PRELIMINARY REPORT: MICROSCOPE LOW COST MOTORIZED STAGE

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BME 300/200

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Abstract:

Inverted fluorescence microscopes are a highly utilized piece of laboratory equipment used in life sciences research. Manually controlled versions of these microscopes are much cheaper than the market-available motorized alternatives, but are not as ideal for teaching and high-throughput research scenarios. The client, Dr. Puccinelli, has tasked the team to create a device capable of adding motorization, automation, and image sequencing capabilities to these microscopes. An account with funds to the amount of $100 has been created through the UW-Madison MakerSpace to aid in the fabrication of a final design. The created device will be generated through fabrication methods centered mainly around 3D printing and laser cutting. This prototype will control the movements of the microscopes stage by manipulating the hanging manual control knobs. This semester's team hopes to improve upon previous designs by redesigning the gearing configuration and changing the mounting methods of the prototype. Current proposed testing methods are aimed towards assessing the accuracy of the movements of the stage and the potential impact of the design's weight on the focus of the microscope. Data analysis of quantifiable success metrics will allow for a precise assessment of success as defined by the PDS-outline requirements of this design. The team is currently in the fabrication phase of the design process, with hopes to have the first iteration of the prototype completed in time for BME show and tell on November 3rd.

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1. Introduction

1.1 Motivation/Global and/or Societal Impact

Motorized stage microscopes are commonly used in the biological research community. The motorized stage is crucial due to its pivotal role in enhancing precision, efficiency, and the quality of research. Motorized stages facilitate the rapid and precise execution of advanced imaging methods like time-lapse image stitching. Nevertheless, microscopes equipped with motorized stages typically come at a considerably higher cost compared to their manual counterparts. This imposes a significant obstacle to the accessibility of the motorized stage microscopes, especially for budget-constrained and teaching laboratories. Therefore, creating an affordable motorized microscope stage is motivated by expanding accessibility and availability to a broader audience. Embracing a cost-effective design that eliminates financial barriers, ensuring more accessible access to this technology. This enhances the overall experience for students and staff utilizing the Biomedical Engineering teaching lab. Furthermore, the integration of image sequencing capabilities into the motorized microscope stage will notably enhance its versatility, making it more robust for applications in both teaching and research.

1.2 Current Competing Designs

Currently, the market offers several commercial motorized stage replacements for conventional microscopes. These products come from established microscopy manufacturers and typically provide advanced motorized stage capabilities. While these options often deliver high performance, they are associated with an extremely high price, which is not feasible. For example, the non-motorized fluorescent microscope that is currently used in the BME teaching lab is a Nikon TI-U, and a brand new motorized version of this microscope is around $70,000-$80,000 [1]. Due to the high cost of the commercial motorized stage, people have come up with lower-cost solutions.

One of these solutions is an open-source project called the Openstage, which is a three-axis drive motorized stage system and a stand-alone controller unit [2]. The performance of this stage is close to and potentially better than those commercial options that are many times its price. Its accuracy in the X and Y directions is 1µm or better. The motion of the stage can be controlled through either a handheld controller or a program. Moreover, the controller software is very flexible and can be easily modified. However, some drawbacks of this design are that the project's total cost amounts to approximately $1000, which is still relatively high. Additionally, this design is too bulky to completely satisfy client needs (Appendix 9.1).

Another competing design is the Openflexture Delta Stage [3]. In this design, the stage is 3D printed, and the base of the stage houses the electronic components, which are powered using a Raspberry Pi. The stage can move in the X, Y, and Z axis using three stepper motors. This design is compact and suitable for a laboratory bench or microbiological safety cabinet. The price of this stage is around $336, which is more acceptable than the previous two options.

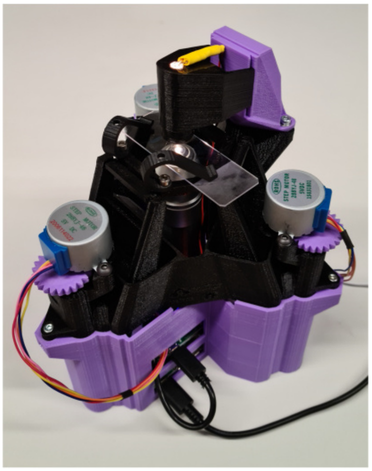


Figure 1: Openflexture Delta Stage [3].

1.3 Problem Statement

The UW-Madison BME teaching lab currently houses two inverted fluorescent microscopes. While these contemporary pieces of equipment are functional in their current state, they leave a great deal to be desired when it comes to laboratory efficiency. Motorized alternatives do exist. However, cost continues to be a factor limiting the exposure students have to this technology. With a working budget of approximately $100, our team seeks to optimize the precision and automation of these microscopes through the creation of a novel microscope stage moving device. This design will allow for sequential, automated imaging of coordinate-based locations on slides. The creation of this device will increase the consistency of measurements, reduce the amount of time spent during data collection, and lower the learning curve for operating this equipment. To remain competitive, design prototypes should be automated in both the X and Y directions and retain high precision and accuracy in translations (1 µm resolution).

2. Background

2.1: Background Research

The BME Teaching Lab at UW-Madison houses, amongst many other pieces of equipment, two inverted fluorescence microscopes-one of which can be seen in *figure 2*. The “inverted” in the name is due to the flipped arrangement of certain parts of the microscope relative to what is normally seen. These microscopes house an objective lens above the stage, with a condenser and light source located below the stage [4]. In addition to an altered arrangement of componentry, inverted fluorescence microscopes also have a unique imaging mechanism that utilizes fluorescent dyes. Dyes are placed within the sample by researchers and excited through the use of a halogen lamp. Differences between input and output emission are used to generate high resolution imagery of things like living cells and tissue culture [5].

Figure 2: Nikon TI-U inverted fluorescence microscope used in the BME Teaching Lab [6].

The advantageous imaging capabilities of these microscopes have garnered them a lot of attention within the scientific community. In specific, these microscopes have very popular applications in the realm of life sciences laboratory research [7].

High throughput has always been the goal, but reaching that goal in a cost effective manner has continued to be an elusive pursuit. Motorization of inverted microscopes, in general, can be achieved through one of two mechanisms. The first, and most obvious, option is buying a microscope designed for motorized microscopy with motorized, rather than manual, stage-driving mechanisms built in. Unfortunately, however, this easy decision incurs heavy financial setbacks, with motorized inverted fluorescence microscopes selling for several thousand to several hundred thousand dollars [8]. The second option involves the modification of a manual inverted fluorescence microscope to add features such as motorization, automation, and/or imaging sequencing software. Many of these options are still very costly [9], but there is more room for thrifty solutions within this category through the use of external motors, 3D printed parts, and other low cost manufacturing methods.

