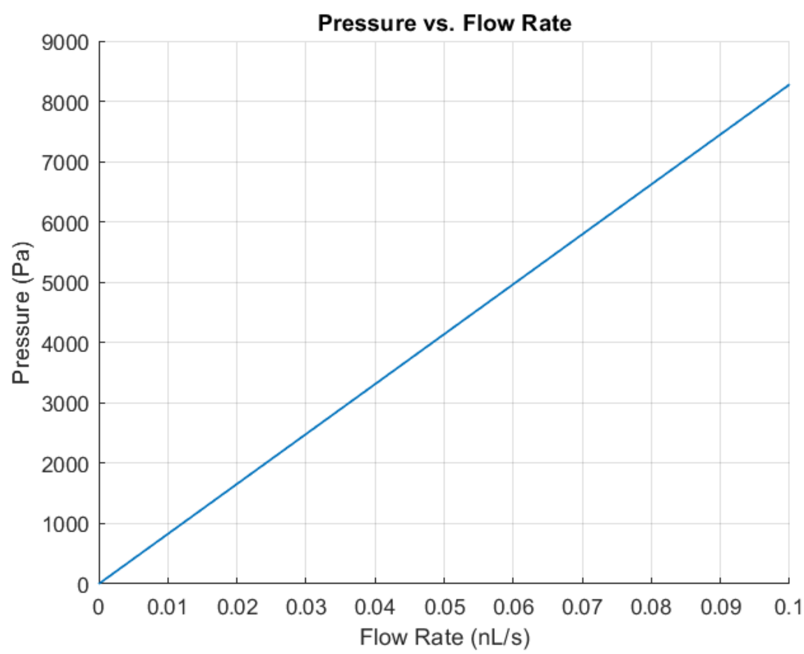


Figure 21. Relationship between desired flow rate and pressure drop required to dispense for a viscosity of 2 Pa-s and our current needle dimensions.

By observing the graph of Figure 21. we can see that there is a linear relationship between flow rate and resulting pressure, and in order to achieve the time requirement of < 10 min per bond with two separate epoxies, a flow rate of around 0.01nL/s and 0.03nL/s is desired to have a reasonable cushion for operator time.

The choice to determine this relationship using the Hagen-Poiseuille method is justifiable on the basis that carrying out empirical tests to accurately determine pressure and dispense volume are not currently at our disposal. Furthermore, more complicated analysis such as a CFD simulation would require a better understanding of such tools in order to confidently interpret the results. The efficacy of this choice is also dependent on a couple underlying assumptions. The first of which is that the pressure drop across the syringe reservoir is negligible compared to the pressure drop across the length of the needle. By considering the disparity between radius of the needle and syringe pump, approximately 25 microns for the needle and over half a millimeter for the syringe pump. The second assumption is that the Hagen-Poiseuille relationship holds at this small scale. This assumption is a challenge to justify for it is contingent on many, if not all, parameters used in the analysis. Therefore we are not entirely confident that this curve is representative of the actual behavior of the epoxy through the needle, and have exercised caution by treating this as an underestimate in terms of required pressure.

We also conducted functional analysis to ensure that a specific needle gauge could dispense epoxy. The needle size used in the current process is a 28 gauge needle that has a beveled tip, similar to that used in the medical field. In an effort to improve accuracy, we proposed a new smaller needle tip (34 gauge) that would be better suited to application. We also proposed a change in the type of needle tip. The proposed needle has a blunt tip which should have a more even flow of epoxy. This is shown in Figure 22. We used qualitative analysis to ensure our proposed needle would work with the viscosity of the epoxies being used. This analysis would ensure that the needle would work in the design and not rely on complicated equations. It did not require any complicated set up so the experimentation process could be quick and simple.

Figure 22. *Needle Tip Types.* The leftmost image shows a bevel tip used in medical applications. The right most tip shows the blunt end on the needle we tested. [27]

The experimentation process included a minimal setup and execution. First, the needle tip was inserted onto the plastic syringe holding the conductive epoxy. The conductive epoxy has a viscosity of 2000 centipoise (cps) [14] and the Biocompatible UV Epoxy has a viscosity of 600 cps. We used the conductive epoxy in our experiment because it has a higher viscosity and therefore could work for the lower viscosity epoxy. The needle tip purchased has a luer lock attachment point so it was easy to replace the needle tip. Once the needle tip was in place, we dispensed the epoxy by pushing down on the syringe. We had to mix up the conductive epoxy at first because the metallic parts had separated from the epoxy itself. In the end it was successful as shown below in Figure 23.

