ME 261: Engineering Design

Final Report

By

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Introduction:

NASA Goddard Space Flight Center has been working for several years to develop a new satellite entitled the International X-Ray Observatory. The new "Great Class" observatory is scheduled to launch in 2021 and will be placed into a second Lagrangian point orbit. Because of its large aperture area and extremely fine resolution it will be at the forefront of X-ray optics technology and will allow scientists to evaluate the origins of black holes and the early moments of the Big Bang. The Flight Mirror Assembly (FMA) is the technology driver for the research and development process. The FMA will contain 14,000 grazing incidence Wolter-I mirrors and each of these will need to be proof tested for the observatory to pass the Critical Design Review and be cleared for launch. The purpose of this project is to develop a design for the proof testing.

Objectives:

In this project the students will design a fixture that is able to proof test a minimum of 14,000 mirror segments. The purpose of the proof test is to ensure that each mirror will survive launch. This involves the design of an apparatus that is able to secure the mirrors and apply a specified stress in a way that emulates launch conditions. Another element of the design involves enclosing the apparatus in a testing cell that can be purged with nitrogen gas. Nitrogen will provide a dry environment which is important because the moisture content of air enhances crack propagation in the mirrors .The final objective is for the system to be automation ready.

Performance Criteria:

For this design there are many performance criteria. Our design in the most basic form is a proof testing machine for many different sizes of glass mirrors. There are 722 shapes of mirrors that our design must accommodate. They vary in radius and azimuth length while height remains constant. The test fixture will need to "grip" the mirror in 8 specific locations. In Figure 1 a finite element model is used to find the maximum stress locations caused by the bonding points. The dark semi-circles show that the mesh becomes considerably finer around the bonding location indicating the stresses are generally localized. Because of the small stress magnitudes it is crucial that the gripping mechanism is in the perfect spot on each mirror. If a gripper is incorrectly positioned any amount it can create unwanted stresses on the mirror before the testing begins.

After each gripper is positioned it must lock onto the mirror simulating as closely as possible the epoxy bond that will be used in final installation. Therefore, a compliant material must be found for use on the grippers that will not only hold the mirrors well and simulate the bond, but not break the glass or induce additional stresses. Also the grippers must be sized appropriately so that they simulate where the epoxy bond will be directly located, on the edge of the glass protruding a semi-circle onto the surface with a radius of 3mm. Once they are all locked in place the machine must be able to rotate each individual point (8 total points) by small amounts, somewhere on the order of a one degree rotation. This rotation is about an axis co-linear with the edge-plane and the optical surface of the mirror segments. This will simulate the stresses and displacements the glass segments will experience during launch.

Crack propagation in glass is caused largely by moisture in or on the glass. The proof testing apparatus will have to be in an enclosure that can be filled with nitrogen and sealed while a glass piece is being tested to ensure that if a crack starts it will not propagate further. NASA has also specified that this device should be of moderate size.

The overall design needs to be completed with automatic control kept in mind. It is desirable that a technician be able to place a mirror in the apparatus and control the test using a computer system. The control system should do everything from adjusting for glass size to applying specified stresses.

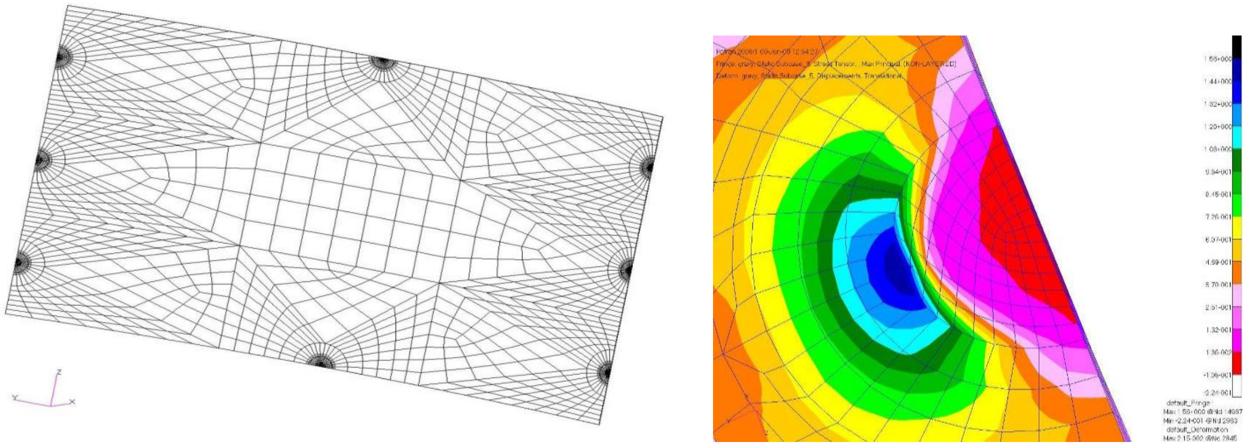


Figure 1: FEA simulation of the mirror stress test

Summary of Performance Criteria:

- Accommodate for all 722 different mirror sizes and shapes.
- Attach to mirror in 8 different spots to simulate bonding points on final assembly.
- Grippers must be in very specific locations before latching on to ensure no pre-testing stresses on material.
- Grab specimen as close to edge as possible to again simulate where they will be bonded on final assembly.
- Use a compliant material that will hold the mirrors well, but also will not break, damage or induce stress on the mirror.
- Perform inside a sealed box filled with nitrogen that can fit comfortably on a large desk.
- The test fixture needs to be capable of automated control.

Concept Development:

An evaluation of the design task revealed three specific focus areas of design. These are positioning, gripping and rotating, and environment control. Position relates to the wide array of mirror sizes that must each be accommodated. Gripping and rotation correspond to the task of emulating the launch conditions. This includes imitating the bond locations, and the stresses that will be experienced by the mirrors. Environment control pertains to eliminating moisture in the area surrounding the mirrors during proof testing. When possible, the group has tried to utilize off the shelf parts to accomplish each of the tasks outlined. In this way, time to manufacture and cost can be reduced.

For elements of the design that could not be accomplished with the following products, the group developed in house solutions. Concepts for these solutions will be discussed in later sections.

Current State of the Art:

There are numerous designs on the market of mechanisms that perform one or more of the tasks needed. Several “off the shelf” components have been investigated that have the requisite precision, and these mainly pertain to positioning. Below in Figure 2 is a motorized positioning device from Newport. Do to the fact that devices such as these are readily available with high levels of precision, the group decided it was unnecessary to design one; rather the task is to make the proper selection.

In order to facilitate the maximum and minimum mirror sizes, it was found that approximately 226 mm of linear travel is needed. Thus a linear positioning device such as the Newport GTS150 seen in Figure 2, which has 150 mm of linear travel per stage (two combined as seen later gives 300mm), and a resolution of .05 µm would suffice for the overall design.

Figure 2: Newport GTS150

Positioning also includes accommodating a wide range of angles in addition to lengths. This is due to the differing radius of curvature among the mirrors. A readily available instrument that was found to be useful to the design was the Newport SR50PP as seen in Figure 3 which is a motorized rotational positioning device.

Figure 3: Newport SR50PP rotational stage with stepper motor

To produce launch like conditions in a testing cell, a device is needed that is able to act as a bond point, and induce the correct amount of stress. No available product was found that could accomplish such a task. Figure 4 shows a gripper design on the market which served as a template for what the group envisioned.

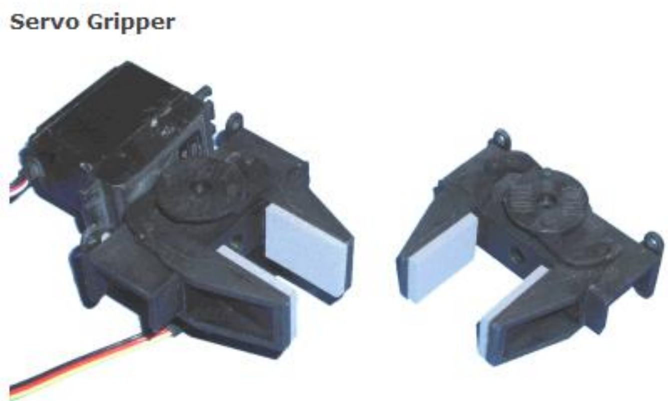


Figure 4: Gripper mechanisms

Positioning Concepts:

To position the grippers in relation to the mirrors, the team looked for linear and rotational stages that had high enough resolution and accuracy for this project. Three stages from the Newport Corporation were found that are able to complete the task. For movement in the x-axis, the GTS150 will be used. For the y axis, the VP-25X will be used. And for the rotations about the z-axis, SR50PP will be utilized. Figure 5 illustrates the reference axes and provides a rough outline of the overall position mechanism.

The purpose of this system is to position the grippers in the correct location on the mirror's edge, and accommodate radius of curvature and width differences. This apparatus is not involved in applying stress, and in fact should induce no distortion or stress in the mirrors.

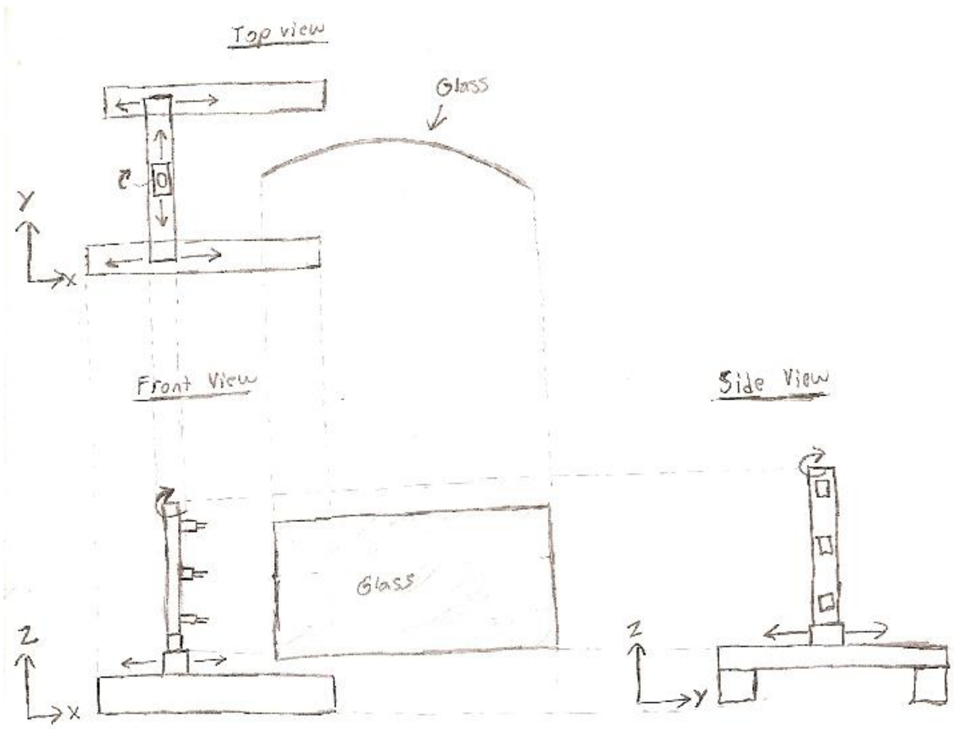


Figure 5: Overall positioning.