Two groups prior to ours have attempted to motorize the manual inverted fluorescence microscopes by attaching gears to the control knobs and manipulating them through gears powered by stepper motors. Each of these teams had their own flaws, which is to be expected when attempting to take on a task such as this within the time frame of one semester. The hope is to use the basics of their projects in a potentially more robust arrangement to create a superior iteration of this design.

2.2: Design Research

Current areas of the design being targeted for improvement can be aptly categorized into changes concerning the gearing configuration and changes concerning the spatial arrangement of the design. While this categorization can assist in the delegation of fabrication roles within in the team setting, it is worth noting that these two aspects are very much intertwined, with gear sizes, gear locations, and the number of gears all having considerable effects on how the overall design can be spatially arranged to integrate into the existing mechanical structures of the microscope.

The main considerations when assessing the category of gearing configurations is the speed, resolution, and spatial use of the various designs. All previously conceived designs have used a 2-gear system, with a gear attached to a stepper motor driving the movements of a secondary gear that is fixed to the manual control knobs. With the primary endpoint of micron-resolution movements, previous groups were able to calculate gearing dimensions using the equation found in *figure 3* [10]. Keeping compactness in mind, gearing configurations using three, or potentially even more, gears could be fabricated to achieve that same gearing ratio with much smaller gears. Three gear designs contain a driver gear, an idler gear, and a follower gear. In this system, the driver-idler and idler-follower gear ratios have a multiplicative effect, which would allow the design to utilize much smaller gears. Although some time would have to be spent perfecting this new gearing system, the space being saved warrants it.

$$\text{First Gear Diameter} = \frac{\text{Total Gear Diameter}}{[1 - (\text{Motor Step Angle} / 1\ \mu\text{m Knob Angle})]^2}$$

Figure 3: Equation from previous design team used to calculate gear dimensions used in a 2-gear system [10].

Now having brought up the topic of the spatial use of our design, a few comments should be made to address why this factor has received so much consideration within the initial stages of our design process. During the first client meeting Dr. Puccinelli made it very clear that, while previous designs did get some things right, their use of the space on the lab counter was suboptimal and due for improvement. The most recent design team made a rail system that the stepper motors were mounted to to allow them to travel with the stage in the Y direction. This system was successful for proof of concept, but cluttered the user spaces around the microscopes and is not super practical real-world applications. Design considerations have involved the use of multi-gear designs to reduce gear dimensions and allow for the motors and gears to be mounted to the right hand underside of the microscope. The structures connected to the microscope will have to not interfere with stage travel or other use-related aspects of the microscope, so cross referencing with the schematics of the microscope will be necessary during generation of CAD files [11].

2.3: Client Information

The client, Dr. John Puccinelli, is the Associate Chair of the Undergraduate Program and Associate Teaching Professor for University of Wisconsin-Madison Department of Biomedical Engineering. He oversees the BME Teaching Lab in ECB 1002 and is responsible for the purchasing and management of all equipment inside. Dr. Puccinelli has tasked our team with the creation of a device to motorize and automate the inverted fluorescence microscopes in the teaching lab to offer a more robust teaching and research experience to biomedical engineering students and staff at UW-Madison.

2.4: Design Specifications

Through collaboration between the client and our team, a Product Design Specifications document was created. This document can be found in its entirety in section 9.1 of the appendix, but will also be touched on here. Our client requested that this device motorize the stage of the microscopes with a maximum fabrication budget of $100. This device must be easily attachable and detachable so it can be used as an accessory, rather than being permanently integrated into the microscope's design. Final prototypes of this semester should be capable of moving the stage of the microscope as directed and be accurate to within a micron (1 μm) of the intended movement input by the user. Inputs from the user should either be directed by a joystick integrated into the circuit or by inputting coordinate-based locations into a user interface (UI) the team would create. The client would be satisfied with inputting these values into the arduino IDE for proof of concept and testing, but would like a more streamlined UI in a final design. This design, at Dr. Puccinelli's request, will interact with the preexisting manual control knob of the microscope. This knob is located very close to many other mechanical structures of the microscope. With this in mind, designs should be compact and modeled in a way such that they won't interfere with functions of the microscope when attached.

3. Preliminary Designs

3.1: Spur Gear Design

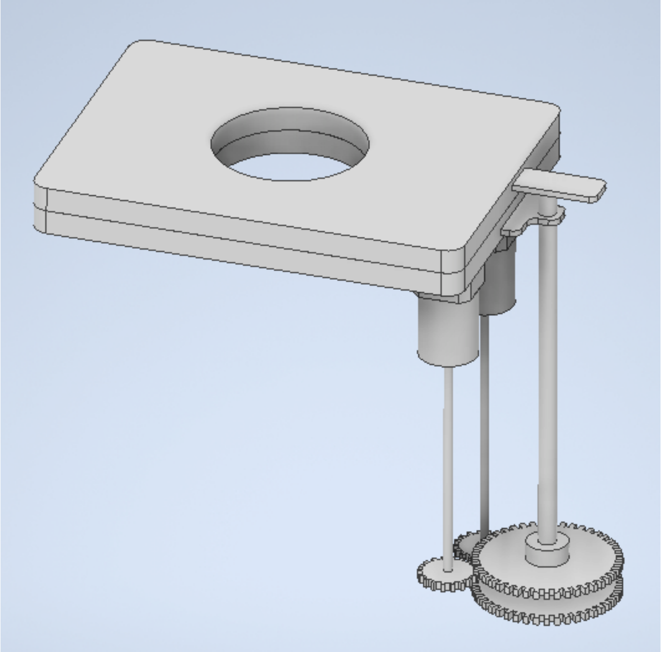


Figure 4: Spur Gear Design

The spur gear design is attached directly under the stage and interacts with the existing control knob. In this design each motor is directly connected to a spur gear. When it rotates, its horizontal alignment and connection with a spur gear would move the control knob to turn, thereby moving the stage in the X and Y direction. The main advantage of this design is that it reduces the size of the device and the space it occupies on the countertop.

3.2: Worm Drive Design

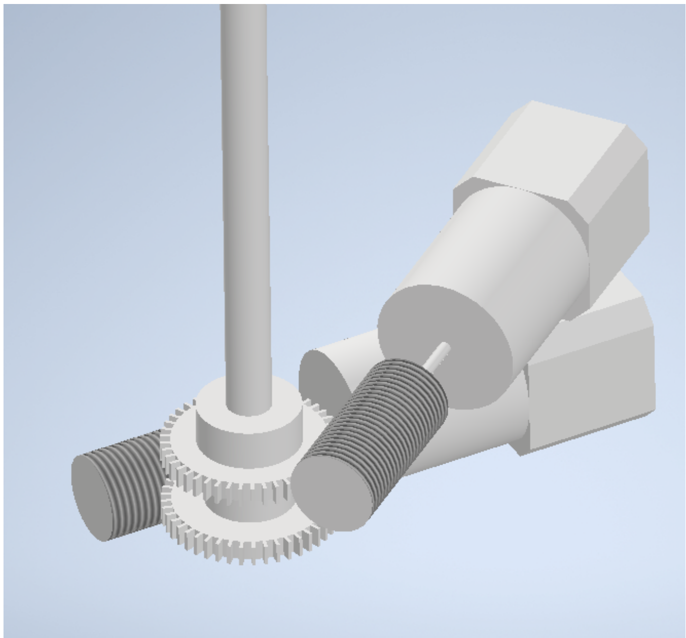


Figure 5: Worm Drive Design

The worm drive design interfaces with the existing manual control knob in order to move the stage. In this design, the manual knob will have spur gears added so that the worm gears can turn the knob. The worm gears will be placed on top of one another to reduce the amount of space used and will be angled so they can easily mesh with their respective spur gear.

