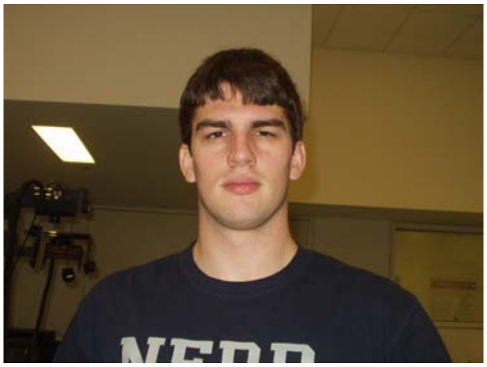
Project #27 – Prismatic Optical Component Alignment System

Final Report



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Optical Component Alignment System

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ABSTRACT

Laser based alignment instrumentation is used in industry for aligning machining and optical systems. A series of beam splitting prisms joined together can split a single laser beam into a number of different beams in precisely aligned directions within the alignment device, reducing the number of independently adjustable components, and increasing system robustness. The goal of our project is to design a six-degree-of-freedom manipulator stage for accurately positioning and aligning two beam splitters to be joined together with high precision. Our project will improve upon an existing assembly system by making the system simpler, more compact and easier to align.

EXECUTIVE SUMMARY

We were tasked by Dr. Stephen Segall, a professor at The University of Michigan, and the Engineering Research Center for Reconfigurable Machining Systems to design a six degree of freedom stage for positioning and aligning an optical component relative to a second optical component. A laser alignment system will determine if the components are correctly aligned. The Optical Component Alignment System consists of two main parts; the upper part will hold a beam splitting prism in place while the lower part will raise a second prism into position such that the two prisms can be adhered. We have successfully designed and manufactured the upper stage of the two stages. We used information from our project sponsor, measurements from the existing design, and the use of our engineering judgment to develop engineering specifications for our project. Each specification describes an aspect of the device in a clear, numerical sense and set specific targets for each design parameter. We developed a QFD to understand and improve our design by evaluating design parameters and comparing the relative value of each in our device.

With the project requirements in mind, we proceeded with problem analysis and a discussion of engineering principles for the project. Working from these principles, we developed several design sketches. We used a functional decomposition diagram to differentiate the aspects of our design and to classify our sketches. Looking at our engineering specifications, along with feedback from our sponsor, we rated each concept and combined the best to produce an alpha prototype. After converting the Alpha Prototype idea into a working CAD drawing, we produced a parts list and assigned a cost to each item. We received final approval of our design from our sponsor and ordered the parts necessary for the next phase in design.

After receiving the ordered components and materials, we developed an Engineering Design Parameter Analysis, a detailed description of our final design, an initial manufacturing process plan to machine our prototype as well as a validation plan for our prototype. We completed machining on all stages and assembled our project for display at the April 13, 2006 Design Expo. Our sponsor has approved of our final design and intends to implement the completed project when the lower portion of the alignment system is finished. The final validation test, laser based alignment, will occur after the lower stage is completed. We recommend that the sponsor replacing the vertical adjustment with a larger model, fasten the support pillars to the base, and put stiffer springs in the tilt stages. Our final report reflects the entire breadth of this design process and includes the above mentioned material as well as final thoughts on safety, environmental impact, as well as a design critique.

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INTRODUCTION

Dr. Stephen Segall, a professor in mechanical engineering at The University of Michigan, needs an improved manipulator stage for adhering beam splitting prisms. The prisms will be used to align machining components and optical systems in the Engineering Research Center at The University of Michigan. Our student team was tasked to improve the upper portion of the existing stage design, as illustrated in Figure 1, with a design that integrates the necessary six degrees of freedom. The project is further complicated in that the manipulator must be mounted on the underside of a support beam. As the components require precise positioning to be adhered, an accurate alignment system is necessary for this positioning. A laser will check the accuracy of the mechanical alignment tool before the system is used for aligning two beam splitters as illustrated in Figure 2.

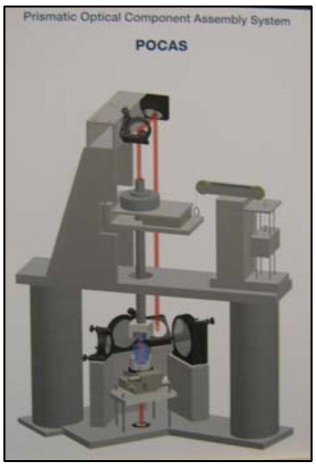


Figure 1: Previous assembly was complicated, unreliable, and bulky

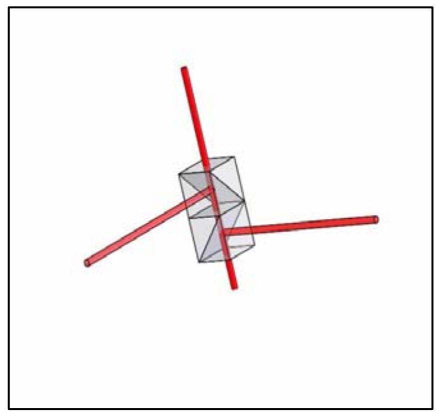


Figure 2: Joined prisms split laser in two orthogonal planes

Our revised design incorporates the following: two support rails to move the x and y stages, a microscope adjustment to move in the z direction, and concentrically aligned stages with a center bore to maintain line of sight. A revised CAD drawing of our design is shown in Figure 3, with the entire assembly illustrated in Figure 4 below.

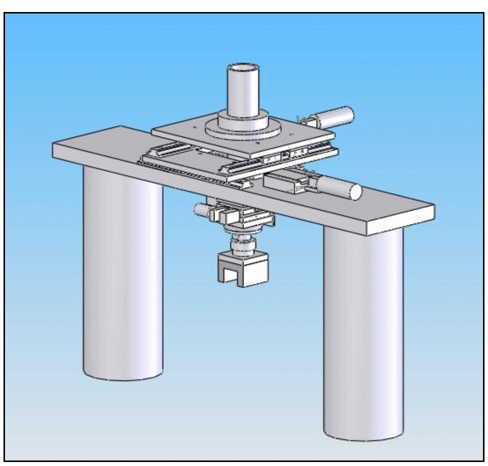


Figure 3: CAD model of our final design

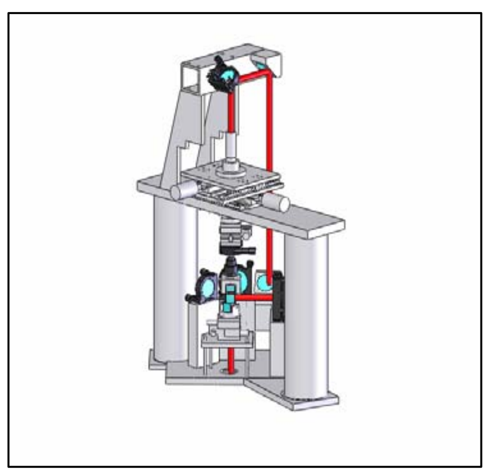


Figure 4: Complete Assembly

This report includes: problem assessment, development of engineering specifications, concept generation, concept selection, alpha design creation, component research and information, and design assessment. This document further expands the discussion of our concept including: engineering design parameter analysis, final design description, manufacturing summary, and our validation plan. This report also includes a detailed list of materials, an updated Gantt chart, as well as safety and failure concerns for our project.

ENGINEERING SPECIFICATIONS

We developed our engineering specifications using input from our project sponsor, measurements from the existing design, and engineering judgment based on previous experience in sizing our project. The requirements for the project include: accuracy in aligning the beam splitters, compact design, and improvement in the simplicity of the device. We developed a QFD comparing the relative importance of these design requirements included in Appendix A on page 53.

Our sponsor required a travel distance in the vertical direction to be 60 mm with precision of ±.02 mm. The tilt adjustment required a range of 15 deg and an accuracy of ±1 arc second. The x and y adjustments should travel 15 mm and be accurate to within ±0.1 mm. We purchased a telescoping adjustment that produces a total of 9.5 mm in z-axis movement with an additional 90 mm in coarse adjustment from our upper support arm. To accommodate our adjustable height post, we negotiated for a revised minimum line of sight of 14mm. The tilt to beam splitter distance did not meet our specification, but we significantly reduced this distance from the previous design from 40 cm to 12.2 cm. In general, the goals set at the beginning of the project are met or exceeded in our current design. Table 1 below summarizes important attributes for the project along with the values for both the initial engineering goal and the specifications of the current design.

Attribute	Goal	Revised Design
Tilt to Beam Splitter Distance	8 cm	12.2 cm
Shaft Sway	0.1 deg	0.1 deg
Line of Sight (Tube Diameter)	undetermined	14 mm
X Travel	15 mm	24 mm
Y Travel	15 mm	24 mm
Z Travel	60 mm	9.5mm fine + 90 mm coarse
X movement precision	0.1 mm	0.002 mm
Y movement precision	0.1 mm	0.002 mm
Z movement precision	1 mm	0.02 mm
Roll range	15 deg	30 deg
Pitch range	15 deg	30 deg
Yaw range	360 deg	360 deg
Roll precision	1 arc second	3.6 arc second
Pitch precision	1 arc second	3.6 arc second
Yaw precision	1 arc second	1.2 arc second
Width (X) limits	300 mm	300 mm
Length (Y) limits	200 mm	300 mm
Height (Z) limits	600 mm	310 mm
Mass of Tilt Platform	7 kg	1.1 kg
Weight Capacity	3 kg	3 kg

Table 1: Comparison between the original engineering targets for the project and the revised specifications of the proposed design is shown.

CONCEPT GENERATION

We developed a functional decomposition diagram to differentiate the aspects of our design. The diagram is illustrated in Figure 5 below. Our first brainstorming session was used to generate the required inputs for the device, the functions inherent to successful operation, and the desired output. Using the project guidelines as well as input from our sponsor, we delineated each function according to the six degrees of freedom required. We each developed concepts to accomplish the required functions and created design sketches that illustrated these concepts.

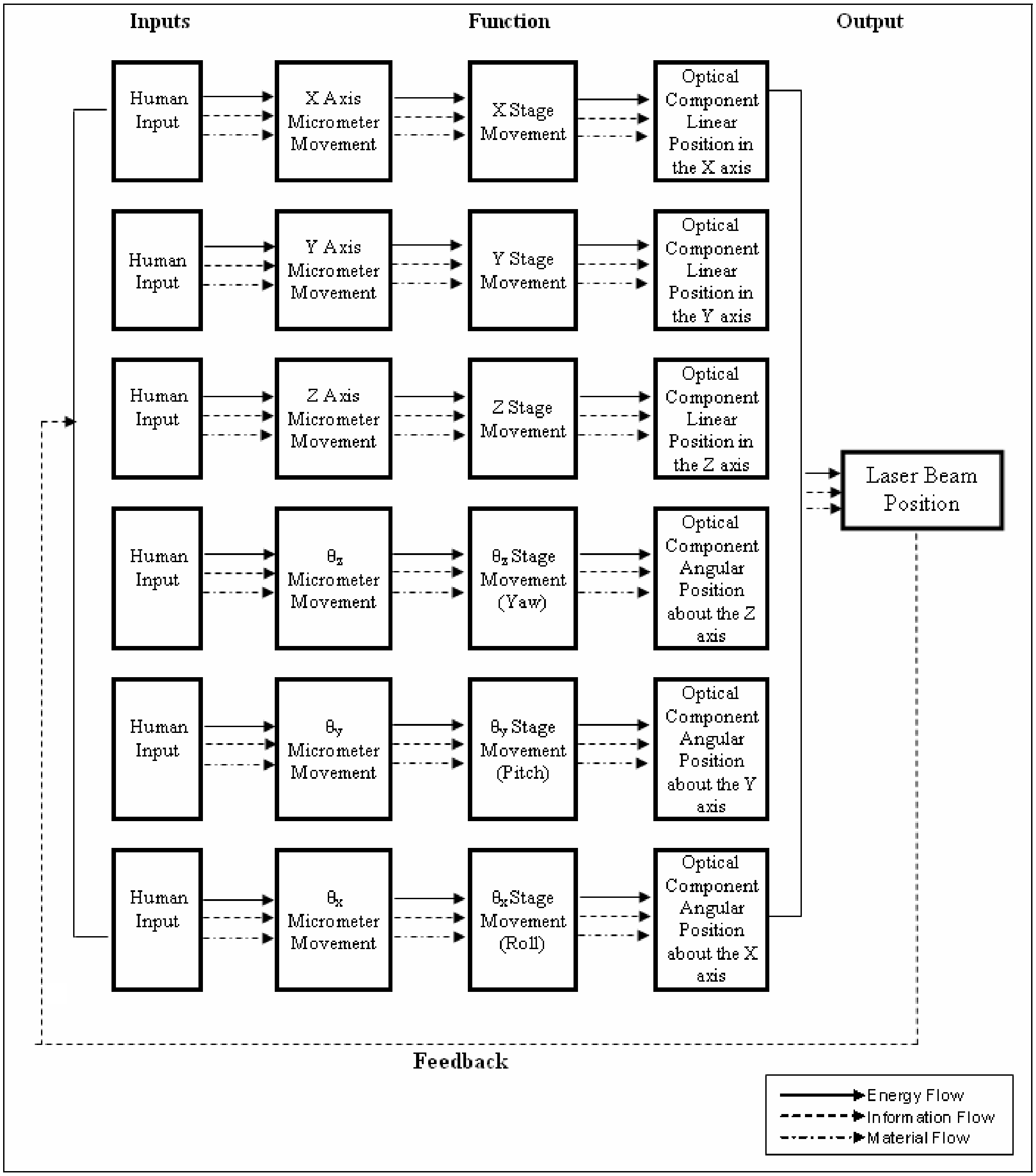


Figure 5: Functional Decomposition Diagram

The generated concepts are divided into three main categories namely, *Main Concepts*, *X-Y Axis Movement Concepts* and *Z Axis Movement Concepts*. The *Main Concepts* are generally methods to incorporate all the components such as the tilt and rotation stages, the x and y axis stages, and the z-axis stages into a single working system. *The X-Y Axis Movement Concepts* are methods or designs for system movement and control in the x and y directions. And finally, the *Z Axis Movement Concepts* are designs for system movement and control in the vertical z-axis. Concept generation for the yaw, pitch and roll platforms are unnecessary as we are incorporating the existing tilt and rotation stages into our design.

Main Concepts

Main Concept Sketch 1

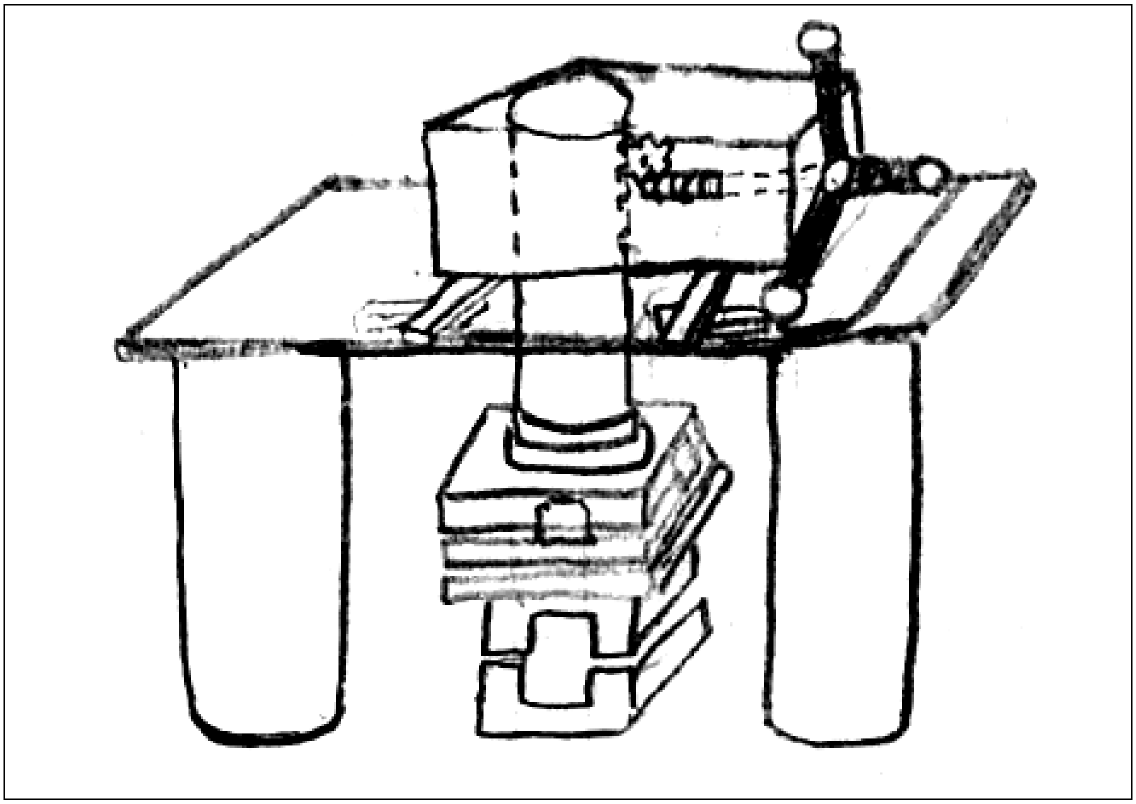


Figure 6: Drill Press Design

Figure 6 above illustrates the Drill Press Design. This design utilizes a drill press style box with a three-pronged handle attached to a screw shaft. The screw shaft when turned rotates a worm gear which, in turn, moves the z-axis shaft which is also a screw threaded shaft. The x and y stages are moved by rails mounted underneath the box and the hollow center of the support beam; they are mounted to provide clearance to the stages below. The two tilt stages as well as the rotation stage are mounted at the base of the z-axis tube and are hollowed in the center to allow for a clear line of sight for the laser beam.

An advantage of this design is that the user has complete control with the drill press handle in maneuvering the apparatus in the z-direction. The movement is very accurate due to the worm gearing between the drill press lever and the column. The design eliminates clearance problems as the entire structure is set on sliding rails. Movement is smooth due to the rails and worm gears.

Conversely, this design operates with the inherent difficulty of mounting a rigid structure on rails which do not rest rigidly, but tend to roll. A major concern during our design process was that the tilt stages could not be suspended. Also, this design was not feasible as we could not salvage a drill press and making such a device would be extremely difficult.

Main Concept Sketch 2

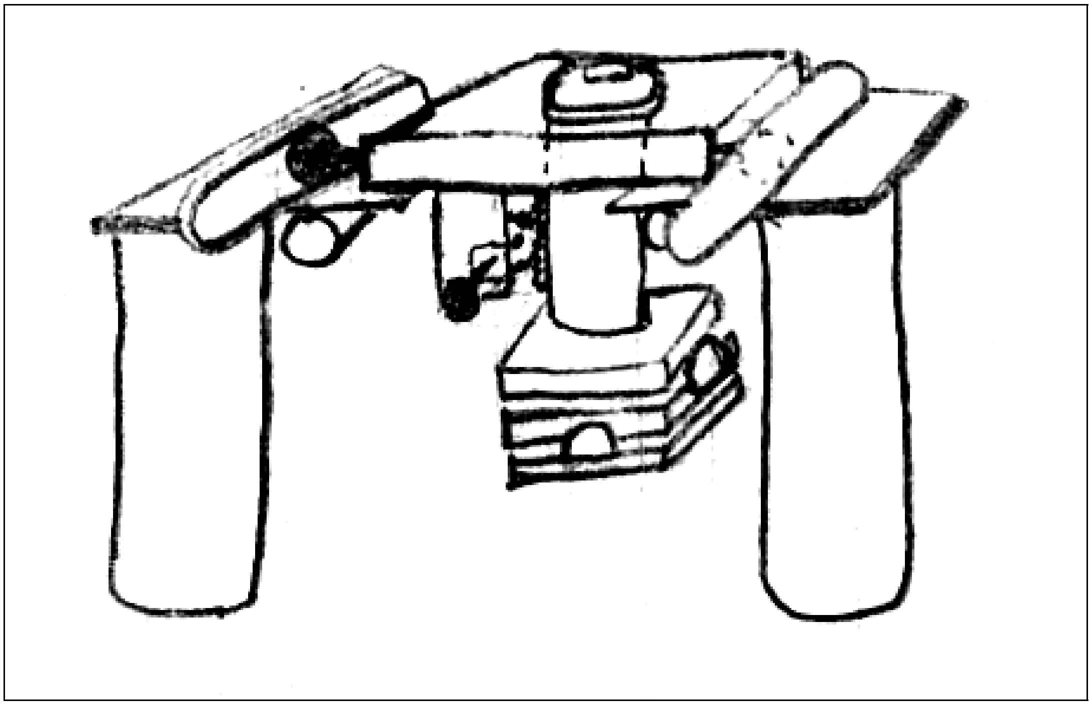


Figure 7: Channels and Rollers Design

Figure 7 above illustrates the Channels and Rollers Design. The upper box of this concept is mounted along two rails by two sets of roller wheels. The rails are vertical and are mounted on top of two rolling cylinders to provide movement in both the x and y directions. The z-stage is a hollow tube with a rack mounted on the side and the rotation stage mounted above to turn the tube. The pinion gear is mounted underneath the support beam and is connected to a handle crank used to turn the pinion and thus move the z-column up and down. The two tilt stages are suspended below the z-column and the entire central structure is hollow to allow for a clear line of sight for the laser beam.

An advantage when using rollers to support the weight of our design is that the rollers will glide smoothly, even under a large suspended weight. The rack and pinion proposed for the z stage has the advantage of being very accurate and lockable. Another advantage of this design is the large range of movement both in the rollers and the rack and pinion.

A disadvantage to this design is the uncontrollable amount of kickback from the rails. The precision required by our sponsor would make manufacturing the rails and channels difficult and require all of those parts to be ordered. We were also concerned with mounting a rectangular rack on the cylindrical tube supporting the tilt stages.

Main Concept Sketch 3

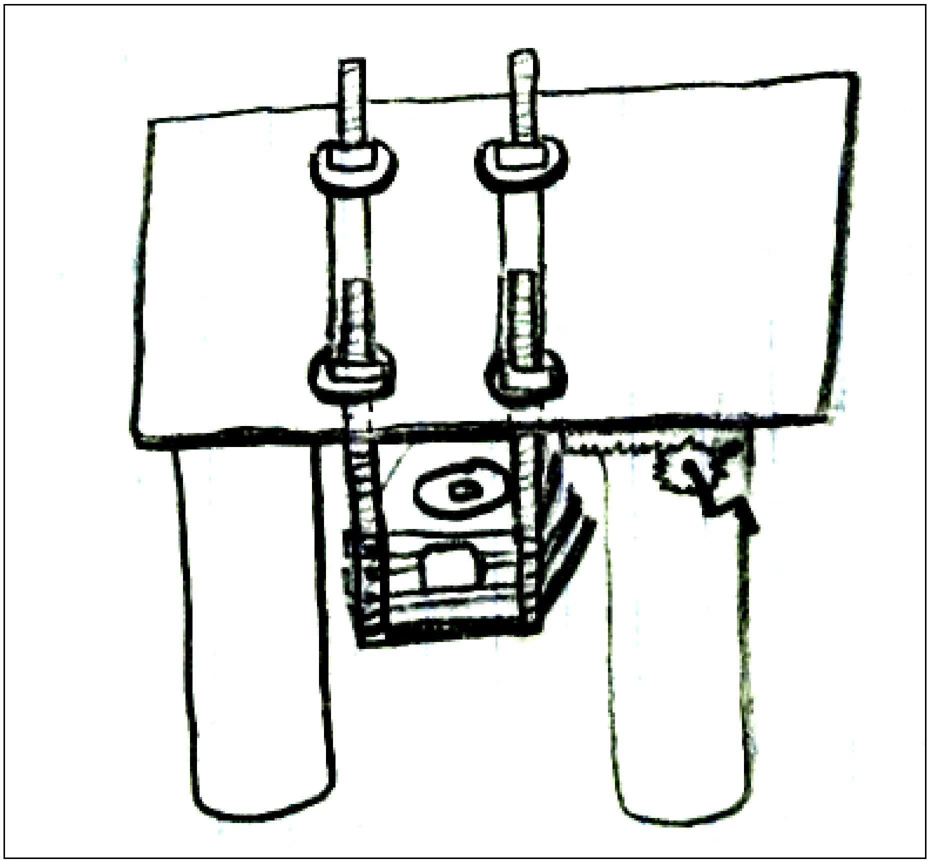


Figure 8: Four-Support Carriage Design

Figure 8 above illustrates the Four-Support Carriage Design. The lower structure of this concept is supported by four threaded rods that go from the base of the carriage plate to above the support beam. The threaded rods are sitting atop washers that run along a channel in the y direction and uses threaded bolts to raise and lower in the z-direction. The entire support beam is moved in the x-direction by a rack and pinion on the front of the structure with the support beams each having rollers for the table to move upon. The two tilt stages and the rotation stage are hollowed at the center to maintain line of sight and are supported from beneath by the carriage structure.

An advantage of using threaded rod with vertical movement controlled by screws is even z-stage movement. This design would eliminate tilt stage suspension problems as the carriage would support the stages. Along those lines, the stages will be mounted right side up and eliminate questions of their functionality when overturned.

However, this design was problematic in that the channels used to support stages are inaccurate and would require manual pushing or pulling. This design also requires us to hollow the tilt stages; an action we thought would cripple the functionality of the stages. Also, the large washers are not reliable for movement as they would produce friction with the top surface.

Main Concept Sketch 4

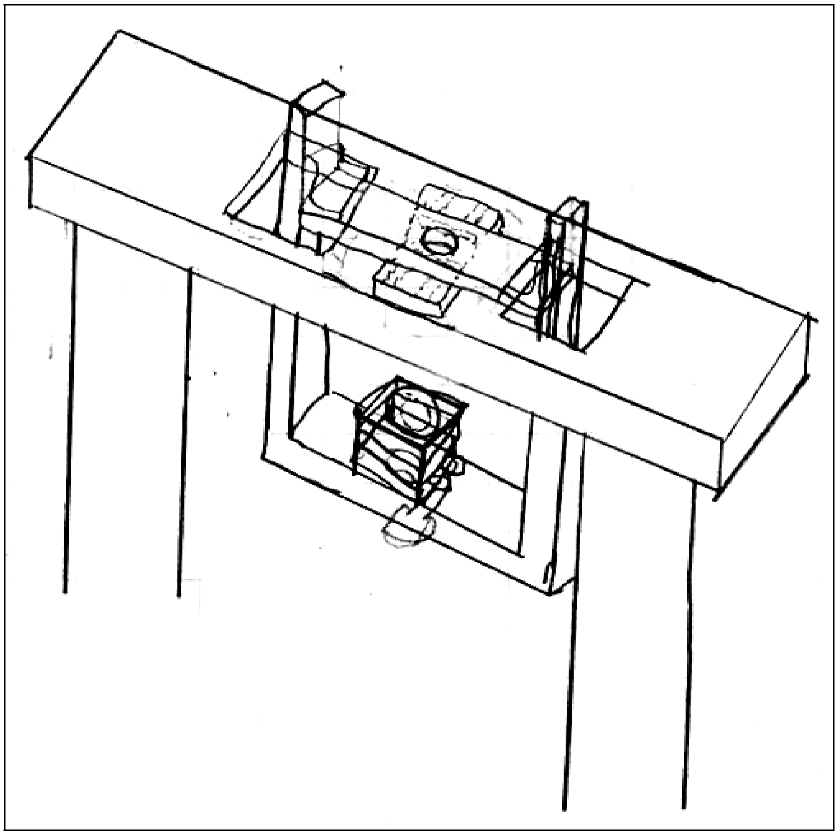


Figure 9: Two Support Carriage Design

Figure 9 above illustrates the Two Support Carriage Design. All aspects of the tilt and rotation movement stages are mounted beneath the support beam. This design reduces overall height of the structure and the height of the movement stages. It also places all of the precision components on one side of the support beam, which resolves the difficulty of supporting different stages through the support beam. This design also supports the tilt stages from below, eliminating the possible problems from suspension.

However, the compactness of this design also introduces the problem of the adjustment controls being very cramped. We were concerned that it would be difficult to make adjustments without inadvertently altering the position of another stage. The design also requires that the x-stage and y-stage rails support all of the weight of the structure. As this would require rails specifically designed to support suspended weight, and not compressive weight, it would require us to check for special engineering specifications. We also anticipated a problem in synchronizing the movements of the two x-stage and y-stage supports. As only one of the supports would have controlled movement, the other would need to follow this movement very precisely.