The design in Figure 5 is for adjusting to the edges of the mirror. Vertical arms to which the grippers attach are mounted to the stages already mentioned. Linear movement along the y-axis adjusts to differing widths (width is the y-axis dimension). Similarly, linear movement in the x-axis will adjust to changes in radius (differing distances from the arc center). Finally, using rotational movement the system will adjust to the angle at which the mirrors enter the gripper.

For the top and bottom center of the mirrors, Figure 6 depicts the concept adopted by the group. Linear and rotational movement in the z-axis allows the top gripper to be moved up and away from mirror edge, allowing for ingress and egress of mirrors.

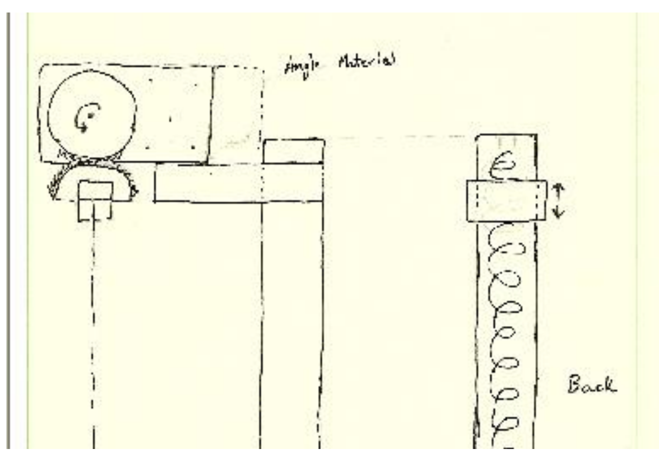


Figure 6: Positioning for top and bottom center

Gripper Concepts:

Gripper designs proved to be much more intricate as they involve small dimensions and clamping as well as rotational movement. This rotation is different than the rotation used in positioning, and is illustrated in Figure 7. In the figure the dot represents the axis running along the edge of the mirror. The arrow in the figure indicates rotation about the edge of the mirror that will recreate launch stresses. While clockwise rotation is shown in the figure, in actuality the system will test both clockwise and counterclockwise rotation.

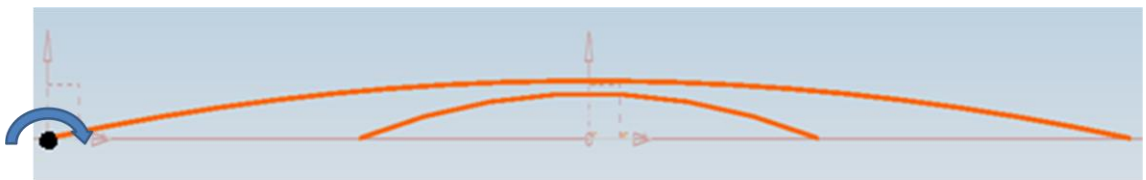


Figure 7: Rotation needed to produce launch stress

Of the designs generated, there were two main types, those that cause the axis of rotation to be on the edge of the mirror in the z direction, and those where the axis of rotation is off the mirror. Figure 8 shows Concept 1 in which the latter is true.

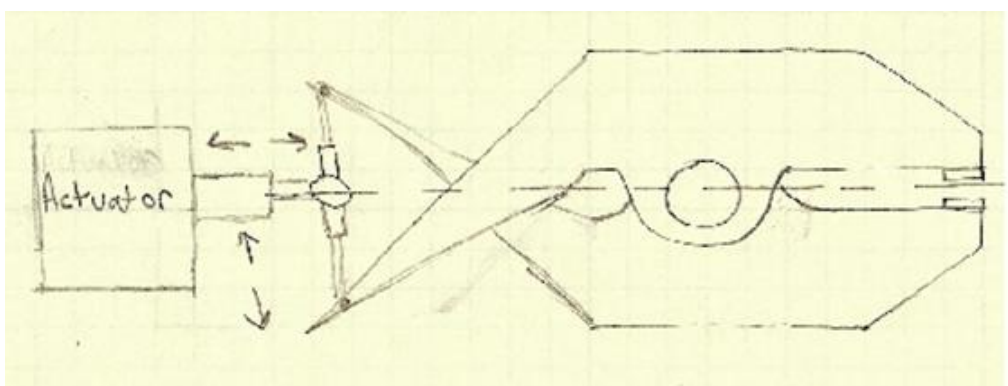


Figure 8: Axis of rotation would not be on the mirror edge

The design in Figure 8 is essentially a Vise Grip© type of instrument that uses linear actuators to cause the needed motions. The benefits of this design are that it would be easy to analyze and manufacture. Its main detractor is that the axis of rotation is not on the edge of the mirror, which is one of the design specifications. Alternatively Figure 9 shows Concept 2, a gripper design in which the axis of rotation is on the edge of the mirror.

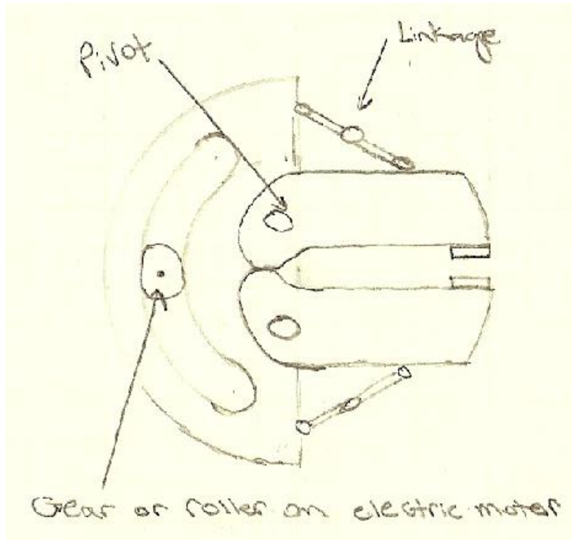


Figure 9: Rotates about edge of mirror

Complications of this design lie in the actuation of the linkage, which lock the jaws in place on the mirror. Also, manufacturing may be more difficult than the previous design.   Another weakness is that when the rotational movement is applied to the mirror, the linkages will not experience equal reactions. Therefore analysis of the linkages and material used is critical.

Since rotating about the correct axis is obviously an important part of the design, the concept in Figure 8 was selected to be the basis of further conceptualization. Figure 10 shows Concept 3, a design in which linkages have been eliminated. The component in Figure 10 is designed to perform the required motions, rotate about the correct axis, and be operated by linear actuators.

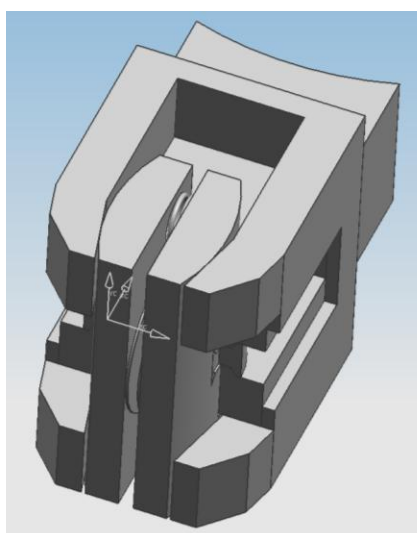


Figure 10: Gripper design using outer structure

Concept 3, a continuation of Concept 2, was further developed to become the final design. In later sections the design is laid out and components are labeled for a common nomenclature.

Nitrogen Tank:

The last aspect of the design task is an enclosure in which the testing system must operate. To meet design criteria, the enclosure must purge moist air, and allow testing to be done in dry air conditions. A solenoid operated 2-way valve was chosen to control the flow of nitrogen gas into the enclosure and can be seen in Figure 11. This valve will also allow automation as opposed to having to operate a valve by hand. To allow air to exit the enclosure, a very low pressure one way valve will be placed near the bottom of the tank on the opposite side of the 2-way valve. A seal made of rubber or some similar material will be placed around the edge of the lid to prevent leakage while testing.

Figure 11: This will enable the nitrogen flow to be turned on/off.

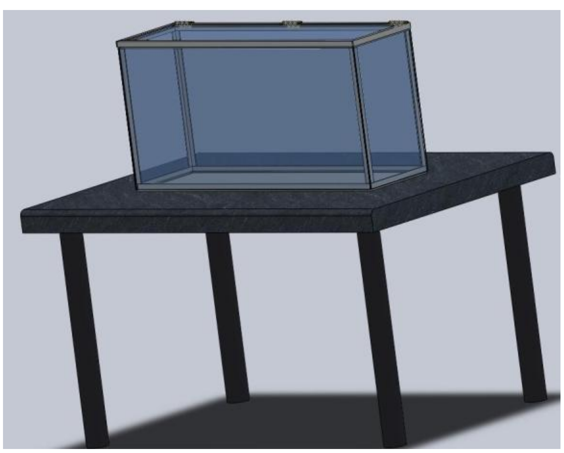


Figure 12a: Nitrogen enclosure closed

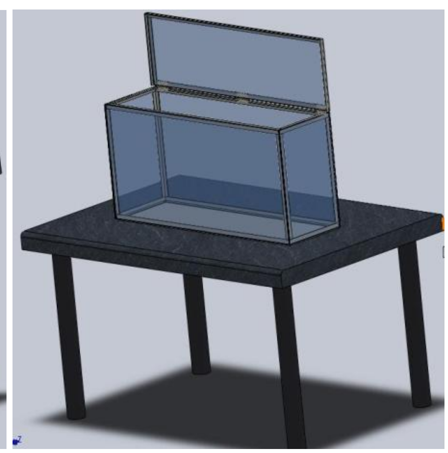


Figure 12b: Nitrogen enclosure open

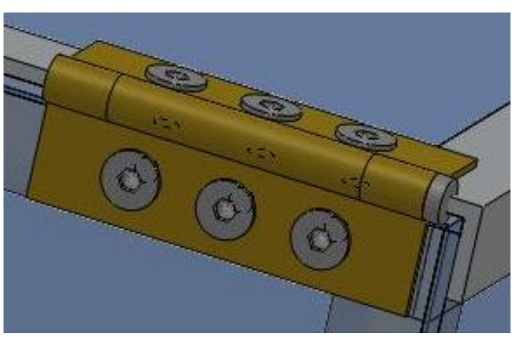


Figure 12c: Hinge used for lid mount

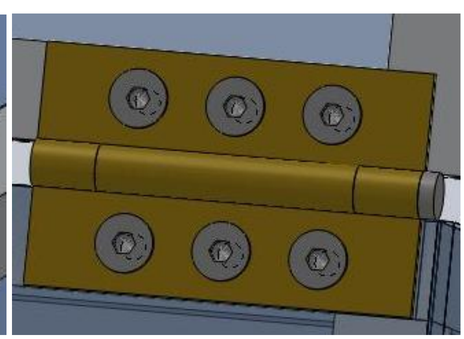


Figure 12d: Hinge in open position

Simple design, off the shelf products, and visibility are the positive attributes of this concept. The structure will be made of aluminum, and the panes of a clear material such as Lexan. It will also have one 2-way valve and one 1-way valve for the ingress of the nitrogen gas and the egress of the air respectively. For any wiring that may need to be run to the actuators and stages, rubber grommets could be easily installed in the Lexan to provide a good seal. Figure 12 shows the current design concept.