3.3: Linear Rails Design

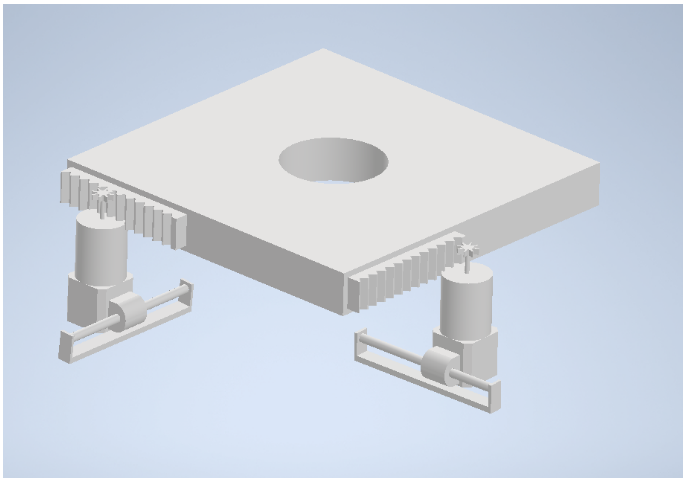


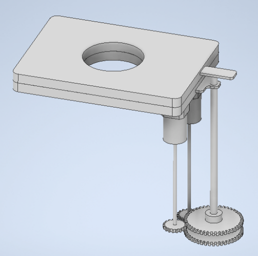
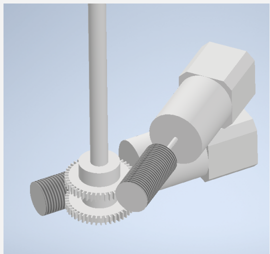
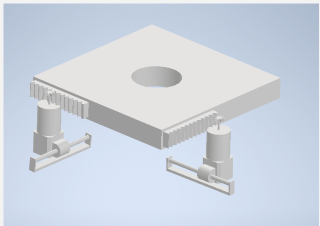
Figure 6: Linear Rail Design

The last design has many major differences to the previous designs. The linear rail design uses stepper motors to directly move the stage. It accomplishes this by having a spur gear on each stepper motor and linear gears attached to the stage. The spur gears can then move the stage by moving the linear gears. In order to keep the spur gear in contact with its linear gear when the stage is moving, there are linear rails attached to each stepper motor. These linear rails let the motor freely move with the stage.

4. Preliminary Design Evaluation

4.1: Design Matrix

Table 1: Design matrix for stage movement designs

Design Categories (Weight)	**Design 1: Spur Gears** 		**Design 2: Worm Drive** 		**Design 3: Linear Rails** 	
Performance (30)	4/5	24	3/5	18	5/5	30
Cost (20)	4/5	16	4/5	16	3/5	12
Mechanical Integration (17.5)	5/5	15	4/5	12	2/5	6
Ease of Fabrication (15)	4/5	12	4/5	12	3/5	9
Size (12.5)	4/5	8	5/5	10	5/5	10
Safety (5)	4/5	8	4/5	8	5/5	10
Total Points:	83		76		77	

4.2: Design Matrix Criteria Explanations

The following criteria were created by the team to evaluate each of the designs in a holistic manner based on requirements detailed in the Product Design Specifications (Appendix 9.1).

Performance of the motorized microscope stage is evaluated on the design's capability to adjust the stage in the x and y axis consistently, precisely, and efficiently. This category is scored the highest in the design matrix due to the high sensitivity, accuracy, and compatibility the client requests. Specific considerations for this evaluation are outlined in the *Performance Requirements* section of the PDS.

Cost is evaluated on the total price of the materials and associated fabrication costs, such as machinery use fees. Cost is ranked higher in the design matrix due to the client's emphasis on remaining under budget and allowing the project to be accessible for those of all economic backgrounds. The total expenses should aim to remain under $100, as outlined in the *Cost* section of the PDS.

Mechanical Integration assesses how effectively the device interacts with the microscope's structural and mechanical elements, considering factors such as the microscope's limited surface area and where the device is mounted. As stated in the PDS's *Size, Weight, Ergonomics, and Spatial Configuration* sections, the device should be light, compact, and not interfere with existing mechanical structures of the microscope.

The Ease of Fabrication category evaluates how easily the device will be able to be fabricated, along with how easy it is for other people to replicate the design in the future. The considered factors are outlined in the *quantity* section of the PDS. This category is less important because although this creates a design that can be easily reproduced by others, the main objective is to make a solution for the BME teaching lab specifically. Therefore, while still being considered, it is not ranked as highly as other metrics in the design matrix.

The Size category considers the final product's physical dimensions within the workspace of the microscope. It is preferred to have a compact product to meet the limitations of a small laboratory area, which puts these criteria at the fourth-highest weight in the evaluation process. Moreover, the product should be relatively small so it does not hinder the operator within the workspace, as stated in the *Size, Ergonomics, Aesthetics, Appearance, and Spatial Configuration* sections of the PDS.

Finally, as all our design concepts utilize electrical power sourced from the teaching lab's wall outlets, inherent safety concerns are associated with each potential prototype. Therefore, the safety category focuses on the potential risks posed to users during the operation of the device, as detailed in the *Safety* section of the PDS.

4.3: Design Matrix Evaluations

Regarding performance, the Linear Rail design scored the highest out of the three designs. This is because the linear rail design is directly attached to the stage. Interacting with the stage will make the device more accurate and precise and leave less room for errors. Both the Spur Gear design and the Worm Drive design move the stage by interacting with the existing control knob, which will require a lot of calibration and testing in order for them to be as accurate as the Linear Rail design.

For the cost category, both the Spur Gear and Worm Drive designs have received the highest score. Compared to the Linear Rail design, these two designs are much simpler and require less materials to fabricate. Furthermore, all the parts to fabricate are relatively simple and come from methods such as 3D printing and laser cutting, which are relatively inexpensive. The Linear Rail design has a lower score, primarily due to the higher expenses associated with its fabrication and materials. Due to the complex nature of the Linear Rail design, some components will need to be purchased instead of fabricated, which significantly raises the cost.