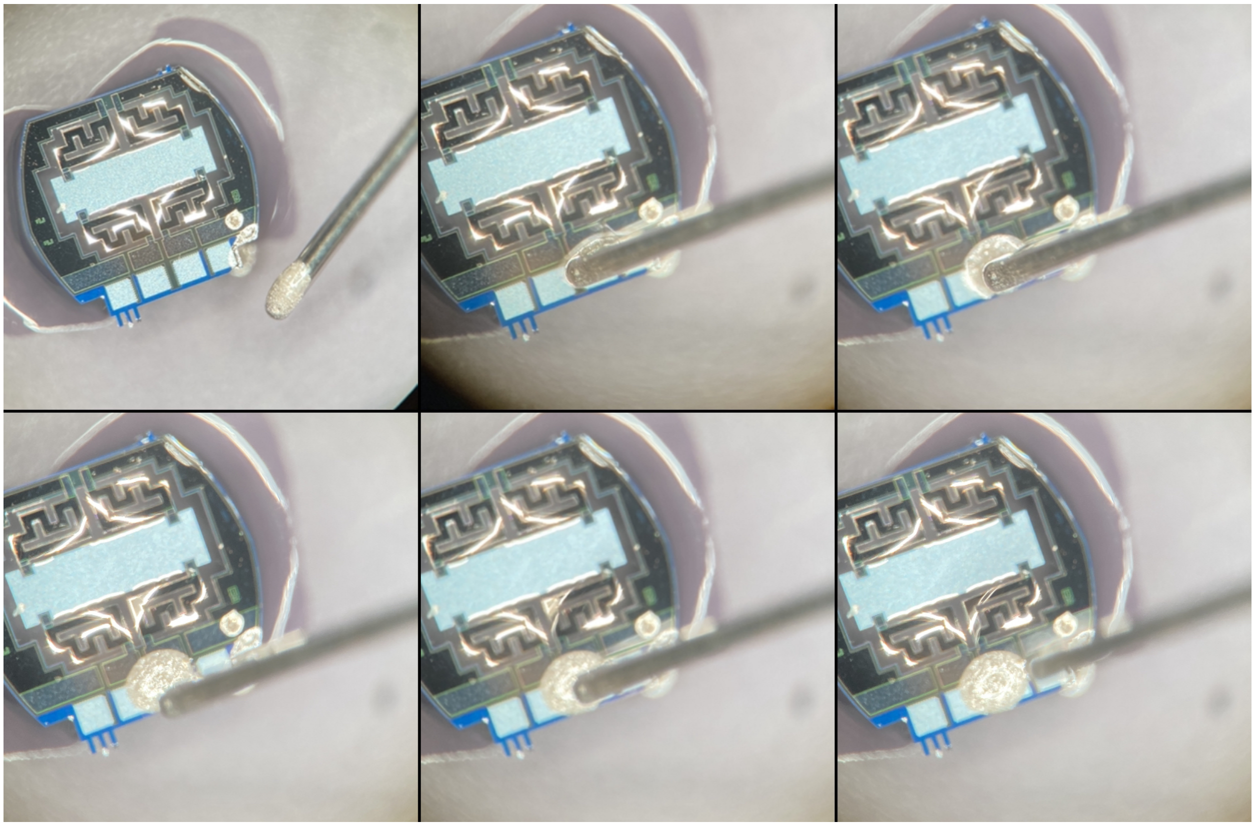


Figure 23. *Application of epoxy using the 34 gauge needle on to the MEMS chip.* As shown in the first rough operation with the new needle, the needle is capable of dispensing the conductive epoxy, though a relatively large amount of force was required.

We have high confidence in the experimentation that we conducted. The epoxy was dispensed in a more concentrated fashion because of the smaller inner tip diameter. This experiment proved that the epoxy could flow through the smaller 34 gauge tip of the needle. We believe this analysis to work with our design because we plan to use a motor to fine tune the amount of epoxy dispensed. We did not need to measure the amount of epoxy dispensed, just prove that the needle could dispense epoxy of this viscosity.

With a decided operating range for dispensing pressure, it was necessary to ensure that the lead screw and motor assembly was properly specified to achieve the necessary performance, specifically torque output of the motor. The analysis conducted to determine the minimum torque required was done computationally with the following derived equation:

$$T = \frac{P \cdot A \cdot L}{2\pi \cdot \eta} \tag{3}$$

Where T is the torque from the motor output shaft (after gearbox) in N-m, P is pressure in Pa, L is lead pitch in m/rev, A is the syringe plunger area in m^2, and η is the efficiency of the leadscrew.

From Equation 3, we are able to illustrate relationships between parameters of our system, specifically plunger area and lead pitch. Figure 24 shows the relationship between motor torque and pressure with varying plunger radius.

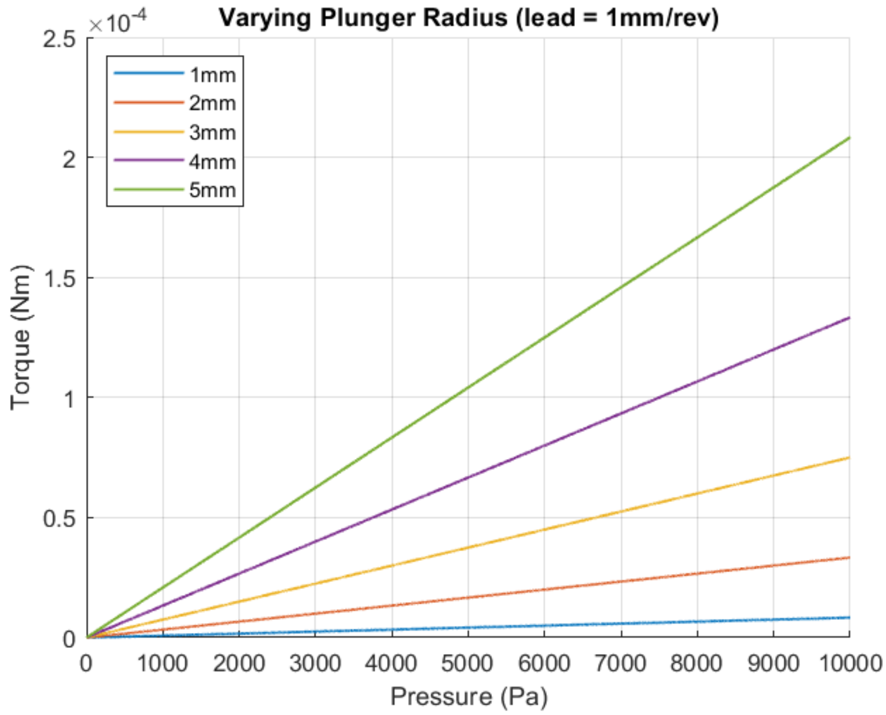


Figure 24. The effect of plunger radius on the relationship between pressure and required motor torque (lead pitch = 1mm/rev).

Given that we want the smallest possible lead to increase the mechanical advantage and the volume resolution, it was of higher priority to see how the plunger radius limits us at high pressures. It can be seen from the figure above that even with a plunger radius of > 5mm, that the torque required is not substantial. This claim is further supported when including a high reduction gear box at the motor output, further increasing the torque capability and increasing encoder resolution. For this specific analysis, we assumed that the flow of the epoxy was fully developed viscous laminar flow and is therefore constant pressure. If the epoxy is not flowing, more torque will be required to start the dispense. However, this increase in pressure is negligible.

From this analysis we can conclude that the motor performance will not be a limiting factor in our dispenser design, and that the steps to achieve higher volume resolution will naturally increase the performance of the overall system. This has informed our decisions to source a syringe with the smallest plunger radius available, a lead screw with lead pitch of less than or equal to 1mm, and a motor with a CPR of over 2000 after gearbox reduction.

FINAL DESIGN

Mechanical Subsystem

From our previous analysis and design selection methods, we had proposed a rough draft of the CAD models of the epoxy dispenser head as shown below in Figure 25. This master model consists of simple geometries which allow for concept sketches, dimensions checks, and a better understanding of the clearances and tolerances we are working with in a part file. Working with this multi-body part, we are able to define geometrical relationships and interaction between each individual component.