Main Concept Sketch 5

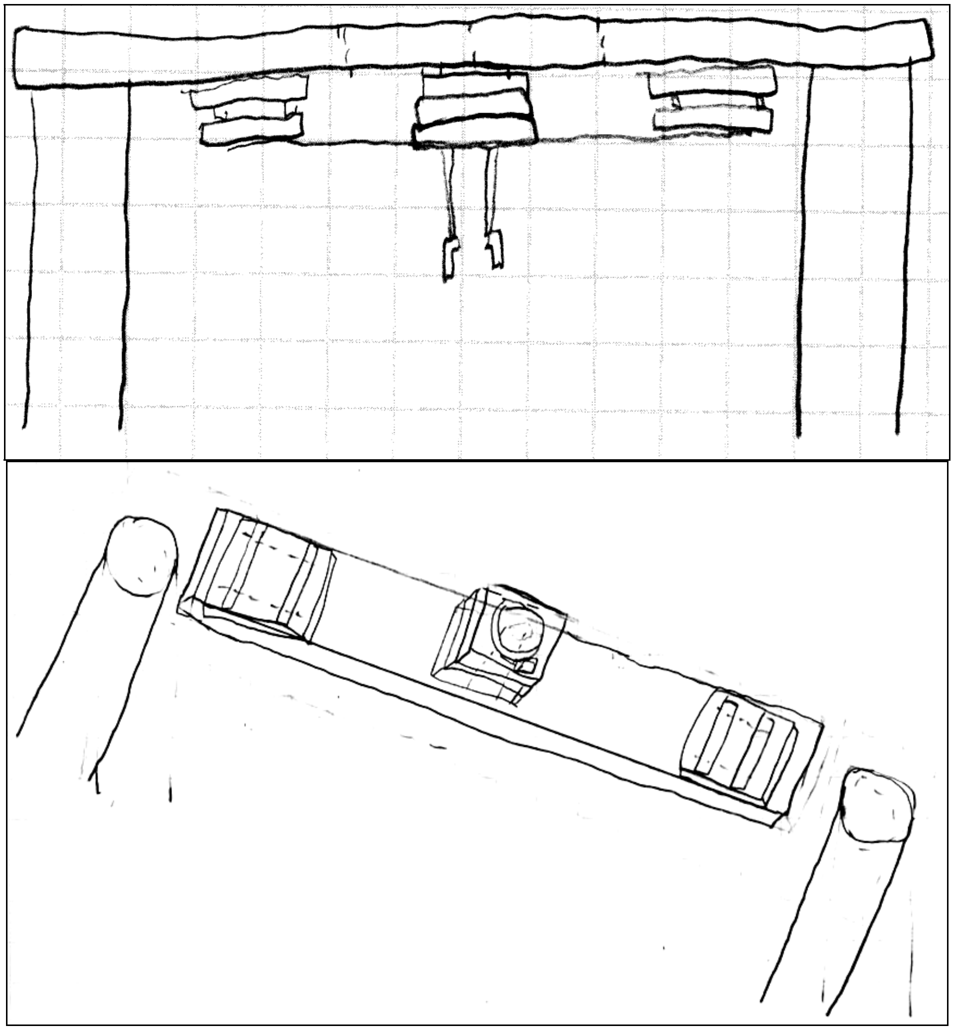


Figure 10: Mounted Below Design

Figure 10 above illustrates the Mounted Below Design. This concept allows for support of the tilt and rotation stages from the linear translation stages. It also incorporates the z-stage movement into this support, decreasing the number of components needed for the device. This design also allows the tilt stages to be placed very close to the beam splitter, which will increase accuracy.

Unfortunately, there is difficulty in synchronizing of the z-stage adjustments as any adjustment must affect both sides simultaneously. The two support tubes as they exist currently would make mounting the adjustments of the tilt stages difficult due to the fact that the stages would be blocking a large portion of the sides of the stages. The supports would also require a large portion of the support beam to be removed to allow for the full range of motion of the support beams. Our concern is that such modifications would decrease the structural integrity of the support beam.

Main Concept Sketch 6

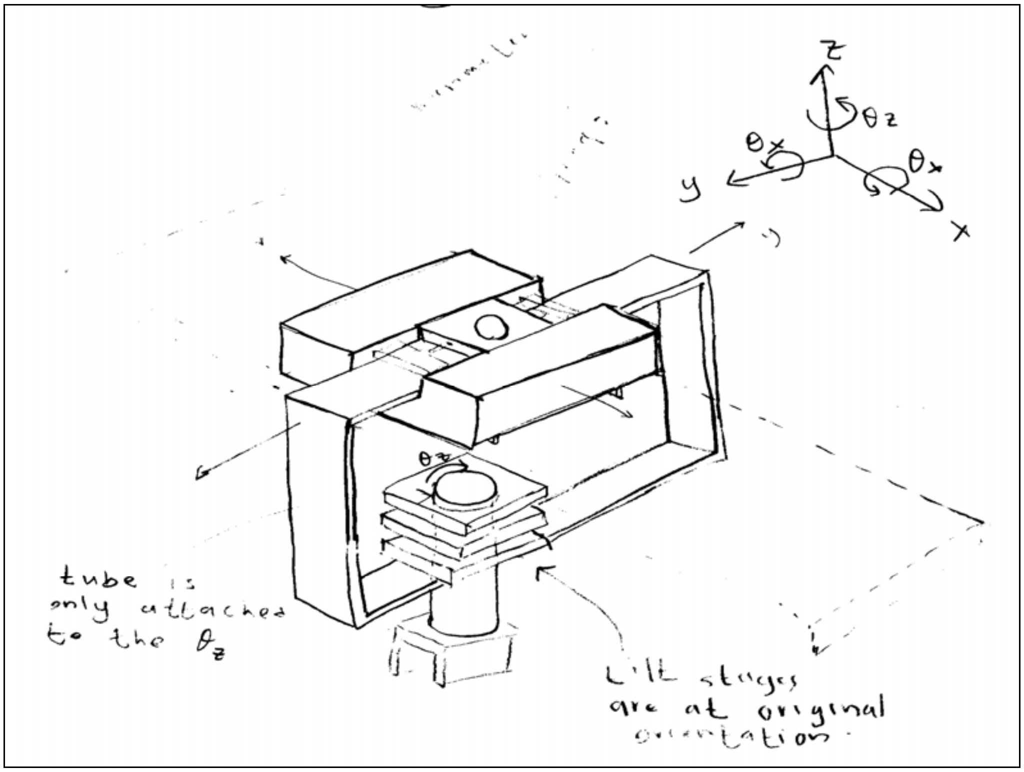


Figure 11: The X and Y movement system attached to the tilt stages via a mount.

Figure 11 above illustrates a method to connect the x and y movement system to the tilt stages while maintaining the line of sight. In this design the tilt stages are mounted in their original orientation, thus requiring a mount to support it from below. The mount also acts as the connection between the tilt stages and the x and y movement system.

The main advantage of this design is that it will allow the tilt stages to operate in the original orientation. This will allow the tilt stages to operate in the manner recommended by the manufacturer. The stress on the z-axis adjuster is also minimized since it will not be supporting the tilt stages.

On the other hand, as the tilt stages are placed far from the component, any angular adjustments made will have a large error. The rigidity of the mounting arms can also add to the error in precision if they are not properly designed.

Main Concept Sketch 7

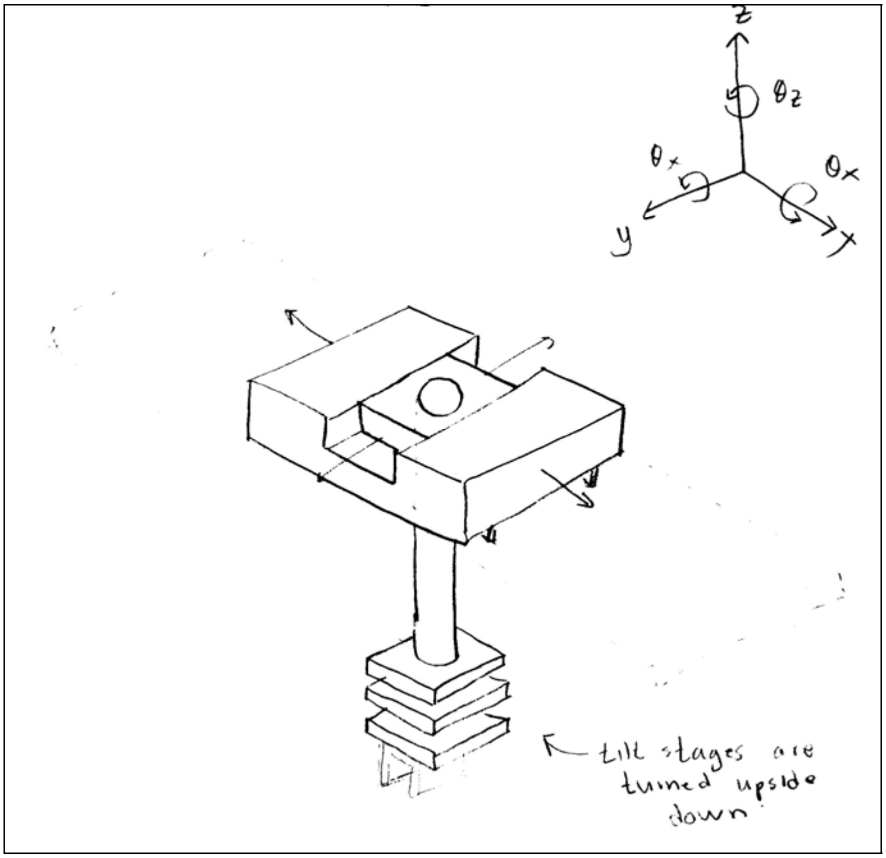


Figure 12: The tilt adjustments stages mounted directly to the end of the support tube.

Figure 12 above illustrates a design in which the tilt adjustment stages are directly mounted to the bottom end of the support tube. In this design, the tilt stages are placed in an upside-down position.

The main advantage of this design is that the tilt stages are mounted as close as possible to the component, allowing the user to make angular adjustments directly. This is also the simplest method that we could implement without requiring any extra mountings.

However, by having the tilt stages upside-down, we were concerned that the accuracy and precision would be compromised. Furthermore, by having the tilt stages at the bottom end of the tube, we anticipated a large stress on the tube that might in turn compromise the accuracy of the x and y axis adjustments on top.

Main Concept Sketch 8

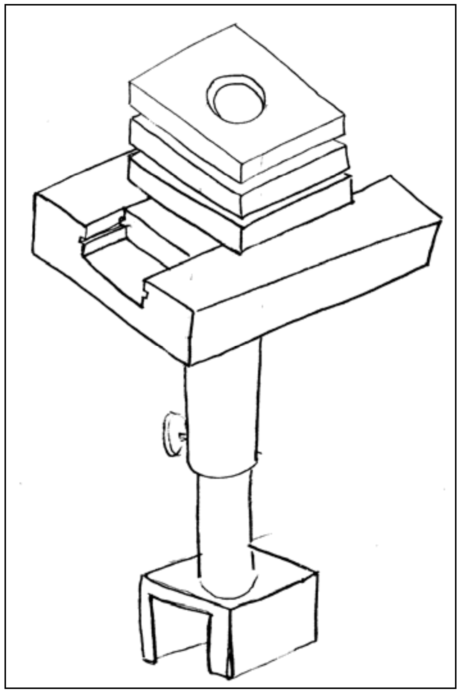


Figure 13: Tilt on Rails Design

Figure 13 above illustrates a design where the tilt stages are placed on top of the x and y axis rails. The tube is connected only to the topmost tilt stage and a telescoping tube is used as the z-axis adjuster.

The main advantage of this design is that it is a very stable design. All the stages are supported on the main stage and the tilt stages are used in their original orientation. There is also less stress in the support tube as only the component is attached at the bottom end.

However, by having the tilt stages at the very top, the errors introduced by the tilt stages will be magnified at the component end, which is also the problem of the original design. The design also violates the requirement of having the tilt stages below the main stage.

Concepts for X-Y Axis Travel

X-Y Axis Concept Sketch 1

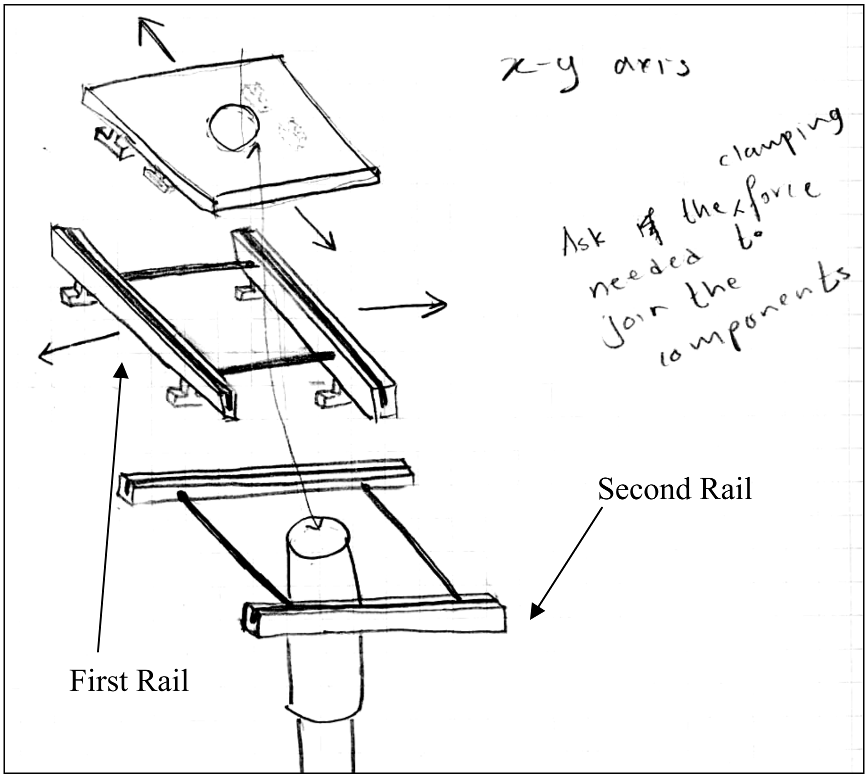


Figure 14: A simple railing system for the X and Y axis movement

Figure 14 above illustrates proposed design for the x and y axis movement of the alignment system. The support tube is attached to the topmost stage. The topmost stage will slide on a pair of rails which in turn slide on a second pair of rails positioned perpendicular to the first rail. The second rail is then mounted rigidly to the main stage.

An advantage of this railing system is that it is lightweight and easy to implement. Micrometers can be easily mounted on the side of these stages to control its movement. The range of movement of these stages is also very large and is only limited by the rail length.

However, for this railing design to have a large range of movement, it will require a large footprint that may not fit on the current main stage. Furthermore, the precision of the railing system will also depend on the rails itself. We assume that we will buy the rails as we do not have the capability of manufacturing to the required level of precision.

X-Y Axis Concept Sketch 2

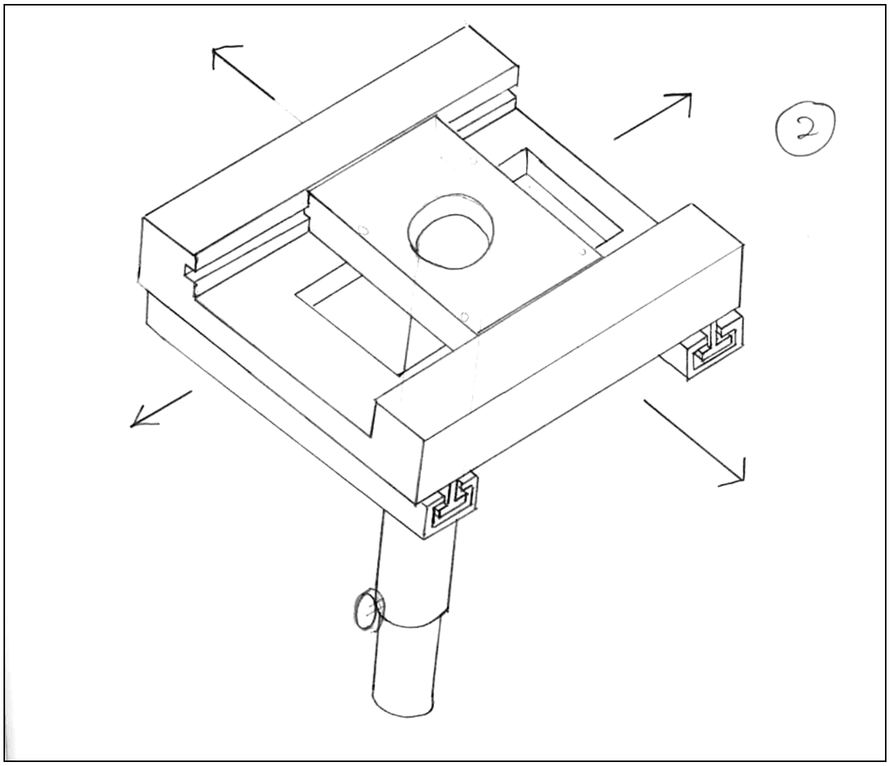


Figure 15: Another concept sketch for the X and Y axis movement

Figure 15 above illustrates another proposed idea for the x and y axis movement of the alignment system. The system implements a sliding slot system for one of the adjustment stages and a railing system for the other. The support tube is attached to the topmost sliding slot stage and the railings are rigidly mounted on the main stage.

The design is good in the sense that it is very compact when compared to the previous design and easy to control. Micrometers can be easily mounted to the stages to control its movements. Also, as it uses a railing system, the range of motion is only limited by the length of the rails.

One of the major drawbacks of this design is that it will be very difficult to manufacture the sliding slot system with the required accuracy and it will be very hard to find an existing product on the market with similar design and functions.

X-Y Axis Concept Sketch 3

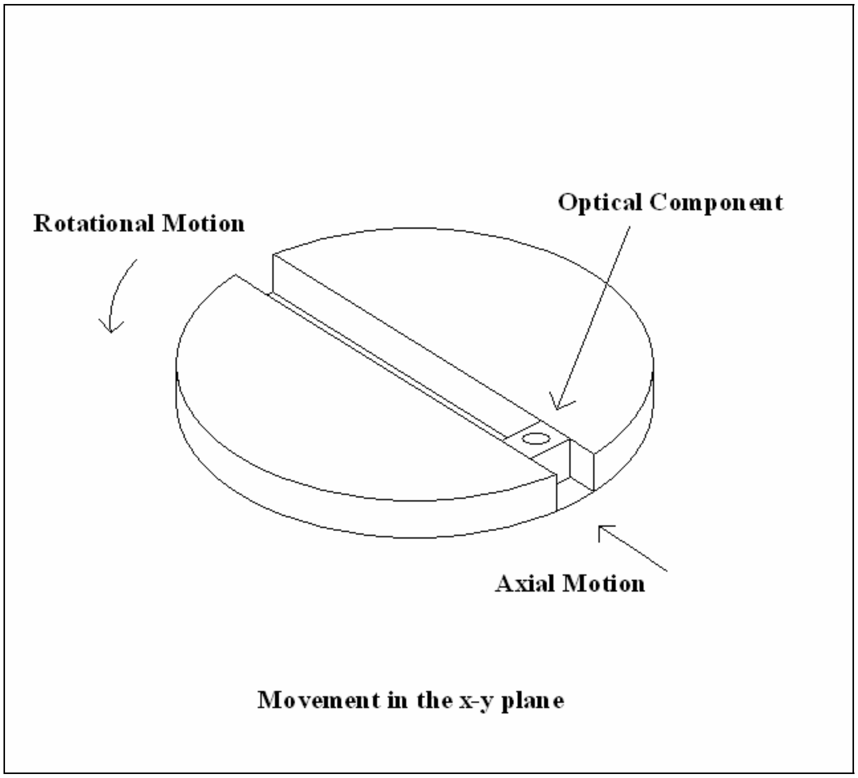


Figure 16: Movement for X and Y stages

Figure 16 above illustrates a rotating concept to move the x and y stages. In this design, a component placeholder or collar is set in a slot that runs along the diameter of a circular platform. This platform would be able to rotate about its center, possibly controlled by a set of gears that mesh with gear teeth outfitted around the platform's perimeter. The combination of axial and rotational movements would allow the component placeholder, which connects this manipulation stage to the others, to move about anywhere within the radius of the circle.

This design is inherently compact compared to other designs that stack up the individual x and y axis manipulation stages upon each other. In the two-level planar manipulation setup, the lower level would need to bear the load of the upper level, as well as all the related components attached to the system. This design saves a significant amount of vertical clearance, and eliminates the potential stress bearing problem mentioned above.

A major disadvantage of this design is in its control. The planar movements could be counter-intuitive to adjust manually, since its operation necessitates the use of cylindrical coordinate system as the positioning reference. It would also be difficult to mount the axial position adjuster, since it will have to be placed on the rotating platform and will get in the way of the gear teeth along the perimeter.

Concepts for Z Axis Movement

Z Axis Concept Sketch 1

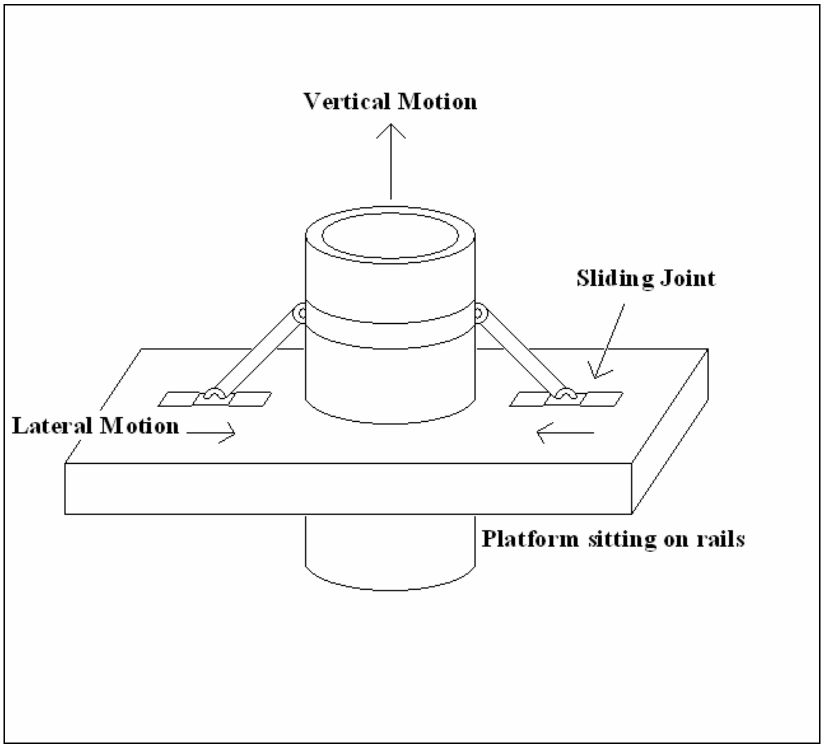


Figure 17: Sliding Joint Vertical Motion

Figure 17 above illustrates a sliding joint concept to achieve vertical motion. This arrangement is designed to manipulate the vertical positioning of the optical component. A tube that maintains the line of sight of the system is held in place by a collar that is attached to a linkage system. Lateral motion of the sliders at the base of the two connector linkages results in the tube being pushed upward or downwards depending on the direction of the motion.

This design eliminates potential problems regarding the perpendicularity of the tube relative to the platform (within a certain tolerance), since any tilting motion would be constrained by the collar and the platform itself. The setup could also potentially support significant loads, compared to telescopic vertical adjustments that place stress on their gear teeth.

However, this design is unreliable in terms of its positioning accuracy, since the system error is a combination of the uncertainties in the two sliding joints. It would be difficult to ensure that both sliders move exactly the same amount inwards or outwards from the tube without a unifying position adjuster, and problems could arise in making and mounting this type of mechanism. The nature of this device prevents itself from being installed beneath the tilt manipulator stages; thus the entire system would be designed around this stage.

Z Axis Concept Sketch 2

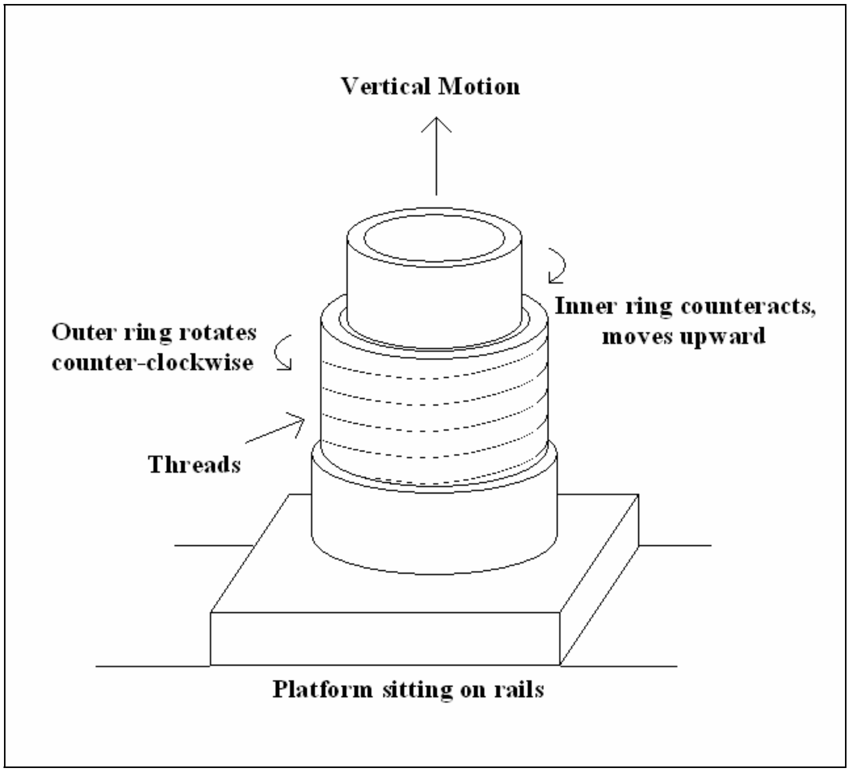


Figure 18: Screw-Action Vertical Motion

Figure 18 above illustrates a screw action concept to achieve vertical motion. This setup is also designed to manipulate the system's vertical positioning. The design consists of two threaded rings or tubes rotating inside a casing. When the outer ring is rotated either clockwise or counter-clockwise, the inner ring will counteract the outer ring's movement, resulting in a vertical motion with its rotation essentially cancelled out.

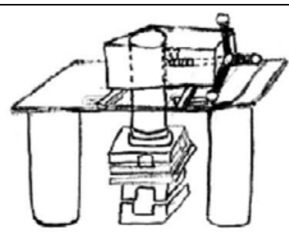
This design is very compact as compared to the above design. The level of precision is determined by the angle that the threads make relative to the platform; we would decide how much of the vertical motion is realized with a single turn of the rings based on that angle.

A major disadvantage of this design is in its difficulty to lock into position after adjustments have been made. The threads for the inner ring need to oppose the outer ring's threads exactly for the design to work properly. Furthermore, the inside of the outer ring and the housing would also require threading. For these reasons the design would be difficult to manufacture.

CONCEPT SELECTION

To select the best concept for our prototype, we constructed a scoring matrix to numerically evaluate and compare our concepts. Each concept is scored according to characteristic based upon the customer specifications and engineering requirements. Those characteristics are then weighted according to their importance. A sub score is then given to each design according to how it satisfies the required characteristics. The score is the sub score multiplied by the weight. The higher the total score, the better the concept is with respect to the required characteristics.