The Spur Gear design has scored the highest in the mechanical integration category. due to the simplicity of the design as well as the relatively low interference with the stage and the area under the stage. Spur gears are very simple to work with and will be easy to mount on the cylindrical control knobs of the microscope. The Worm Drive design received a lower score due to issues with combining both spur gears and worm gears. The Linear Rail design scored the lowest because of the possible interference it could have with the stage and other components of the microscope as it bypasses the manual control knobs and moves the stage directly, which may cause it to limit the stage's movement.

Considering the simplicity of the two designs, the Spur Gear and Worm Drive both score the highest in the ease of fabrication category. These two designs have fewer moving parts compared to the Linear Rail design, which is one of the reasons they scored higher in this category. Fewer steps are needed to fabricate the device for these two designs. Moreover, both the Worm Drive and Spur Gear designs have been fabricated by previous groups. This means that information on how to fabricate them can be gained by looking through previous groups' works and notebooks. Furthermore, it is certain that the Spur Gear and Worm Drive designs can be successfully fabricated because of the work done by previous groups. The Linear Rail design is entirely new, and it is uncertain what fabrication methods are needed in order to complete a physical product. There are no notes or experiences from previous groups that can be used as reference, making it a lot harder to fabricate compared to the Spur Gear and Worm Drive design. As for the size category of the design matrix, both the Worm Drive and the Linear Rails were awarded the highest score. Given their tendency to provide a more compact structure in contrast to the Spur Gear design, these two designs scored slightly higher. This compactness is particularly important when considering the size category due to the limited space for the microscope setup in the BME teaching lab. Moreover, Spur gears can have larger gear diameters, potentially interfering with adjacent equipment or the operator's workspace.

For safety considerations, the Linear Rail design was the most secure option. All three designs are reasonably safe, but safety does have to be considered because the device is powered by the lab's wall outlets. The Spur Gear and Worm Drive designs scored slightly lower on safety due to the positioning of the device. These two devices are attached to the manual control knob, where the person will have to come in close contact to operate the microscope. This orientation of these two designs increases the possibility of an injury, such as pinching, to the operator of the microscope.

5. Fabrication/Development Process

5.1: Materials

The low cost motorized stage adjustment device consists of several components that will be created from several different materials. The main components that are involved in this design are the gears mounted on the microscope manual control knobs, the gear shafts from both stepper motors to both gears on the control knobs, the housing unit for the stepper motors, an arduino board and stepper motor driver, as well as screws to secure the device to the underside of the microscope stage.

The material of the stepper motor casing needed to be something that would be mildly resistant to heat due to the possibility of stepper motors running at over 100°C [12]. However, this temperature is usually from constant use within 3d printers, and the device won't be quite as active and therefore will result in a lower temperature, but a material with a higher softening point is still necessary to preserve structural integrity. Standard PLA filament begins to soften and warp at around 50°C which will decrease the strength of the casing, especially if it is supporting the hanging weight of the stepper motor on the underside of the microscope stage [13]. Therefore, the material that should be utilized due to its physical strength and heat resistance is Polycarbonate. PC has the ability to withstand temperatures of up to 110°C without warping which exceeds the temperature that the stepper motors would be able to reach at maximum performance [16]. At the moment, the quantity of Polycarbonate listed below is purely theoretical, and when fabrication begins this value may go up or down.

Previous Groups have utilized laser cut Acrylic for their gears, however, despite the benefits of acrylic as a material, the makerspace laser cutter only permits a certain width of gear to be cut. This is because too thick of certain materials begin to have issues on the laser cutter as it is not able to effectively cut through them past a certain depth, in the case of acrylic, it is limited to a depth of a ¼". Instead, the decision has been made to make our Gears out of Nylon filament. Using Nylon filament allows the 3d printing of the gears, which in turn enables the gears to be much thicker. Thicker gears allow for more surface area to make contact, and this will overall improve the efficiency and performance of the device. Nylon is also a very heat resistant material, meaning it will begin to warp at higher temperatures than PLA or Tough PLA would. This heat resistant property stays true to the requirements set by the PDS (Appendix 9.1) Nylon has the ability to withstand 160°C without warping, which may be useful due to friction between the gears. Also, Nylon has the benefit of not requiring lubricant which is ideal for continuous use and low maintenance [15].

There are also a few other components that the team won't be manufacturing but will still be included in the design, the first of which includes screws that will be used to attach the device to the underside of the stage via the available screw holes on the microscope. The screws listed below are roughly the size of the necessary screws needed to complete this project, so the price will be very similar, however the team was not able to get precise measurements using a dial caliper due to complications with the team lab as well as not having access to the teaching lab.

The arduino board, arduino breadboard, stepper motor driver, and the stepper motor have all been passed into the current team's inheritance from previous groups as listed below. The stepper motors will enable rotation of the fabricated gears. The bread board, arduino board, and stepper motor driver will allow for the application of the software to our stepper motors.

Table 2: Materials and costs

Component	**Material Type**	**Quantity**	**Price/Unit**
Stepper motor casing	Polycarbonate	150 Grams	$.12 per Gram $18
Control Knob spur gears	Nylon	100	$15
Screws	#6-32 ¼" UNC Screw	8 Pack	$1.64
Arduino Board	Arduino Board	1	$10(previous group)
Stepper Motor	Nema 17 Stepper motors	2	$28(previous group)
Bread Board	Bread Board	1	$3(previous group)
Stepper motor driver	Stepper Motor Driver Nema TB6600 boards	1	$19.96(Previous group)
			Total: $95.6

5.2: Methods

At this point, there are no finalized fabrication methods, however, a plan on how to start approaching fabrication of the device is being formed.

<u>5.2(a): Stage Movement Device Fabrication</u>

1) 3D printed parts:
    a) 3D print motor brackets, electronics housing, and manual knob attachment parts using Polycarbonate. Slicer settings can be set to 20% infill, 0.16 mm layer height, and a 0.4 mm nozzle.
    b) 3D Print Nylon Spur gears to be mounted on manual control knobs
    c) Remove supports and clean any rough edges with a file and/or sandpaper.

The stepper motors should be attached to their brackets, then the brackets can be attached to the 4 available screw holes on the bottom and side of the stage. The manual knob attachment parts and gears can be added next. Make sure that the amount of horizontal movement in the manual knob is minimized as much as possible while leaving the rotational movement unhindered. The drive rod and spur gears can now be attached to the stepper motors. The spur gears should line up and stay meshed even when they are turning. Next, the motor wires need to be connected to the stepper drivers which in turn must be connected to the arduino.

5.3: Initial Prototyping and Testing

While physical prototyping hasn't begun yet, 3D models that depict the design have been made and plans for testing have been established. Some of the established testing procedures are as follows:

1. Performance: Determining both accuracy and repeatability of the stage movement over a lengthy testing period. Previous groups had issues with their systems losing accuracy as they tested. There are a few tests that could be performed:
    a. A microscope stage calibration grid could be used by noting how far the lines move in the field of view as the stage is moved by the device. This setup would be able to test for both the repeatability and accuracy of movement.
    b. Another option is to have a slide with fluorescent beads of a known diameter which can be put in the field of view. The starting position of the beads would be noted, then the device could move the stage a set distance and the position of the beads could be noted again.