Summary:

Accommodating the various mirrors should be fairly straight forward utilizing products readily available on the market. A gripper design suitable to the design task has been identified and further analysis of forces along with methods of obtaining rotational and clamping motion in a small package are developed in the next section of the report. Figure 13 shows a solid model of the overall positioning system using the Newport products, with the grippers in place as well.

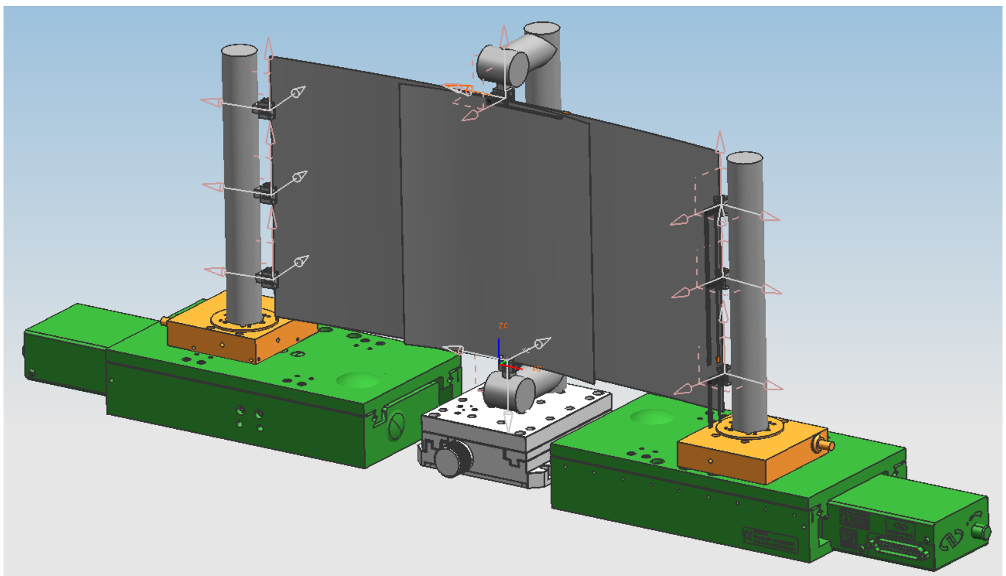


Figure 13: Solid model of the overall concept

Final Development of Concepts:

After outlining satisfactory concepts, further details were worked out for each design. The positioning design required determining how the various linear and rotational stages were to fit inside the nitrogen tank. Consideration had to be given to possible interferences due to the range of mirror sizes. Additionally, designs had to be worked out as to how the grippers would attach to the vertical arms, and the design of the arms themselves.

For the nitrogen tank, further development consisted of detailed models and parts specifications. This aspect of the project was straight forward and thus the final designs in this report are all but ready for prototyping.

The gripper required a significant amount of development after the concept stage. Elements of this development included designing for manufacturability and assembly, actuator specification, and how the grippers would be integrated into the system as a whole. Final designs presented in this report fall short of being ready to prototype. This is due to details such as tolerance and scale that need to be finalized. However, the models are detailed enough to demonstrate that the final system is realizable, and that assembly and interference issues have been accounted for. Analysis which is contained in this report provides further support for the sufficiency of the final gripper design.

Positioning:

For this element of the design task, the group was able to utilize off the shelf parts. Figure 14 shows the positioning design with the mirrors and grippers.

In Figure 14 the positioning system is shown in an orientation that would fit the largest mirror segment. The smallest mirror is also shown in the model. It is important to note the orientation of the translational stages. They must be placed in a manner that does not create interference with the center linear stage when testing smaller mirror segments is in progress.

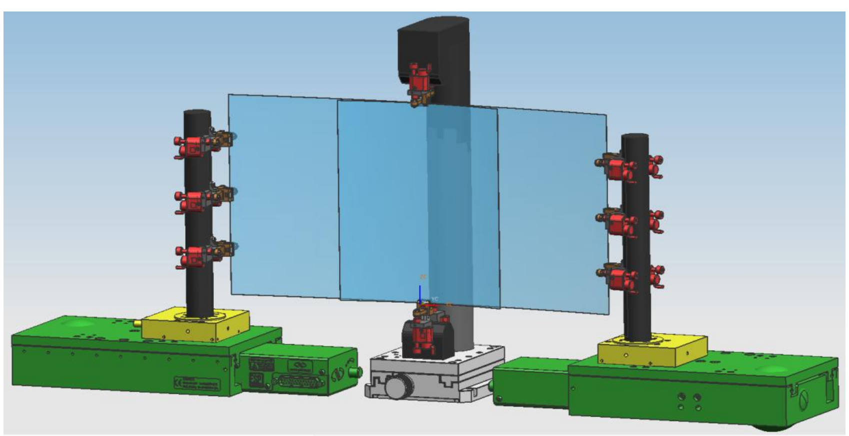


Figure 14: Overall positioning system

The system consists of three linear stages (two green, one gray), two rotational stages (yellow) and three uprights (dark gray). This design is based on the principle that the edges of the mirrors, regardless of size, can be contained in by the same plane. Figure 15 is an illustration of this principle.

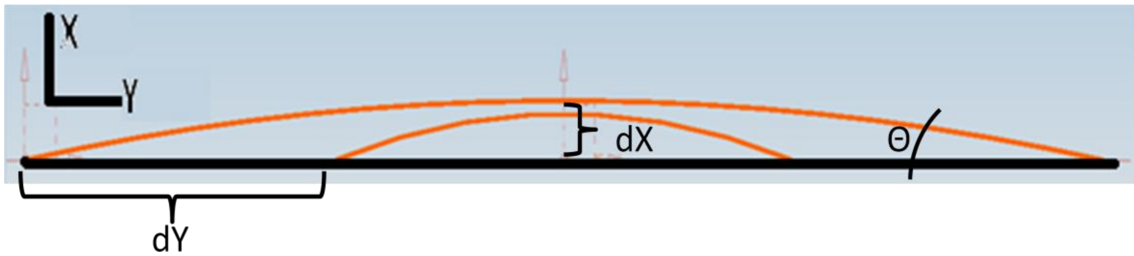


Figure 15: Mirrors in the same plane reduces required degrees of freedom

Mirror profiles of the largest and smallest dimensions are represented by orange lines. The bold horizontal line represents the plane in which the edges of the mirrors, no matter what dimension are able to lie.

In the figure above, dY represents the width difference between mirrors and dX represents the difference in radius. Theta is the angle at which the gripper must be in order to go on to the mirrors. Theta is different for each mirror and must be accommodated. The green linear stages in Figure 14 will adjust for dY, the gray center stage for dX, and the yellow rotational stages for theta. Figure 16 shows theta on the final system. In this figure the bold line is the plane which contains the mirror edges and the light gray line is the mirror. Theta changes according to mirror dimensions which is why the rotational stage (yellow) is needed.

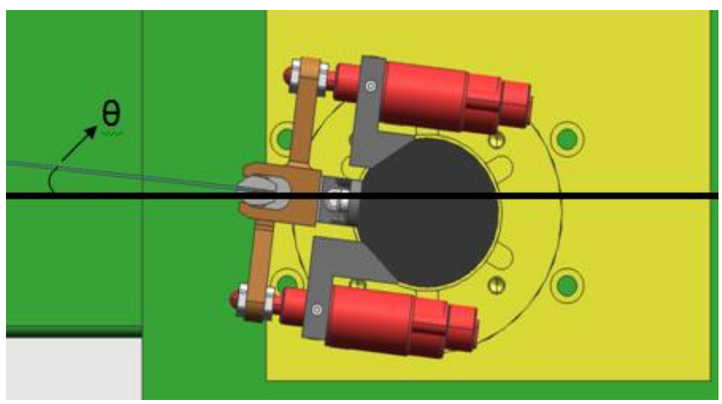


Figure 16: Differential Theta

The uprights (dark gray) which hold the individual gripping mechanisms will be cylindrical with three portions milled flat. Holes will be drilled into these three flat surfaces so the grippers may be bolted in at locations along uprights corresponding to bond locations (as outline in the performance criteria). The flat surfaces will also ensure that each gripper is at the same differential angle θ regardless of upright orientation. Further illustration can be seen in Figure 17 where the uprights are shown with mounting holes exposed as well as with a gripper assembly installed.

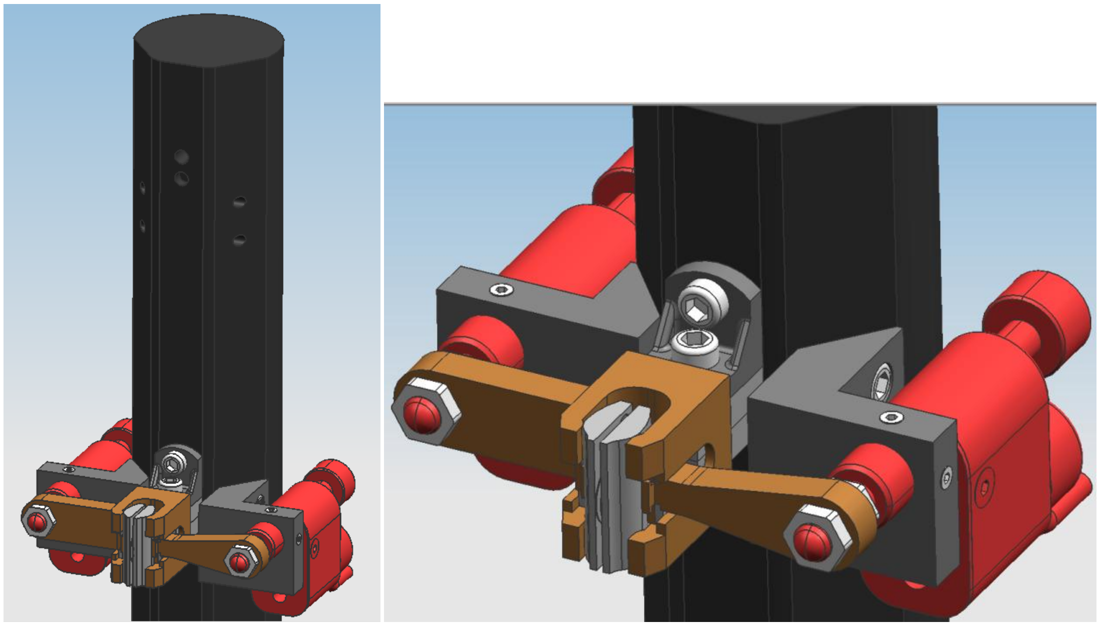


Figure 17: Upright

It is a desirable for the technician running the tests to have minimal interface with the system. The overall positioning system has been designed so the mirror can be placed into the bottom gripper while the top gripper has been rotated out of plane 90 degrees. Once the mirror is secured on the bottom the top gripper may be rotated back into place. From this point forward the automated positioning system will complete the process of securing the mirror. Figure 18 is an illustration of the top gripper being maneuvered.