Main Concepts

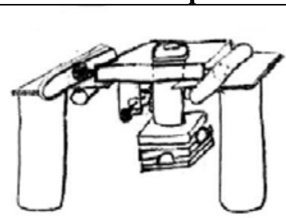


Pros:
- Accuracy
- No Clearance Issue
- Smooth Movement

Cons:
- Delicate equipment suspending large weight
- may not be suspendable
- Unless salvaged, drill press is difficult to manufacture

Characteristic	Weight (1-10)	Sub Score (1 -10)	Score
Precision/Accuracy	9	7	63
Availability of parts in the market	9	2	18
Durability	5	5	25
Stability	5	5	25
Ease of Use	5	7	35
Maintains the line of sight	9	8	72
Manufacturability	8	4	32
		Total Score	**270**

Figure 19: Main Concept #1

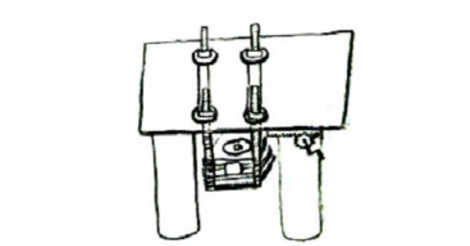


Pros:
- Very Smooth
- Rack and Pinion Accuracy (z-stage)
- Large Range of Movement

Cons:
- Does not reduce cylinder height
- Kickback from Rails
- Difficult to Mount a Rectangular Rack on a Cylinder

Characteristic	Weight (1-10)	Sub Score (1 -10)	Score
Precision/Accuracy	9	5	45
Availability of parts in the market	9	3	75
Durability	5	6	30
Stability	5	4	20
Ease of Use	5	7	35
Maintains the line of sight	9	8	72
Manufacturability	8	3	24
		Total Score	**253**

Figure 20: Main Concept #2

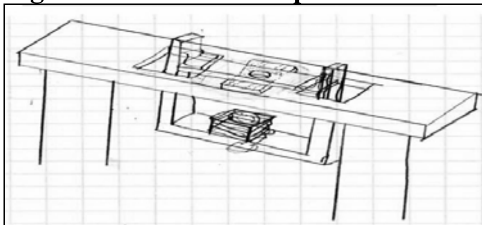


Pros:
- Even z-stage Movement
- Tilt Stages are Mounted Right Side Up completely beneath the support beam
- No Suspension Issue

Cons:
- Channels are inaccurate
- Requires hollowing of tilt Stages
- Large Washers are not Reliable

Characteristic	Weight (1-10)	Sub Score (1 -10)	Score
Precision/Accuracy	9	2	18
Availability of parts in the market	9	7	63
Durability	5	3	15
Stability	5	2	10
Ease of Use	5	3	15
Maintains the line of sight	9	7	63
Manufacturability	8	8	64
		Total Score	**248**

Figure 21: Main Concept #3

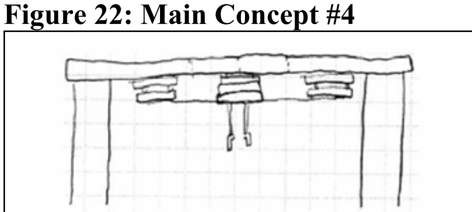


Pros:
- Greater Stability than four support design
- Tilt Stages are Right Side Up beneath the support beam
- No Suspension Issue

Cons:
- Difficult to synchronize z-stage movement
- Would require significant hollowing of the support beam
- May be difficult to manipulate the tilt stages

Characteristic	Weight (1-10)	Sub Score (1 -10)	Score
Precision/Accuracy	9	4	36
Availability of parts in the market	9	7	63
Durability	5	3	15
Stability	5	2	10
Ease of Use	5	3	15
Maintains the line of sight	9	7	63
Manufacturability	8	8	64
		Total Score	**266**

Figure 22: Main Concept #4

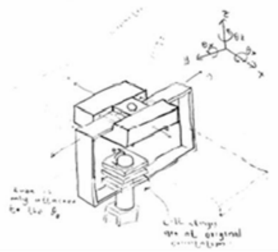


Pros:
- Structure is mounted on one side of the support beam
- No suspension Issue
- Very compact

Cons:
- Difficult to synchronize x and y stage movement
- Adjustments would be cramped
- Rails on the x and y stages would support significant weight

Characteristic	Weight (1-10)	Sub Score (1 -10)	Score
Precision/Accuracy	9	6	54
Availability of parts in the market	9	5	45
Durability	5	5	25
Stability	5	6	30
Ease of Use	5	3	15
Maintains the line of sight	9	7	63
Manufacturability	8	5	40
		Total Score	**272**

Figure 23: Main Concept #5

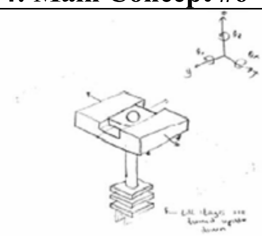


Pros:
- Low stress on Z adjuster
- Tilt stages are kept upright

Cons:
- Supporting pillars add stress to planar stages
- Rigidity of mountings is questionable

Characteristic	Weight (1-10)	Sub Score (1 -10)	Score
Precision/Accuracy	9	8	72
Availability of parts in the market	9	5	45
Durability	5	4	20
Stability	5	4	20
Ease of Use	5	7	35
Maintains the line of sight	9	7	63
Manufacturability	8	5	40
		Total Score	**295**

Figure 24: Main Concept #6

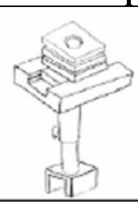


Pros:
- Minimizes error
- Tube length is minimum
- Simple to implement

Cons:
- Large stress on tube and Z adjuster
- Tilt stages will have to be turned upside down – this may cause problems

Characteristic	Weight (1-10)	Sub Score (1 -10)	Score
Precision/Accuracy	9	8	72
Availability of parts in the market	9	8	72
Durability	5	7	35
Stability	5	7	35
Ease of Use	5	8	40
Maintains the line of sight	9	7	63
Manufacturability	8	7	56
		Total Score	**373**

Figure 25: Main Concept #7



Pros:
- Stable Design
- Tilt stages used in correct orientation
- Less stress on support tube

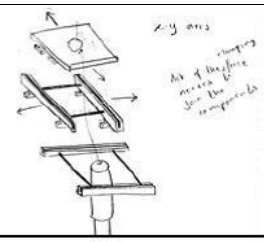
Cons:
- Length from tilt stages to base
- Tilt stages above support beam

Characteristic	Weight (1-10)	Sub Score (1 -10)	Score
Precision/Accuracy	9	2	18
Availability of parts in the market	9	8	72
Durability	5	7	35
Stability	5	8	40
Ease of Use	5	8	40
Maintains the line of sight	9	7	63
Manufacturability	8	7	56
		Total Score	**324**

Figure 26: Main Concept #8

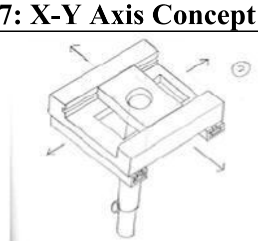
Our scoring matrices rated *Main Concept 7* best among those considered. Although the other proposed designs accomplish similar objectives, most of them are too complex to manufacture. *Main Concept 7* is the simplest of the designs and it meets all of our requirements. By having the rotation stage nearest to the component, the precision and accuracy of the adjustments is maximized. Another advantage of this design is that the precision components needed for implementation can be easily obtained. We have also learned that the tilt stages can be mounted upside-down and a hole can be drilled through the stages, thus making the design easier to manufacture. Furthermore, after consulting our sponsor, we decided to use some tilt stages from the lab that are smaller and lighter, greatly reducing the stresses in the support beam.

Concepts for X and Y axis movement



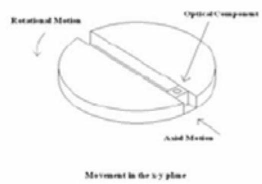
Characteristic	Weight (1-10)	Sub Score (1 -10)	Score
Precision/Accuracy	9	8	72
Availability of parts in the market	9	8	72
Durability	5	7	35
Stability	5	8	40
Ease of Use	5	8	40
Maintains the line of sight	9	7	63
Manufacturability	8	7	56
		Total Score	**378**

Figure 27: X-Y Axis Concept #1



Characteristic	Weight (1-10)	Sub Score (1 -10)	Score
Precision/Accuracy	9	8	72
Availability of parts in the market	9	6	54
Durability	5	7	35
Stability	5	8	40
Ease of Use	5	8	40
Maintains the line of sight	9	7	63
Manufacturability	8	5	40
		Total Score	**344**

Figure 28: X-Y Axis Concept #2



Pros:

- Compact design
- Simultaneous movement in x and y axes
- No stacking required for x and y stages

Cons:

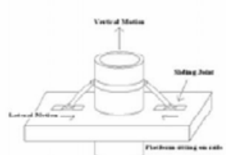
- Counter-intuitive positioning
- Difficult to mount controllers
- Lack of precision

Characteristic	Weight (1-10)	Sub Score (1 -10)	Score
Precision/Accuracy	9	8	72
Availability of parts in the market	9	4	36
Durability	5	7	35
Stability	5	8	40
Ease of Use	5	4	40
Maintains the line of sight	9	5	45
Manufacturability	8	5	40
		Total Score	**288**

Figure 29: X-Y Axis Concept #3

From the scoring matrices, we rated *X-Y Axis Concept 1* as the best design to be incorporated into the alignment system. The rails used in the design can be easily obtained and the stages are simple to manufacture. *X-Y Axis Concept 3* was not a good choice as it would have been difficult to control with micrometers and very difficult to manufacture to the required level of precision. There are no existing products similar to the design of *X-Y Axis Concept 2*. This is compounded by the difficulty in manufacturing the concept to the required level of precision.

Z Axis Movement Concepts



Pros:

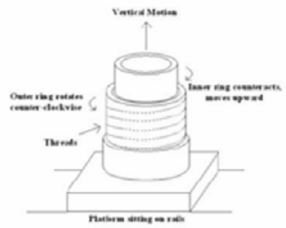
- High weight capacity possible
- Collar prevents unwanted rotational movement

Cons:

- Difficult to maintain perpendicularity between tube and platform
- Control issues
- Low accuracy

Characteristic	Weight (1-10)	Sub Score (1 -10)	Score
Precision/Accuracy	9	5	45
Availability of parts in the market	9	4	36
Durability	5	8	40
Stability	5	5	25
Ease of Use	5	4	20
Maintains the line of sight	9	8	72
Manufacturability	8	5	40
		Total Score	**278**

Figure 30: Z Axis Concept #1



Pros:

- Compact
- Variable precision based on thread angle

Cons:

- Difficult to manufacture
- Control issues
- Locking into position once adjustments have been made is difficult

Characteristic	Weight (1-10)	Sub Score (1 -10)	Score
Precision/Accuracy	9	8	72
Availability of parts in the market	9	8	72
Durability	5	8	40
Stability	5	5	25
Ease of Use	5	4	20
Maintains the line of sight	9	8	72
Manufacturability	8	7	56
		Total Score	**357**

Figure 31: Z Axis Concept #2

From the above scoring matrices, we evaluated *Z Axis Concept 2* as the best design to incorporate into our alignment system. We have found a similar precision device on the market, the Standa 5HP18 Adjustable Height Post. Our modifications to the post are detailed in the Modifications to the Standa z Adjustment in the Manufacturing section on page 42.

ENGINEERING DESIGN PARAMETER ANALYSIS

Our engineering approach used to determine specific parameters for our design began with two goals in mind: make each of the six stages concentric, and combine these elements in a simple yet robust manner. The primary dimensions of our design were derived from combining the precision equipment used for the tilt, rotation, and z adjustment stages. In combining these elements, our primary engineering decisions were focused on producing the precision specified by our sponsor. Some considerations include: design for manufacturability, problem analysis and engineering fundamentals, failure and safety charts, shear forces in the support tube and set screws, concentricity and moments, as well as human operation errors. The following describes how we used engineering analysis to develop our design from concept to final design.

Design for Manufacturability/Assembly

Throughout the design phase of our project, we were careful not to develop design ideas that were difficult or unnecessarily complicated to manufacture. We seamlessly moved from design to fabrication by incorporating manufacturing strategies with design ideas so as to reduce the amount of redesign necessary. The project is intended as a single lab device, not a mass produced product, with many of the precision parts requiring significant modifications. We incorporated existing elements into our design where relevant, but we were careful not to limit our design to only those pieces.

To produce the six degrees of freedom required by our sponsor, we combined conceptualizing new ideas with integrating existing structures. We used a press fit, for example, to attach the beam splitter holder to the z stage fine adjustment piece. We cut this piece to a slightly smaller diameter than the z adjustment piece and sanded it down until we achieved the desired fit between the pieces.

Component Manufacturability and Ease of Assembly
Most of the supporting structure, collars and tubes, in our project are designed with precision components available to us or were purchased. We had no major problems concerning the manufacturability of these joints as our designs incorporated contingencies to ensure proper mating of each part. However, some parts were manufactured with a high level of accuracy to maintain the alignment of the gaps and screw holes. These particular parts, such as pockets and hollowing the adjustable height post were entrusted to professional machinists and shop supervisors namely, Bob Coury, Steve Emanuel, and Steve Erskine.

Problem Analysis and Engineering Fundamentals
In this section, we discuss the major challenges of the design and how we addressed those challenges, along with engineering analysis.

Shortening the length between the adjustment and component end
The previous design placed the yaw-pitch-roll adjustment platform at one end of a tube and the optical component to be joined on the other end. This is a major drawback as any angular adjustment made will also produce a displacement it the x, y and z-axis. Another undesired characteristic of the previous design is that any movement or disturbance at the yaw-pitch-roll platform will be magnified at the component end of the tube, as illustrated in Figure 32 below.

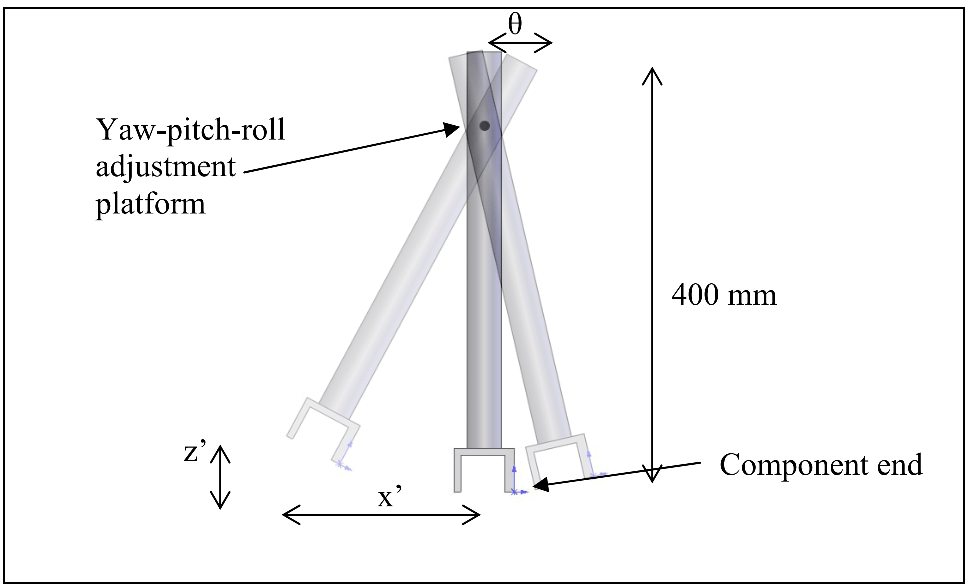


Figure 32: Displacement at the top end of the tube is magnified at the component end of the tube. A small angular change θ will result in a magnified displacement x' and also a vertical displacement z' at the component end of the tube.

We have reduced the amount of sway in the tube by shortening the overall length and placing the yaw-pitch-roll adjustment platform underneath the stage. Our proposed design now suspends only 170 mm, only 43% of the previous design. We anticipate a limited amount of sway using the coarse z-adjustment as we must exert a side force to manipulate the microscope adjustment. An advantage in our design is yaw-pitch-roll adjustment platform as it is directly mounted at the component end, allowing direct adjustment of the angular position of the component without introducing any undesired displacements. The reduced length and proposed mounting are made possible because the smaller stages do not lose functionality when mounted upside-down.

Reducing the mass of the adjustment platform

Platform mass was mounting issue as we intended to put the yaw-pitch-roll adjustment platform at the component end of the tube. The previous stage was quite heavy and the mass was not symmetrically distributed. Our preliminary estimations showed that the mass will produce stress at the component end of the tube as well as produce a bending moment due to the asymmetry as illustrated in Figure 33.

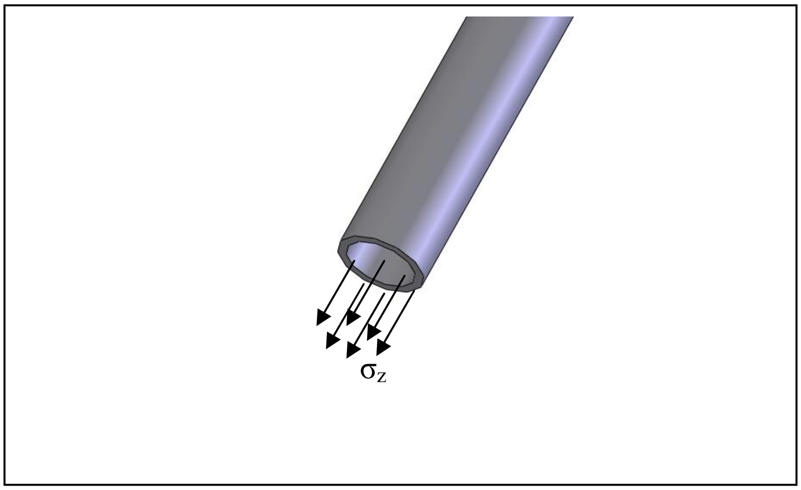


Figure 33: Stress levels at the component end of the tube would be high if the weight of the yaw-pitch-roll adjustment platform is not reduced.

Our design eliminates the necessity of the counter balance as all components are mounted in direct alignment. We have chosen the smaller yaw-pitch-roll adjustment platform, 60 mm by 60 mm base as opposed to the 100mm by 100mm to reduce overall mass. We aligned both tilt stages and the rotation stage with the support tube and center bored each to maintain the line of sight. Our design reduced overall mass from 10 kg to 1.1 kg and the center alignment of the concept eliminates the large bending moment present before. The addition of the z adjustment, a telescoping arm, to the base of the rotation stage adds only .2 kg mass to the suspended load.

Counter balance system is bulky and does not function satisfactorily

The previous design employed a counter-balance system to adjust the position in the z-axis. That method made vertical adjustment of the component difficult and introduced problems that detracted from the robustness of the system. As seen in Figure 34, if the pulleys and the counterweight were not properly set-up, only the left end of the platform lowered and an unnecessary angular movement θ was introduced. Furthermore, the platform was only supported by a metal wire on one side, reducing the rigidity of the platform. Any disturbance would cause the platform to vibrate, an undesired effect when considering the precision level of the system.

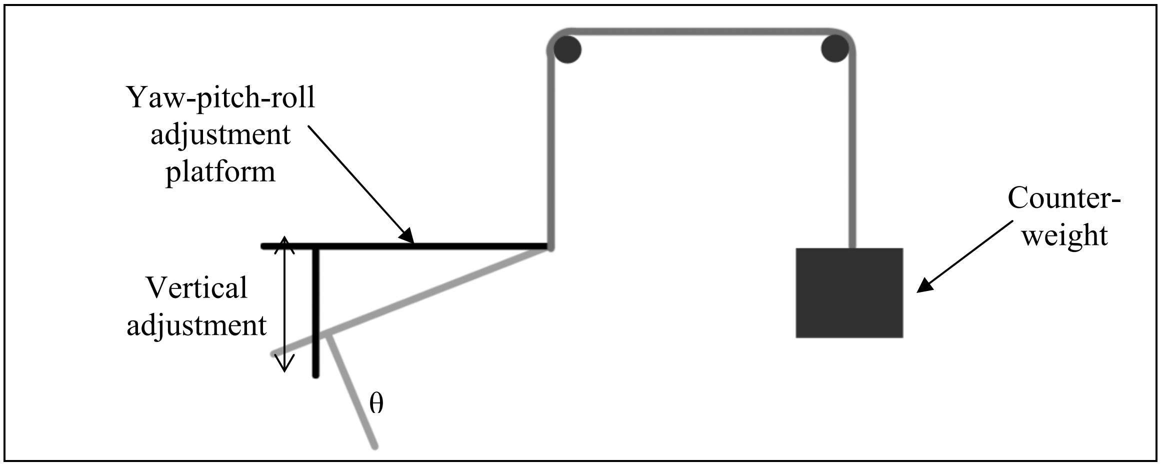


Figure 34: A vertical adjustment caused the platform to introduce an angular change to the position of the optical component.

We eliminated the counterweight from the original design and replaced the suspension support, with railings for the x and y axis movement. The railings provide a stable and even movement in the x and y directions. For the rails to function, we cut a square opening in the support beam that maintained the necessary envelope for the suspended components to travel.

Failure and Safety Assessment

We have assessed the safety level of the system that we designed using the DesignSafe 3.0 software. There are four main failure modes that we have identified which are the sharp edges, unsecured screws, instability, and fatigue.

There exist many components with moderately sharp edges in our system. Most of the components that are milled have sharp edges and these edges will require filing. The risk level given by DesignSafe for this mode of failure is Low.

Most of the parts in the system are held on by set screws; therefore, if unsecured parts could fall and cause injury. Our solution is to warn users to check that the screws are secured before operating the system. The risk level given by DesignSafe for this mode of failure is Moderate.

As most screws tend to be loose after some period of time and use, some components may fall down if not checked periodically. Therefore, the screws should be checked and re-fastened periodically. The risk level given by DesignSafe for this mode of failure is Low.

The pillars supporting the main stage is quite high (20 Inches) and the pillars are not secured (welded/screwed) to the base and main stage. This may cause the system to become unstable if excessive force is applied to it. Our solution is having the pillars secured to the main stage and the base by either screws or welds.

The duration of use and further modification of the system is under the discretion of Dr. Stephen Segall of the NSF Engineering Research Center. The risk assessment and designsafe report generated by the program can be found in Appendix G on page 77.

Other Considerations

As the primary components of our design are aluminum, the shear forces of the support tube are not significant. Our design is completely concentric and as such there are no relevant moments acting on the stages. Also, as the adjustments are hand actuated there are no dynamic effects on the structure as we would anticipate from a motor, thus simplifying our analysis. We can rectify user error by the final laser alignment in which the user sends the beam through the beam splitting prisms. The reflected beams are sent to mirrors set at both orthogonal (90 degrees) directions and at 45 degrees which will reflect directly back to the source if the beam is aligned correctly. This procedure is discussed in our Validation Test Results section on page 46 with a visual representation of the procedure, Figure 53 on the same page. Any misalignment can be corrected by the user as long as the errors are not beyond the range of the adjustments listed as design specifications in Table 1.

We used set screws between stages and support collars which applied pressure to the outside wall of the supports to suspend the components. There are three support collars in our design, each using set screws to suspend the structure below. To analytically determine the forces required to have screw slip, we made an assumption that the forces encountered in normal operation, equation 1 below, are less than the force of static friction due to the set screws. [7]

$$(1)\ F = n * \frac{T}{d} * \mu_f$$

Where F is the applied force to cause slip in Newtons, n is the number of set screws, T is the twist moment per turn in N-m, d is the inward travel per turn in m, and μ_f is the coefficient of static friction for the aluminum typically 1.05 to1.35. [7]

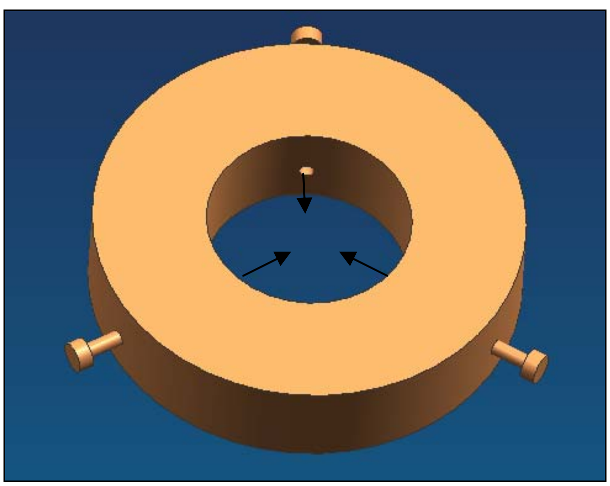


Figure 35: Force applied by set screws to resist slip

Not content with our assumption, we assured ourselves of the reliability of the set screws through trial and error. We tightened the set screws onto the cylinder that we will be using in our design and then attempted to pull the tube from the set screws. Even pulling at full force, we were unable to cause the tube to move relative to the set screws. As the force exerted in these trials was much greater than the force that will be exerted during operation, we are confident that the set screws will provide a robust connection in our design.

FINAL DESIGN

For our project, we did not produce a prototype as we intend for our design to be used in the lab immediately. Additionally, the majority of our costs are from the purchase of precision equipment and it would be wasteful to purchase these components for a prototype. Before developing our final design, we proposed an initial design to our sponsor. After showing him our CAD model, we received feedback and suggestions that led us to our final design.

Our Initial Design

Using the scoring system developed in our concept selection we combined the elements of the general concept, x-y concept, and z-stage concept into the first revision of our concept sketch. We developed a CAD model combining those concepts as illustrated in Figure 36 below. From our initial analysis, we sought out to determine the possible strengths and weaknesses of our design with respect to the previous design and the predetermined engineering specification.

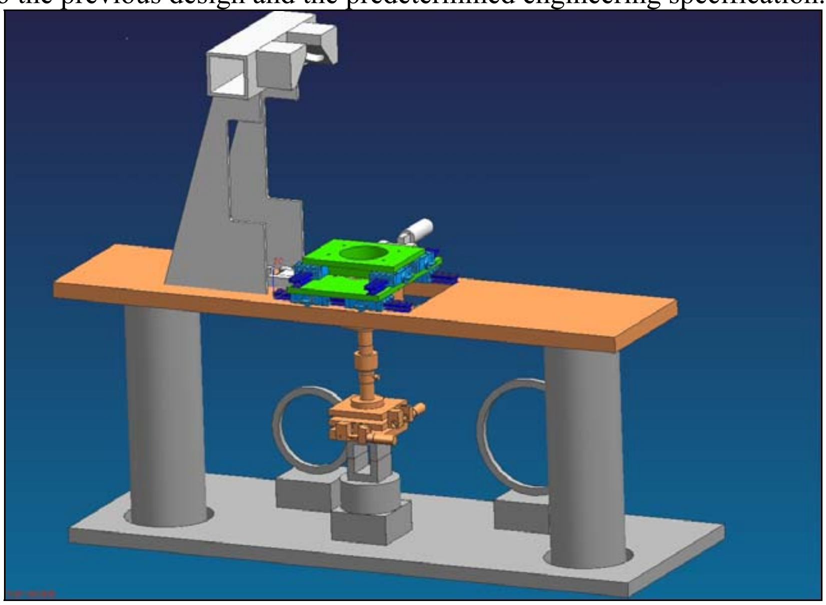


Figure 36: CAD model of the first prototype design, combining the design elements chosen by the concept selection process.

One of the major goals of our project is to have a z-axis manipulator stage that is stable and precise. The z-axis adjustor must provide axial motion without introducing unwanted, additional axial rotation or tilts; this design fulfills the requirement. As all of the manipulator stages must be obtained from commercial sources, this design would provide the required motion within the specification limits of precision and accuracy. Also, the tilt stages are situated close to the beam splitter; this minimizes possible adjustment errors from these stages.

However, we exposed several deficiencies in the design; errors that our sponsor suggested we rectify before the design met with his approval. The rotation stage was situated under the upper platform, above the tilt stages. Any adjustment errors in the rotation stage would cause residual errors to the motion stages beneath, thus the accuracy and precision of the tilt stages would be lost. The upside-down orientation and position of the rotation stage also requires that it support a significant amount of weight from the tilt stages. We felt that the ungainliness of the large platform would affect the durability and the robustness of the mechanisms contained in the rotation stage; something very delicate. Finally, the tilt stages would also be mounted upside down in this configuration, possibly affecting the precision and the component reliability.

Design Alterations and Final Design Advantages
The major differences between the initial design and final design are summarized in Table 2.

Revision	Benefit/Reason
Rails change from locking to non-locking	Manufacturer availability
Moved tilt and rotation stages above z adjustment	Increase reliability
Reduced size of stages to 60 mm by 60 mm base	Decrease weight
Increased support pillar height to 20"	Range of movement
Upper collar added for coarse z movement	Range of movement

Table 2: Summary of changes between initial and alpha prototypes

An advantage of our final design is that the z stage is the lowest mounted element and supports only the weight of the beam splitting prism and its holder. As no bending moments are produced by heavy stages below, we anticipate even movement. The arrival of the rails and z-stage led us to change some of the engineering specifications between the initial and final design as was previously discussed in Table 1 on page 5 in our Engineering Specifications section.

One potential oversight in our design was the effect of manipulating the z stage on the sway of the tube. With the tilt stages mounted above the microscope adjustment, a small deviation below will not be visible in the manipulator stage above. More of the engineering issues and the means by which our final design accomplishes or fails to resolve these issues are detailed our Validation Test Results section on page 46 as well as the previously discussed Problem Analysis and Engineering Fundamentals section on page 26.