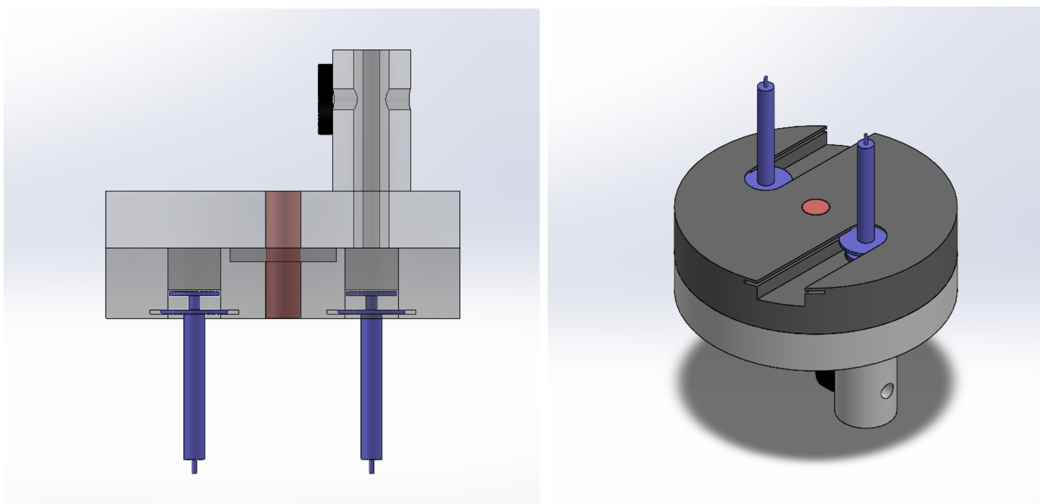


Figure 25. *Preliminary CAD models for the epoxy dispenser.* This CAD shows the beginnings of the revolving head of the epoxy dispenser. It also includes the two syringes each with their individual epoxy. The assembly contains two assembly blocks. The middle red cylindrical tubing represents the shaft which is attached to flanged bearings in the top and bottom assembly block. The top assembly block is the housing for the lead screw and bevel gear.

Based on our engineering analysis and feasibility check of our selected concept, we were able to simplify our previously selected design of ball screw + revolver for simplicity and ease of assembling. The proposed epoxy dispenser subsystem design concept consists of an electric motor, a coupler, a lead screw, a plastic flanged nut, a 3D printed attachment, a 3D printed housing, a 3D printed bushing and a glass syringe pump, as shown in Figure 26.

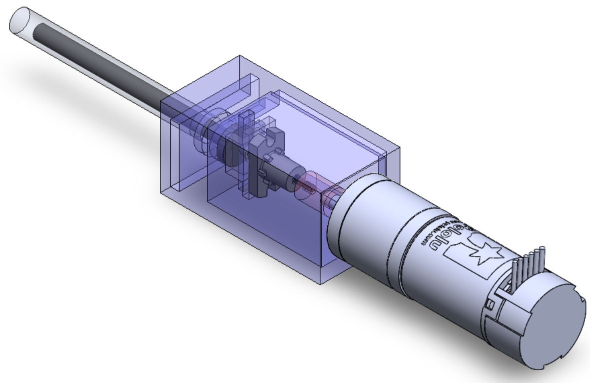


Figure 26. Isometric view of CAD model of epoxy dispenser subsystem

The epoxy dispenser subsystem is then attached to a commercial positioning system and swivel joints for accurate placement. The detailed parts numbers selected are included in Table 5 (BOM). Some of these purchased components had CAD models provided by the vendor (Pololu, McMASTER-Carr) while others contained only brief descriptions of the dimensions of the part (syringe pump). In the latter case, we had to come up with a rough sketch based on the dimensions given of the part and could be easily subjected to further adjustments. Thankfully, Solidworks is a powerful tool that would allow for easy subsystem adjustments in CAD when other parts have dependencies driven off the syringe model. In the end, we created these purchased components in a part file and started designing custom parts (3D printed) around the known geometrical relations of the purchased part files. Figure 27 gives a good description of how we are working around known part files to design custom parts which will be fabricated through 3D printing.

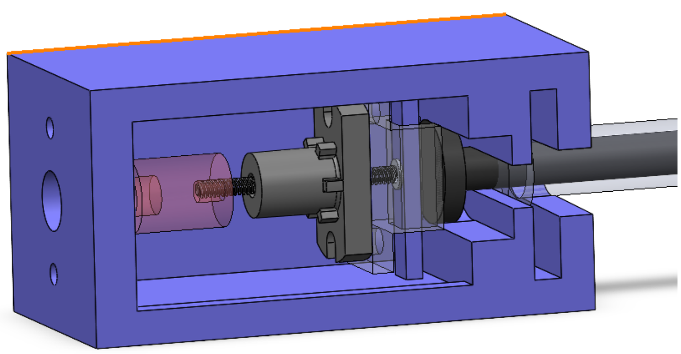


Figure 27. Scaled Isometric View of CAD model of epoxy dispenser subsystem (excluding motor). The 3D printed housing (blue) contains motor holes and a shaft hole for motor mounting based on the geometries in the motor and snap-fit mounting for the syringe pump (black and transparent gray). The 3D printed attachment (transparent

white) utilizes the mounting holes of the plastic threaded flanged nut to mount upon and pushes the syringe pump.

The cross section view across the midplane of the assembly gives a better illustration of the working mechanical principle of the epoxy dispenser subsystem, as shown in Figure 28. The electric motor, which is driven and controlled by an Arduino Uno (see electronics subsection for more details), has an output shaft that is attached to a motor coupler, which uses set screws to pin both ends of the motor coupler. The other end of the motor coupler is attached to a lead screw, which is threaded through a plastic flanged nut. The flanged nut is then rigidly attached to a custom designed 3D printed part. The other end of the lead screw is threaded through a 3D printed bushing to avoid axial load. The custom designed 3D printed part reaches around the bushing mount and pushes the syringe pump. All parts are mounted through a 3D printed housing, which contains screws for motor mounts, a vertical wall for lead screw bushing, and a snap fit mechanism that allows the syringe to easily be contained within the housing without falling out easily.

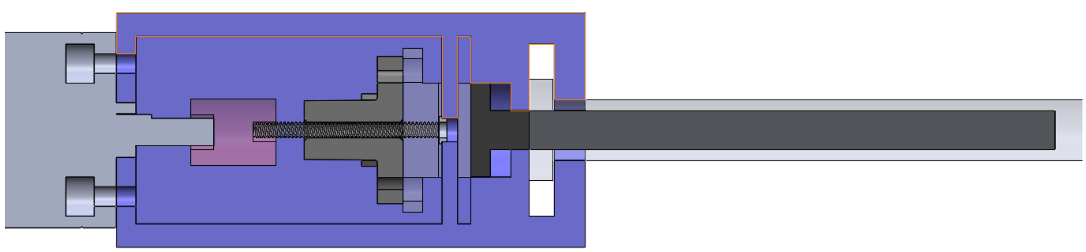


Figure 28. Midplane Section View of CAD model of epoxy dispenser subsystem.