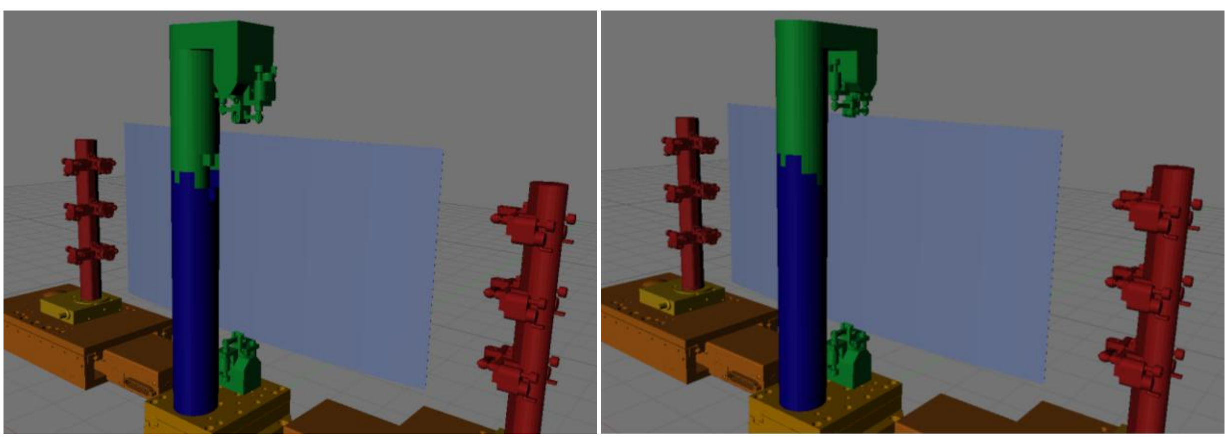


Figure 18: Top gripper maneuvers

Gripper:

Before going into a detailed discussion of the gripper design, some basic definitions of the components of the gripper are needed. The following figures illustrate each of the components and give a definition of each.

Below in Figure 19 is the component about which the entire gripper is assembled. This will be referred to as the Rotator.

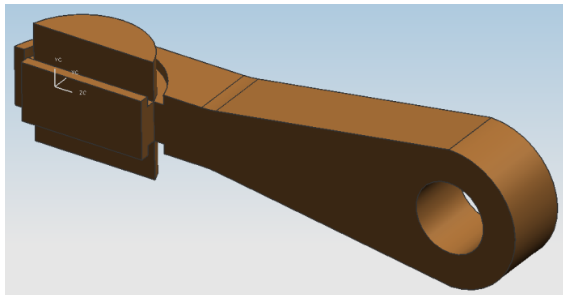


Figure 19: Rotator

The Rotator is fixed between the two halves of the Ground Structure, seen below in Figure 20.

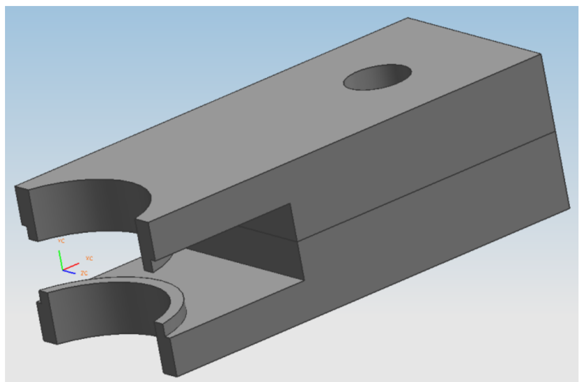


Figure 20: Ground Stucture

The Pad Supports shown in Figure 21, are comprised of two identical halves. They slide onto the Rotator (assembly shown later). The springs fit into the small recesses on the Pad supports and allow the gripper to open and release the glass.

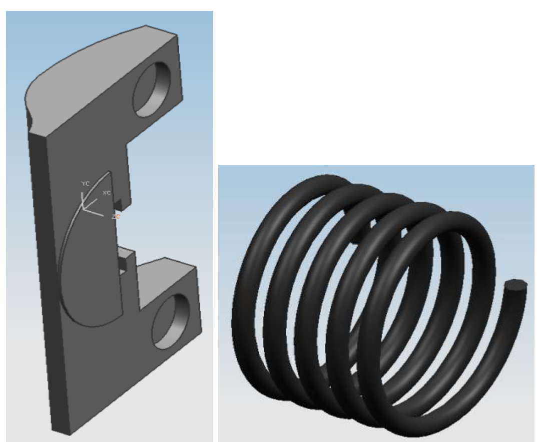


Figure 21: Pad Support and Spring

Shown in Figure 22 is the component called the Wedge, which slides over top of all previous components. It initiates the clamping motion.

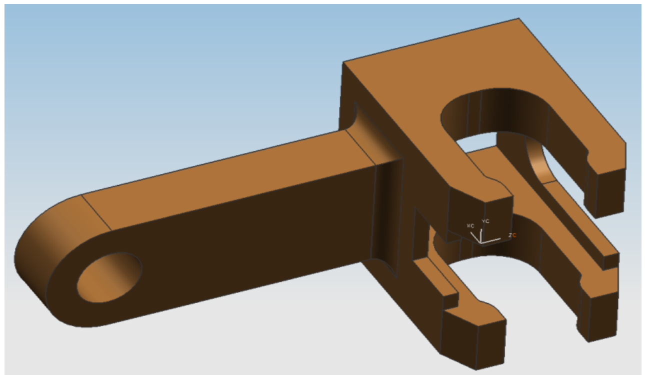


Figure 22: Wedge

Figure 23 shows the Ground Brackets. These attach the gripper mechanism to the positioning system. They also hold the Actuators (Figure 24) which induce the clamping and rotational movements of the gripper assembly.

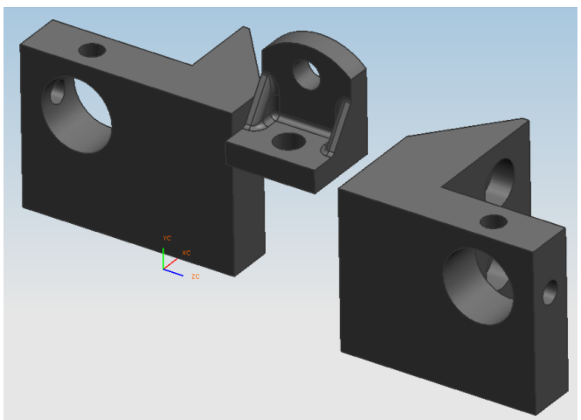


Figure 23: Ground Brackets

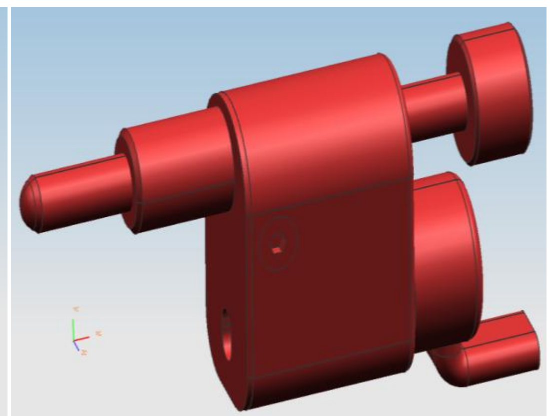


Figure 24: Actuator

The gripper is composed of many moving parts, all of which are very small. Below in Figure 25 an assembly progression of these parts is displayed.

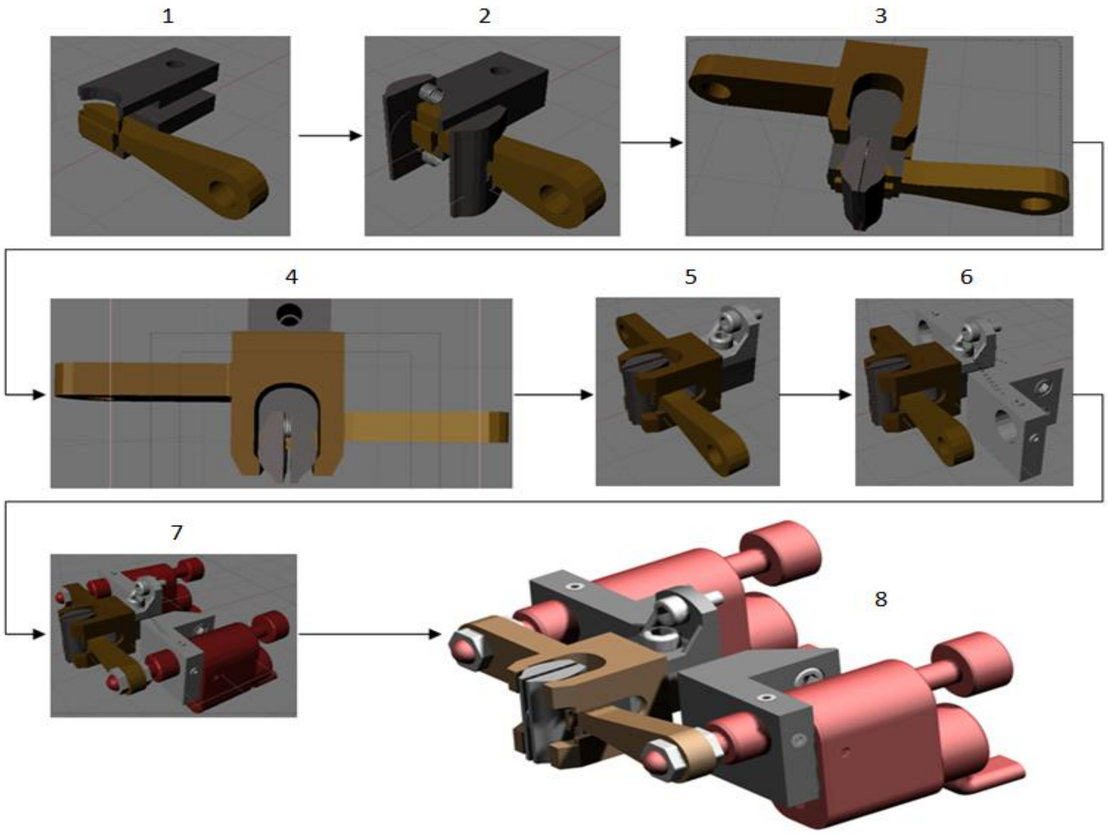


Figure 25: Assembly Progression

Stage 1 shows the Rotator being clamped between the two halves of the Ground. This is followed by stage 2 as the Pad Supports and Springs move into place on the male end of the t-slot. At this point there is nothing holding the assembly together, to secure these components the Wedge must be used. Stage 3 shows the Wedge moving in through the back side of the ground, notice the Pad Supports are squeezed together to allow the wedge to pass by. Once the Wedge is pushed past the Pad supports the Springs force them open and the Wedge is locked in place, this is shown in stage 4. Stages 5 and 6 show the placement of the Ground Brackets, these will be fixed to the uprights in the overall positioning system. The actuators are added in stage 7 and the final modular gripper assembly is in stage 8.