2. Deflection of stage: The weight of the device should not tilt the stage sideways. Even a few microns of movement could cause problems when focussing on a sample. This will be very important to test because the stepper motors are fairly heavy. A counterweight may be needed on the opposite side of the stage if the motors and other parts are too heavy. In order to test the deflection of the stage, an object would have to be brought into focus on one side of the field of view and moved to the other side of the field of view. If the object is then blurry, then it can be assumed that the stage is not level and a counterweight may need to be added to the opposite side of the stage from the hanging motors.

6. Discussion

The team was tasked with creating a motorized stage that moves in the X and Y directions with micron mechanical positioning, with an allocated budget of $100 or less. The motorized device should also possess image sequencing capabilities, interface with nikon elements software, and integrate with any type of positioning device such as a joystick.

Creating a cost effective motorized microscope stage allows for multiple benefits. An inexpensive price point allows resources to be more widespread. Instead of only being able to purchase one motorized stage, multiple could be made or purchased which utilizes less of a budget to allow for additional resources to be purchased. The possible smaller budget allocation also allows for a more equal opportunity to have the same learning tools. Smaller schools or individualized research could benefit from a motorized stage but may not be able to have one due to budget constraints. In addition, creating a custom design for the microscope allows for specialized mechanical integration, such as the motorized stage being controlled by the manual knobs and not a replacement stage. Another benefit is that the design does not require the permanent or semi-permanent alteration of the microscope.

Currently all motorized stages cost thousands of dollars, such as Zaber's motorized stage [9], and are not easily removed should the manual knobs need to be used. Creating an inexpensive motorized stage that does not require intense set up or removal will save time and resources. Also, image sequencing and ultimately image stitching allows for a wider scope view and for a wider view which carries more depth [14].

The Spur gear design hangs from the stage and uses multiple spur gears attached to motors and the manual control knobs as pictured above in section 3.1, *Figure 4*. The design minimizes the devices occupied space while allowing for it to manipulate both directional knobs. Since the spur gear design is directly attached to the stage less parts will need to be fabricated to support the design due to the support being moved to the stage. However, this design is not without faults. One major area of concern is the slack the manual knobs have. The device can only be as accurate as the knobs can be. Should the knobs only be able to move the stage 10 micrometers at once the device will not be able to move the stage more finely. Additionally, slippage between the gear and the control knob or even the two gears can occur which messes with the gear ratios, torque, and turnage of the design. Additional problem solving or design analysis is necessary to determine how to eliminate or reduce the design's faults.

One benefit of creating a low cost motorized microscope page is the boost of inclusivity it creates. The motorization of the stage allows for those with limited movement to better use the microscope because they are able to use the integrated joystick which should only require limited movement. Effects of other limitations such as tremors, which affect one's steadiness in positioning, impaired vision, and more can also be mitigated by the mechanical positioning of the device. As previously stated, the lower cost of the motorized microscope stage will allow for a more widespread access to learning tools to advance the knowledge of students who attend universities or schools with a restricted budget.

Additionally, the stage will most likely not make the use of the microscope more safe. The device does have the potential to cause harm to the operator. However, the risk of the deceive causing harm is rather low. To limit the potential harm of the circuitry the wires should all be permanently attached to the breadboard and other circuitry elements such as the arduino. Additionally, the circuitry will be looked over by and tested with at least one expert in the field to assure there is limited possibility of injury. There is also a slight concern of pinching should someone place their fingers near the gears. In the future a casing unit could be fabricated to place over the device to eliminate the possibility of an injury.

7. Conclusion

The team is currently in the fabrication phase of this project. Having made decisions on the current directions of the designs, fabrication may begin. Due to an unexpected loss of access to ECB our team was unable to access the microscopes for an extended period of time. Thus, the team is actively taking measurements of the microscopes to update roughly-created CAD files. Upon finalization, these files will be used to 3D print, laser cut, and test various parts of our prototypes.

Future work for the project includes finalization of fabrication protocols, defining and testing success metrics for our prototypes, and the development of an image sequencing software system. Later phases of this project will attempt to integrate the software and hardware elements of this design once they have both been fabricated and validated independently of each other. All fabrication steps should be capable of being done within the MakerSpace and TEAM lab spaces of UW-Madison. In the coming weeks the team hopes to collaborate with several staff members at UW-Madison to develop a capable first prototype to be presented at show and tell on November 3rd of this year.

8. References

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9. Appendix

9.1: Product Design Specifications

PRODUCT DESIGN SPECIFICATIONS: MICROSCOPE LOW COST MOTORIZED STAGE

September 22, 2023

BME 300/200

Clients: Dr. John Puccinelli

Advisor: Dr. Joshua Brockman

Team Members:

Team Leader: Tyler Haupert

Communicator: Nicholas Symons

BWIG: Sawyer Bussey

BPAG: Jerry Zhaoyun

BSAC: Julia Salita

Function:

The inverted fluorescence microscopes of the UW-Madison BME Teaching Lab are manually controlled microscopes that allow users to observe and collect data on cell and tissue culture. While the technology exists to convert these microscopes into motorized and automated devices, it is very expensive and beyond the budget of the school. The client, Dr. John Puccinelli, has requested the fabrication of a device to serve as a solution to this problem. The final working prototype should include mechanical, software, and hardware components to allow for the automation of manual inverted fluorescence microscopes. The physical structures of this device will interface with the manual adjustment knob on the right-hand side of the microscope. It will be capable of moving the stage in a coordinate-based fashion in both the X and Y directions. Software elements will be created to direct the movement of the stage. Finally, the client has also requested the development of software to process and stitch input images to add a scanning feature to the microscopes.

Client Requirements:

1. The device must be a motorized mechanism that controls the stage movement through the manual stage adjustment knobs.
2. The stage should be movable by using a joystick, computer keys, or by inputting values into the user interface.
3. The movements of the stage should be precise down to the micron range, with acceptable deviations within one order of magnitude.
4. The software created must be integrated into the existing NIS-elements software and assist in both taking images of the field of view and stitching them together.
5. The device will be powered by the wall outlets in the lab.
6. The project must remain under a final cost of 100 US dollars.