Final Design
Our concept generation process culminated with our final design. This design represents the combined features of the design sketches, feedback and sizing from manufacturers and suggestions made by our sponsor to improve our initial design. In this section we will present the inner workings of our final design and how the different elements in our design attach to each other. Figure 37 below shows two views of our final design, with all the fasteners included. The following sections will provide a components list detailing material selection and the means by which we will obtain these components. Detailed engineering drawings of each part are illustrated in Appendix D.

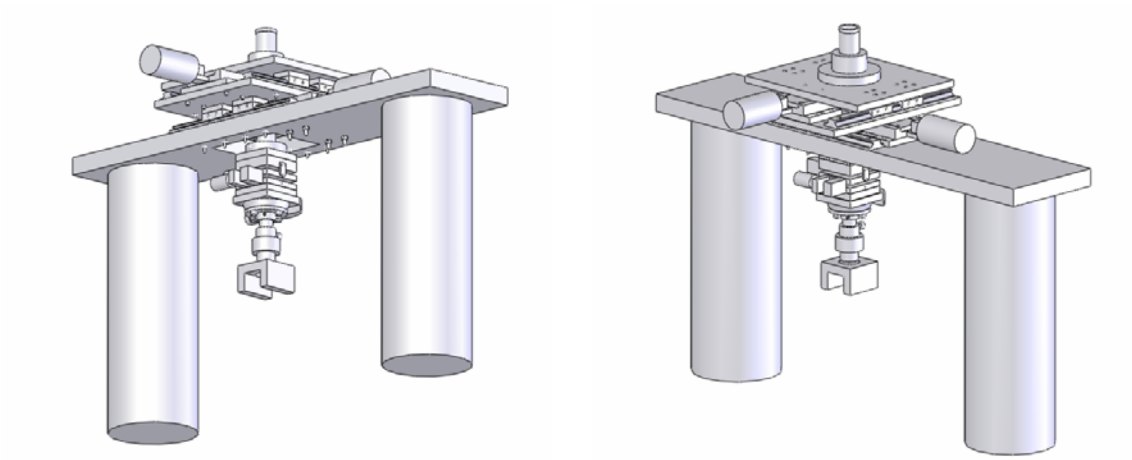


Figure 37: The Final Design including fasteners

X and Y Movement

The movement for the X and Y axes are controlled by linear micrometers. As illustrated in Figure 38, each plate is placed on a pair of rails. A micrometer is attached to each plate and it pushes the plates to create precise linear movement. As the tube is attached to the top plate, it will follow the movement of each plate, allowing the user to control the x and y position of the beam splitter attached at the base of the apparatus. The tube is allowed free range of movement with in the x and y travel as the plates and main stage are hollowed out in the middle as seen in Figures 39 and 40. The tube is held at the top plate by a collar which serves as a 90mm coarse adjustment for the z stage.

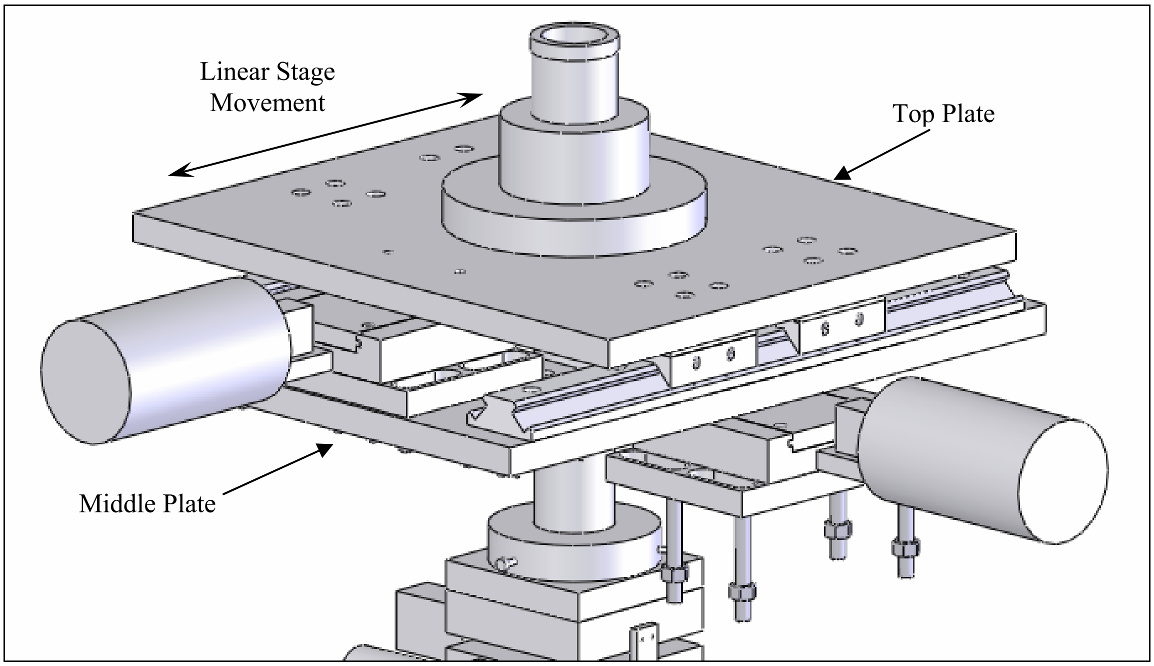


Figure 38: The stages moves on rails and controlled by micrometers

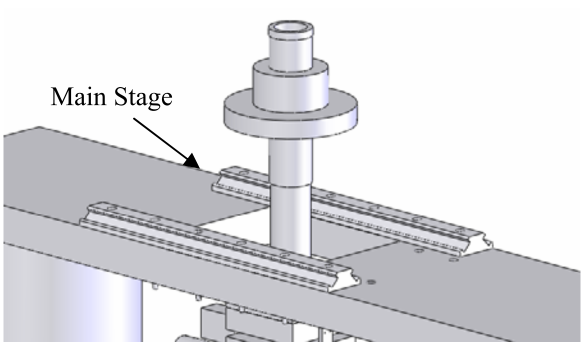


Figure 39: The main stage is hollowed out to allow for the tube movement

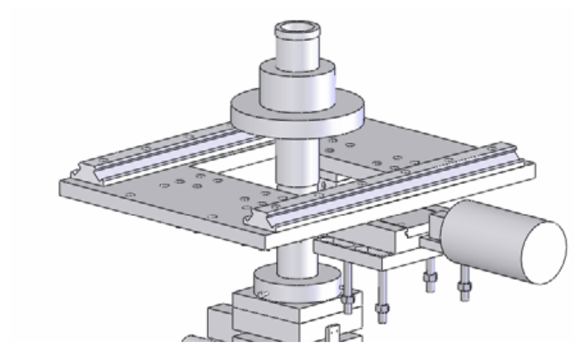


Figure 40: The middle stage is also hollowed out to allow for the tube movement

Tilt and Rotation Stages

The tilt and rotation stages are placed at the base of the support tube before the Z axis adjuster as illustrated in Figure 41. The support tube is affixed by a collar and 3 set screws which are also affixed to the topmost of the tilt stages. The tilt and rotation stages are controlled with precision by micrometers. The tilt stages create an angular movement that will propagate at the tube end where the beam splitter is placed. Figure 42 shows one of the tilt stages with an angular adjustment. The Z adjustment platform is attached to the rotation stage which controls the θ_z angular adjustment of the beam splitter.

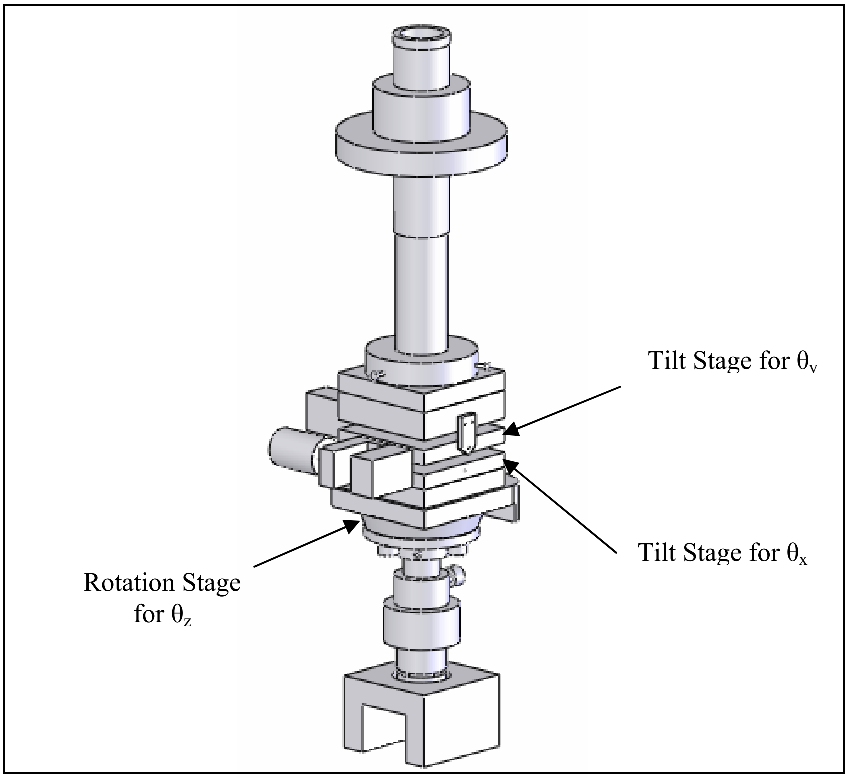


Figure 41: The position of each rotation and tilt stages at the tube.

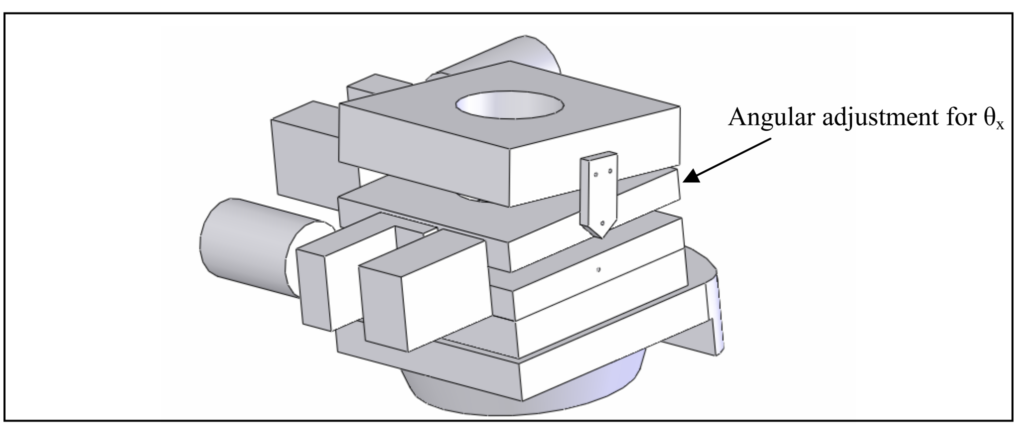


Figure 42: The tilt stage with an angular adjustment at the first stage.

Z axis movement
The Z axis position is controlled by the Standa model 5HP18, Adjustable Height Post as illustrated in Figure 43. The z adjuster consists of a system of threads, one internal, which moves the center tube up or down when the adjustment ring is turned and a small peg on the inside pushes on the channel affixed to the outside casing.

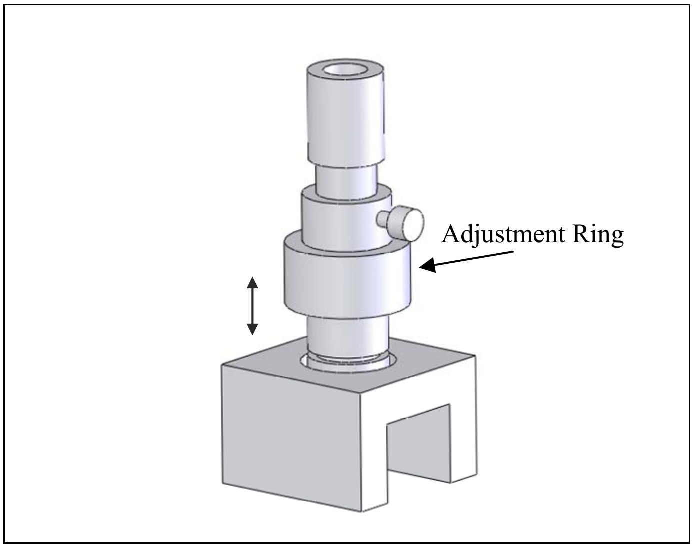
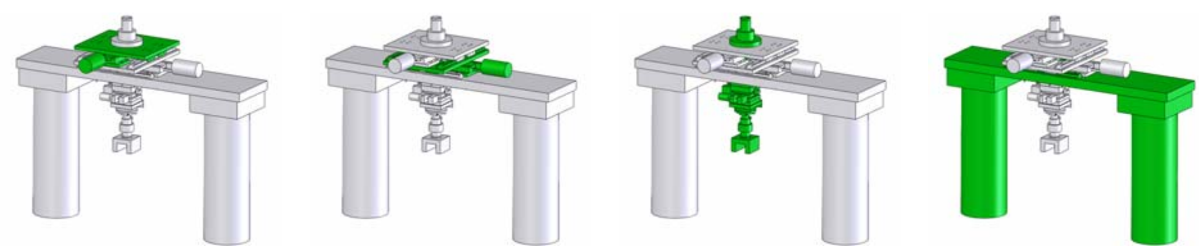


Figure 43: The Standa height adjuster moves the component in the direction of the Z axis

Component Assembly
The system is divided into 4 subassemblies to simplify the description of how each of the parts is attached. The system uses screws, bolts and a pressure fit to fasten the parts together. Figure 44 shows how the subassemblies are divided.



Subassembly 1	Subassembly 2	Subassembly 3	Subassembly 4
Top Plate	**Middle Plate**	**Tilt and Rotation**	**Main Stage**

Figure 44: Summary view of the 4 subassemblies

Subassembly 1 – Top plate
As illustrated in Figure 45, the micrometer is attached to the upper plate with two screws and also attached to the middle plate with four bolts. The plate is attached to the four rail shuttles with socket cap screws and a spacer is placed between to compensate for the height of the micrometer. The plate was designed with a hole in the middle to maintain line of sight for the structure and to allow the tube freedom of movement.

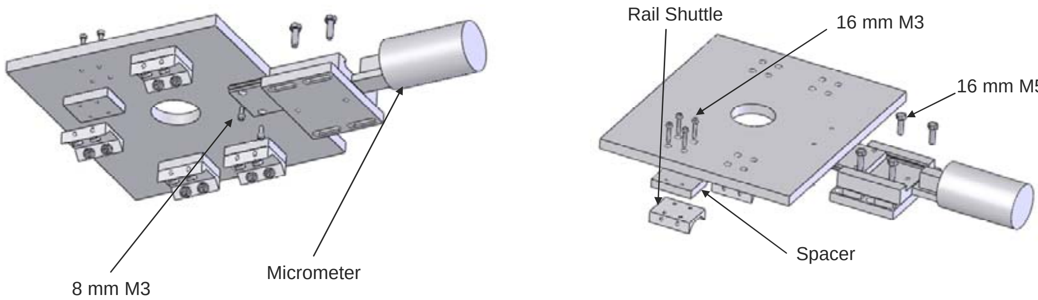


Figure 45: Components in the top plate and how they attach together

Subassembly 2 – Middle Plate
The second micrometer is also attached to the middle plate with two screws through the bottom. The micrometer is affixed to the main stage with four bolts. Four screws attach the rail shuttles to the middle stage with a spacer mounted between. The rail for the top plate is fastened to the top of the middle stage with six bolts. A square cavity is milled out to allow freedom of movement for the tube.

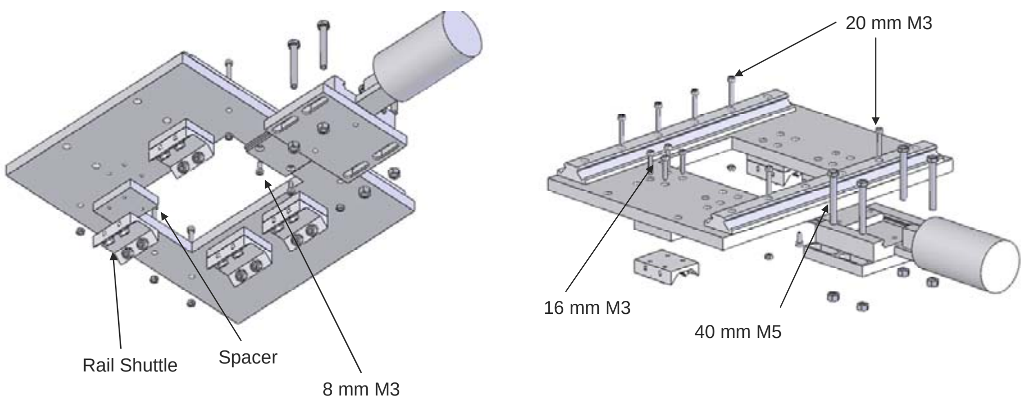


Figure 46: Components in the middle plate and how they attach together

Subassembly 3 – Tilt and Rotation Platforms
As illustrated in Figure 47, the support tube is attached to the tilt stages via a support collar. The support collar uses a set screw attached to the tube and screws that directly mount the collar to the tilt and rotation stages. The tilt and rotation stages are attached to another collar with socket cap screws and the Standa height adjuster is then mounted to the collar with set screws.

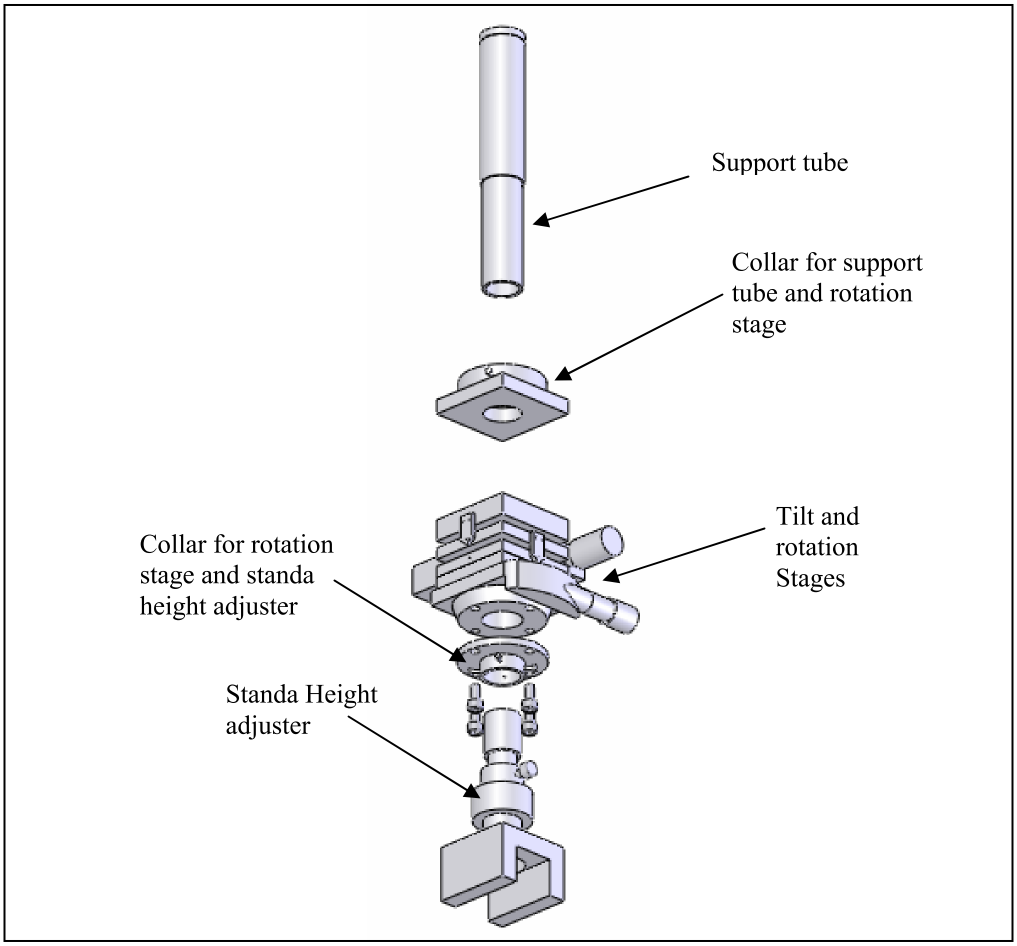


Figure 47: Components in the Tilt and Rotation assembly and how they attach together

Subassembly 4 – Main Stage

Two rails for the middle stage movement are attached to the main stage using 8 bolts. Two spacers are placed between the stage and the two pillars to increase the stage height to accommodate the length of the new stages, illustrated in Figure 48 below.

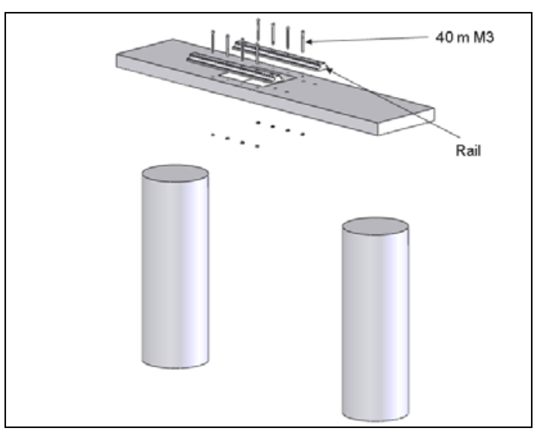


Figure 48: The Main stage assembly

Components List

Provided in this section is a list of all components used in the Final Design. Detailed engineering drawings for the parts are provided in Appendix D.

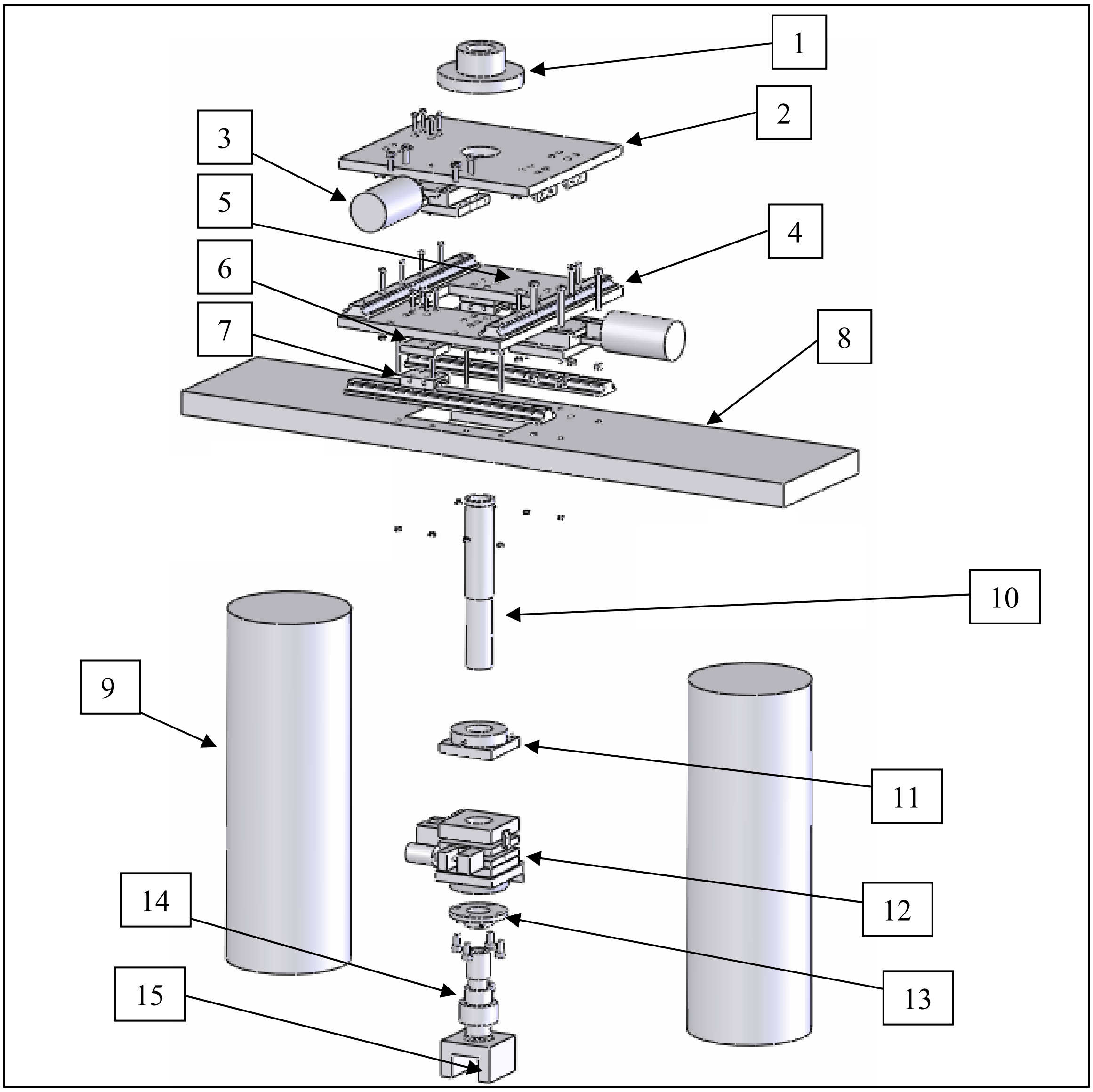
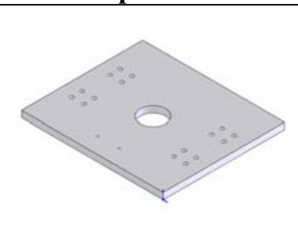
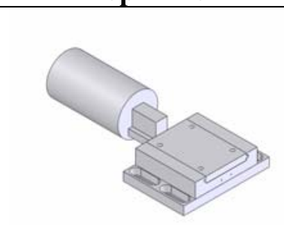
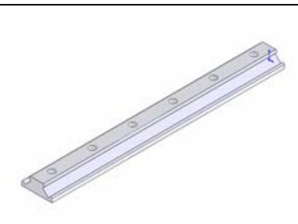
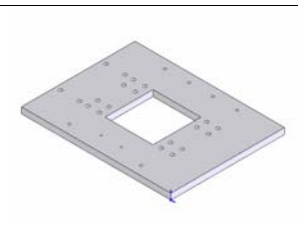
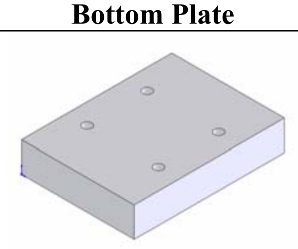
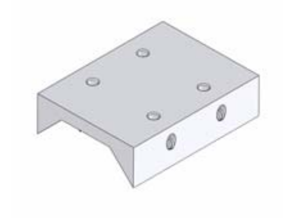
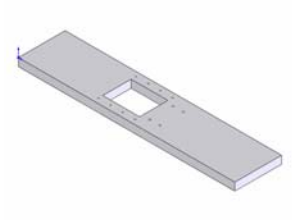
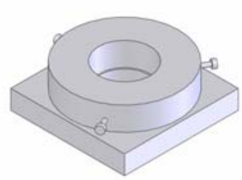
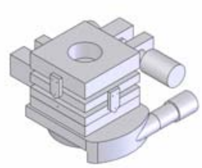


Figure 49: Expanded view of our final design to highlight separate components

No	Component	Comments	Material	Quantity
1	 **Top Collar**	Already available from the previous project	Aluminum 6061 T6	1
2	 **Top Plate**	Manufactured from aluminum stock	Aluminum 6061 T6	1
3	 **Micrometer**	Already available	N/A	2
4	 **Misumi Rails JKSGR-16230**	Purchased from Misumi Inc.	Aluminum 7075	4
5	 **Bottom Plate**	Manufactured from aluminum stock	Aluminum 6061 T6	1
6	 **Spacers for shuttles**	Manufactured from aluminum stock	Aluminum 6061 T6	8

7	 **Rail Shuttles**	Purchased from Misumi Inc.	Aluminum 7075	8
8	 **Main Stage**	Already available from previous project. Holes and pocket cut	Aluminum 6061 T6	1
9	 **Pillar**	Already available from previous project	Aluminum 6061 T6	2
10	 **Support Tube**	Already available from previous project with minor modifications	Aluminum 6061 T6	1
11	 **Collar for Tilt stages and support tube**	Already available for previous project	Aluminum 6061 T6	1
12	 **Tilt and Rotation stages**	Already available from previous project	N/A	1

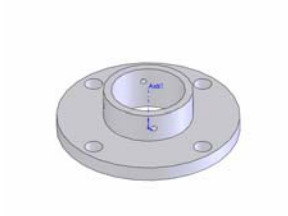
13	 **Collar for Rotation Stage and height Adjuster**	Manufactured form aluminum stock	Aluminum 6061 T6	1

Table 3: List of components and availability

MANUFACTURING

One of the customer requirements for this project is to construct a working model of our design that represents a one-time final product. Considering our time constraints, our initial manufacturing plan bypassed the prototype fabrication and prototype testing aspect of the design process; all of the product testing will be done to the actual model. Also, as the end-product of our project will not be put into mass-production, a plan that allows for such will not be considered.