The system starts working when the electronic motor is driven through an input signal from the Arduino. This then drives the motor coupler and then the lead screw to spin at the same speed as they are uniaxial. Rotation of the lead screw is then converted to translation through the plastic flanged nut and moves the flanged nut to the right. The flanged nut, which is rigidly attached to the 3D printed attachment, then pushes the inner barrel of the syringe pump and then dispenses epoxy. The maximum travel in the system is constrained by the distance between the right end of the housing for the inner barrel of the syringe to the vertical wall of the bushing (6.85 mm) and the length of the lead screw minus the total length of the flanged nut plus the 3D printed attachment (21.3-15.2 = 6.1 mm).

Based on the above dependencies in the part file, we were easily able to convert the geometrical dependencies into the assembly file utilizing the ‘save-bodies’ function in Solidworks. Individual adjustments to each part were made for ease of 3D printing, assembling, and structural stability. The final assembly file is shown in Figure 29.

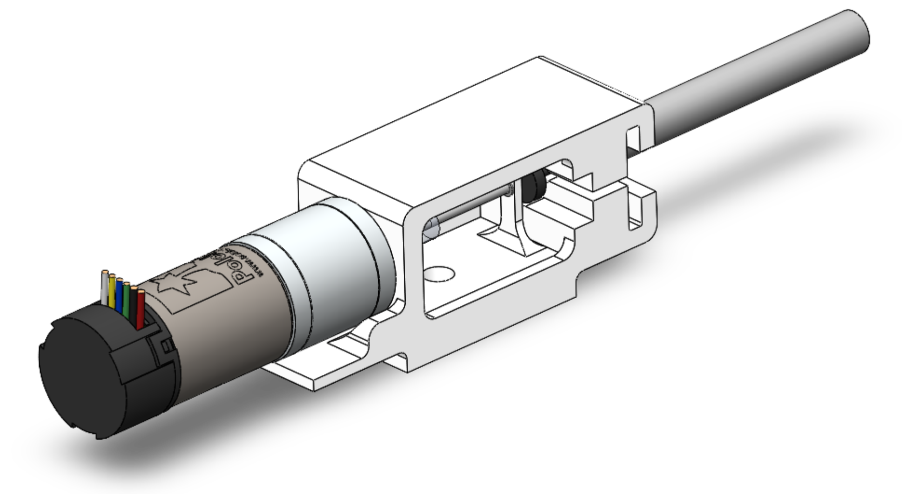


Figure 29. Isometric View of CAD Assembly.

Electrical Subsystem

As the dispensing system will be actuated by the gearmotor, a safe and efficient electrical system is required as shown in Figure 29.

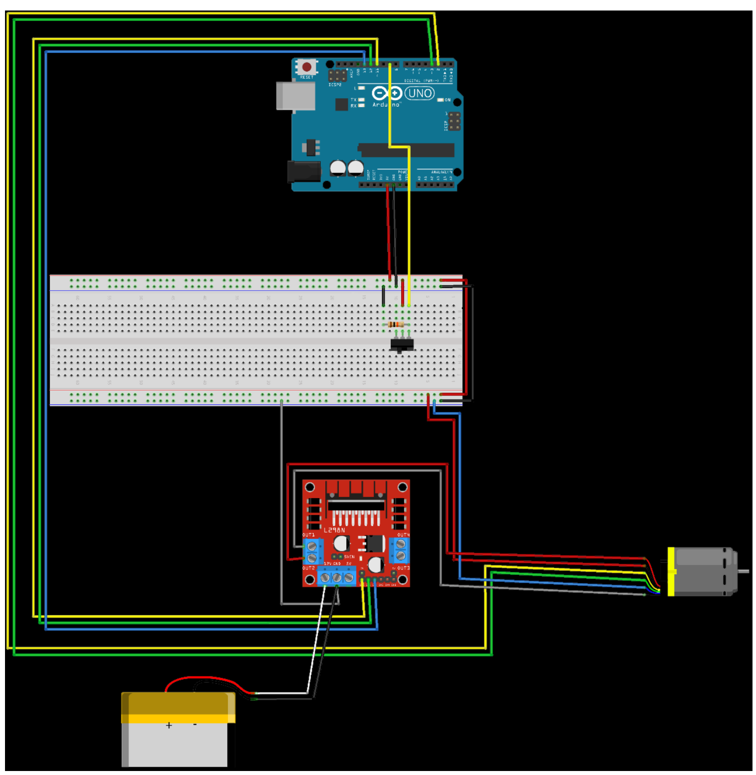


Figure 30. The electrical wiring diagram.

For the entire electromechanical system, we have an arduino UNO microcontroller that will be controlling the gearmotor to rotate forward and backward for a certain angle with the help of feedback signals from the rotary encoder attached to the gearmotor. As this is a DC motor that requires a driving voltage higher than the maximum voltage an arduino UNO can provide, we need to control this gearmotor via a motor driver. With a limit switch added within the system, the user can interact with the system and dispense a certain amount of epoxy by clicking on the limit switch.

The basic logic of the arduino code is that, when the limit switch is activated, the arduino will output analog PWM signals to the motor driver so that the gearmotor will be supplied with 0V-6V from the external 6C power supply and thus driven at a different speed. While the gearmotor is running, the encoder attached to the gearmotor sends back four bits digital signals to the arduino that provide us the direction of the rotation and the position of the gearmotor. By knowing the angular position of the motor, we can apply a control system with a certain signal gain based on the unity feedback to improve the rotating performance.

VERIFICATION AND VALIDATION PLANS

To verify that our design meets the requirements and specifications that we have generated from stakeholder analysis we will conduct a series of tests with the assembled prototype. The first set of tests will be to ensure that the device is operational and that subsystems are interacting as expected. The first preliminary test includes testing the controller logic and electrical subsystem. Specifically, we will ensure that the motor is properly controlled by ensuring that overshoot of the encoder position is less than 10% and that the steady state error of position is less than 5%. This is assuming that the control script works as expected and that the hardware has been properly implemented. However, this initial test will also be an indicator of its functionality.

The second preliminary test before validating the specifications is to ensure that the dispensing mechanism is operational. To test this, we will operate the mechanism without epoxy and observe any mechanical play, interferences, and other unexpected issues that may occur. We will also run these tests at a reduced voltage of 4.5V (75% nominal operating conditions) to prevent any catastrophic failure of mechanical components. Once these two tests are complete, we will proceed to test our specifications.