Design Requirements:

1. Physical and Operational Characteristics:

a. *Performance Requirements:*

   i. The device should be able to adjust the microscope stage in both the x-axis and the y-axis using the manual adjustment knobs

ii. The software must be able to participate in image sequencing and be easy to use

iii. The field of view should be movable by using an interfaced joystick or computer keys such as the keypad arrows

b. *Safety*

i. The device should not be hazardous.

ii. The device should not harm the user in any way, including electrical shock [1], physical pinching, or loud sound levels.

iii. The device should not damage the microscope while ensuring smooth operation.

iv. The cords of the device should be safely arranged so that it does not block off the user’s workspace. Moreover, the cords should not be placed near or be in contact with any liquid.

v. Labeling

	Signifies that the main plug must be disconnected from the wall outlet prior to maintenance [2].
	Indicates that the equipment labeled is suitable for the use of alternating current only [3].
	Specifies that the operator's manual should be referenced and used during use of device [4].

c. *Accuracy and Reliability*

i. The device should have a movement resolution of 1µm.

ii. The movements should be repeatable without having to recalibrate the device.

d. *Life in Service*

i. The device should be reliable and last at least 10 to 15 years [5].
ii. The stepper motors have a lifetime of 20,000 hours[6], which translates to 2,500 8 hour work days or 500 5 day work weeks. This matches our requirement of a 10-15 year lifetime.
iii. The device should not break easily and withstand daily wear and tear.
iv. The device should be capable of undergoing regular sanitation via autoclaving and/or harsh cleaning chemicals.

e. *Shelf Life*
  i. To ensure the longevity of the device while stored, the device should be kept dry and at regular room temperature and pressure.
  ii. All materials used for the device should be stable at standard lab temperature and humidity conditions.
  iii. The device should be able to be stored either attached or detached from the microscope at normal room conditions.

f. *Operating Environment*
  i. The laboratory will be kept within a temperature range of 20-25 degrees celsius with a relative humidity of 35-50 percent [7].
  ii. The device will be kept in the BME teaching lab and should be able to operate in the above conditions.

g. *Ergonomics*
  i. The device must be small and not disrupt the normal operation of the Nikon TI-U and Olympus IX71 microscopes.
  ii. The software must be operable with the nikon elements software and must have a user-friendly interface.

h. *Size*
  i. The device should take little to no table space next to the microscope.

   ii. Ideally, the entire device should be encased to minimize device interference and malfunction due to exposure.

i. *Weight*
   i. The device should be lightweight to minimize interference and damage to the function of the microscope.
   ii. Weight should not limit usage and accessibility of the microscopes for all users.

j. Materials
   i. All materials purchased, altered, and used must comply with the guidelines for a biosafety level 1 laboratory listed in the Biosafety in Microbiological and Biomedical Laboratories (BMBL) 6th Edition [8] by the Centers for Disease Control and Prevention (CDC) [9].
   ii. 3D printing should be utilized to print most plastic prototypes using the FDM and FFF printing methods [10], [11].
   iii. The Universal ILS9.150D [12] laser cutter will be used to accurately cut precise pieces necessary for maintaining accuracy of movement of the microscope stage.
   iv. Soldering [13] may be used to stabilize the electronic connections within the necessary circuitry.
   v. All included materials must be resistant to the degradative effects of harsh chemicals used for regular sanitization of lab equipment.
   vi. Plastic gears should be used rather than metal gears to eliminate the need for lubricant, this would decrease the amount of maintenance needed in order to keep the device operational [14]. Additionally, plastic materials will also help to lower cost.
   vii. Plastic materials expand and lose structure at increasing temperatures. Thus, material choice should consider the rate at which different plastic materials heat or cool.
   viii. Materials used for gears should be made out of a plastic with a low thermal diffusivity, which is defined as the thermal conductivity ratio to the specific heat capacity of the material. Materials of large Thermal Diffusivity will respond quickly to changes in heat and Materials of low Thermal Diffusivity will respond slowly [15]. Thermal Diffusivity

of PVC (7.8E-6 m^2/s) [16], this is a low Thermal Diffusivity meaning the material heats up slowly. The equation for this value is: α=k/pCp

1. a= thermal diffusivity
2. k= material conductivity
3. p=density of material
4. Cp=specific heat of material

- *k.* *Aesthetics, Appearance, and Finish*
    - i. The device should not be distracting to the user.
    - ii. The final product should be neat and blend in with surrounding equipment.
    - iii. All edges should be smooth and not pose a threat to users operating the device.
- *l.* *Spatial Configuration*
    - i. The device should not hinder or block movement of the existing mechanical components of the microscope
    - ii. The device should be secure and stable on the points that it mounts to the microscope.
        1. Ex. screw holes, clamp points, adhesion points.

2. Product Characteristics

- *a.* *Quantity:*
    - i. Only one device will be manufactured for the client
    - ii. The device should be replicable in order to produce additional products if necessary or to potentially be mass produced.

- *b.* *Target Product Cost:*
    - i. The target budget is to remain under a total of $100 for the final cost of the device.
    - ii. The allocated budget for development is $300.
    - iii. The team should use previously purchased materials to keep costs low and reduce waste, however, the team should present the final total price to reflect the total cost if the device is to be replicated.

3. Miscellaneous

a. *Standards and Specifications*
    i. All aspects of the device's design must comply with the many guidelines provided by the CDC for biosafety level 1 laboratories [8].
    ii. The device should follow all guidance outlined in the FDA's "Chemical, Metals, Natural Toxins & Pesticides Guidance Documents & Regulations" to ensure safety and producibility should the device be reproduced [17].
    iii. The following standards are to be referenced and used as guidelines throughout the development and implementation electrical systems designs [18].
        1. ISO 9001 Standard: Quality Management System.
        2. ISO 14001 Standard: Environmental Management System.
        3. ISO SOC Standard: System and Organisation Controls
        4. ISO 27001 Standard: Information Security Management.
        5. ISO 45001 Standard: Occupational Health and Safety Management System.
        6. ISO 10002 Standard: Complaint Management Systems
        7. ISO GDPR Standard: General Data Protection Regulation

b. *Customer*
    i. While the team's client has a sole interest in the design, there is a potential for a more broad potential application of our design. If fabrication methods can be simplified and streamlined, it is likely that many universities and budget-aware labs would be keen to utilize our low-cost solution to the problem of motorizing and automating manual microscopes.

c. *Patient-Related Concerns*
    i. The device should not inflict any danger to the surrounding users and equipment
    ii. This device should be capable of undergoing regular maintenance and cleaning with harsh chemicals [8].
    iii. No paper, cardboard, or other organic materials should be utilized in the final design.

d. *Competition*

i. The OpenFlexture project is an open-sourced, 3-D printable microscope that can be created and constructed for approximately $200, with multiple stages available to add motorized and automated functionality [19].

ii. One example of market-available motorized stages is Zaber's ASR series motorized XY microscope stages [20].

    1. While these are functional, accurate to within 12 µm, and available, they do not meet client criteria due to cost and the way they interact with the microscope.

iii. Detailed in a 2017 article, a group of German-based scientists created an automated, motorized, 3-D printed inverted fluorescence microscope. The article includes all necessary CAD and software files for construction, as well as a step-by-step instruction manual to aid users in building their device [21].