The focus of our project is component assembly rather than the design of an entirely new concept. The subtleties between the two are reflected in our manufacturing plan, which ensured a seamless integration of various mechanisms to produce the requested outcome. Our two main tasks were:
1) To modify the manipulator stages to fit the design specification
2) To fabricate the connectors and fasteners that would join the components together.

The manufacturing process

Table 4 shows a summary of the machining tasks to complete this project. The specification of the components listed is as shown on Table 3 in the Prototype Description section of this report.

Task No	Components Involved	Machining Task
1	Support Tube	Trim from aluminum stock
		Drill side holes for set screws
		Affix with Top Collar
2	Top Collar	Manufacture from aluminum stock
		Drill side holes for set screws
		Fasten to Support Tube
		Attach to Top Plate
3	Top Plate	Manufacture from aluminum stock
		Attach with Top Collar
		Affix to Micrometer
		Mount on Shuttles
4	Rails And Shuttles	Fit to Top Plate and Bottom Plate
5	Micrometer	Fit to Top Plate and Bottom Plate
6	Bottom Plate	Manufacture from aluminum stock
		Affix to micrometer
		Mount on shuttles
7	Tilt and Rotation Stages	Affix with collars

8	Collar between Rotation Stage and Height Adjuster	Manufacture from aluminum stock
		Fasten to Rotation Stage
		Fasten to Adjustable Height Post
9	Adjustable Height Post	Widen the center clearing
		Thread the connectors
		Affix with collars
10	Main Stage	Widen the center gap
11	Collar between Height Adjuster an Beam Splitter Holder	Manufacture from aluminum stock
		Fasten to Adjustable Height Post
		Thread the connectors
		Fasten to Beam Splitter Holder
12	Beam Splitter Holder	Manufacture from aluminum stock
		Thread the connector
		Affix with collar

Table 4: Summary of Machining Tasks for Components the product components

List of materials
Each of components in our assembly were machined from 6061 T6 stock aluminum. To lower the production cost, we salvaged aluminum blocks from various machine shops. Some of the raw materials needed to be substantially larger than the final product to fixture the stock properly on the machines, and we accounted for this in our stock material list. Table 5 lists the aluminum stock needed for manufacturing and the location.

Type	Dimension (mm)	Location
Block	70 × 70 × 25	Bottom Collar
	306 × 306 × 15	Top Plate, Spacers
	306 × 306 × 15	Bottom Plate, Spacers
Cylinder	29.5 outer D, 28 inner D × 180 long	Support Tube
Cylinder	127 outer D, 114.3 inner D × 508 long	Support Pillars
Screws	¼ - 20 various lengths	Plate Joints
	¼ - 28 × 9.5 long	Set Screws

Table 5: Summary of Raw Material Needed for Machining

Machine tools and machine operation
Most of the machining was done using lathing and milling machines available in the ERC lab at the Wu Manufacturing Center and in the student Auto Lab at G.G. Brown. Firstly, the aluminum stock was trimmed to size using a band saw or a lathe. For some of our components, the subsequent machining operations were programmed into the Gibbs CAM software. This program generated the G-code needed to interface with the CNC milling machines. Next, the aluminum stock was milled and the surfaces cut to specification with an end mill. Finally, the holes for screws and bolts on the components were drilled by a mill or drill press and threaded by hand where necessary. Table 6 lists the machining operations and the associated machining tools used in product manufacturing.

Machined Components	Machining Operation	Tool Bit
Support Tube	Screw hole drilling	0.236 in. Spot Drill
Top Collar	Course milling	0.25 in. Rough End Mill
	Fine milling	0.25 in. Fine End Mill
	Screw hole drilling	0.236 in. Spot Drill
Top Plate	Course milling	0.25 in. Rough End Mill
	Screw hole drilling	0.236 in. Spot Drill
Bottom Plate	Course milling	0.25 in. Rough End Mill
	Screw hole drilling	0.236 in. Spot Drill
Collar between Rotation Stage and Height Adjuster	Modifications to stock	Lathe Machine
	Course milling	0.25 in. Rough End Mill
	Fine milling	0.25 in. Fine End Mill
	Screw hole drilling	0.236 in. Spot Drill
Collar between Height Adjuster an Beam Splitter Holder (3 interchangeable units with different lengths)	Modifications to stock	Lathe Machine
	Course milling	0.25 in. Rough End Mill
	Fine milling	0.25 in. Fine End Mill
	Screw hole drilling	0.236 in. Spot Drill
Beam Splitter Holder	Course milling	0.25 in. Rough End Mill
	Fine milling	0.25 in. Fine End Mill
	Screw hole drilling	0.236 in. Spot Drill

Table 6: Summary of Machining Operation and Machining Tools for Component Manufacturing

As illustrated in Table 6, nearly all of our machining was done by CNC milling machines, including the drilling of holes for screws to ensure precision and the ease of integration between the components. We also utilized CAM software instead of typing in G-code manually at the CNC machines for some of our components, making machining procedure shorter and simpler, especially for some of the small modifications.

Critical component and surface tolerances

The datum point on our product was the center of the support tube along top face of the main stage. This point was used to calibrate the positioning of all components in the system.

The most critical surface tolerance was the line of sight of the system, a requires 14 mm in diameter. Therefore, each component associated with maintaining this attribute met the tightest tolerance possible. The tilt stages and rotation stages were hollowed to accommodate this tolerance. The x and y platforms, along with the support tube suspended from those plates each maintained this tolerance as they are hollow. As the adjustable height post from Standa was not hollow, we asked the manufacturer for prescribed methods to alter the piece. The modifications made to the part are discussed in the following section.

Modifications to the Standa z adjustment

To accomplish movement in the vertical z-direction, we chose the Standa model 5HP18 Adjustable Height Post. An engineering drawing, including dimensions is presented in Appendix D.15 on page 71. The following sections detail the individual parts of the Standa piece, illustrate how the post functions, and explain the modifications we made to the part to meet our design requirements.

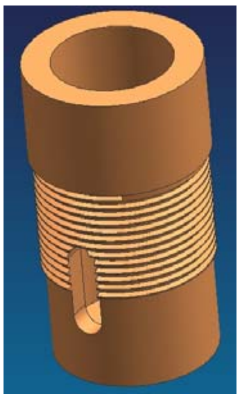
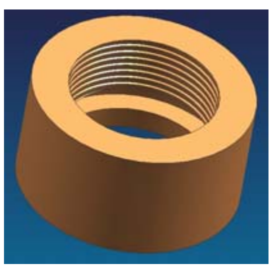
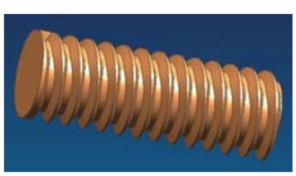
Component	Comments	Material
 **Mounting Post**	**Had set screw to hold optical components**	Coated Steel
 **Chuck**	**Has set screw to hold mounting post, threaded**	Coated Steel
 **Collar**	**Threaded internally along with channel**	Coated Steel
 **Pin**	**Mounted inside of chuck, runs along channel**	Coated Steel
 **Set Screw**	**Set into top of chuck, holds pin in place**	Coated Steel

Table 7: Parts List for Standa Model 5HP18 Adjustable Height Post

Operation
The Standa piece uses a concentrically spinning collar to move the mounting post vertically. Figure 50 illustrates the threading on the chuck the collar spins about. With the pin sliding inside the channel, the collar moves the adjustable height post 9.5 mm with a fine adjustment. The pin rests inside the chuck to allow for the collar removal and is pushed into the channel via an access hole from the opposite side along the outside ring of the collar.

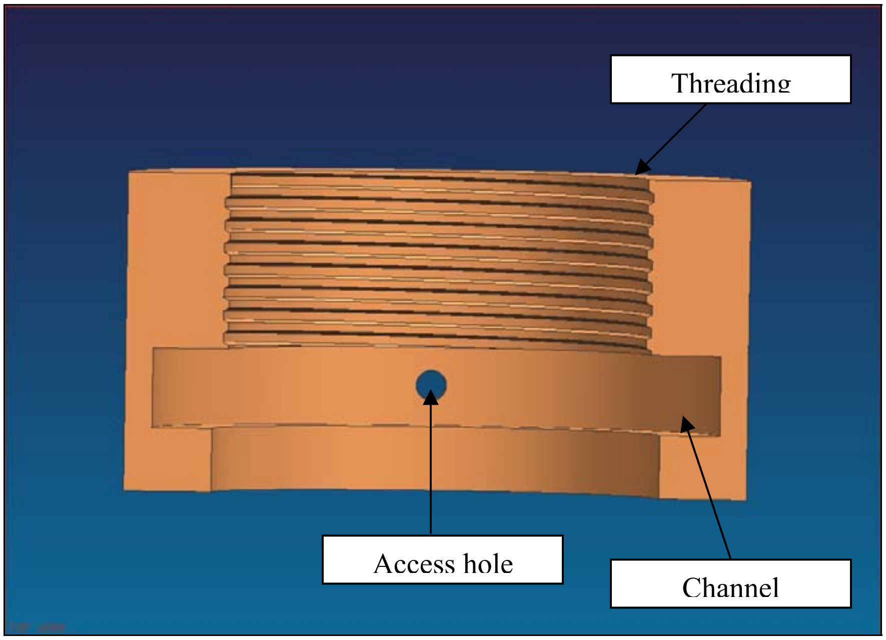


Figure 50: Standa collar showing threading and channel

As shown in cutaway view in Figure 51 below, the collar is threaded along the inside to pair with the threading on the outside of the chuck. The pin runs through the channel along the inside of the collar and holds the piece from falling out during operation.

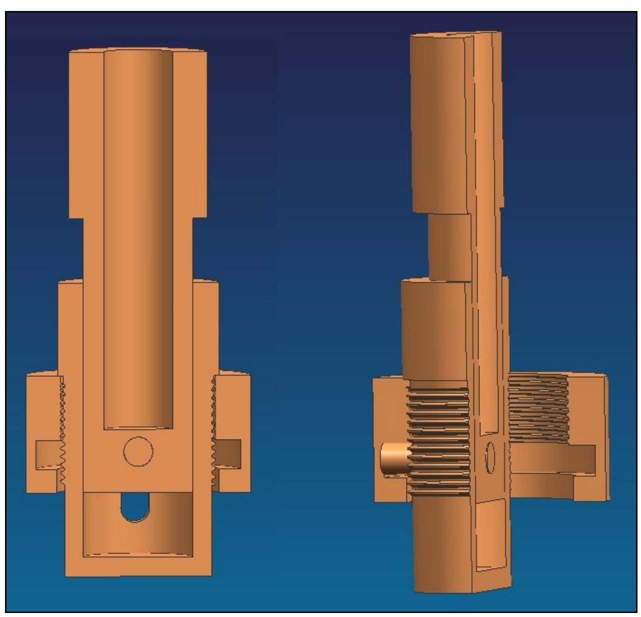


Figure 51: Cutaway view showing the thread and channel that allows the piece to move

Modifications
To integrate the Standa post into our design we hollowed it to achieve the required line of sight, 14 mm. For our first step, we bored a 9/16 inch hole through the center of the Standa piece, opening it from 12mm, to achieve the necessary line of sight. We then proceeded to bore a hole thorough the existing support strut hole, which had a diameter of 0.197”, with a 7/32 inch drill bit. This hole was threaded with a ¼-28 threading through all but the last 1mm of the hole. We then took a 3/8 inch long ¼-28 set screw and, using a metal file, we filed down all but the last 2 threads of the screw to a diameter of 0.197”. We then assembled the piece and secured the set screw in the sidewall of the mounting post. Our modifications to the screw and to the Standa chuck and mounting post are illustrated in Figure 52.

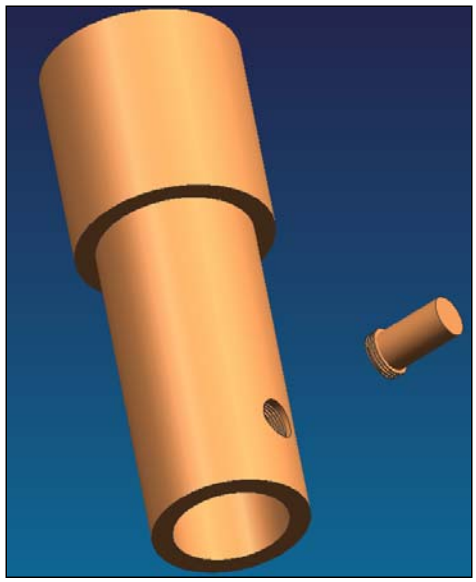


Figure 52: Modifications to the Standa screw and cylinder

VALIDATION TEST RESULTS

With our design finalized, we have developed experiments to verify that the design specifications have been met. What follows is a summary of those experiments along with a description of how our design fared.

Measurement of System Performance
As shown in Table 1 on page 5, the majority of our engineering specifications rely on range of movement and precision. The weight capacity for the rotation stage is also provided by the manufacturer.

The range of movement for the x and y stages are measured by ruler from the two extreme positions with a total travel of 24 mm. The z-movement is divided into coarse and fine ranges, the former being measured 90 mm from the support tube and the latter defined as 9.5 mm from the manufacturer. The range of movement for the tilt stages were measured from the two extreme positions with a protractor centered at the pivot giving 30 degrees travel from one position to the other. The rotation stage rotates the component 360 degrees which is readily verified on the dial.

We evaluated the precision for a micrometer adjustment as one half multiplied by the smallest incremental adjustment printed on the micrometer. We justify this precision as we are able to visualize half of an increment between to lines, but are not confident in any further refinements. The resulting micrometer precisions are: x and y stages ±0.002 mm, tilt stages ±3.6 arc seconds, and rotation stage ±1.2 arc seconds. As the z-adjustment turns about a threaded center we estimate the precision as ±0.02 mm as the finest adjustment that can be made by hand. Although we can only estimate the precision of the z-component, our estimated value is two orders of magnitude below our engineering specification from Table 1 on page 5, 0.02 mm as compared to 1 mm.

Laser Based Precision Tests
Although we have design specifications for each stage separately, the precision of entire structure is subject to combination of the stages produce precision errors. Figure 53 illustrates the precision test by laser. The laser beam is sent through a suspended beam splitting prism and reflected at a 90 degree angle. The platform is then manipulated so that the prism turns 45 degrees and the system is adjusted to realign the beam to a second mirror. A CCD is used to photograph the laser and verify that there is no incidence angle, meaning that the prism is correctly aligned to the surface. Until the lower stage is completed, we will not have the mirrors and laser setup to test the accuracy of our components.

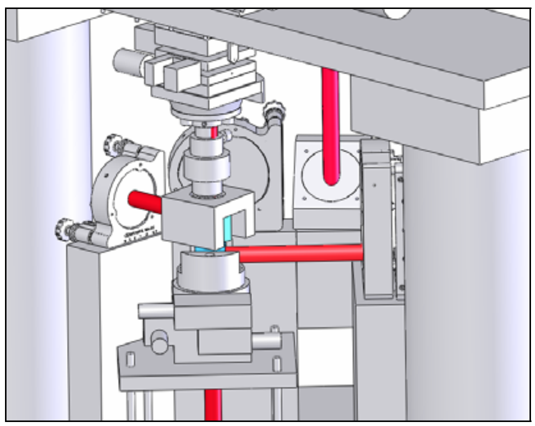


Figure 53: A laser is sent through a beam splitting prism and reflected off two mirrors to measure the combined precision of our components

Sway Test
As noted in our engineering specifications, our desired sway in the support tube due to operation was less than .1 degree. To determine the sway of our final design, we intend to measure the movement of the optical component holder during regular operation. By taking the arc tangent of the side movement divided by the shaft length as shown in equation 3, we determined the angle of shaft sway and found negligible results during normal operation. Figure 54 illustrates an exaggerated view of the shaft sway caused by normal operation.

$$(3)\ \text{Shaft Sway (deg)} = \tan^{-1}\left(\frac{side\ \ movement}{shaft\ \ length}\right)$$

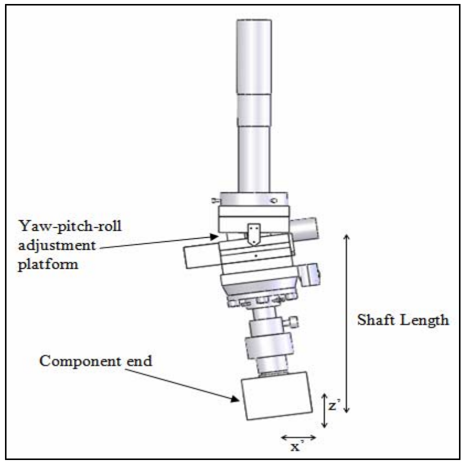


Figure 54: Shaft sway due to operation

Disturbance due to rotation
During adjustment, the z-adjustment stage undergoes side forces from the user. Figure 55 below illustrates how the forces are implemented on the device and are broken into components. The separate components, when combined, produce a moment that acts against the springs of the tilt stages. The restoring force of each spring is 15 N-mm at the pivot. For combined forces from the operator less than 0.30 N in the pitch plane and 0.35 N in the roll plane, the springs will counteract the moment and the piece will remain stationary. During testing, the user applied no considerable side forces to the z-adjustment.

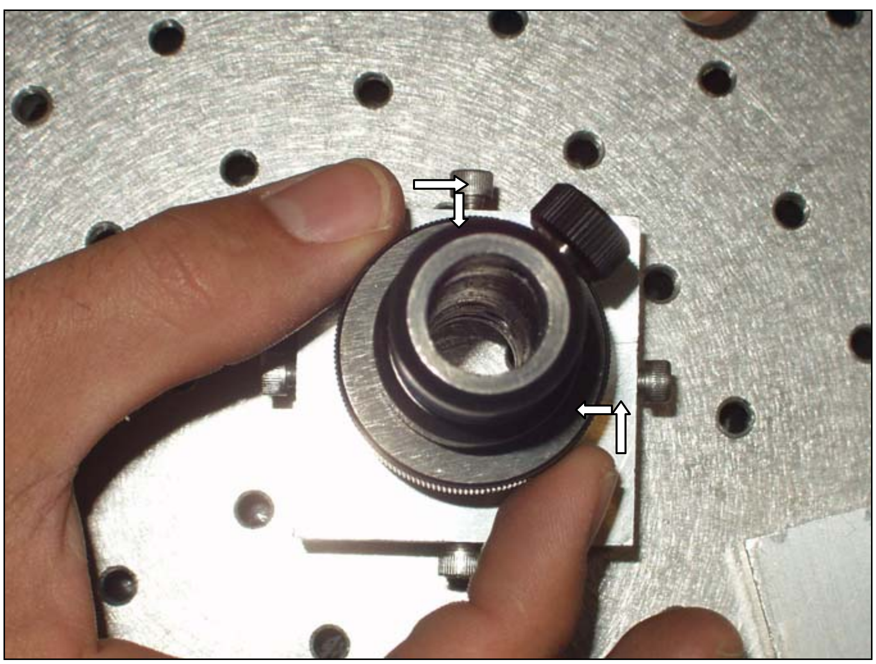


Figure 55: Forces applied during operation for z adjustment

INFORMATION SOURCES

Our benchmarking and market research is included in Appendix C on pages 55-56.

Additional Information Provided by Manufacturers

To determine the feasibility of our design, we contacted numerous companies regarding the acquisition of the necessary components to construct our prototype. For the x-stage and y-stage, we looked into purchasing a single component to accomplish this task. After looking at a variety of products from Standa [1], we realized that this would be cost prohibitive. We decided to purchase rails for the x-stage and the y-stage. The stages we initially selected were locking rails from Igus [2]. We were later informed that these rails would be backordered until late March and we opted for our second choice, Misumi [3]. To control the z-stage of our design, we selected a post height adjustment made by Standa [4]. As we needed to alter the device to make it compatible with our design, we contacted Standa to see if our proposed designs would be feasible, and we were informed such modifications were feasible.

For our proposed design to function, we needed to hollow, invert, and suspend the tilt stages. As we were unsure if the stages would perform under these conditions, we contacted Physik Instrumente, the manufacturer of the tilt stages to verify that these procedures would not be detrimental. From our correspondence with them, we learned that the tilt stages would work as intended in our design [5]. We also learned from these correspondences that the tilt stages provide a restoring moment of 15 N-mm and will hold the unit in position until that threshold is reached. We also learned that the rotation stage can support 3 kg suspended from it in an inverted position.

DISCUSSION

With the design process and the validation tests, with the exception of the laser based alignment, completed, we assert that our system meets all of the engineering requirements it was designed to achieve. Therefore, we find that it is unnecessary to perform a complete re-design to any of the fundamental aspects of our system. However, we have identified some issues in our project that can be rectified given adequate time and resources; we feel that our suggestions below would help improve upon our current design while maintaining the functionality that the system has already attained.

Obtain a different component for the vertical-stage adjuster

We believe there is a better component to provide vertical movement for the system that could be purchased or constructed. In the current design, the z-axis adjuster component was modified from an adjustable height post acquired from Standa. The minimum inner diameter for this component was initially 12 mm; we were barely able to increase this diameter to 14 mm to accommodate the engineering requirement of maintaining the line of sight. Ideally, we would prefer to have a minimum inner diameter of up to 20 mm for the entire part to get a larger tolerance window. Also, due to the inherent design constraints in the component, we produced only 9.5 mm of vertical travel through fine adjustment from the part. An improved design for the z-stage adjustment would manipulate the device in both the course and fine vertical positioning adjustments with a larger range of travel.

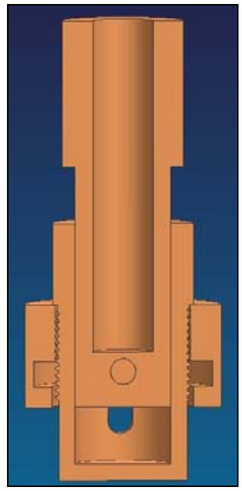


Figure 56: The z-axis adjuster has a minimum inner diameter of 14 mm

Press fit designs should be avoided
We needed to install a collar to the bottom of the of the vertical stage adjuster to combine with the existing beam-splitter holder. Due to spacing constraints regarding vertical travel of the moving parts in the component, we had no excess room to affix it with set screws or threads to the collar. This left us with no other option but to press fit the two pieces together. The press fit worked to some extent, but we found it very difficult to mount the collar exactly parallel to the z-axis adjuster. Also, the press fit was not sufficiently tight, as the connection between the two pieces could be loosened by exerting a significant disturbance at the point of contact. Based on our experience, we recommend that press fitting components in any of the mechanisms be avoided to ensure structural rigidity and positioning precision during the use of the system.

Springs on tilt stages should be stiffer
If the sides of the suspended components are subjected to a significant disturbance, the positioning of the beam splitter will change in compliance with the applied force. As the external forces are removed, the system will return to the original state with restoring force from pre-loaded springs in the tilt and the planar adjustment stages. However, we found that the stiffness in these springs was inadequate; the system should be resistive to greater external forces. Therefore, we recommend that the springs in the stage manipulators be replaced with those that have a higher spring constant so that unwanted travel in the system can be eliminated.

Design can be improved given better understanding of the bigger picture
In this project, we were required to build around a previous design, and the revised design would have to be compatible with the other parts in the system. However, we had limited information regarding the specifications of the system components that are not within the scope of our project. We assume that having a better understanding of the larger concept would have helped us develop a better solution to our portion of the assembly. This is evident in the uncertainties concerning the height constraint of both our part of the design and the other parts in the entire system. Our estimation of this attribute frequently changed when new information on system components was produced. The situation was unavoidable given the differences in our project schedule, but we would have liked to have better communication with the people working on the lower stage so that the basic concepts of the system was clear from early on.

RECOMMENDATIONS

We recommend that the sponsor consider replacing the Standa z-adjustment with a piece that functions similarly, but has greater z-travel distance. In particular, it should have in inner diameter line of sight of 20 mm. Also, instead of only having one support post, it should have three support posts to improve its structural stability while in operation. Also, the base of the apparatus should be one piece instead of three separate pieces to provide a more secure fixture. Furthermore, the longer support pillars produce some instability as they are not fixed to the base; these pillars should be attached to both the top and bottom supports with brackets, eliminating the possibility of shifting during operation. The springs in the tilt stages should be replaced with stronger springs to provide a higher threshold against a disruptive force manipulating the device. Also, the press fit should be replaced with set screws similar to those used throughout our design, as the press fit was implemented due to space limitations imposed upon us by the Standa piece.

CONCLUSION

We conclude our project with a summary of the entire process. The goal of our project was to design a six-degree-of-freedom manipulator stage for accurately positioning and aligning two beam splitters to be joined together with high precision. We have accomplished this goal and have returned our system to the Engineering Research Center. The system meets all engineering specifications and our sponsor promises to implement the system for use in the future. After developing the specifications we developed design sketches in three categories: x-y movement, z movement and main concepts. We evaluated each sketch based on our engineering specifications and produced a concept description. With our concept fully described we produced a detailed problem analysis including movement, precision, stresses, as well as safety and failure considerations. In our final design description, we detailed our apparatus to the fastener level and detailed our manufacturing process. We modified the Standa z-adjustment stage by hollowing the piece to maintain line of sight, but we recommend replacing the piece with a vertical microscope adjustment. We described validation plan test results for movement, precision, sway, and rotation disturbances due to operation. We have left the laser based validation as a recommended process for individuals such as En Hong, Max Byers and Dr. Segall to pursue for their use in future semesters. We discussed our final design including a design critique where we noted that the press fit between the z stage and component holder is insufficient. Some recommendations for this project include replacing the press fit at the base of the structure and bracketing the support pillars of the system. On April 13, 2006 we presented our system at The University of Michigan College of Engineering Design Expo. We anticipate completion of the lower manipulator stage by another student group and are confident that the integration of the two will produce a fully functional device for adhering beam splitters.

ACKNOWLEDGEMENTS

Dr. Muammer Koç, Assistant Research Scientist and Adjunct Lecturer in Mechanical Engineering, College of Engineering

Dr. Stephen Segall, Senior Research Associate Engineer, Mechanical Engineering

En Hong, Research Fellow, Mechanical Engineering, College of Engineering

Max Byers, Engineer in Research, Mechanical Engineering

Bob Coury, Marv Cressey, Steve Emanuel, & Steve Erskine, Shop Supervisors

REFERENCES

[1] **Standa** "7T167-25 - Aluminium Translation Stages Low Profile" http://www.standa.lt/products/catalog/translation_rotation?item=40&prod=aluminium_tr ansl ation_stages_low_profile

[2] **Igus** "Drylin® T Linear Guide Systems" http://www.igus.com/show_dt.asp

[3] **Misumi** "Simplified Linear Guides for Jigs" http://www.misumiusa.com/PDFViewer.aspx?Metric=true&Page=245

[4] **Standa** "5HP18 - Adjustable Height Post" http://www.standa.lt/products/catalog/optical_positioners?item=152&prod=adjustable_he ight _ post

[5] **PI** "Hexpods/Micropositioning" http://www.physikinstrumente.com/en/products/

[6] **Mcmaster-Carr** Aluminum Stock - Part Number: 8974K791 http://mcmaster-carr.com

[7] **Roymech** "Friction Factors" http://www.roymech.co.uk/Useful_Tables/Tribology/co_of_frict.htm

[8] **Matweb "**Alclad Aluminum 6061-T6, http://matweb.com/search/SpecificMaterial.asp?bassnum=MA6061AT6

GROUP BIOGRAPHIES

Brandon Schoonmaker – Born March 6, 1984 in Lansing, Michigan. Attended Grand Ledge Public Schools and graduated Valedictorian from Grand Ledge High School, class of 2002. My interest in Mechanical Engineering was seeded in my childhood as I was always taking things apart to see how they functioned. It has been my lifelong goal to design a product that would change the world. I accepted a job at Westinghouse Electric Company, nuclear power division, and will start in June 2006 as a field services engineer.