The gripper serves two purposes, to hold the mirror in place and to induce a stress through rotation about the mirrors edge. Both of these tasks are executed by the actuators, one for clamping, and the other for rotation. Because the gripper must only rotate ≈1° the total arc length the actuator must travel is approximately .3mm. Since the distance is so small the rotation may be achieved through a linear actuator. Below Figure 26 shows the gripper moving from its open to closed position. Figure 27 shows the gripper moving through rotation about the mirrors edge.

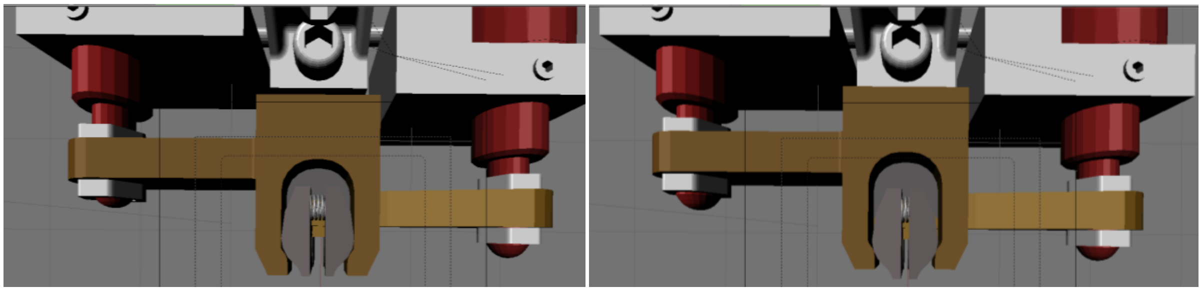


Figure 26: Gripper Clamping

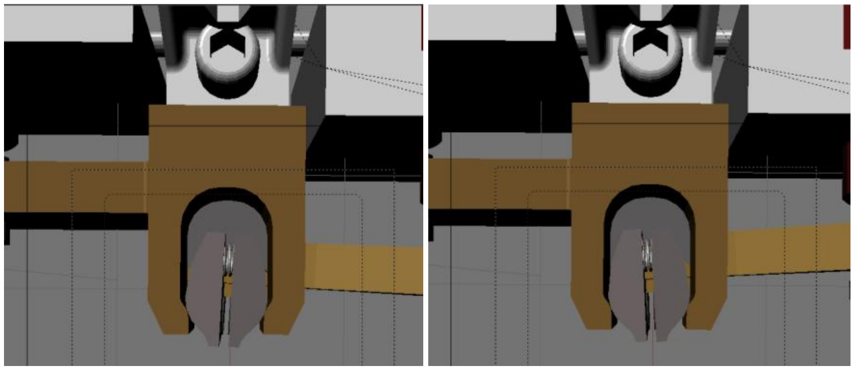


Figure 27: Gripper Rotation

Nitrogen Tank:

Few changes were made to the concept already discussed for the nitrogen tank. The models presented below in Figures 28 and 29 show finalized models. Detailed drawings could easily be made up from these models should the design move to the prototyping phase.

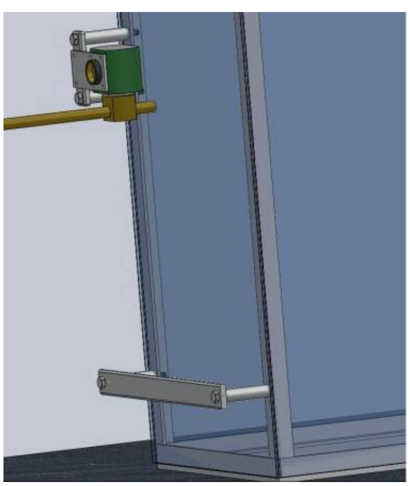


Figure 28: Valve on enclosure

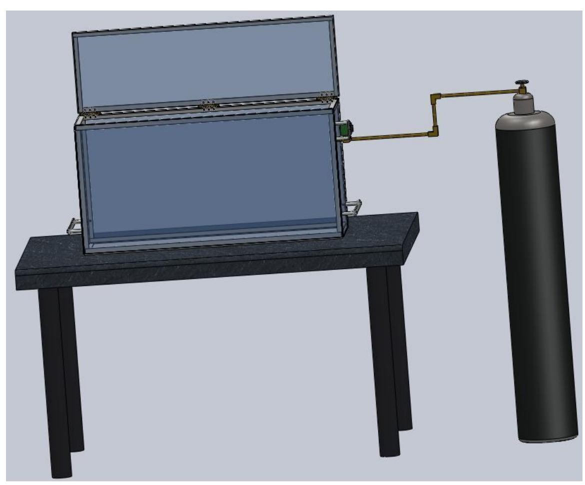
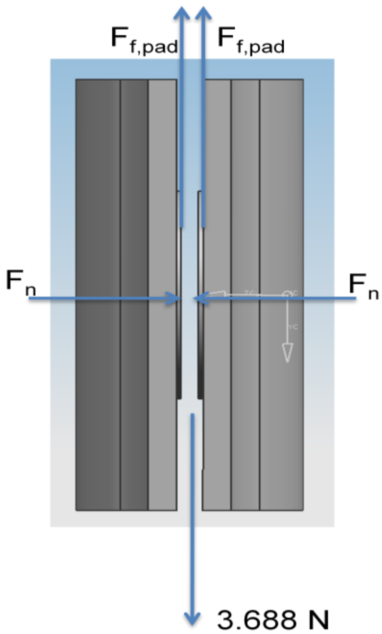


Figure 29: Nitrogen enclosure open

Analysis of Gripper:

The purpose of the gripper is to produce launch like conditions. In order to do this the gripper must be able to induce the correct stress on the mirrors, and hold on while doing so. To find out approximately what forces are needed to fulfill this requirement, the following analyses were performed.

Force:
A static force analysis was performed on the gripper mechanism to determine the necessary actuator forces. This actuator force creates the necessary reaction forces to retain the mirror in the correct location while rotation (inducing stress) occurs.



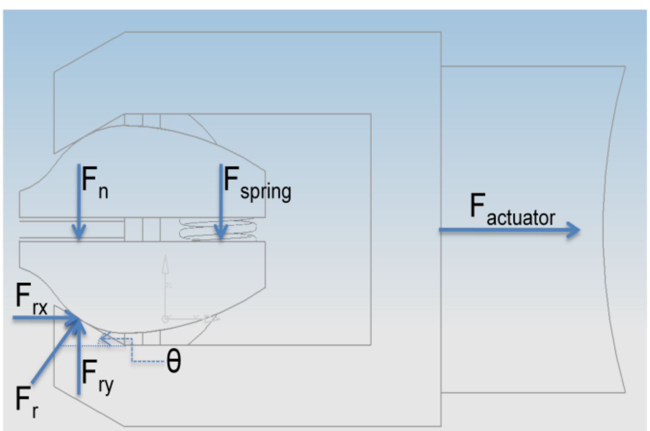
$$Given\ F_{mirror} = M_{mirror}\ g * 40 \quad where \quad M_{mirror} = V * \rho$$

$$\rho = 2510\ \frac{Kg}{m^3} \quad V = 2.99 * 10^{-5}\ m^3 \quad => \quad M_{mirror} = .0752\ Kg$$

$$\therefore\ F_{per\ mirror} = 3.688\ N$$

$$Assuming\ silicon\ bond\ pad\ and\ \mu = .39$$

$$\frac{1}{2} F_{per\ mirror} = \mu F_n \quad => \quad F_n = 4.728\ N$$



$$\sum F_y = -F_n - F_{spring} + F_r \cos\theta = 0 \quad Picking\ \theta = 25^{\circ}$$

$$\mu_{AB,SS,Lubricated} = .15$$

$$F_f = \mu_{AB,SS,Lubricated} * F_n \quad where \quad F_n = F_x = F_{wedge}$$

$$\therefore \sum F_y = -F_n - \mu_{AB,SS,Lubricated} * F_r * \sin\theta + F_r \cos\theta = 0$$

$$=> \quad F_{rx} = 2.371\ N \quad F_{spring} = .356\ N \quad F_{actuator} = 4.742\ N$$

The force required to create deflection of 1 degree in the mirrors is found in the calculation below.

$$y_{max} = -\frac{Fl^3}{3EI} \quad Where:\ E = 46.2\ GPa \quad l = 3mm\ and\ y_{max} = .0523mm$$

$$I = \frac{.003 * .0004^3}{12} = 1.6E^{-14}$$

$$\therefore F_{mirror} = 4.295N$$

Comparatively FEA returned a value of F_{mirror}=4.74N; this value will be used for further calculations. The force to rotate the mirrors is designed to come from an actuator, as shown in Figure 30. Thus based on the value for F_{mirror} and using a calculation such as the one seen below, a force requirement for the actuator was determined.