The first test that will be performed will verify that we have met our volume specification of 0.5-4nL. This test will consist of the user dispensing the epoxy onto a damaged/failed MEMS device and directly observing if the epoxy has been successfully deposited within the confines of the bond pad via microscope. This test will be averaged over several trials and the overall success rate will be recorded. A successful test will have no conductive epoxy outside the bond pad and will be accomplished with the expected input of the user. A successful verification test will have a bond success rate of at least 95%. This will translate to a 77% success rate of completing the 5 bonds required to assemble each MEMS device.

By conducting this test, we are assuming that volume flow rate is what we expect from the analysis. A potential drawback of this assumption is that if we get inconsistent flow rate the user may be more susceptible to creating errors. The limitations of this test are the presence of this user error and the inability to measure the volume of epoxy dispensed directly. Without being able to directly measure the volume, we are unable to determine the uncertainty of dispense volume, which will essentially determine the minimum predictable volume that can be dispensed. This test is intended to give a qualitative understanding of whether this requirement was met. This method was chosen because it directly addresses the requirement and is relatively easy to conduct with a working prototype. It is the simplest and most pragmatic approach while still being directly applicable.

The second test that we will be performing is to verify that the bond can be done in less than 10 minutes. This test will include the primary user, Joonyoung, using the prepared device to create a bond. The average time over 4 or more trials will be recorded and compared to the specification. Furthermore, to eliminate the influence of prior experience, a second, inexperienced individual will conduct the same test. The average of this subject will be referenced with Joonyoung's average to observe the influence of the usability of our device.

The main limitation of this test as well as the first test is that we cannot completely eliminate the influence of usability. Usability is implicit to the nature of both tests given that someone must operate the device. This may pose a challenge because the cause of a failed test will be difficult to differentiate between the functionality of the device and the usability of the device.

As for validating our design, we will observe Joonyoung carry out a bond from the initial device setup to a completed MEMS assembly. Factors that we will be considering include whether the bonds were successful, usability and ease of setup, and general stakeholder satisfaction.

In terms of the timeline regarding these tests, there were technical issues when assembling the device and a second iteration that is more assembly oriented will be fabricated shortly after this report has been completed. Therefore, verification tests have yet to be completed and results are pending.

PROBLEM ANALYSIS

Based on our engineering analysis and specifications listed, we have identified potential issues in the system. The first issue we see potentially affecting the functionality of our design is properly constraining the lead screw. If the lead screw is not properly constrained, it can lead to excessive loading in the radial direction, which can result in stripping of the lead nut and bending of the lead screw over time. This will eventually cause mechanical failure in the device and is the main concern of the current design. Furthermore, if the lead screw is not properly aligned with the motor shaft and bushings, similar problems could arise as well as inaccuracies in dispense volume and limited thrust capability. In the case of such failure, we will be able to 3D print another lead nut with better mechanical properties using a higher strength material. Furthermore, if we are able to identify the source of misalignment we can make the adjustments accordingly in the CAD assembly and reprint components.

A second issue that has been a subject of concern is properly securing the borosilicate glass syringe. If the syringe is not properly secured, the force of the lead screw actuator could cause the syringe to be displaced and even fall out during operation. This could potentially lead to damage of the syringe and MEMS device or even injury. In the case of such failure, or perhaps proactively, we plan on adding a second locking mechanism as a safety precaution. This will also further reduce any present play in the fixture as well.

DISCUSSION

Within the problem and design we developed, we think there are weaknesses and strengths. We would like to highlight them to establish where we could do better in the future and what to continue to do as we work towards being professional engineers.

The problem definition could have been better defined by observing more researchers that work with MEMS chips. As part of our concept generation process, we met with the nanofabrication lab and they spoke of how common an issue micro bonding to MEMS chips was. Looking back, we met with this group far too late in our process and missed this key detail in our initial problem definition. It could have been very beneficial to survey and observe multiple researchers in the area instead of just one. We could have come up with a design that was more suited to more users rather than just our sponsor by generating requirements and specifications that were oriented towards solving the general problem as opposed to a single case with our stakeholder.

We also think we could have benefitted from prototype probing with our sponsors. We were able to get insight on our alpha design choice but a more continuous input would have been helpful throughout our design process. Using non functional prototypes along the way would have better shown how the device would potentially be used. It also could have changed the way we designed the device because we could have had a better understanding of how it would potentially be used by observing early interactions between our stakeholders and these early prototypes, along with feedback from secondary stakeholders like the nanofabrication laboratory.

One of the major strengths that our design exemplifies is that the materials and design work are significantly simpler and more accessible than any benchmarked design we have encountered in research, commercial, or patent literature. If this design can even be partially successful in fulfilling the prescribed specifications while remaining significantly cheaper and simple, it will be an indicator of the promise this design has to be a solution for a niche market of stakeholders in academia working with MEMS chips. A second major strength of this design is the high ceiling for growth. This design can be improved in many ways with the current architecture with the cost of better manufacturing methods and more costly components. In the case of a high volume production setting, this will not have a significant impact on the accessibility of this device. All the components and mechanisms used in this device are also well understood in industry, so improvements can be readily implemented without a steep learning curve.

A major weakness of this design is that we did not realize that our focus should be narrowed on the dispensing mechanism quickly enough. We found that throughout the design process that our resources and focus were far too spread out among the different subsystems, resulting in the delayed generation of more detailed design concepts. This consequently led to a rushed final design where many key aspects were overlooked including ease of assembly, tolerance stacks, and constraining methods of key components, which ultimately has led to the design not being completely realized and assembled. Specifically, components such as bushings or bearings, guide rails, and other constraining methods should be improved and/or implemented to ensure that the lead screw mechanism operates properly. Furthermore, the housing of the dispenser could be made larger to improve clearances for fittings and make assembly easier/possible.

A second major weakness of this design was the manufacturing method used. The current manufacturing process for this device does not provide the precision required to make the device easy to assemble and will potentially introduce large amounts of error in the expected functionality. A suggested fix to this issue would be to use a 3-axis CNC milling machine and adjust features of the design accordingly. This will also help with mounding issues encountered from 3D-printing, specifically mounting and fittings.