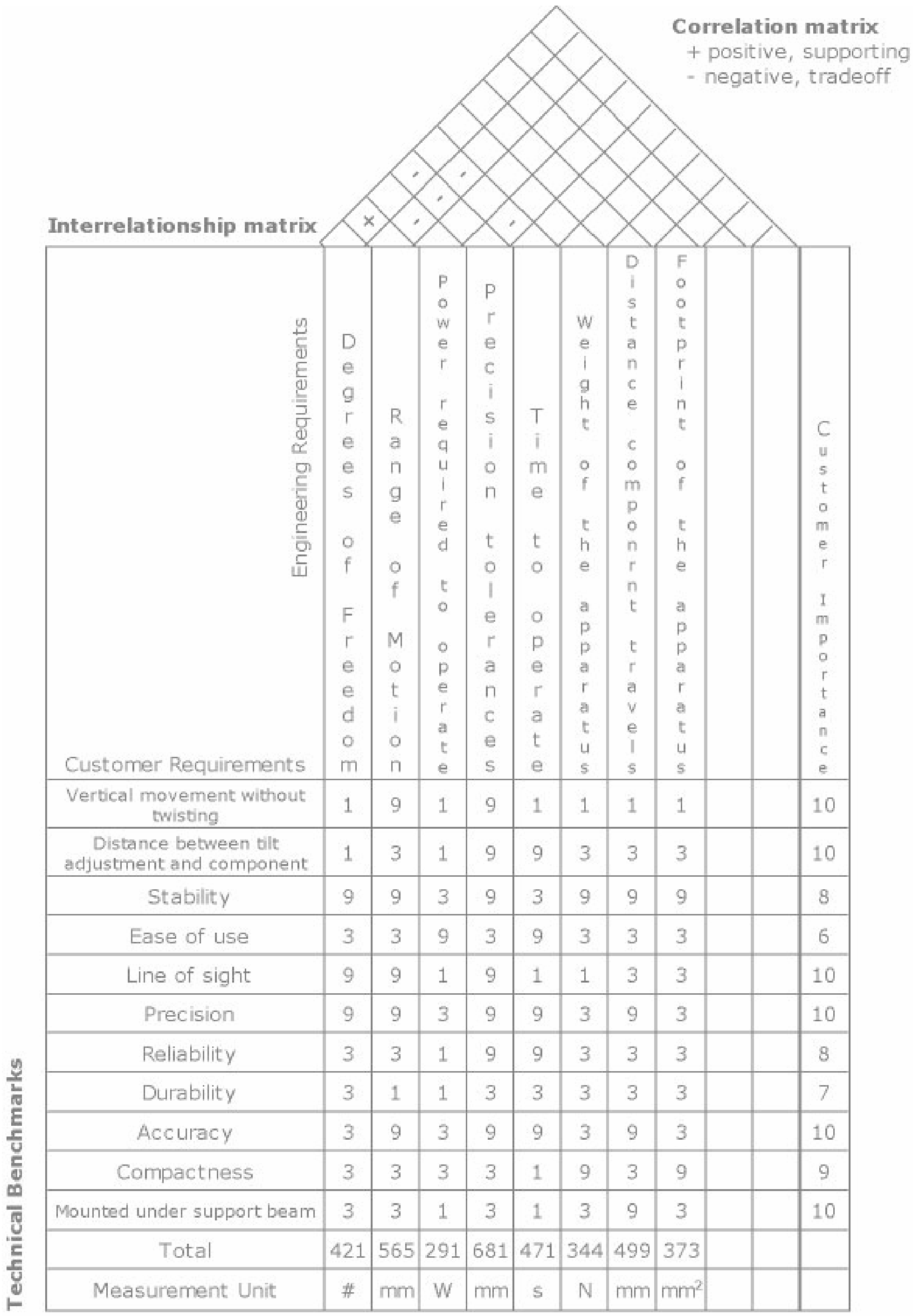
Douglas Anderson – Farmington Hills, Michigan. He is pursuing his degree in mechanical engineering because of his life long fascination with understanding how mechanical devices work and trying to create or improve upon designs. This fascination also stems from his deep interest in mathematics, which he has excelled at throughout his life, receiving numerous accolades for his work in high school. Despite this deep interest in academics, Douglas also excelled in numerous other activities in high school, including numerous awards in his years of participating in cross country, swimming, and track & field. Although a few years removed from his high school, Douglas continues to return to coach pole vault, an event in which he particularity excelled. Douglas now spends much of his free time listening to music, watching movies, and playing World of Warcraft on his computer. He plans to eventually find a job working in industry before returning to school to receive his masters in mechanical engineering. He is currently also pursuing a minor in economics during his time at the University of Michigan.

Akmal Mohammed - Senior in mechanical engineering at the University of Michigan. He is an international student from Malaysia under a government scholarship. His hometown is a city with a population of 1.5 million people called Johor Bahru, situated right across the causeway from Singapore. He came to Ann Arbor as a Literature, Science & Arts student in the winter of 2003, and was admitted into the engineering program in the fall of 2004. He had always intended to study mechanical engineering, and this strong desire is rooted in his inherent curiosity towards the how and the why in machines. His other passion is in understanding human culture; he's fascinated by the fact that something very strange in the eyes of one person can be very common in the mind of another. As a means of learning different cultures, he has already gotten down the basics of the Arabic language through his two years worth of classes, and he informally studies the Japanese language during his free time. Akmal is actually not very far off from the stereotypical college student, as he is an avid fan of music, computer games and various sports. He plans to return to Malaysia after graduation, hoping to bring back valuable knowledge an experience to his community from the time he spent leaning at one of the best universities in the world. In a few years, he will eventually return to learning, possibly getting a masters degree from another foreign school yet to be determined.

Irfan Zainal Abidin – He was born and reared in an island state of Penang in northern Malaysia. His passion for science and technology started since childhood when he first encountered a magnifying glass that ultimately led him to pursue an engineering degree. After graduating high school, he was awarded a scholarship to further his studies at the United States and is currently studying at the University of Michigan. His interest for mechanical engineering mostly started as a fascination for cars, which is still one of his passions today. Other than that, he absolutely loves electronic gadgets and occasionally plays basketball with his friends. He spends his free time mostly listening to music and developing websites. He currently manages the web portal for his high school alumni association and the University of Michigan Malaysian Student Association. In the future, he hopes to gain a few years of work experience in engineering and after that perhaps pursue a master's degree.

APPENDICES

Appendix A - QFD Chart

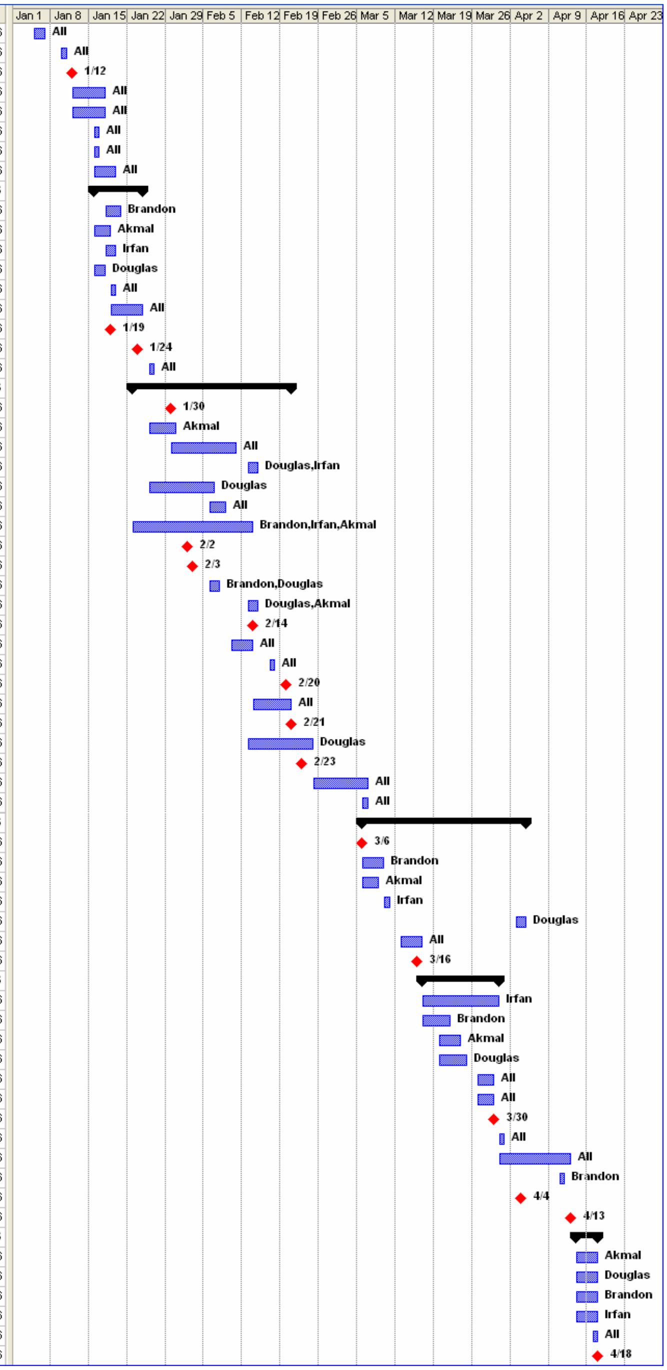


Customer Requirements	Degrees of Freedom	Range of Motion	Power required to operate	Precision tolerances	Time to operate	Weight of the apparatus	Distance componrnt travels	Footprint of the apparatus			Customer Importance
Vertical movement without twisting	1	9	1	9	1	1	1	1			10
Distance between tilt adjustment and component	1	3	1	9	9	3	3	3			10
Stability	9	9	3	9	3	9	9	9			8
Ease of use	3	3	9	3	9	3	3	3			6
Line of sight	9	9	1	9	1	1	3	3			10
Precision	9	9	3	9	9	3	9	3			10
Reliability	3	3	1	9	9	3	3	3			8
Durability	3	1	1	3	3	3	3	3			7
Accuracy	3	9	3	9	9	3	9	3			10
Compactness	3	3	3	3	1	9	3	9			9
Mounted under support beam	3	3	1	3	1	3	9	3			10
Total	421	565	291	681	471	344	499	373			
Measurement Unit	#	mm	W	mm	s	N	mm	mm^2			

Figure A.1: Quality Function Deployment Chart

Appendix B – Complete Gantt Chart

Task Name	Duration	Start	Finish
Project Description and Selection	2 days	Thu 1/5/06	Fri 1/6/06
Group Formation	1 day	Tue 1/10/06	Tue 1/10/06
Sponsor Meeting	0 days	Thu 1/12/06	Thu 1/12/06
Literature Review	4 days	Thu 1/12/06	Tue 1/17/06
Concept Generation	4 days	Thu 1/12/06	Tue 1/17/06
Gantt Chart - General	1 day	Mon 1/16/06	Mon 1/16/06
Engineering Spec & QFD	1 day	Mon 1/16/06	Mon 1/16/06
Concept Selection	4 days	Mon 1/16/06	Thu 1/19/06
Presentation & Report Prep	**7 days**	**Mon 1/16/06**	**Tue 1/24/06**
Gantt	3 days	Wed 1/18/06	Fri 1/20/06
Benchmarking and Market Research	3 days	Mon 1/16/06	Wed 1/18/06
Concept Sketches	2 days	Wed 1/18/06	Thu 1/19/06
QFD	2 days	Mon 1/16/06	Tue 1/17/06
Engineering Specifications	1 day	Thu 1/19/06	Thu 1/19/06
Collaboration and Design Review #1 Writing	4 days	Thu 1/19/06	Tue 1/24/06
Sponsor Meeting	0 days	Thu 1/19/06	Thu 1/19/06
Design Review #1	0 days	Tue 1/24/06	Tue 1/24/06
Post Feedback Meeting	1 day	Thu 1/26/06	Thu 1/26/06
Concept Generation	**21 days**	**Mon 1/23/06**	**Mon 2/20/06**
Sponsor Meeting	0 days	Mon 1/30/06	Mon 1/30/06
Measurements and Spacing	3 days	Thu 1/26/06	Mon 1/30/06
Final Sketches	10 days	Mon 1/30/06	Fri 2/10/06
QFD Review, Modifications	2 days	Mon 2/13/06	Tue 2/14/06
Part Search	8 days	Thu 1/26/06	Mon 2/6/06
Design Specifications	3 days	Mon 2/6/06	Wed 2/8/06
CAD Model	16 days	Mon 1/23/06	Mon 2/13/06
Meeting with En Hong	0 days	Thu 2/2/06	Thu 2/2/06
Meeting with Dr. Segall	0 days	Fri 2/3/06	Fri 2/3/06
Contacting Manufacturers	2 days	Mon 2/6/06	Tue 2/7/06
Presentation Slides	2 days	Mon 2/13/06	Tue 2/14/06
Meeting with Dr. Segall	0 days	Tue 2/14/06	Tue 2/14/06
Mini Presentation Prep	2 days	Fri 2/10/06	Mon 2/13/06
Gibbs CAM	1 day	Fri 2/17/06	Fri 2/17/06
Pre-Presentation to Dr. Segall	0 days	Mon 2/20/06	Mon 2/20/06
Design Review #2 Writing	5 days	Tue 2/14/06	Mon 2/20/06
Design Review #2	0 days	Tue 2/21/06	Tue 2/21/06
Part Ordering	10 days	Mon 2/13/06	Fri 2/24/06
Midterm Evaluation	0 days	Thu 2/23/06	Thu 2/23/06
Spring Break	7 days	Sat 2/25/06	Mon 3/6/06
State of the Project Meeting	1 day	Mon 3/6/06	Mon 3/6/06
Final Design Prep and Engineering Analysis	**22 days**	**Mon 3/6/06**	**Tue 4/4/06**
Sponsor Meeting	0 days	Mon 3/6/06	Mon 3/6/06
Final CAD Drawings	4 days	Mon 3/6/06	Thu 3/9/06
Engineering Analysis	3 days	Mon 3/6/06	Wed 3/8/06
QFD Review and Comparison	1 day	Fri 3/10/06	Fri 3/10/06
Purchase request for support tubes	2 days	Mon 4/3/06	Tue 4/4/06
Design Review #3 Writing	4 days	Mon 3/13/06	Thu 3/16/06
Design Review #3	0 days	Thu 3/16/06	Thu 3/16/06
Prototype Construction	**10 days**	**Fri 3/17/06**	**Thu 3/30/06**
Machining	10 days	Fri 3/17/06	Thu 3/30/06
Component Selection and Acquisition	3 days	Fri 3/17/06	Tue 3/21/06
Rail Setup	4 days	Mon 3/20/06	Thu 3/23/06
Adjustments	5 days	Mon 3/20/06	Fri 3/24/06
Validation Using Engineering Specifications	3 days	Mon 3/27/06	Wed 3/29/06
Design Review #4 Presentation Preparation	3 days	Mon 3/27/06	Wed 3/29/06
Design Review #4	0 days	Thu 3/30/06	Thu 3/30/06
Feedback Meeting	1 day	Fri 3/31/06	Fri 3/31/06
Final Machining and Adjustments	9 days	Fri 3/31/06	Wed 4/12/06
Install New Support Tubes	1 day	Tue 4/11/06	Tue 4/11/06
Section Evaluations and Expo Logistics	0 days	Tue 4/4/06	Tue 4/4/06
Design Expo	0 days	Thu 4/13/06	Thu 4/13/06
Final Report	**2 days**	**Fri 4/14/06**	**Mon 4/17/06**
Collecting/Updating Previous Reports	2 days	Fri 4/14/06	Mon 4/17/06
Imaging and Appendices	2 days	Fri 4/14/06	Mon 4/17/06
Executive Summary, Results, Conclusions	2 days	Fri 4/14/06	Mon 4/17/06
Misc. and Body	2 days	Fri 4/14/06	Mon 4/17/06
Reviewing and Proofreading	1 day	Mon 4/17/06	Mon 4/17/06
Final Report Due	0 days	Tue 4/18/06	Tue 4/18/06



Appendix C - Benchmarks

We selected two of the commercially available alignment systems as benchmarks for our future design. The first benchmark is the “Fast 6 Optical Align - Six-Axis Optical Alignment Stage” manufactured by Palomar Technologies, and the second benchmark is the “Hexalight 6-Axis-Parallel Kinematics Microrobot” manufactured by Physik Instrumente GmbH & Co.

We found that the attributes of these two products match our design goals most closely. The precision and accuracy of the two devices are very high, but we believe the relatively high product cost would be detrimental to our project spending limits.

Benchmark 1 - Fast 6 Optical Align - Six-Axis Optical Alignment Stage by Palomar Technologies: http://www.palomartechnologies.com/products/fa/fast6/products_fa_f6.htm

This product, shown in Figure 1, is a 6-axis optical alignment system used for laboratory testing and industrial applications. The system is electronically monitored. A custom-made Windows NT-based software for instrument operation and process controls comes with the device. The moving parts of the instruments are driven by non-contact, direct-drive motors. These motors operate at considerably high speeds, but they are also precise and reliable. The no contact feature of the drive motor and encoder systems minimizes wear and maintenance. This product is designed to be robust; the production grade construction is specifically designed for non-stop use 24 hours a day.

The controls for linear motions as well as the pitch, roll and yaw are modular, and this allows for flexible travel options and user selectable configurations. The system software can be programmed to have virtual pivot points for motion about the true optical center. The system itself operates at a fine resolution in all directions of travel.

The Fast 6 does not allow a tube to be mounted through the center of the device, a trait necessary for our application.

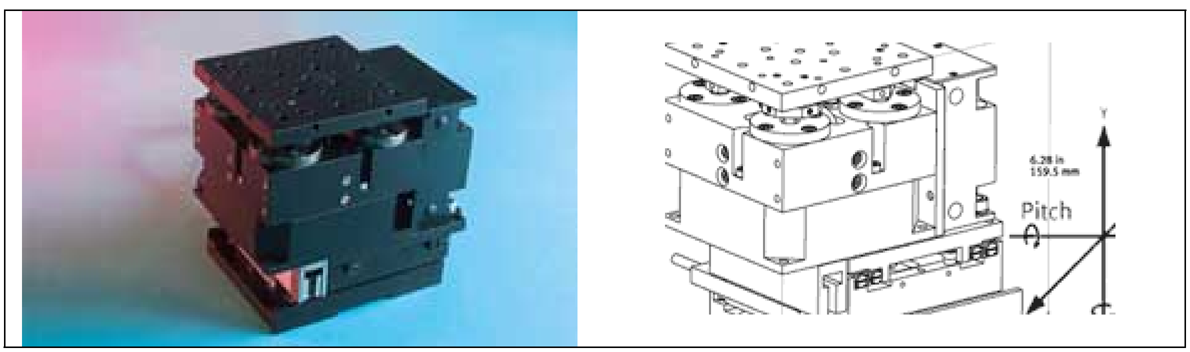


Figure C1: Visuals for the Fast 6 Optical Align system

Benchmark 2 - Hexalight 6-Axis-Parallel Kinematics Microrobot by Physik Instrumente: http://www.physikinstrumente.com/en/products/prdetail.php?VID=LVgpzeTJoC0dpPgZ&sortnr=700810

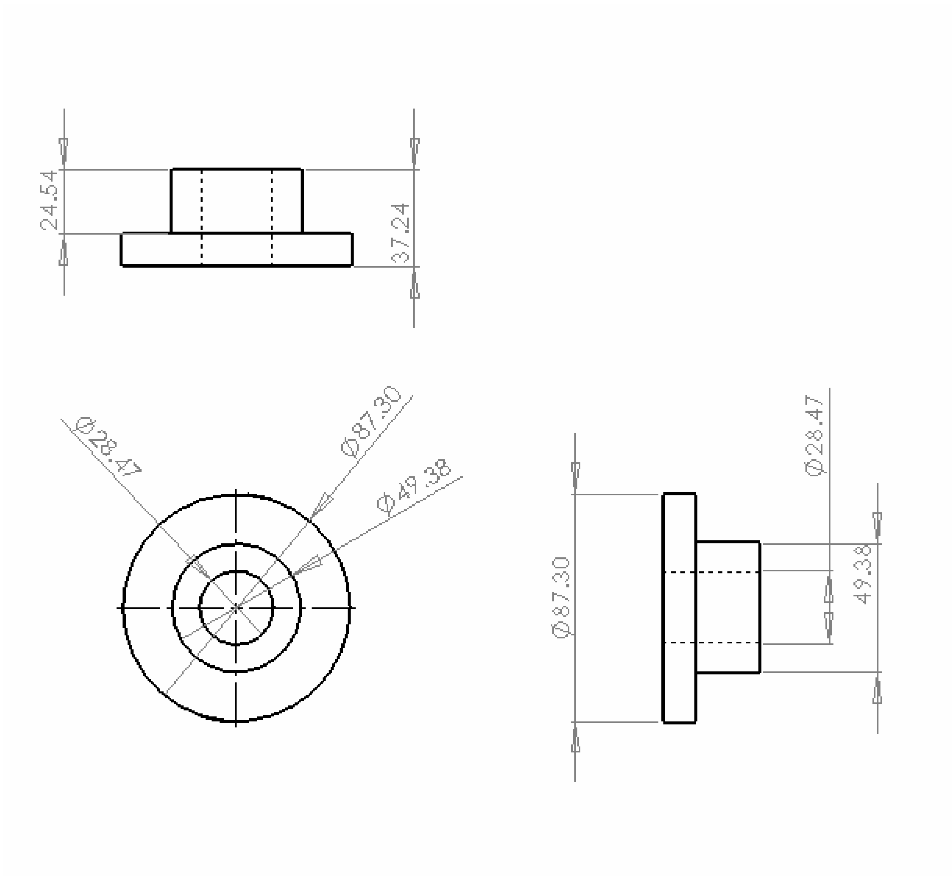
This product, shown in Figure 2, is micro-positioning system that could also accommodate motions in 6 degrees of freedom. The system is driven by six high-resolution actuators each connected directly to the same moving platform. The system user can choose from a selection of piezomotors, DC servo-motors, stepper motors or hybrid systems to drive the system actuators. Each type of motor includes its own vector algorithm based controllers and software.

Because of the low mass of the moving platform, positioning operations can be performed with far lower settling times than with conventional, stacked multi-axis systems. The system does not have moving cables, and coupled to its low inertia, the accuracy and repeatability of the product is improved compared to stacked multi-axis systems. Similar to the Fast 6 Optical Align system, the software allows its user to choose any point in space as the pivot point for its rotation axes. The product has a load capacity of 10 kg; another version of the product could support up to 200 kg.

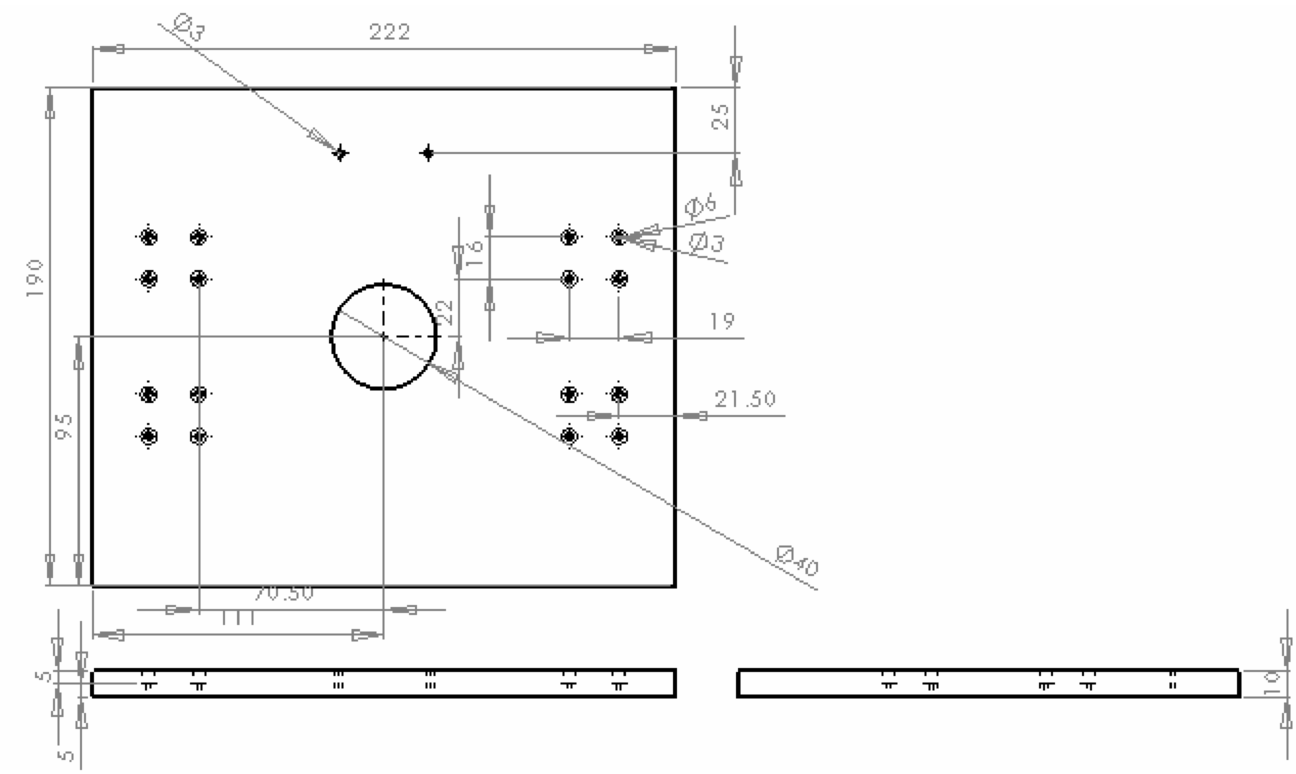
Figure C2: The Hexalight 6-axis-Parallel Kinematics Microrobot and its base