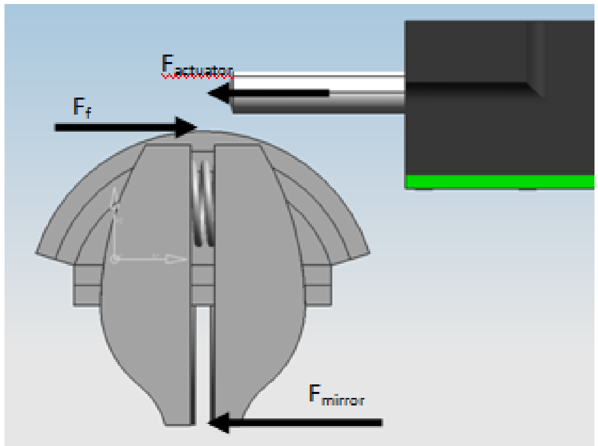


Figure 30: Actuator creates the force for rotation.

$$\sum M = -F_{mirror} * (.003) - F_f * (.0043526) + F_{actuator} * (.005) = 0 \;\therefore\; F_{actuator} = 4.907N$$

Surface Fatigue/Wear:

Given the sheer number of mirrors that need to be tested, it is quite clear that surface fatigue and wear were important aspects to be considered. Surface wear occurs when material is lost due to interaction with the environment (Chattopadhyay 2). Surface fatigue is the result of cyclical application of high contact stresses (Norton 465). In this design, the concern is the contact area between the pad supports and the wedge. At these locations, the surface interaction can be characterized by rolling and sliding, which is why both wear and fatigue are a concern. However, the onset of these negative effects is caused when the applied stress is greater than the yield strength (Chattopadhyay 14). Thus by selecting materials with high yield strengths the possibility of wear and fatigue can be reduced (Norton 466). Analysis of the contact area shows the applied stress to be a maximum of about 7.7 MPa at the surface. This is well below the yield strength of most metals, including aluminum bronze (240 MPa) and stainless steel (205 MPa) which are the materials suggested by NASA. According to Norton, all materials will experience surface failure if exposed to enough stress cycles, there is no endurance limit.
By using the equation Norton provides for predicting cycle life, the group was able to roughly estimate the life of the gripper design at 4x10^45 cycles using the recommended materials. So all things considered, wear and surface fatigue should not create a performance issue for the current design. The equations below were used to calculate the values that have just been discussed.

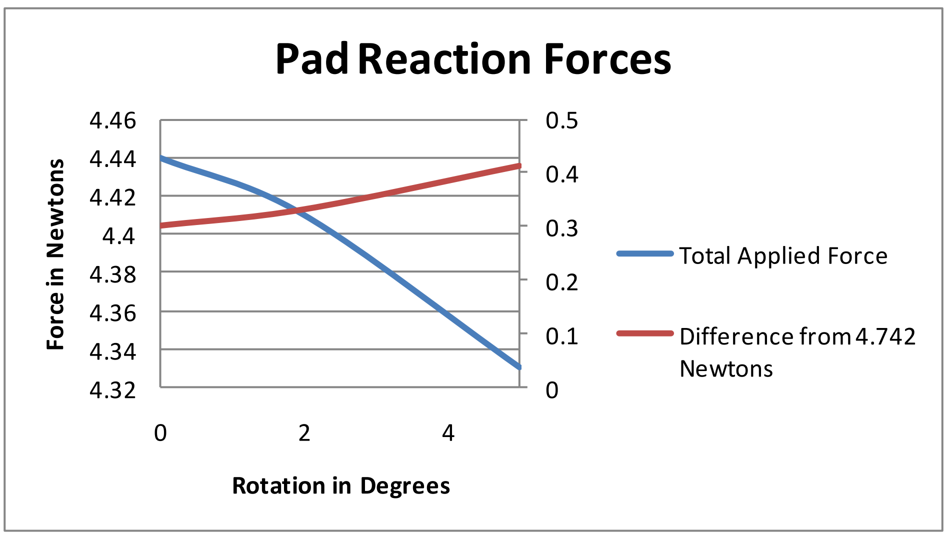
$$P_{max} = \frac{2F}{\pi a L} \text{ where } L = depth$$

$$a = \sqrt{\frac{2(m_1 + m_2)F}{\pi B L}} \quad \text{where } m_1 = \frac{1 - v_1^2}{E_1} \text{ and } m_2 = \frac{1 - v_2^2}{E_2}$$

$$B = \frac{1}{2}\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$

FEA:
After the preliminary static force calculations were made, an analysis using Solid Works FEA software was used. This was to verify that the gripper was capable of applying the same clamping force after strain, friction and rotation were accounted for. The purpose of the FEA study was to characterize stresses induced, deflection and contact force between moving parts. The study was performed using the forces found from the static calculations. In the simulations all friction coefficients were assigned to mated parts and degrees of freedom were defined. The portion of the grounding structure that is to be attached to the positioning system was fixed. Although a mirror was not present in the model the force was accounted for. All other parts were allowed to move as they would in the actual system.

The simulation was run in three positions, zero, 2 and 5 degree rotations of the gripper. Although the mechanism will most likely never rotate past 1 degree we wanted to verify that the clamping force applied would remain constant through any rotation. It was found that the amount of force used in strain and friction accounts for an average loss of .317 Newtons. See plot 1 below.



Plot 1: Pad Reaction Forces

It can be found from this data that the compressive force on the glass varies about 6.7% throughout the rotation from 0-5 degrees. The forces in the preceding figure are the reaction at the pads based on the force applied to the wedge as outline before. These reactions average .4N less than what is needed, thus the force applied to the wedge must be increased in order to meet the required compressive force.

The maximum stress incurred by the mechanism is at the interface of the rotator and the grounding structure. Because of the angle at which the wedge contacts the pad support most of the force is in the y-component, therefore pushing the rotator into the ground structure. Some stress concentrations can be seen in Figure 31 below. However, this is due to two reasons. First the mesh is less dense at these points because they are less critical and second the model stresses have been scaled because they are so low. The factor of safety for the highest stress concentration is on the order of 20.

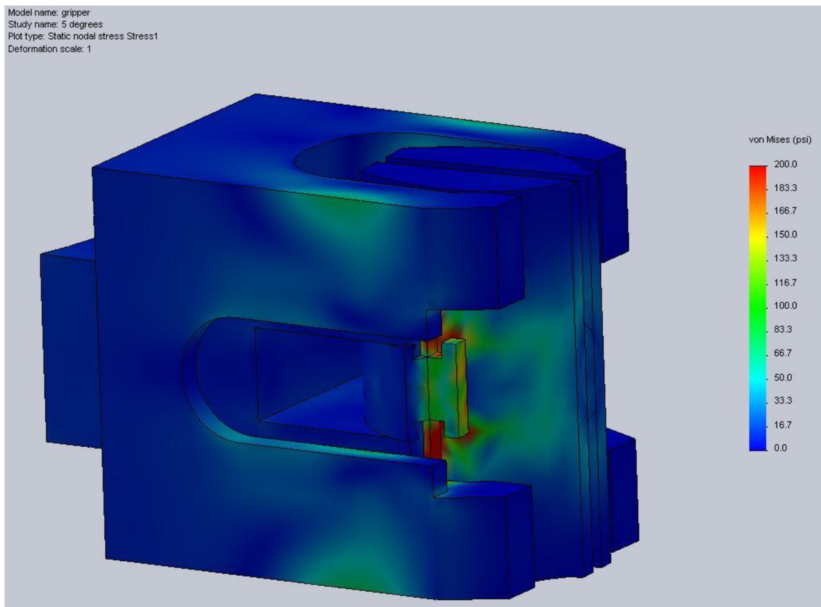


Figure 31: FEA stress analysis

A concern for the design was the possible deformation that may occur in the arms of the wedge when the clamping force is initiated. The deformation can be seen in Figure 32. Maximum deflections are on the order of 100 nanometers therefore fatigue due to repetitive deflection is negligible.

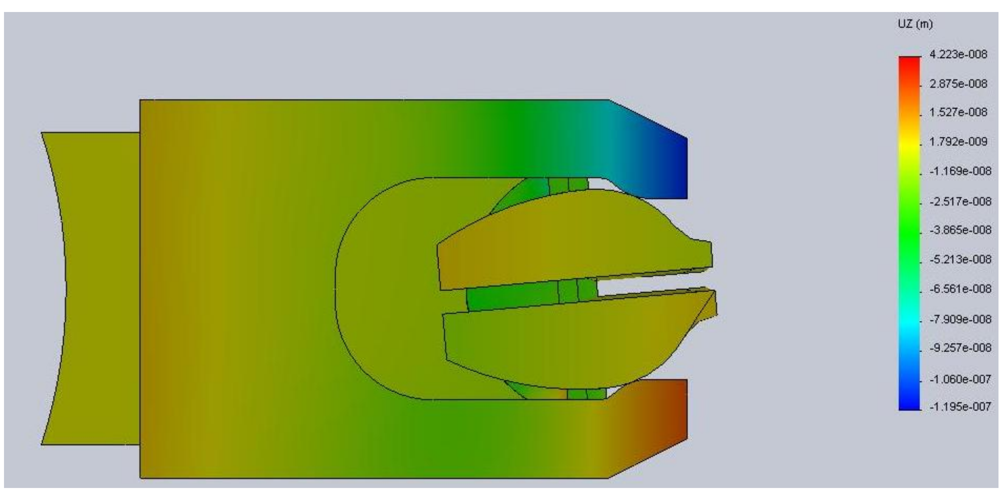


Figure 32: FEA deformation analysis

Actuator Compatibility/selection:

When selecting the actuators that control the movement of the gripper, many constraints came into play. Due to the size of the grippers, it was desired that the actuators be as small as possible. However, the actuator also needed to have the ability to apply at least 5N. This force was determined in the previously outlined analysis of the gripper design. Additional factors included resolution of the actuator's step size. High resolution is needed for smooth operation and low error. Both of which are imperative qualities due to the scale of movement required. There was some difficulty in finding a sufficient actuator. After a thorough search, a Pico Motor model 8353 from New Focus products was decided upon. This particular actuator is readily available from vendors such as Newport. A downside to this actuator is that the piston rotates and the gripper design had to be modified accordingly. Nonetheless, the actuator meets all of the previously mentioned requirements. Technical specifications can be seen in Table 1. Lifetime of the actuator is an important specification in addition to the resolution and force capabilities. This is because a large number of mirrors need to be tested, and because the actuators are expensive. The final drawback to this actuator, as has been alluded to, is that the cost is approximately $550. With the need for 16 per testing system the cost for actuators is close to $9000.

Minimum Incremental Motion	<30 nm
Angular Resolution (1)	0.6 µrad
Maximum Load	3 lbs (13 N)
Torque	2 oz-in (0.014 N·m)
Lifetime (2)	>$1.5x10^8$ steps
Linear Travel	0.50" (12.7 mm)
Speed (@ 2 kHz pulse rate)	N/A
Max Speed (@ 1.75 kHz pulse rate)	1 mm/min.
Operating Temperature	10-40 °C
Mounting	0.25" (6.4 mm) Shank
Connector Type	4-Pin
Cable Length	7 feet (2.1 m)

Table 1: Actuator specifications

Cost Analysis:

The sources of costs for this project have been divided into the categories of manpower, parts for prototyping, positioning, materials, outsourcing, and incidental costs. Manpower includes the engineers, technicians, and programmers needed for the project. These positions may be half time or full time as needed, and for varying duration. For prototyping, an estimated cost of $35,000 was set aside for the gripping mechanism alone and another $15,000 for other costs that may arise. The stages and actuators that will possibly be used for the mobility of the design have been tentatively chosen. Other costs have been allotted for materials needed to mount the devices and build the enclosure, and assemble the prototype. Outsourcing pertains to costs arising from testing and analysis that the design team is not able to perform. The final category is incidental costs which would include items and services not belonging to the other categories. Items in this category may include software, training, and materials for publishing the progress of the project.