REFLECTION

There are many factors that impacted our design and that our design will impact. These considerations are discussed below.
Our specific design does not impact public health, safety and welfare directly, but the application of the MEMS chip being developed does. It is to be implemented in an endomicroscopy device that will be able to scan inside the body instead of having to remove tissue from the body.
The global context of our design focuses on MEMS chip researchers and their development of one off designs. Our design aims to make the bonding to MEMS chips easier for all research and developers in the area. There are minimal social impacts with the manufacturing, use, and disposal of our design. The impact of our design is specifically focused on MEMS chip researchers and assemblers. The potential economic impacts of our design are focused in the area

of time. Our design will save time for researchers that usually do the work by hand. The design also has a low cost and can use existing equipment in a laboratory so there should be minimal economic stress in the implementation of the design. We conducted a few interviews with our primary and secondary stakeholders to understand the common issues existing in this field, which many experts in this field are facing. By finalizing our design and making it widely available, we will be making a positive societal impact by contributing to technology development and economic development.

The approaches we took to our problem differed based on each individual's culture, privilege, and identity. It also differed on our stylistic differences when approaching a problem and the associated design. Each individual on our team had their own culture and identity which made the process different for each of us. Some of us could relate more to our sponsor as they had worked in research before and also had a similar background. Some of us felt more out of place in the research setting and led to different people taking the front seat in different environments. This led to problem exploration differently for each of us. There were members of the group more focused on solving an individual problem for our sponsor and some members who wanted a border scope to include more researchers like him. This came from the different relationships each of us had with the sponsor based on our own culture, privilege, and identities. In discussion of our different identities, we had members of our group who were more comfortable speaking up and sharing their ideas and some members who were less comfortable. We tried to respect the boundaries of each member but would also request different members share their ideas and perceptions of the problem or design. We also tried to let each member work in their area of perceived expertise while still coming together as a group. One specific member was better in the area of electronics while another member flourished in the area of team management and outreach to stakeholders. Everyone was still involved with each process but the lead of each section fell onto a specific member.

The discussion of power differences is very interesting in our problem definition and design. Our stakeholders were in two different locations for the duration of our semester. We found a more even power with our stakeholder who was a PhD student. He would work with us for development of requirements and give insight into design exploration. This relationship occurred because he had a similar stylistic idea with the group and also had a closer identity with the group. He was a student, a PhD student, but still a student similar to us. The relationship of power differed with our other stakeholder, a professor. As was stated before, he was in a different country which made interfacing a little more difficult. The power dynamic was different as the professor had far more authority over our team. His suggestions in our design development were implemented without any pushback. We felt that this was natural though because he did have more expertise in the area.

The power dynamics in our group itself were balanced. Each team member felt comfortable in their own area of work and were happy to contribute. The members who had worked in research labs before held more power when working with our sponsors because they could relate better. On the other hand, some members were better suited with management and held more power when assigning tasks. Altogether I would say the power dynamic was give and take between every member. Mutual respect was established early on in the project when we discussed our own strengths and weaknesses which made it easier for us to be upfront with one another.

As we worked through our problem and design, our perspective changed to better understand our stakeholders. We observed the struggles that they were going through and when developing our design felt the struggle while trying to design a solution. We also learned their perspective better as we understood how small everything was. The wire they use is the thickness of a piece of hair and the bond pad is the size of the thickness of a fingernail. As we explained our problem in various design reviews, we got a better perspective into the problem. It also helped us understand the difficulty our sponsors go through.

The biggest ethical dilemma we faced was handling the completion of the design. This was definitely a personal ethics issue rather than a professional one. We had to balance a design that was good enough but not perfect or a perfectly functioning device. The team was divided on how to proceed because some of us were feeling burnt out while others felt a need to provide our sponsors with the best work. It was difficult to make a decision with the limited time we had. The team wanted to give the best possible design but time did not exactly permit us to.

Upon entering the marketplace, this design would not present many ethical issues. We could possibly predict an ethical issue with the epoxy stored in the device. Epoxy can have toxic qualities so keeping it unsealed could be dangerous. With the scale of our design we do not see this being a likely outcome.

Our personal ethics do differ from the professional ethics we are expected to uphold. The group understood that this was both an assignment for a grade and a device that could significantly help a group of people out. There was a balance between what is reasonable to present to our stakeholders and what will get us a good grade. We leaned to the side of creating something great for our stakeholders and were less reliant on the grade. We still think this is important to note because in a typical work place someone would always want to do the best they possibly could. You would always want to cut down on cost or make the most efficient design. In our case, we did the best we could with the time we were given.

FUTURE WORK RECOMMENDATIONS

For future iterations of this project we recommend that the design changes described in the discussion be implemented for improved functionality and safety. Specifically, implementing a guide rail and bushings to radially constrain the leadscrew as well as a push ring to further constrain it axially. Furthermore, the housing design can be expanded to facilitate ease of assembly. To improve performance, the leadscrew could be replaced with a ball screw to improve efficiency and thrust capacity. In terms of manufacturability and better tolerances, separating the housing into several components that can be easily milled. Lastly, a more robust locking mechanism for the syringe is necessary for the extended life of the device and safety of the user.

CONCLUSIONS

The novel endomicroscopy device described here requires systems that have been traditionally limited to large-scale lab environments be miniaturized to fit in an incredibly small system. Due to this fact, innovations must be made to obtain the same reliability and performance as their large counterparts, resulting in the need for high precision and repeatability in their function as well as fabrication. Therefore, it is important for us to design a wire bonding process that yields reliable, repeatable results in a timely manner that conforms to requirements and specifications generated from stakeholder engagement, existing literature, and engineering standards. Alongside these standards, it is imperative that we acknowledge contextual factors beyond that of the immediate stakeholders and construct priorities in the decision making process based on ethics, internal power dynamics, and inclusivity despite the seemingly narrow scope of this project. The final outcome was not what we predicted. We could not provide an adequate design for the completion of verification and validation. We require further iteration upon our design moving forward.

ACKNOWLEDGEMENTS

Throughout the project we have received a great deal of support and assistance.
We would first like to thank our sponsors Dr. Kenn Oldham and his PhD student Joonyoung Yu. Dr. Kenn has been supporting us and providing critical feedback throughout this semester even if he is not available in-person. Joonyoung has been tremendously helpful in providing feedback, refining and testing the design, updating our progress to Dr. Kenn, and etc. It is a true pleasure to work with both of our sponsors.

We would like to acknowledge our ME 450 instructors. We gained useful feedback during the project on problem identification, concept generation, and design finalization. We would like to express our great appreciation to Professor Kathleen Sienko for providing detailed feedback and supporting us throughout the semester consistently.