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9.2: Design Matrix

DESIGN MATRIX: MICROSCOPE LOW COST MOTORIZED STAGE

September 29, 2023

BME 300/200

Clients: Dr. John Puccinelli

Advisor: Dr. Joshua Brockman

Team Members:

Team Leader: Tyler Haupert

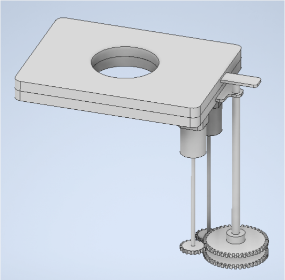
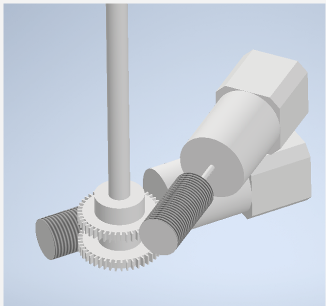
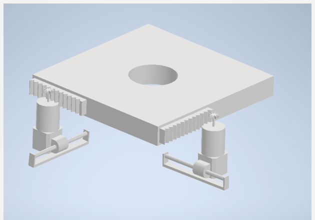
Communicator: Nicholas Symons

BWIG: Sawyer Bussey

BPAG: Jerry Zhaoyun Tang

BSAC: Julia Salita

<u>Design Matrix</u>

Design Categories (Weight)	**Design 1: Spur Gears** 		**Design 2: Worm Drive** 		**Design 3: Linear Rails** 	
Performance (30)	4/5	24	3/5	18	5/5	30
Cost (20)	4/5	16	4/5	16	3/5	12
Mechanical Integration (17.5)	5/5	15	4/5	12	2/5	6
Ease of Fabrication (15)	4/5	12	4/5	12	3/5	9
Size (12.5)	4/5	8	5/5	10	5/5	10
Safety (5)	4/5	8	4/5	8	5/5	10
Total Points:	83		76		77	

Designs:

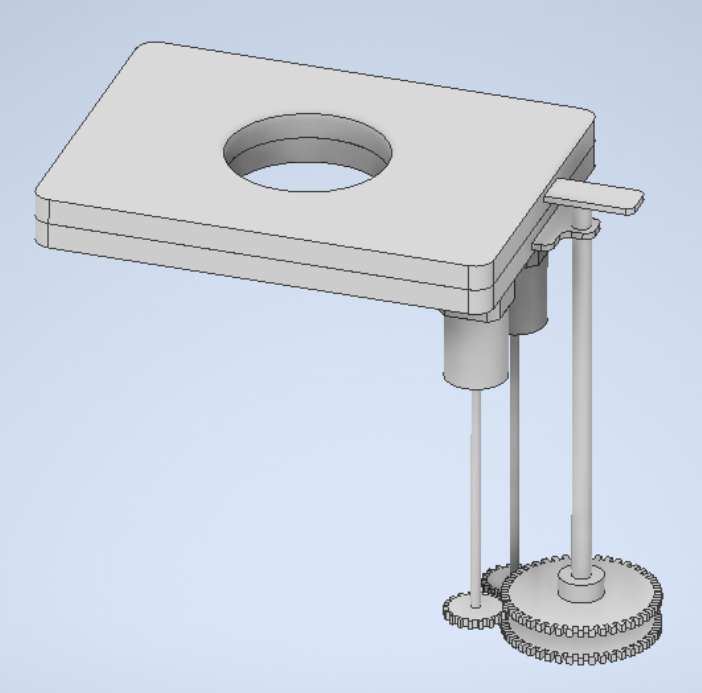


Figure 1: Spur gears design.

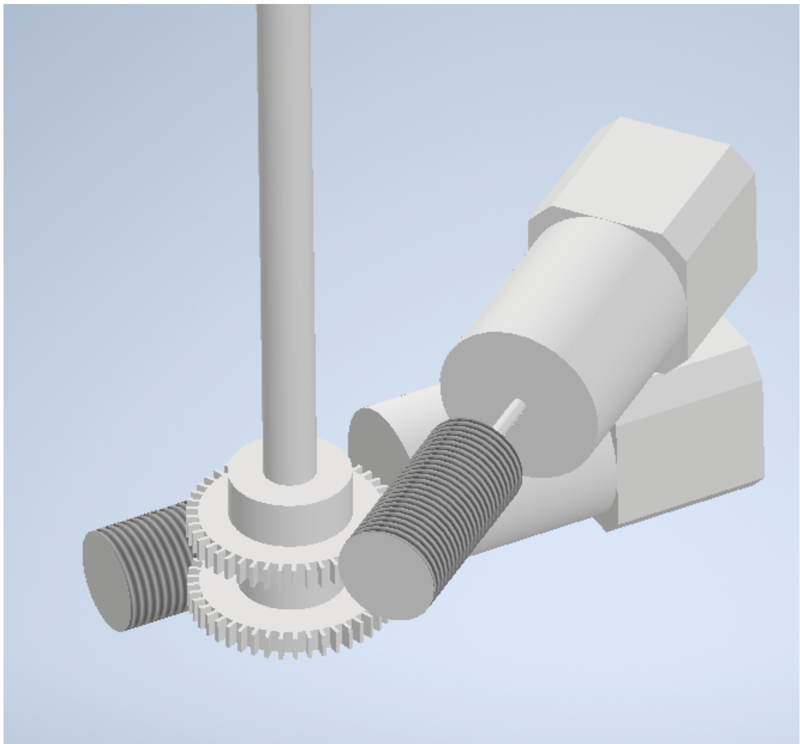


Figure 2: Worm gear design.

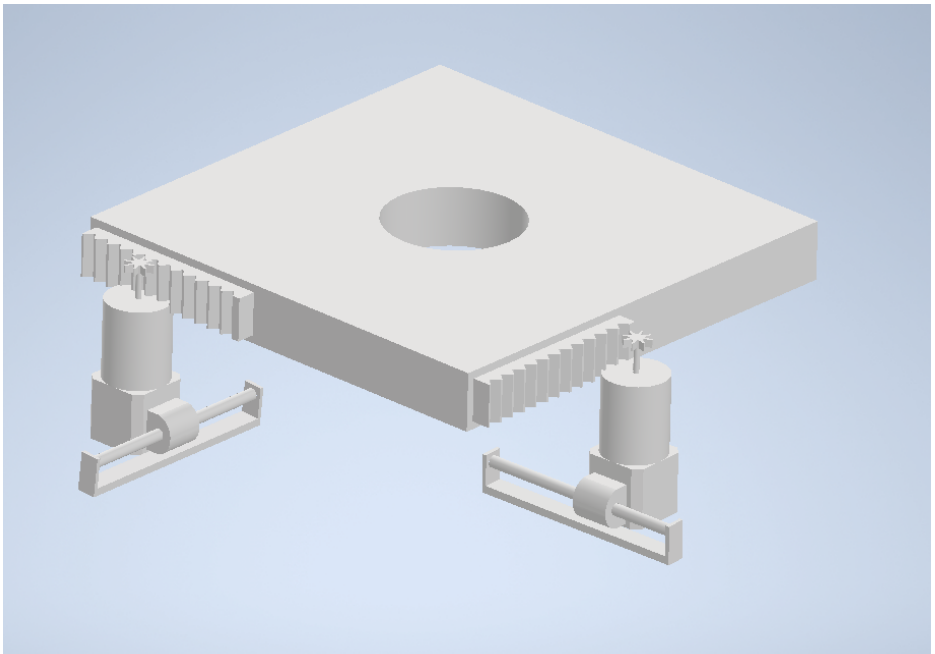


Figure 3: Linear rails design

Determination of Criteria and Weights: Collaboratively the team generated 6 evaluation criteria that were determined to give the most accurate representation of each design's overall practicality. Each of the criteria serve to score these designs based on the previously documented Product Design Specifications (PDS).