Appendix D - Engineering Drawings

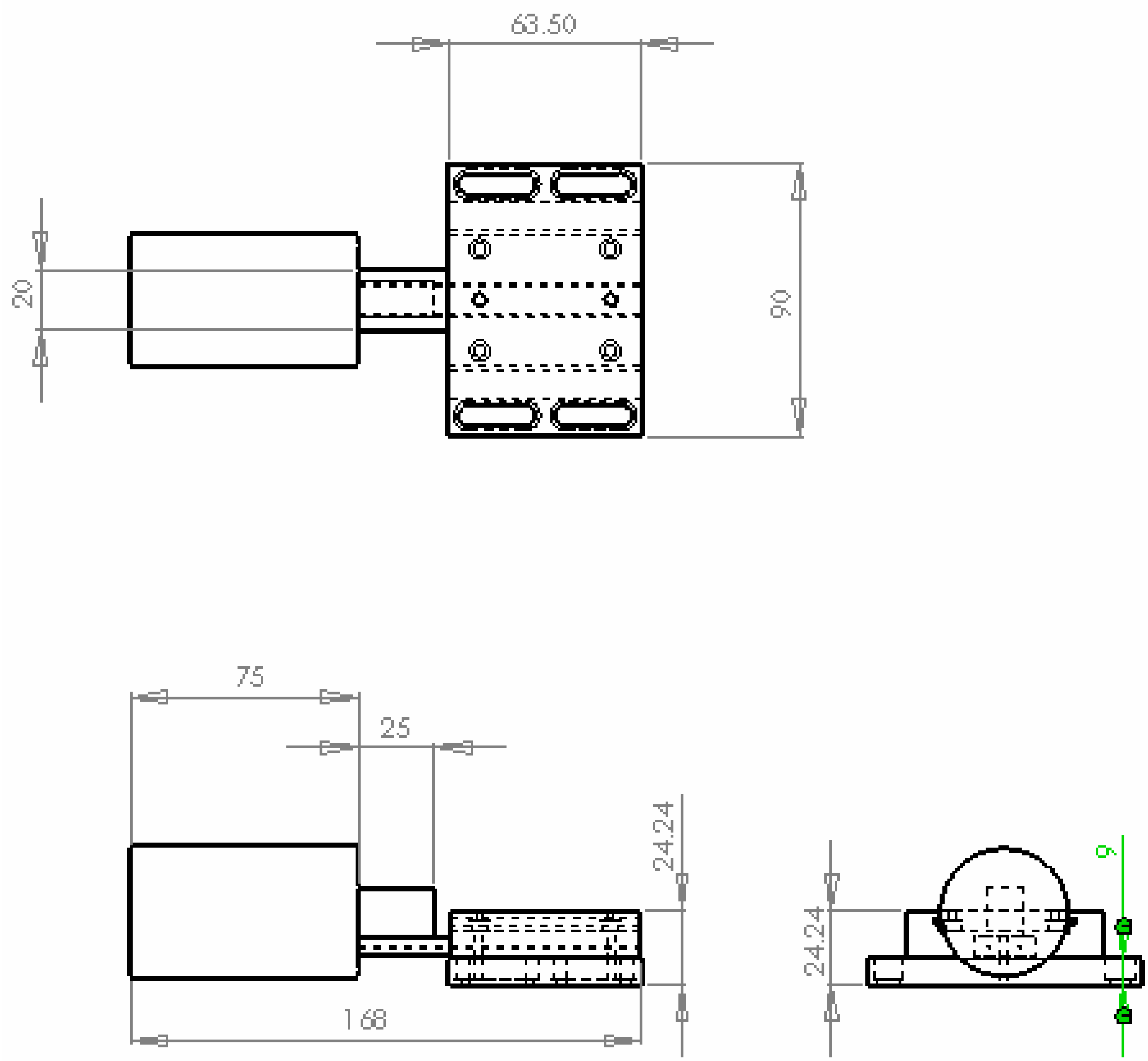
Appendix D.1 – Top Collar



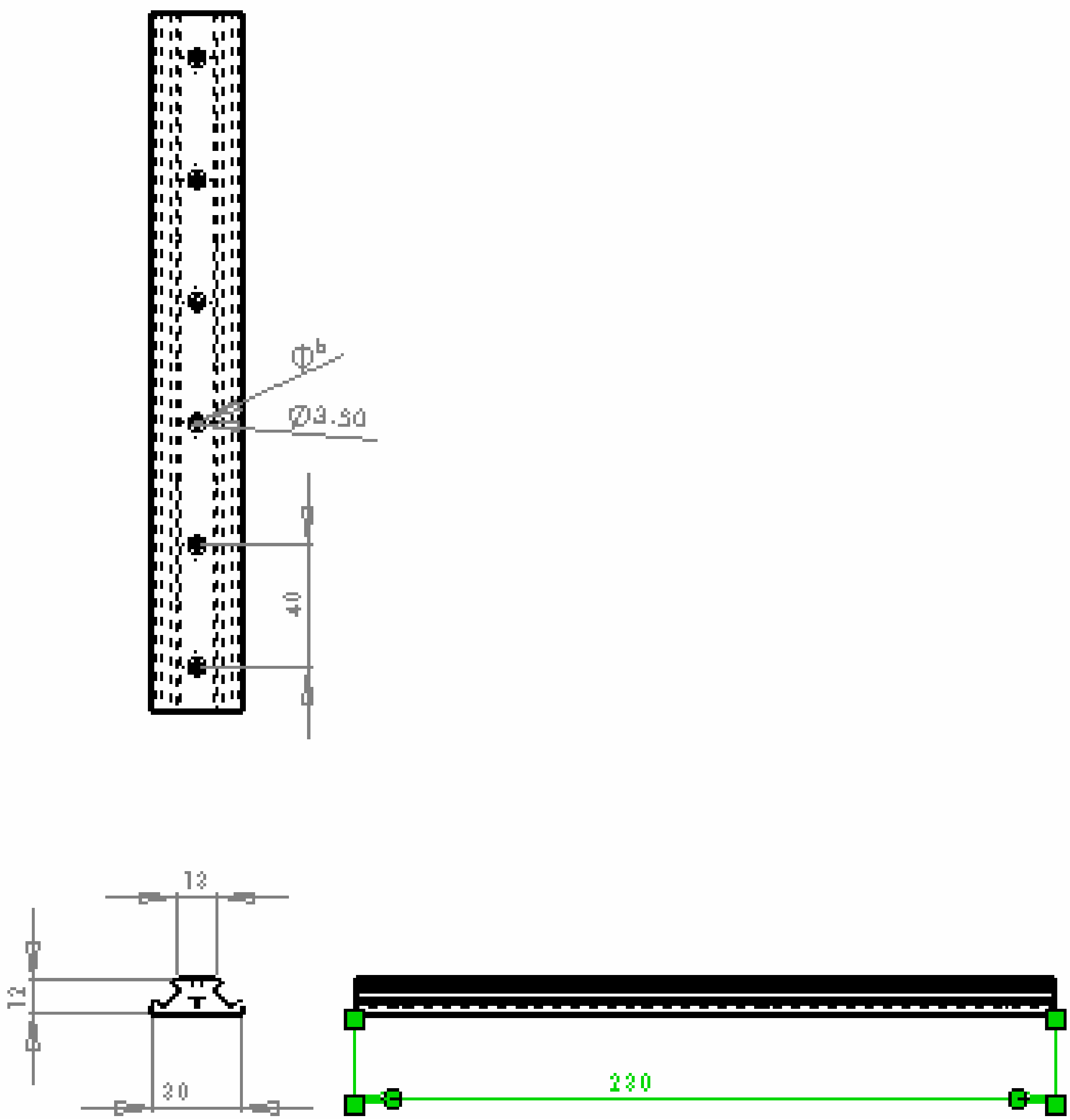
Appendix D.2 – Top Plate



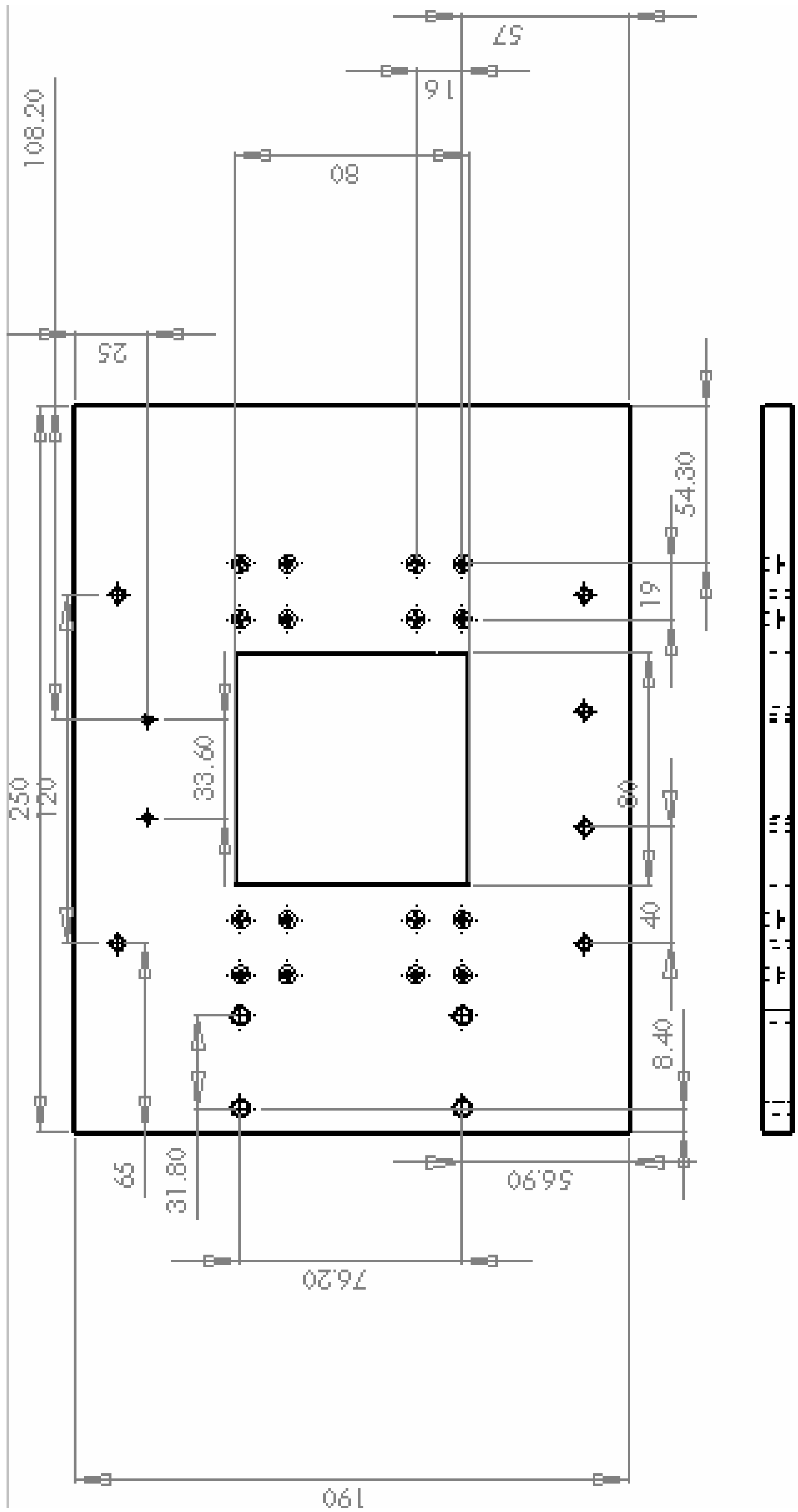
Appendix D.3 - Micrometer



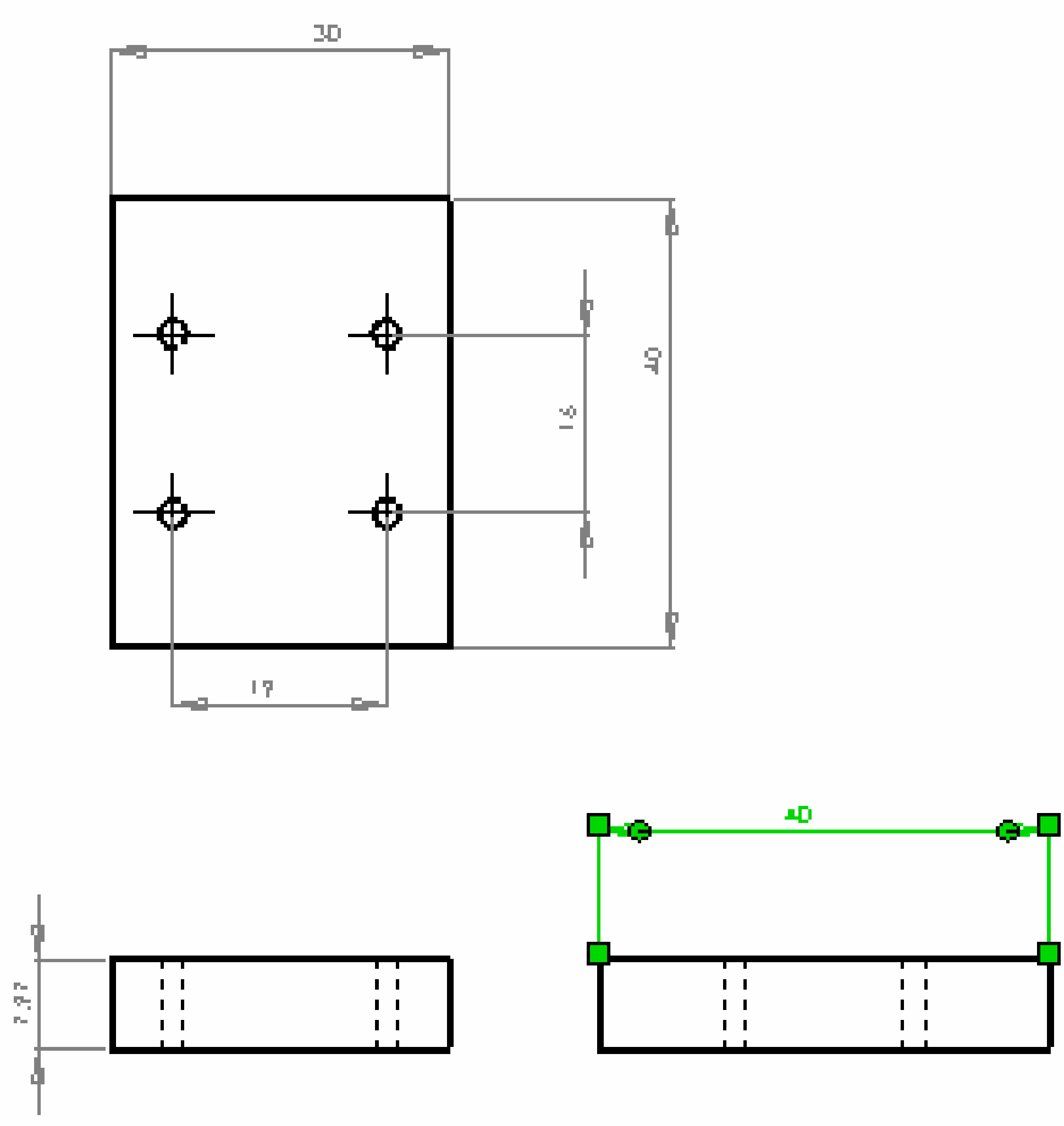
Appendix D.4 – Rail



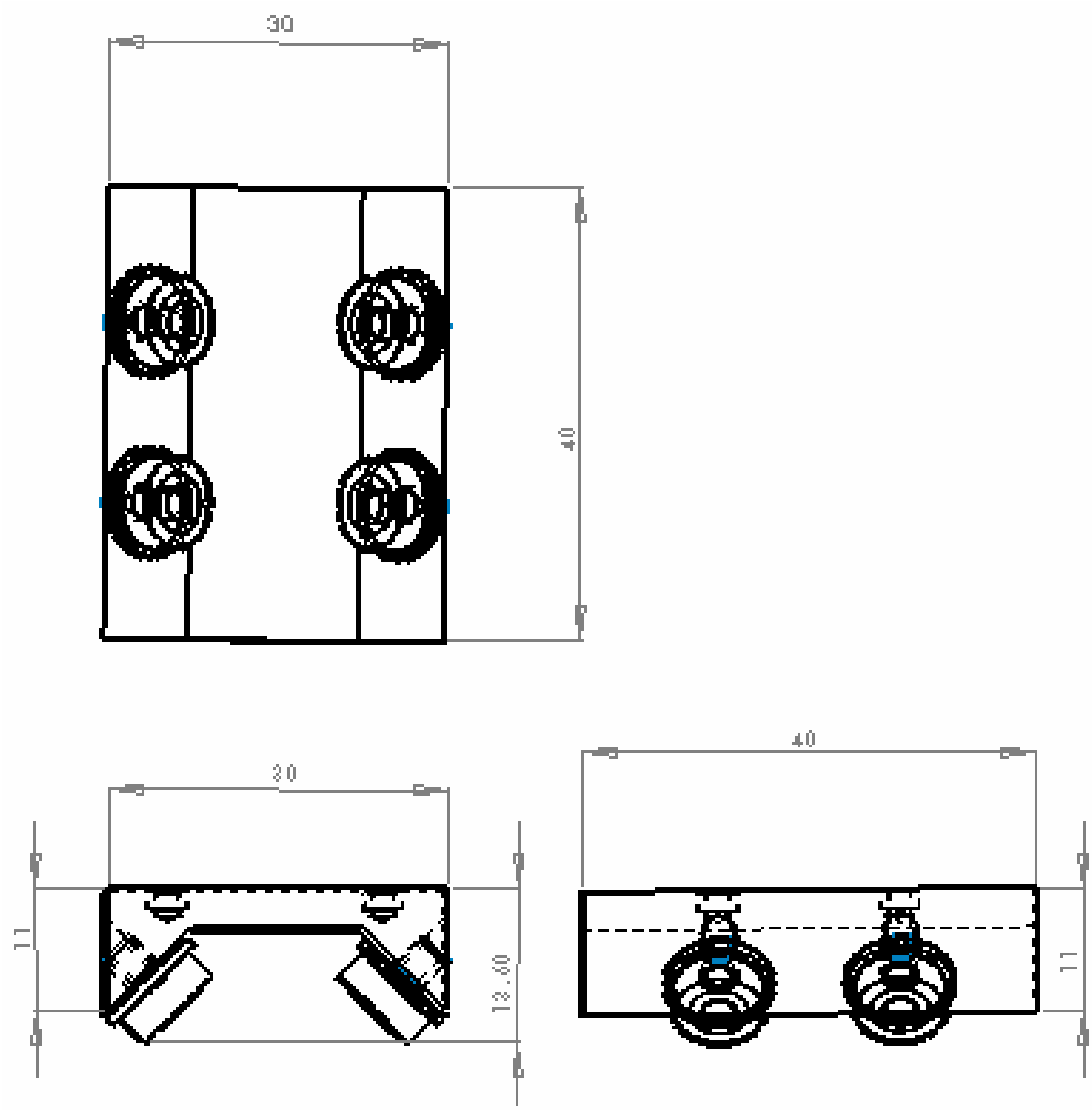
Appendix D.5 – Bottom Plate



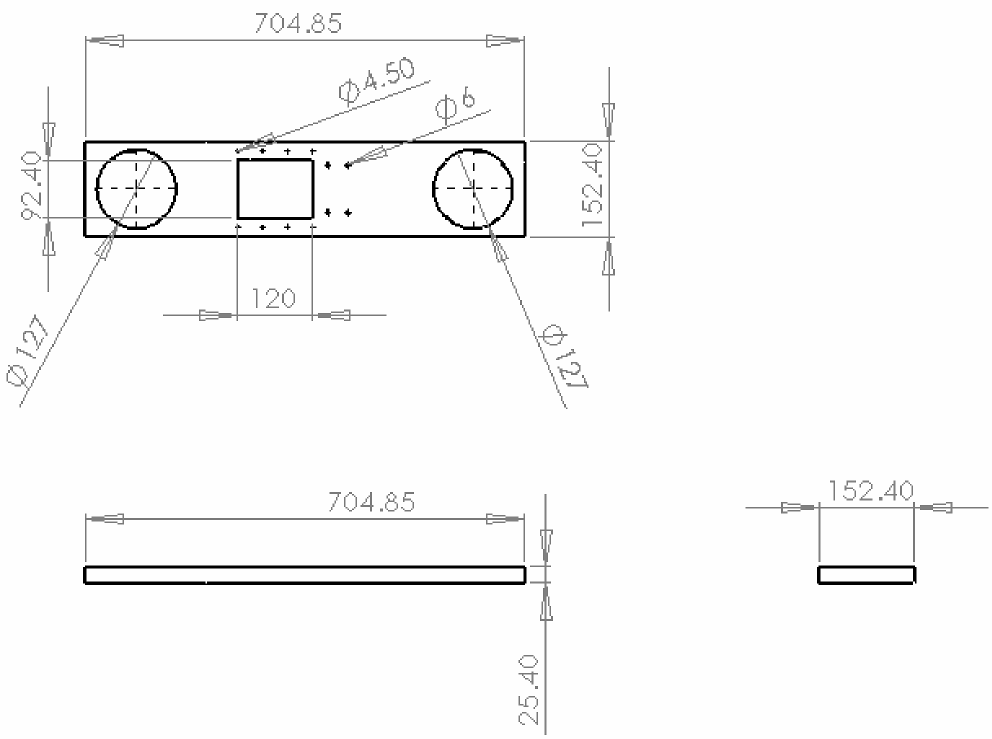
Appendix D.6 – Spacers for shuttles



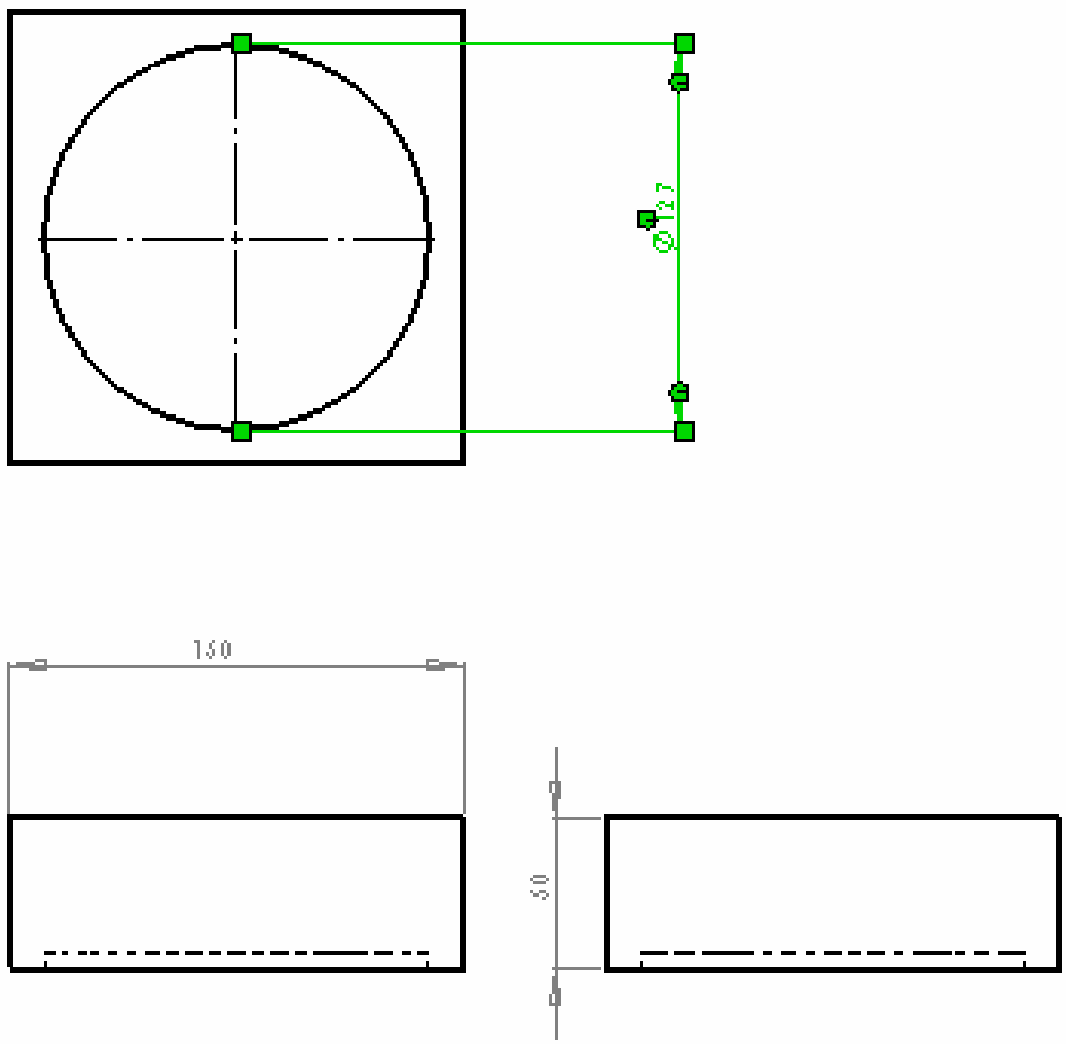
Appendix D.7 – Misumi Rail Shuttles



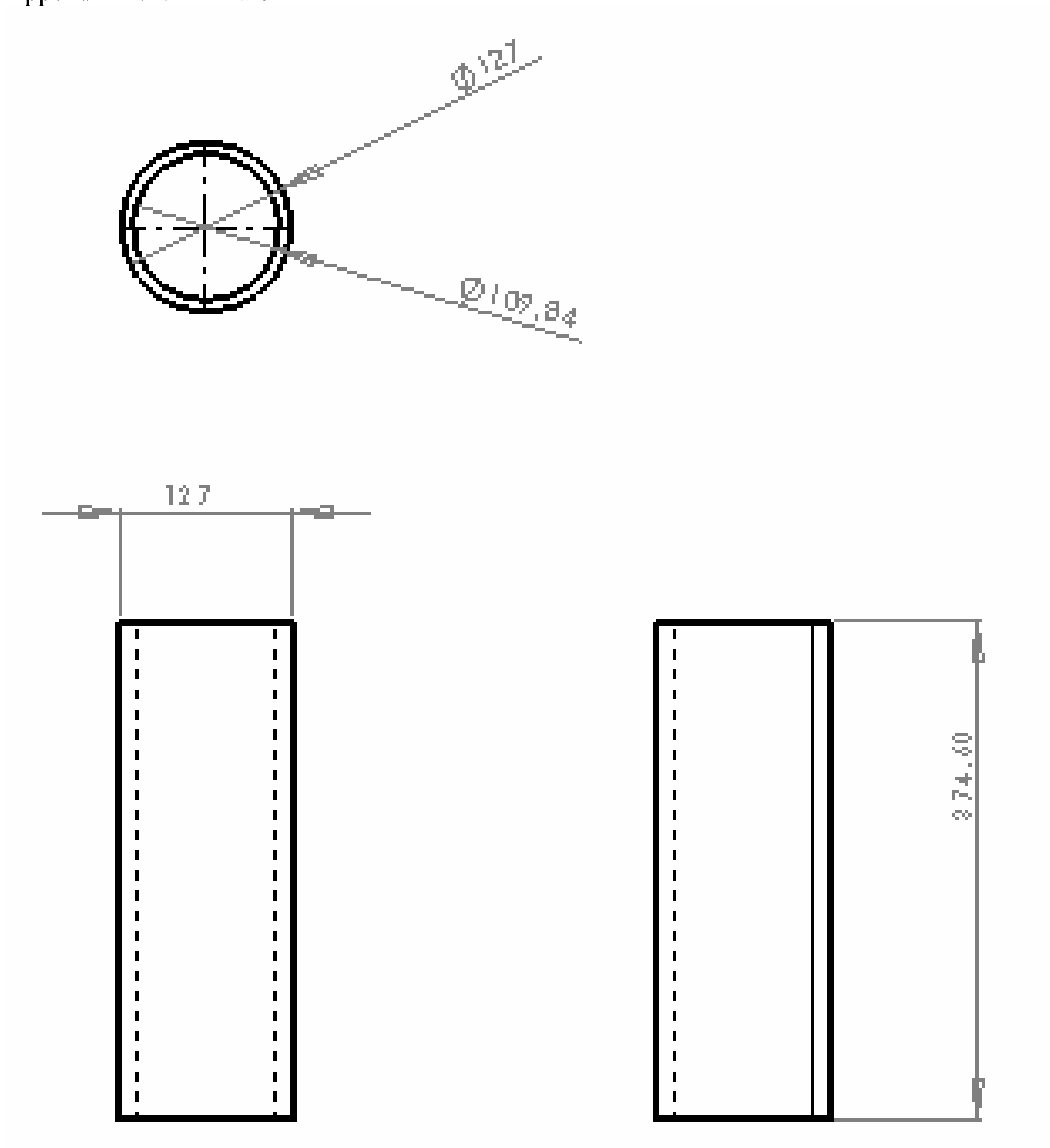
Appendix D.8 – Support Beam



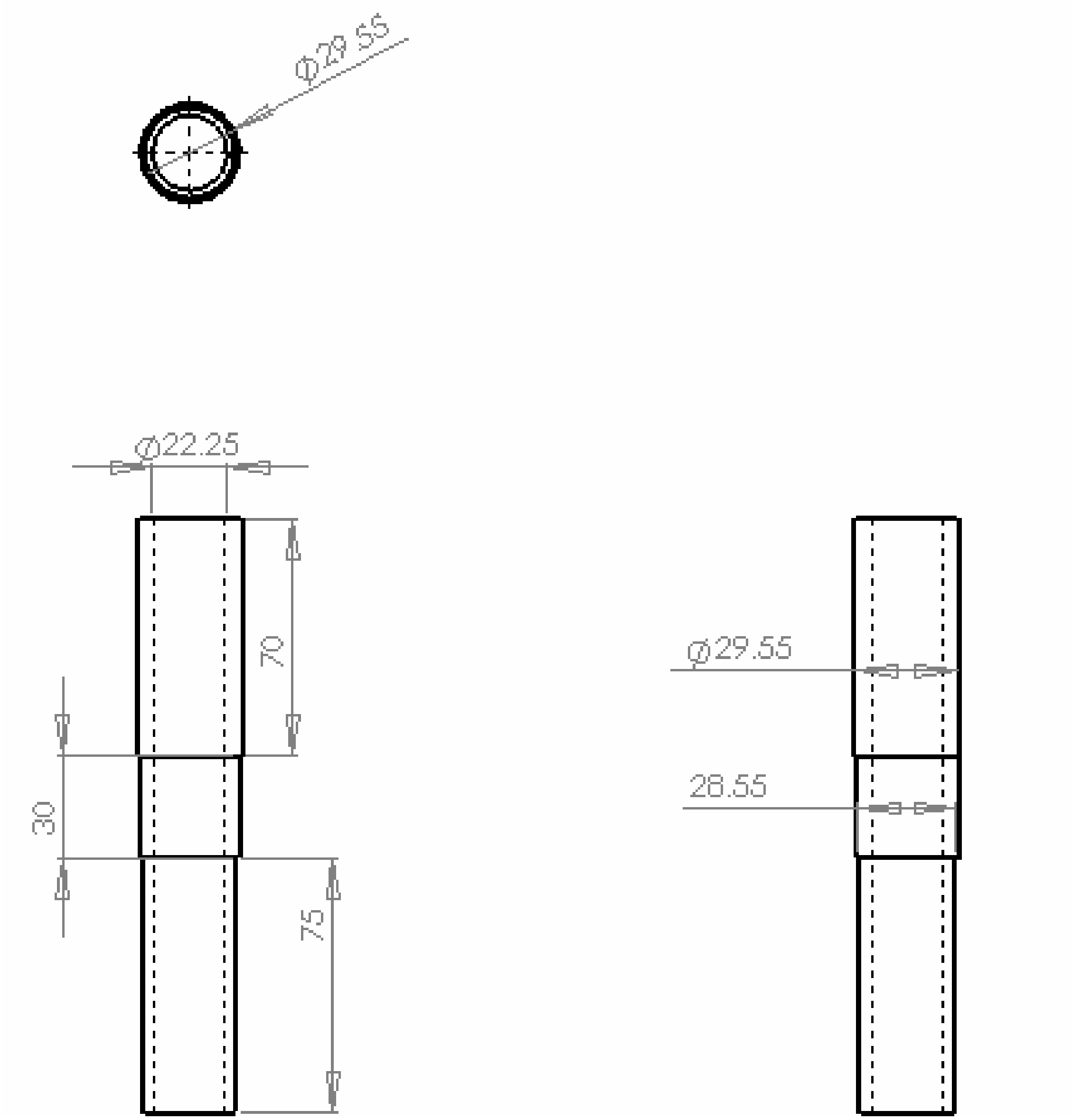
Appendix D.9 – Pillar Spacer



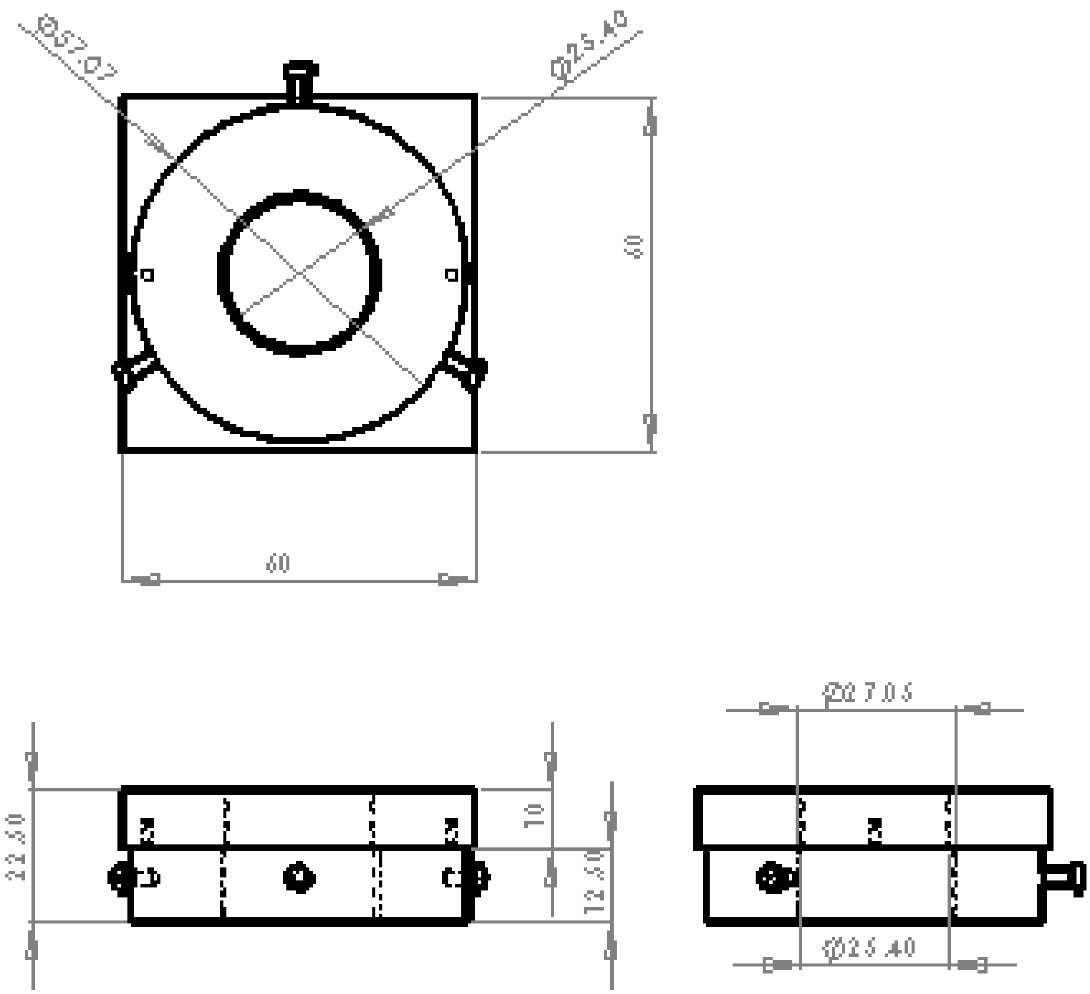
Appendix D.10 – Pillars



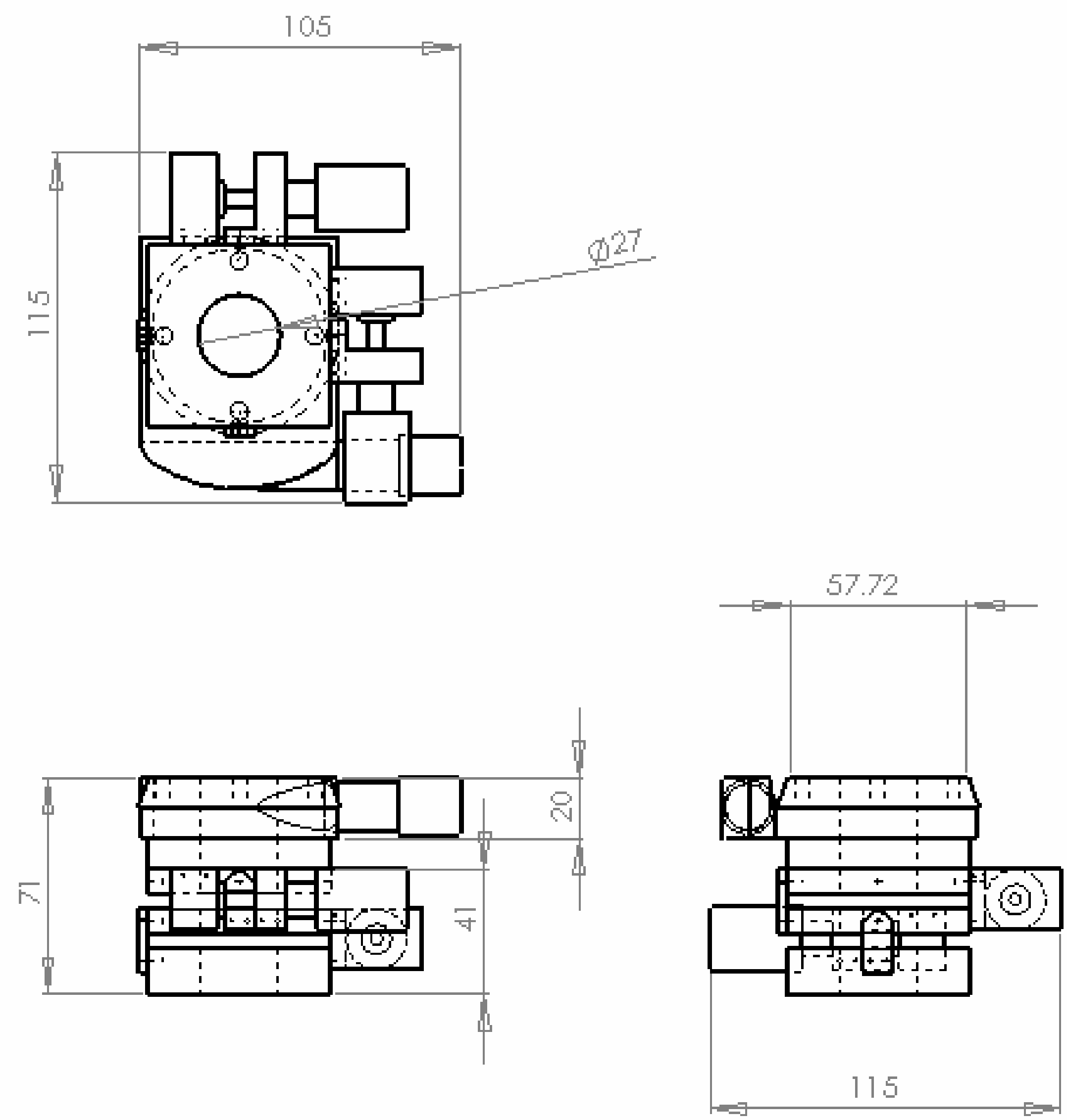
Appendix D.11 – Support Tube



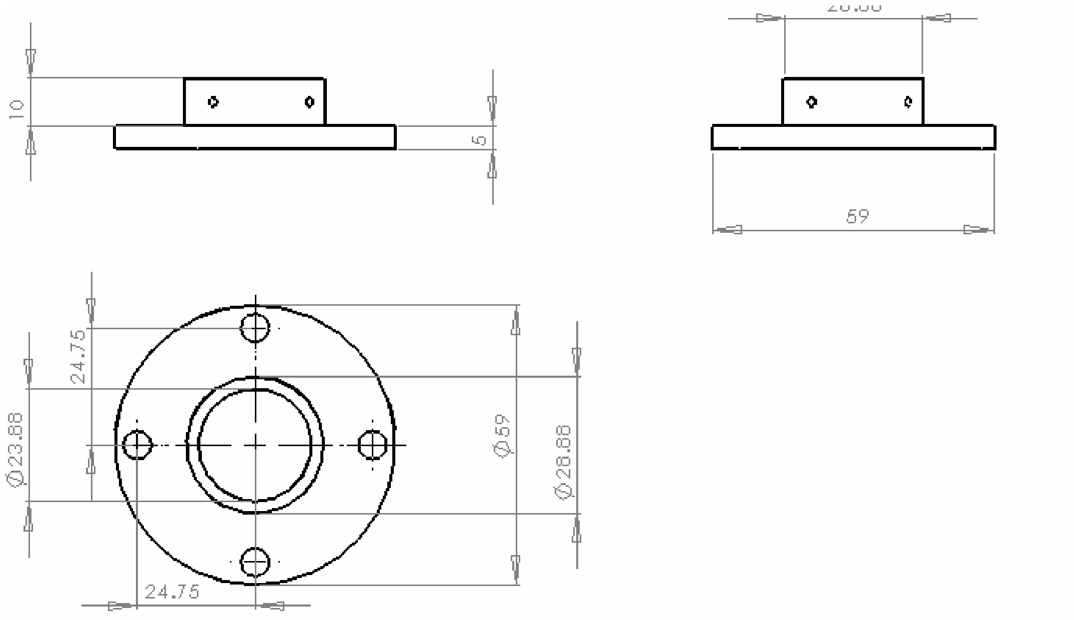
Appendix D.12 – Collar for Support tube and Tilt Stages



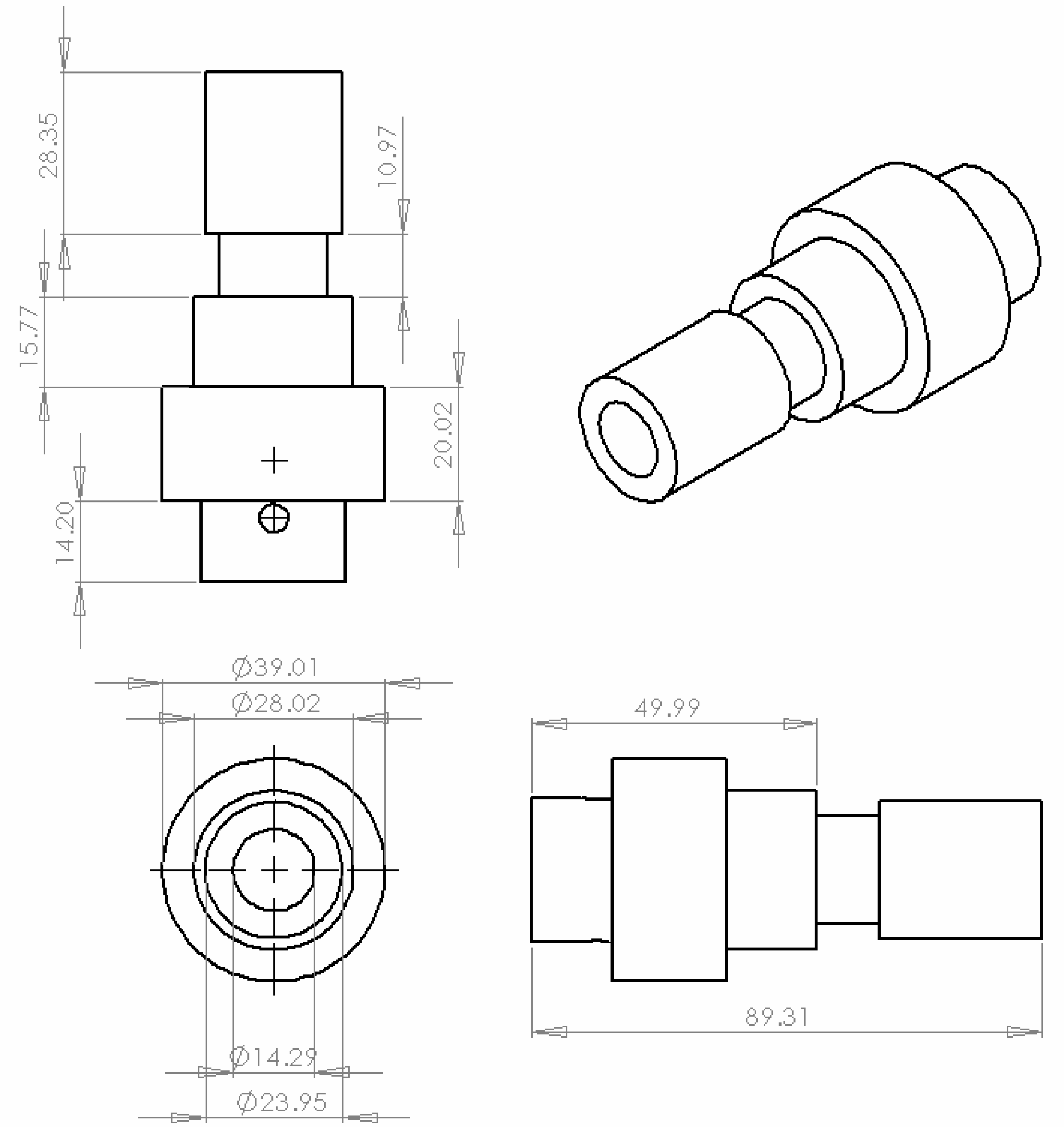
Appendix D.13 – Tilt and Rotation Stages



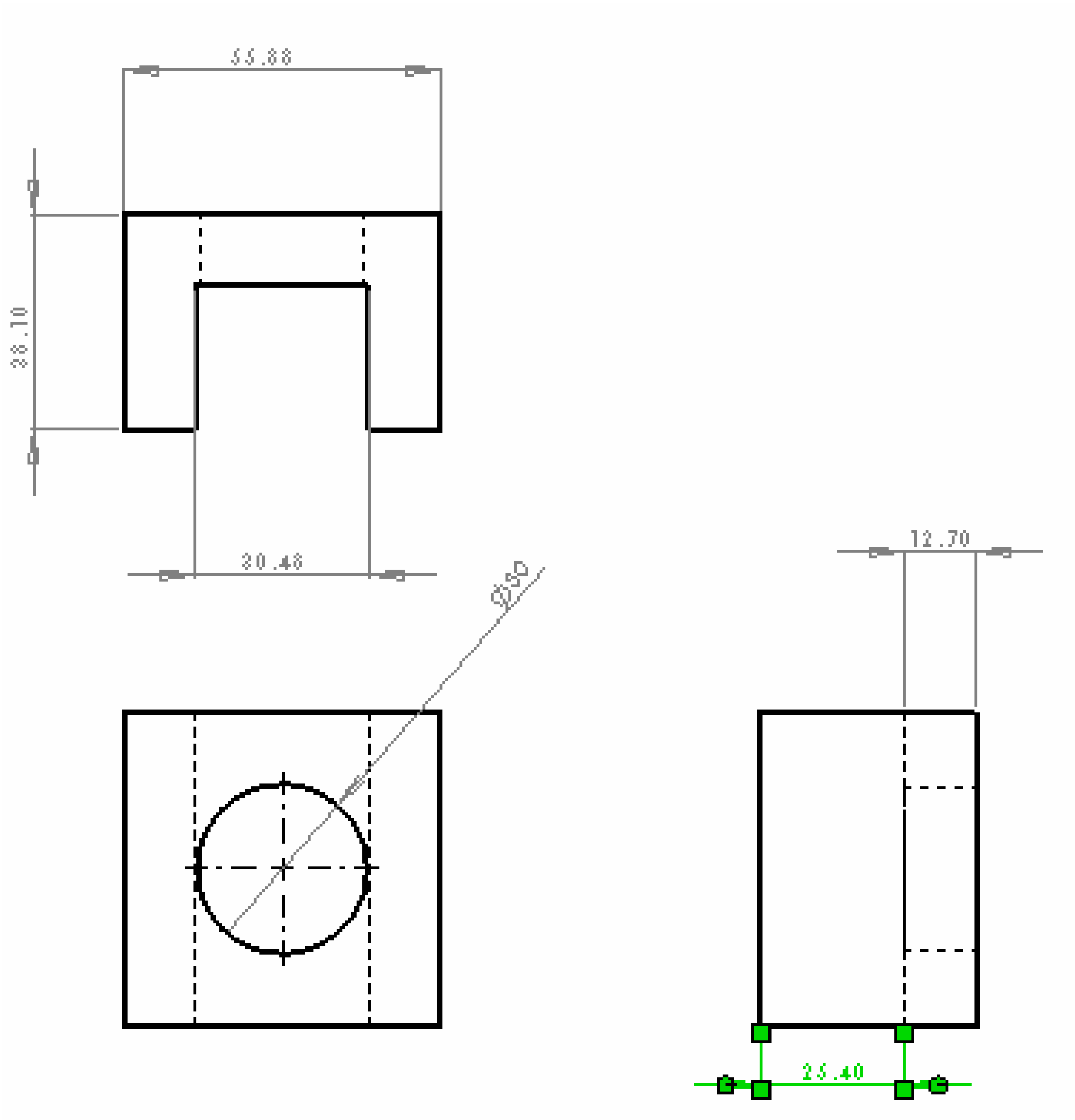
Appendix D.14 – Collar for Rotation Stage and height Adjuster



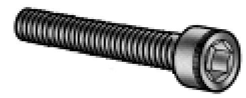
Appendix D.15 – Standa Model 5HP18 Adjustable Height Post



Appendix D.16 – Component Holder



Appendix E – List of Fasteners

<table>
<tr><th>Fastener no.</th><th>Description</th><th colspan="2">Specifications</th><th>Quantity</th><th>Comments</th></tr>
<tr><td rowspan="8">1</td><td rowspan="8">Socket Cap Screw</td><td>Head Style</td><td>Standard</td><td rowspan="8">4</td><td rowspan="8">
Rotation Stage and collar attachment</td></tr>
<tr><td>Drive Style</td><td>Hex Socket</td></tr>
<tr><td>System of Measurement</td><td>Metric</td></tr>
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<tr><td>Metric Thread Pitch</td><td>1 mm</td></tr>
<tr><td>Length</td><td>12 mm</td></tr>
<tr><td>Thread Style</td><td>Right Handed</td></tr>
<tr><td>Thread Length</td><td>Fully Threaded</td></tr>
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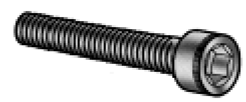
<tr><td rowspan="8">2</td><td rowspan="8">Socket Cap Screw</td><td>Head Style</td><td>Standard</td><td rowspan="8">4</td><td rowspan="8">
Set screw for Standa Height Adjuster and collar</td></tr>
<tr><td>Drive Style</td><td>Hex Socket</td></tr>
<tr><td>System of Measurement</td><td>Metric</td></tr>
<tr><td>Thread Size</td><td>M2</td></tr>
<tr><td>Metric Thread Pitch</td><td>0.4 mm</td></tr>
<tr><td>Length</td><td>8 mm</td></tr>
<tr><td>Thread Style</td><td>Right Handed</td></tr>
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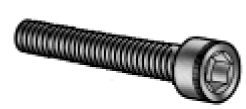
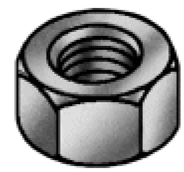
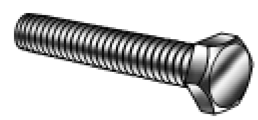
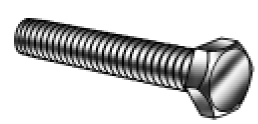
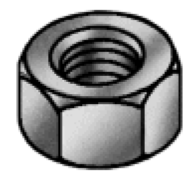
<tr><td rowspan="9">3</td><td rowspan="9">Socket Cap Screw</td><td>Head Style</td><td>Standard</td><td rowspan="9">6</td><td rowspan="9">
Mounting rails on top of bottom plate</td></tr>
<tr><td>Drive Style</td><td>Hex Socket</td></tr>
<tr><td>System of Measurement</td><td>Metric</td></tr>
<tr><td>Thread Size</td><td>M3</td></tr>
<tr><td>Metric Thread Pitch</td><td>0.5 mm</td></tr>
<tr><td>Length</td><td>20 mm</td></tr>
<tr><td>Thread Style</td><td>Right Handed</td></tr>
<tr><td></td><td></td></tr>
<tr><td>Thread Length</td><td>Fully Threaded</td></tr>
</table>

Fastener no.	Description	Specifications		Quantity	Comments
4	Nuts for Fastener 3	Nut Type	*Machine Screw and Hex Nuts*	6	 Mounting rails on top of bottom plate
		Machine Screw and Hex Nut Type	*Hex*		
		System of Measurement	*Metric*		
		Thread Size	*M3*		
		Metric Thread Pitch	*.5 mm*		
		Width	*5.5 mm*		
		Height	*2.4 mm*		
		Thread Type	*Standard Threads*		

Fastener no.	Description	Specifications		Quantity	Comments
5	Bolts	Head Style	*Standard Hex*	4	 Mounting Linear Micrometer to support beam
		System of Measurement	*Metric*		
		Thread Size	*M5*		
		Metric Thread Pitch	*.8 mm*		
		Length	*40 mm*		
		Thread Style	*Right Handed*		
		Thread Length	*Fully Threaded*		

Fastener no.	Description	Specifications		Quantity	Comments
6	Bolts	Head Style	*Standard Hex*	4	 Mounting Linear Micrometer to bottom plate.
		System of Measurement	*Metric*		
		Thread Size	*M5*		
		Metric Thread Pitch	*.8 mm*		
		Length	*16 mm*		
		Thread Style	*Right Handed*		
		Thread Length	*Fully Threaded*		

Fastener no.	Description	Specifications		Quantity	Comments
7	Nuts	Nut Type	*Machine Screw and Hex Nuts*	8	 Nuts for Fastener 5 & 6.
		Machine Screw and Hex Nut Type	*Hex*		
		System of Measurement	*Metric*		
		Thread Size	*M5*		
		Metric Thread Pitch	*.8 mm*		
		Width	*8 mm*		
		Height	*4 mm*		
		Thread Type	*Standard Threads*		

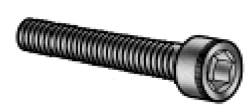
Fastener no.	Description	Specifications		Quantity	Comments
8	Socket Cap Screws	Head Style	*Standard*	24	 Mounting Misumi Shuttles to plates.
		Drive Style	*Hex Socket*		
		System of Measurement	*Metric*		
		Thread Size	*M3*		
		Metric Thread Pitch	*0.5 mm*		
		Length	*16 mm*		