We would also like to thank all the other people for their contributions to this project, including members from Nanofab Lab at the University of Michigan. They helped us to identify the

common issue within the field and potential importance of our project, which gave us the motivation to produce a better design.

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APPENDICES

Appendix 1: Gantt Chart for Project Schedule

Wire Bonding Mechanism for Microsystem Assembly

ME 450 Team 23
Chloe Kimberlin, Enrico Braucher, Tim Zhang, and Sean Ye

Project Start: Mon, 1/17/2022

Display Week: 1

TASK	ASSIGNED TO	PROGRESS	START	END
Design Review 4				
Assembling and Manufacturing	Team	25%	4/1/22	4/14/22
Finalize CAD	Tim, Enrico	25%	4/6/22	4/11/22
Testing Entire Mechanism	Team	0%	4/7/22	4/17/22
Poster Design	Team	0%	4/5/22	4/17/22
Design Expo	Team	0%	4/14/22	4/14/22
Final Report	Team	0%	4/14/22	4/20/22

Figure 1.A *Gantt Chart for Project Schedule*. The project schedule is mainly split into four portions from the design review. The specific tasks, assigned person, and progress are shown.

Appendix 2: Benchmarking Devices

Pictures of the benchmarking devices are listed below and shown in Figure 2 - Figure .

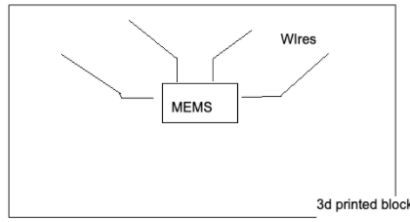
Figure 2.A *Micro-Dot™ Hand-Held Manual Syringe Dispenser.* The Micro-Dot™ hand-held syringe dispenser delivers accurate and consistent fluid deposits from pre-packed 3, 5, and 10 mL disposable syringes. This dispenser can be set to dispense a wide range of fluid shot volumes. [7]

Figure 2.B *Preflow EcoPen.* This is a volumetric dispensing system that applies the smallest amounts of single-component fluids – for high-precision dispensing technology. [8]

Figure 2.C *SUPERJET Dispenser.* This dispenser is non-contact and designed with super high speeds of 1200Hz and capable of small volume dispensing under 0.5 nL/shot. [9]

Figure 2.D *Biofluidix PipeJet Nanodispenser.* This dispenser allows for single droplets with adjustable low volumes from 2 to 70 nl and non-contact drops.

Appendix 3: Initial Generated Concepts

<table>
<tr>
<td>
System of wire holders on a secure set up.</td>
<td>

- 3D printed block to set outline and angle of wires and direct connections for epoxy distribution</td>
</tr>
<tr>
<td>
Syringe system held up by heavy wire holders</td>
<td>
An epoxy stamp that will stamp the chip with epoxy on the bond pads</td>
</tr>
</table>

Figure 3.A Initial concepts from individual concept generation

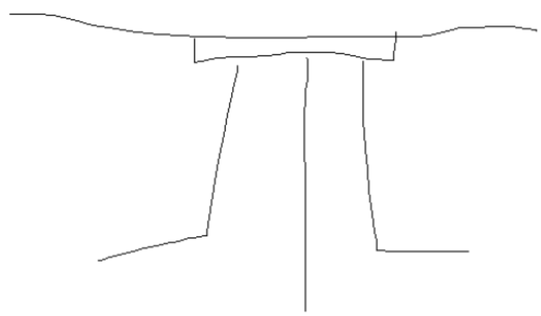
<table>
<tr>
<td>
Clamp all of the components down to the side of the stage to ensure stability. This can also use pre-existing devices in the lab.</td>
<td>Mount the chip upside down and bring down onto wires that have already got epoxy applied. The wires should be in precise locations.
</td>
</tr>
<tr>
<td>Use a 3D printed device to run the wires through to get a perfect bend only where it is needed.</td>
<td>Program a robot to make the connections .</td>
</tr>
</table>

Figure 3.B Initial concepts from individual concept generation

Bill of Materials

Bill of Materials for the epoxy dispenser final design.

Part	Manufacturer	Part Number	Cost
Lead Screw	McMaster Carr	97783A120	$20.88
Flange Nut	McMaster Carr	97783A240	$24.57
Blunt Tip Dispensing Needle	Bstean	DN-05-YL-34	$16.89 for 50 $0.34 for 1
Metal Gearmotor	Pololu	4831	$45.95
Luer-Lock Glass Syringe (25µL)	Hamilton	HM-1702	$90.42
3 Pin Tact Micro Limit Switch	MXRS	0757173501338	$6.99 for 12 $0.58 for 1
Swivel and Tilt Monitor Mount	SmallRig	2904	$34.39
Motor Drive Controller Board DC Dual H-Bridge	ACEIRMC	B07V3DRMGW	$11.69 for 5 $2.34 for 1
M3 x 0.5 x 6 Steel Socket Head Screws	McMaster Carr	91274A102	$5.75 for 50
18-8 Stainless Steel Nuts	McMaster Carr	91828A211	$5.27 for 100
Housing (PLA)	Made in house	N/A	$1.18 per hour
Arduino UNO	Arduino	A000066	$23.00
Bread Board	REXQualis	RG-BK-4	$12.49 for 4
Universal AC DC Adapter Multi-Voltage Power Cord	JOVNO	B08LK22GH9	$15.69 for 1
Jumper Wire	Dragonpad	B0040DEI9M	$7.99 for 75

Manufacturing Plan

As mentioned previously in the mechanical subsystem, the assembling of the system starts with the parts as shown in Figure 30. We see the syringe pump, the outer housing, the electric motor, the 3D printed housing, the two piece glass syringe, a motor coupler, the lead screw, and a 3D printed attachment. Fasteners include 4 M3 bolts and 2 M3 hex nuts for mounting the motor and attaching the 3D printed attachment to the flanged nut and are not shown in CAD for simplicity.

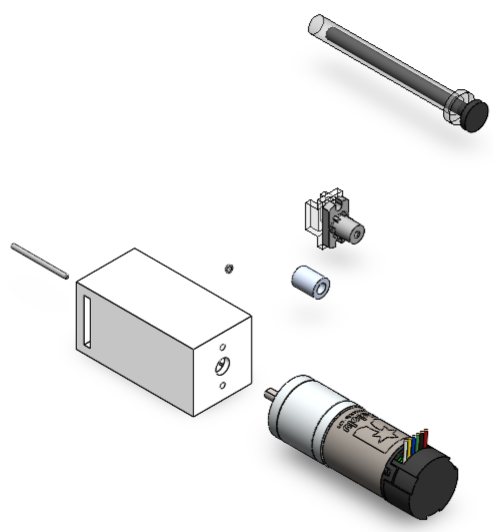


Figure M1. Exploded View of Epoxy dispenser subsystem assembly with individual parts.