Cost estimations are based on internet research and the suggestions of those familiar with this type of project. One particular suggestion is that of an adjustment factor, or overhead factor. This adjustment creates a buffer in the cost analysis to cover replacement costs, cost increases, or wage changes. Table 2 shows the projected costs.

Category	Positon/Duration/Description	Cost	Adjustment	Total
Manpower	Senior Engineer/4 months	$ 25,000.00	2	$ 50,000.00
	Engineer/4 months	$ 16,250.00	2	$ 32,500.00
	Engineer/4 months	$ 16,250.00	2	$ 32,500.00
	Engineer/4 months	$ 16,250.00	2	$ 32,500.00
Prototyping	Gripper Material for testing	$ 500.00	2	$ 1,000.00
	Gripper mechanism proof of concept	$ 17,000.00	2	$ 34,000.00
	Unforseen costs	$ 7,500.00	2	$ 15,000.00
Positioning	Newport VP-25X Compact Linear Stage	$ 5,022.00	1	$ 5,022.00
	Newport GTS150 Linear Stage	$ 6,650.00	2	$ 13,300.00
	Newport SR50PP Rotational Stage	$ 1,978.00	1	$ 1,978.00
	Actuators	$ 510.00	16	$ 8,160.00
Materials	Seamless SS tube 304/3041	$ 36.48	1	$ 36.48
	Aluminum 6063 T-52 Angle (34')	$ 19.07	1	$ 19.07
	Lexan 9034 .125"x4'x8'	$ 168.14	1	$ 168.14
	Gas spring	$ 25.00	2	$ 50.00
	Hinges (3"L x 1 3/4" W)	$ 3.00	6	$ 18.00
	Aluminum 6061 T-6 Plate .25"x12"x48"	$ 88.50	1	$ 88.50
	Soleniod 2-way Valve	$ 50.35	1	$ 50.35
	Other Materials and Assembly	$ 24,800.48	1	$ 24,800.48
Outsourcing	Stress Analyst/4 months/Part-time	$ 11,875.00	2	$ 23,750.00
Incidental	Software	$ 5,000.00	2	$ 10,000.00
	Programming	$ 5,000.00	2	$ 10,000.00
	Training	$ 2,500.00	2	$ 5,000.00
	Foam Board for poster presentation	$ 13.49	2	$ 26.98
	Printing for poster	$ 16.00	2	$ 32.00
			Gross Cost:	$ 300,000.00

Table 2: Anticipated costs

Future Work:

The designs that have been discussed in the report are not yet to the prototyping stage. The work that remains pertaining to the models includes tolerances, final material selection, and finishing details such as hardware specification. Apart from the models, work remains in the area of automating the system. This includes designing a feedback control system that minimizes error. This is done using sensors to collect physical data about what the system is doing, and feeding that data into a computer control system. The controller then compares the physical data to desired data about what the system should be doing. A more detailed description of this process, as well as a preliminary block diagram design is included in the following section.

Controls Logic:

One of the elements of the system is that the final product will be automated. An integral part of the automation that will be a feedback control system. This will regulate the positioning and gripper system in such a way that error is reduced to a minimum.

Control of the positioning system is outlined in the following block diagram (Figure 33). Inputs are based on the movements required to position the grippers on the mirrors. These movements are based on the size of the mirror being tested. In the automated system, it is envisioned that a unique code which contains dimension data will be assigned to each mirror. Thus based on a code entered by a technician and using a combination of linear and rotational movements, the grippers will be moved into place. Data pertaining to the actual location of the grippers will be fed into the controller and compared to where the grippers need to be. This will create an error that can be corrected by the controller.

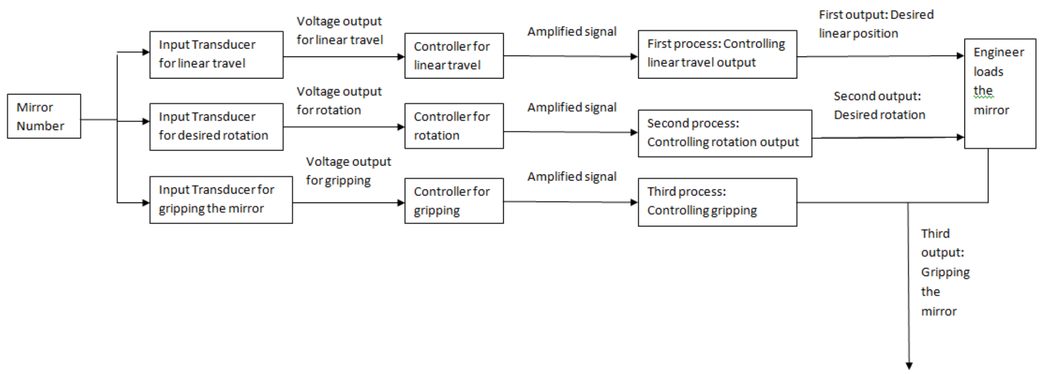


Figure 33: General positioning system block diagram

Another block diagram which is shown in Figure 34 shows a block diagram for control of the gripper. This pertains to inducing the correct launch stress on the mirror, and gripping the mirror with enough force such that it does not slip out of the gripper during testing. Similar to the positioning system, physical data concerning the gripper will be compared to desired data, and an error between the two created. The error is then corrected by a suitable controller and thus minimized.

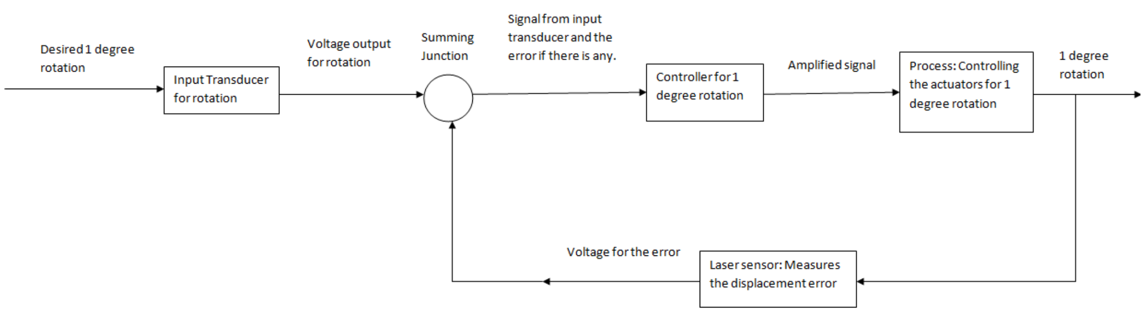


Figure 34: General gripper control block diagram

Conclusion:

Each task outlined by the performance criteria and objectives have been addressed. Designs have been modeled in detail, and shown to be viable through analysis. The positioning system utilizes current technology which keeps in house manufacturing to a minimum for this element of the overall system. Conversely, the gripper will require extensive custom manufacturing resulting from the uniqueness of the designs and requirement of precision. Concerning control of the test cell environment, a nitrogen tank design has been detailed. It consists of a simple design and uses off the shelf parts. The design in its current state is steps away from being ready to prototype.

For completion of the proposed system, several items must be addressed. Models require further refinement in order to be ready for manufacture. Some general testing needs to be done which will yield empirical data such as friction coefficients. Once this data has been compiled, a mathematical model can be found on which to base control system architecture. Upon a control system being implemented the proposed design may approach completion and ultimately be utilized for proof testing of flight mirror segments.

Appendix

References:

Chattopadhyay, R. Surface Wear: Analysis, Treatment, and Prevention. Materials Park: ASM International, 2001.

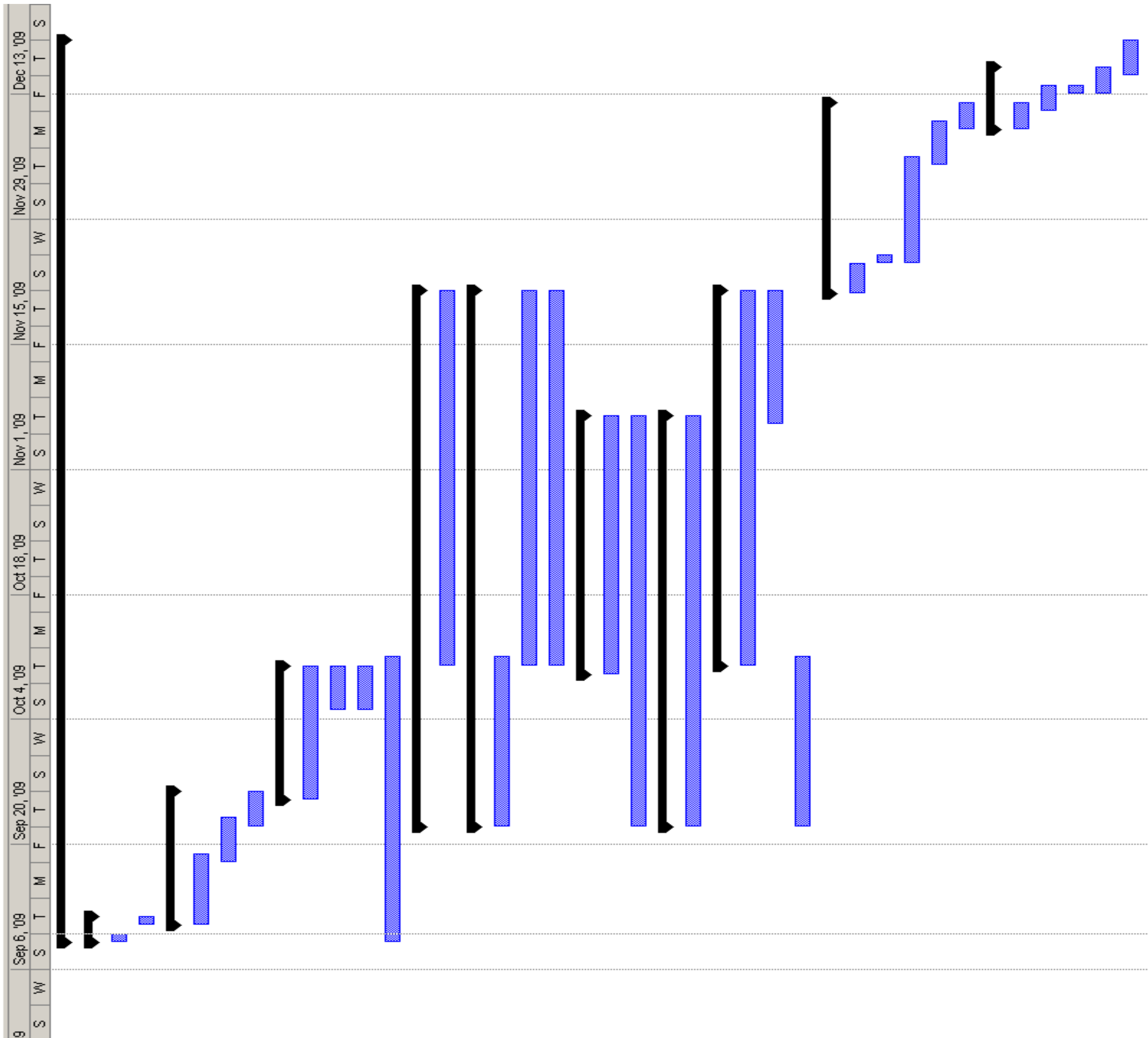
David Robinson, Ryan McClalland. "Mechanical Overview of the International X-Ray Observatory." IEEE (2009).