Performance:

The performance criteria of the Motorized Microscope design matrix is representative of the proposed design's ability to modulate the position of the stage in a consistent, precise, efficient manner. Factors considered in this evaluation are outlined in the *Performance Requirements* section of the PDS (Appendix 9.1).

Cost:

The cost category is scored based on the expenses of the materials as well as any additional costs associated with the use of machinery for fabrication of the final product.The score for this criteria is ranked high in the design matrix compared to other categories because one of the project's main goals is to create the device for an affordable price. The materials and fabrication of the device should remain under or close to $100 as outlined in the cost section of the PDS (Appendix 9.1).

Mechanical Integration:

Mechanical Integration is based on how efficiently the device interacts with the structure and mechanical components of the Microscope. It takes into account the limited surface area of the microscope as well as the restricted screw thread hole locations for mounting the device. This criteria evaluates the *Size, Weight, Ergonomics* and *Spatial Configuration* sections of the PDS (Appendix 9.1).

Ease of Fabrication:

The ease of fabrication category is based on how easily we would be able to fabricate the design along with how easily other groups of people would be able to recreate our design. We considered factors outlined in the *quantity* section of the PDS (Appendix 9.1). This category's score is ranked fairly low because while we want to create a design that can be easily made by many other people, the main objective is to make a solution for the BME teaching lab specifically. Because of this, we don't consider it a high priority to have the design ready for mass production.

Size:

The main factor considered for the size category is how much space the final product is going to occupy within the microscope workspace. This is primarily determined by the physical dimensions of the final product. This receives the fourth highest weight because a compact product is preferred due to limited lab space. Moreover, the product should be relatively small so it does not hinder the operator within the workspace. This criteria evaluates the *Size, Ergonomics, Aesthetics, Appearance, and Finish, and Spatial Configuration* sections of the PDS (Appendix 9.1).

Safety:

Due to the fact that all of our designs require electrical power via the wall outlets of the teaching lab, there is an intrinsic safety concern with each of our potential prototypes. Additional safety concerns will be evaluated on an individual basis, specifically in regards to the risk the design poses to the user during time of operation. The *Safety* section of the PDS is assessed by this metric, and more specific details regarding this subject can be found there (Appendix 9.1).

Justification of Assigned Scores:

Performance:

The linear rails design scored the highest in this category of the design matrix. The rationale behind this decision was the mode of interaction between the device and the stage. The linear rails design directly modulates the position of the stage with the motor, while the remaining designs interact with the manual control knobs. There is a certain undefined amount of movement and travel of this control arm, so it was decided that there would be more potential for inaccuracies in movement driven by interactions with it.

Cost:

The spur gear and worm drive designs scored the highest because all of the parts to fabrication are relatively simple and come from methods such as 3D printing and laser cutting which are rather inexpensive processes. The linear rails design scored lower due to the projected cost of the materials. The materials and fabrication needed to create the rails and attachment pieces are estimated to cost more.

Mechanical Integration:

The Spur Gear design received the highest score due to the simplicity of the design as well as the relatively low interference with the stage and the area under the stage. Spur gears are very simple to work with and will be easy to mount on the cylindrical control knobs of the microscope. The Worm gear design scored slightly less than the Spur Gear design because some issues were foreseen with combining both spur gears and worm gears in the Worm Gear design. The Linear Rail Design scored the lowest because of the possible interference it could have with the stage and other components of the microscope as it bypasses the manual control knobs and moves the stage directly which may cause it to limit the stage's movement or accuracy.

Ease of Fabrication:

The worm drive and spur gear designs scored highest in the ease of fabrication section because they have less moving parts such as the linear rails and the spur and linear gear interactions. Both the worm drive and spur gear designs have been fabricated by past groups, so we have information on how we can fabricate them and know that they work on a basic level.

Size:

The worm drive and linear designs were awarded a slightly higher score because they often offer a more compact design compared to spur gears. This compactness is particularly valuable in microscopy setups where space is limited. Spur gears can have larger gear diameters, potentially interfering with adjacent equipment or the operator's workspace.

Safety:

The spur gear and worm drive designs scored slightly lower on safety due to the positioning of the device. The device is closer to where the person operating the microscope is residing, which increases the possibility of an injury, such as pinching, to the user of the microscope.

9.3: Material Rationale

The design is primarily made up of a few key materials, including a plastic mounting bracket to hold the stepper motors, Nylon Filament Spur Gears, and plastic parts to hold the manual knob steady and attach the gears to.

The motor bracket will be made out of 3D printed polycarbonate so that it is strong enough to hold the motors steady when they are moving and has enough heat resistance to not soften under the potential heat released by the stepper motors when they are under load. 3D printed plastic is being used for the brackets because CAD models using the dimensions from the microscope will be able to be fabricated very easily. Polycarbonate is an especially good choice for this design because it has a high tensile strength of about 70 MPa and thermal resistance up to 110 degrees celsius [1]. Both of these are needed as the motors are fairly heavy and produce heat as they work.

The spur gears are going to be made out of 3d printed Nylon filament material. Nylon filament has a higher heat resistance than acrylic gears which is what previous groups decided to make their gears out of. Nylon is also a very strong material that does not require lubrication. Nylon is a material that could be printed in the makerspace and is readily available.

The manual knob supports will also be 3D printed with polycarbonate because of its high tensile strength. These supports will need to stop the manual knob from moving horizontally while letting the knob continue to rotate freely.

Component	**Material Type**	**Quantity**	**Price/Unit**
Stepper motor casing	Polycarbonate	150 Grams	$.12 per Gram $18
Control Knob spur gears	Nylon	100	$15
Screws	#6-32 ¼” UNC Screw	8 Pack	$1.64
Arduino Board	Arduino Board	1	$10(previous group)
Stepper Motor	Nema 17 Stepper motors	2	$28(previous group)
Bread Board	Bread Board	1	$3(previous group)
Stepper motor driver	Stepper Motor Driver Nema TB6600 boards	1	$19.96(Previous group)
			Total: $95.6

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9.4: Solidworks Files

LINK to folder with all project CAD files.