The epoxy dispenser subsystem can be assembled in the followed steps:

Step 1: Mount motor into 3D printed housing through the shaft hole. Insert 2 M3 bolts into the bolt holes on the 3D printed housing, as shown in Figure 31.

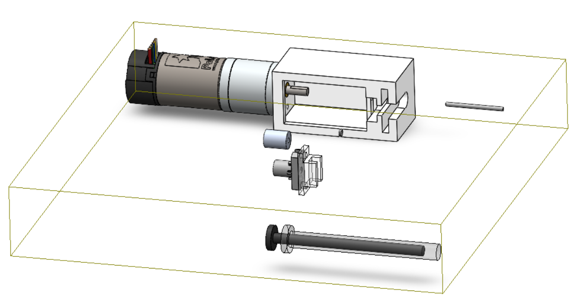


Figure M2. Step One of Assembly Plan.

Step 2: Attach motor coupler to the end of the motor shaft. Insert the set screw and tighten with appropriate allen key, as shown in Figure 32.

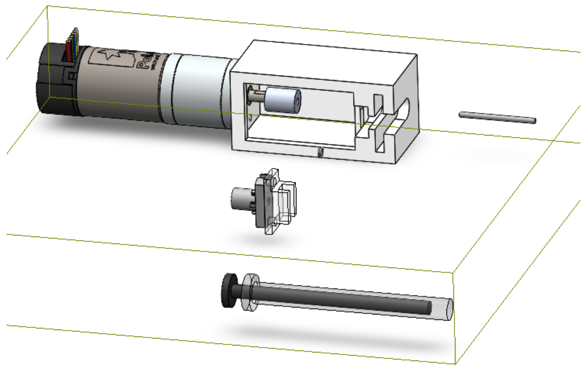


Figure M3. Step Two of Assembly Plan.

Step 3: Insert 3D printed bushing into 3D printed housing. Press firmly for good connection and prevent loosening, as shown in Figure 33.

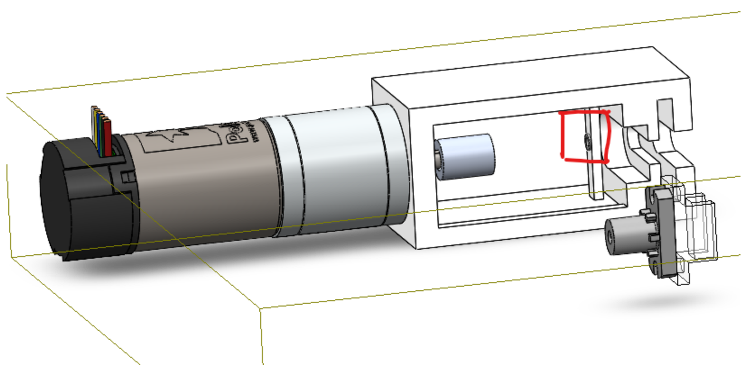


Figure M4. Step Three of Assembly Plan.

Step 4: Mount the 3D printed attachment to the plastic flanged nut using two M3 bolts and two M3 hex nuts.. Line up the on the attachment, flanged nut, and 3D printed bushing. Hold 3D printed attachment and flanged nut in place, as shown in Figure 34.

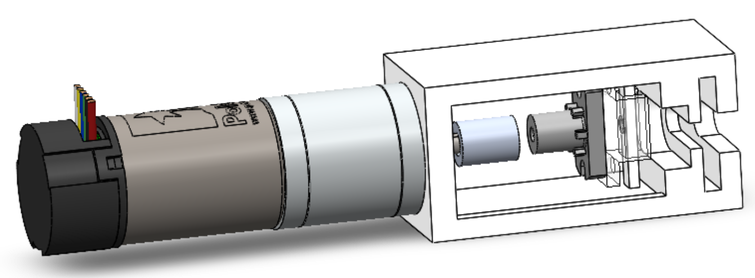


Figure M5. Step Four of Assembly Plan.

Step 5: Insert the threaded rod through the holes in the 3D printed housing, flanged nut, 3D printed attachment and motor coupler from the right side of the 3D printed housing. Tighten the set screw on the motor coupler.

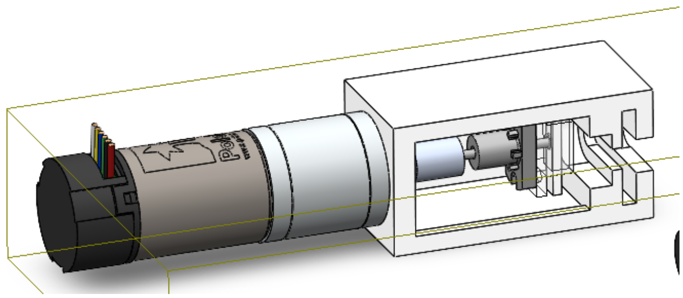


Figure M6. Step Five of Assembly Plan.

Step 6: Press the glass syringe into the snap-fit mechanism in the 3D printed housing. Lightly press once again to make sure the connection is firm. The fully assembled system is shown in Figure X.

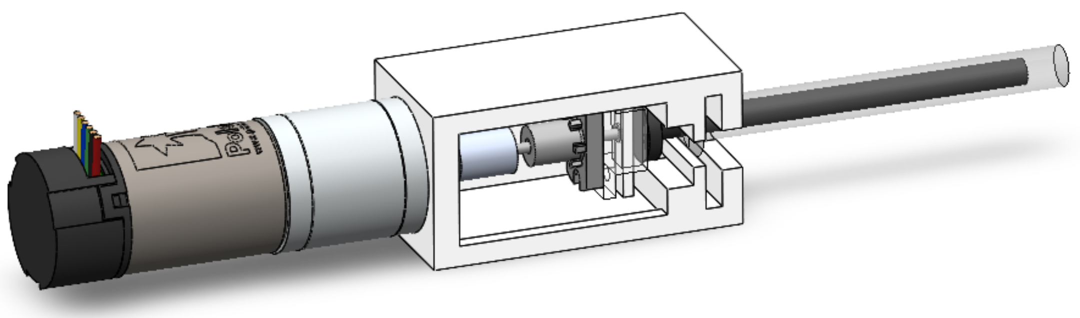


Figure M7. Fully Assembled Epoxy Dispenser Subsystem