Norton, Robert L. Machine Design: An Integrated Approach. Upper Saddle River: Pearson Prentice Hall, 2006.

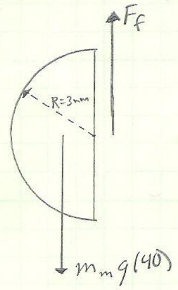
Ryan S. McClalland, Timothy Carnahan, Michael Choi, David Robinson, Timo Saha. "Preliminary Design of the International X-Ray Observatory Flight Mirror Assembly." SPIE (2009).

Project Timeline:

Task Name	Duration	Start	Finish
Senior Design	**92.04 days?**	**Wed 9/9/09**	**Fri 12/18/09**
Deliverable I	**2.38 days?**	**Wed 9/9/09**	**Fri 9/11/09**
Performance Criteria	1 day?	Wed 9/9/09	Thu 9/10/09
Cost Analysis	1 day?	Thu 9/10/09	Fri 9/11/09
Deliverable II	**14.38 days?**	**Fri 9/11/09**	**Fri 9/25/09**
Preliminary Concept Generation	7.38 days?	Fri 9/11/09	Fri 9/18/09
Preliminary Concept Drawing	4.38 days?	Fri 9/18/09	Tue 9/22/09
Discussion of Concepts	3.38 days?	Tue 9/22/09	Fri 9/25/09
Deliverable III	**14.38 days?**	**Fri 9/25/09**	**Fri 10/9/09**
Cost Estimation	14.38 days?	Fri 9/25/09	Fri 10/9/09
Discussion of Chosen Concept	4.38 days?	Mon 10/5/09	Fri 10/9/09
Introduction	4.38 days?	Mon 10/5/09	Fri 10/9/09
Mid-Semester Presentation	31.38 days?	Wed 9/9/09	Sat 10/10/09
Design Review	**59.38 days?**	**Tue 9/22/09**	**Fri 11/20/09**
Draft of Design Report	41.38 days?	Sat 10/10/09	Fri 11/20/09
Gipper Design	**59.38 days?**	**Tue 9/22/09**	**Fri 11/20/09**
Mechanisms	18.38 days?	Tue 9/22/09	Sat 10/10/09
Modeling	41.38 days?	Sat 10/10/09	Fri 11/20/09
Simulation	41.38 days?	Sat 10/10/09	Fri 11/20/09
Compliance Determination	**28.38 days?**	**Fri 10/9/09**	**Fri 11/6/09**
Experimental Determination	28.38 days?	Fri 10/9/09	Fri 11/6/09
Supporting Structure	45.38 days?	Tue 9/22/09	Fri 11/6/09
Translation Mechanics	**45.38 days?**	**Tue 9/22/09**	**Fri 11/6/09**
Linear Feedback	45.38 days?	Tue 9/22/09	Fri 11/6/09
Rotation Mechanics	**41.38 days?**	**Sat 10/10/09**	**Fri 11/20/09**
Shaft Encoding	41.38 days?	Sat 10/10/09	Fri 11/20/09
Material Specification	14.38 days?	Fri 11/6/09	Fri 11/20/09
Actuator Selection	18.38 days?	Tue 9/22/09	Sat 10/10/09
Final Design Report	**12.71 days?**	**Fri 11/20/09**	**Fri 12/11/09**
Review of Previous Reports	0.67 days?	Fri 11/20/09	Mon 11/23/09
Assign Sections	0.33 days?	Tue 11/24/09	Tue 11/24/09
Compose Second Draft	6.04 days?	Tue 11/24/09	Sat 12/5/09
Editing	4.38 days?	Sat 12/5/09	Wed 12/9/09
Final Compilation	2.38 days?	Wed 12/9/09	Fri 12/11/09
Design Poster	**6.38 days?**	**Wed 12/9/09**	**Tue 12/15/09**
Layout Design	2.38 days?	Wed 12/9/09	Fri 12/11/09
Photo, Data, and Text Selection	2.38 days?	Fri 12/11/09	Sun 12/13/09
Proofing	1 day?	Sun 12/13/09	Mon 12/14/09
Printing	2.38 days?	Sun 12/13/09	Tue 12/15/09
Design Showcase	3.38 days?	Tue 12/15/09	Fri 12/18/09



Calculations:



$M_m g\,40 = F_f$ for all 8 points

for singular point:

$\frac{M_m g\,40}{8} = F_f$ where: $g = 9.81\ m/s^2$

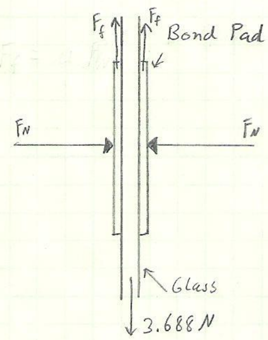
Volume of largest mirror:

$29955.3029\ mm^3 \Rightarrow 2.99 \times 10^{-5}\ m^3$

Density of D263: $2510\ kg/m^3$

$M_m = .0752\ kg$

$F = \frac{.0752(9.81)(40)}{8}$ $F = 3.688\ N$ per point



$2F_f = 3.688$

$F_f = 1.844\ N$

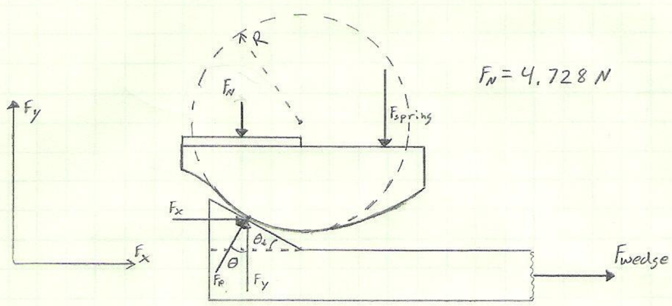
we assume the bond pad is silicon and the $\mu = .39$

$1.844 = \mu F_N \therefore \boxed{F_N = 4.728\ N}$

$F_N = PA \quad A = \pi(.003)^2$

$\therefore P = 167226\ N/m^2$

or $167.226\ kPa$



$F_N = 4.728\ N$

$\sum F_y = -F_N - F_{spring} + F_R\cos\theta = 0$ picking $\theta = 25°$

Material assumptions: Ground is stainless
grippers are stainless
wedge is aluminum-bronze
rotation/translation is aluminum-bronze

$\mu_{AL,BN,Lubricated} = .15$

In the gripper to gripper translation interface:

$F_f = \mu F_N$ where $F_N = F_{x,wedge}$

F_f is the minum spring force

$\therefore \sum F_y = -F_N - \mu F_R \sin\theta + F_R\cos\theta = 0$

pick $\theta = 25°$ $\mu = .15$
$F_N = 4.728\ N$

$\Rightarrow F_R = 5.609\ N$

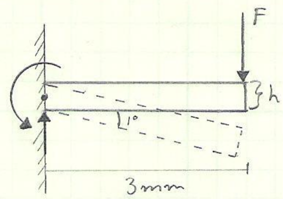
$F_{wedge} = F_R \sin\theta$

$\boxed{F_{wedge} = 2.371\ N}$

$F_{spring} = .15 F_R \sin\theta$ $\boxed{F_{spring} = .356\ N}$

$F_{actuator} = 2 F_{wedge}$

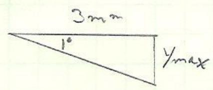
$\boxed{F_{actuator} = 4.742}$



rotate 1°

$$y_{max} = -\frac{Fl^3}{3EI}$$

$E_{Glass} = 46.2\ GPa$



$$\tan(1) = \frac{y_{max}}{3\,mm} \Rightarrow y_{max} = .0523\ mm$$

$l = 3\ mm$

~~$I = \frac{m}{12}(h^2 + l^2)$~~ ~~$m = \frac{lh\rho}{g}$~~ $\rho = 2.51\ g/cm^3$

$$\frac{g}{cm^3} \cdot \frac{1\,kg}{1000\,g} \cdot \frac{1000000\,cm^3}{1\,m^3} \Rightarrow \rho = 2510\ kg/m^3$$

~~$m = \frac{(.003)(.003)(.0004)(2510)}{9.81}$~~

$$I = \frac{m(h^2 + l^2)}{12} \qquad m = \frac{lh\rho}{g} = \frac{.003(.003)(.0004)(2510)}{9.81}$$

$$\frac{kgs}{m}(m^2) = kgs\,m \qquad \frac{m^3(kg/m^3)}{m/s^2} = \frac{kg \cdot s}{m}$$

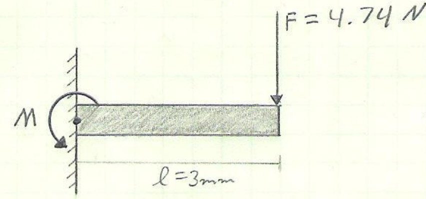
~~$\frac{N\,m^3}{N/m^2\ kgs\,m} = \frac{m^4}{kgs}$~~

~~$I_x = 3.0001$~~ $I_x = \frac{.003\,(.0004)^3}{12} = m^4$

$$\frac{N\,m^3}{N/m^2\ m^4}$$

$$y_{max} = \frac{Fl^3}{3EI} = \frac{F(.003)^3}{3(46200000000)\,I_x} = .0000523$$

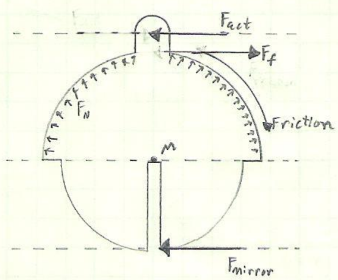
$F = 4.295\ N$



$M = 4.74(.003) = .01422 \ Nm$

The actuator is 5mm from the center of rotation

$F_{act, mirror} = \frac{.01422}{.005} = 2.844 \ N$ to overcome force from mirror



$\mu_f = .15$

$F_{friction} = \mu F_N$

$F_N = F_{wedge,x} = F_R \sin\theta = 2.37 N$

$\therefore \ F_f = 2.37$

$\Sigma M_m = -F_{mirror}(.003) - F_f(.0043526) + F_{act}(.005) = 0$

$\therefore \ F_{act} = 4.907 \ N$