		Thread Style	*Right Handed*		
		Thread Length	*Fully Threaded*		

Table E.1: List of specific fasteners to be used in assembly

Appendix F- Cost of Materials

As mentioned in the project plan and information sources, we are unable to manufacture some of the components in our apparatus due to capability limitations of our machining equipment in attaining high precision. Therefore, we purchased these components from commercial manufacturers. Table F.1 below lists the costs that have been incurred towards the manufacturing of the design prototype.

Item	Source	Catalog No.	Dimensions in mm	Cost per unit	Quantity	Total
XY-stage						
Rails	Misumi	JKSGR16-230		$17.50	4	$70.00
Shuttles	Misumi	JKSGB16		$24.80	8	$198.40
Shipping						$26.50
	tkelley@misumiusa.com				Total	$294.90
Z stage						
Microscopic adj.	Standa	5PH18		$90.00	1	$90.00
Shipping						$26.50
	sales@standa.lt				Total	$116.50
Miscellaneous						
Support Tube	ASAP Source	Online Catalog	127 Diameter	$57.50	2	$115.00
Cylinder	ASAP Source	Online Catalog	60.3 Diameter	$2.61 / in. length	1	$5.22
Block	ASAP Source	Online Catalog	305 by 305 by 9.5	$58.90	2	$117.79
	sales@asapsource.com					
Shop supplies	Ace Barnes Hardware		M6 Screw	$0.15	1	$0.15
	http://www.acehardware.com		M5 Screw	$0.15	8	$1.20
					Total	$239.36
					Grand Total	$650.76

Table F.1: Bill of materials needed to assemble the design prototype

Appendix G.1 – Risk Assessment

Risk Level Report

Application:	Prismatic Optical Component Alignment System	Analyst Name(s):	Irfan Zainal Abidin
Description:	A six degrees of freedom stage that is used to precisely align two beam splitters together.	Company:	Reconfigurable Manufacturing Systems. University of Michigan
Product Identifier:		Facility Location:	Meteorology Laboratory
Assessment Type:	Detailed		
Limits:			
Sources:	Federal Regulation, ANSI Standard		

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Final Assessment Severity Exposure Probability	Risk Level	User / Task	Hazard / Failure Mode	Risk Reduction Methods / /Comments	Initial Assessment Severity Exposure Probability	Risk Level	Status / Responsible / /Reference
		All Users All Tasks	mechanical : cutting / severing Therer are a few components with sharp edges on the system.	Substitute less hazardous material / methods. (The sharp edges will have to be filed down)	Slight Remote Unlikely	Low	
		All Users All Tasks	mechanical : fatigue Since most of the parts are held on by screws, they may beoom loose with time	Special procedures (All users must be reminded to make sure the set scrwes are secured)	Minimal Remote Unlikely	Low	
		All Users All Tasks	mechanical : break up during operation Most of the parts are fastened using set screws, thus wil fall down if not properly secured.	Special procedures (All users must be reminded to make sure the set scrwes are secured)	Slight Remote Possible	Moderate	
		All Users All Tasks	slips / trips / falls : instability The pillars supporting the main stage is quite high (20 Inches) and the pillars are not secured (welded/screwed) to the base and main stage. This may cause the system to become unstable if excessive force is applied to it.	Substitute less hazardous material / methods (The pillars will have to be secured with screws or welded to the main stage and the base.	Slight Remote Possible	Moderate	

Appendix G.2 – designsafe Report

designsafe Report

Application:	Prismatic Optical Component Alignment System	Analyst Name(s):	Irfan Zainal Abidin
Description:	A six degrees of freedom stage that is used to precisely align two beam splitters together.	Company:	Reconfigurable Manufacturing Systems. University of Michigan
Product Identifier:		Facility Location:	Meteorology Laboratory
Assessment Type:	Detailed		
Limits:			
Sources:	Federal Regulation, ANSI Standard		

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	mechanical : cutting / severing Therer are a few components with sharp edges on the system.	Slight Remote Unlikely	Low	Substitute less hazardous material / methods. (The sharp edges will have to be filed down)			
All Users All Tasks	mechanical : fatigue Since most of the parts are held on by screws, they may becom loose with time	Minimal Remote Unlikely	Low	Special procedures (All users must be reminded to make sure the set scrwes are secured)			
All Users All Tasks	mechanical : break up during operation Most of the parts are fastened using set screws, thus wil fall down if not properly secured.	Slight Remote Possible	Moderate	Special procedures (All users must be reminded to make sure the set scrwes are secured)			
All Users All Tasks	slips / trips / falls : instability The pillars supporting the main stage is quite high (20 Inches) and the pillars are not secured (welded/screwed) to the base and main stage. This may cause the system to become unstable if excessive force is applied to it.	Slight Remote Possible	Moderate	Substitute less hazardous material / methods (The pillars will have to be secured with screws or welded to the main stage and the base.			