Thrust Vector Control

Stellar Explorations

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Statement of Disclaimer

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Abstract

The objective of this project was to design, build and test a thrust-vectoring system for a solid booster rocket. The project was sponsored by Stellar Exploration. A two member team of Harsimran Singh and Dane Larkin worked toward the objective.

CHAPTER 1-Introduction

The project described in this document is a thrust vectoring system that will be implemented in Stellar Exploration's solid fuel test rocket. This document will outline Background research on the status of thrust vector control, the project requirements and objectives, how the success of the project will be evaluated, and prototype design. In addition the methods used and the timeline the project will follow will be thoroughly outlined. The success of this project is dependent on the cooperation of Dane Larkin and Harsimran Singh and on the participation of their sponsor Stellar Exploration at each part of the process. Dane Larkin and Harsimran Singh are responsible for delivering a viable prototype to Stellar Exploration. Stellar exploration is expected to review the progress and design reviews at each stage of the design. The final goals of this project are to design and build a functioning thrust vectoring system for use by Stellar Explorations.

CHAPTER 2-Background

Stellar Exploration Incorporated is a small technology company which focuses on low-cost scientific and space exploration projects. The company hires approximately three full time engineers. Stellar Exploration requires a thrust vectoring system for its Silver Sword rocket. By allowing operators to control the direction of thrust, the thrust vectoring system will make up for the drag produced and loss in performance incurred by the rocket fins. What follows is a list of background research on different thrust vectoring systems which have been used in the past.

Fixed nozzle systems

Fixed nozzle systems as the name states refer to nozzles that are solid mounted in the frame of the vehicle. The flow inside the nozzle itself is then changed to move the thrust vector. These were some of the first systems of thrust vector control developed in the Polaris and minute man rockets. The classification of fixed nozzle systems falls into these categories, secondary injection systems where the flow is the nozzle is changed by the addition or rerouting of fluid flow, and mechanical deflection where a mechanical element changes the direction of flow.

Liquid injection

Liquid injection encompasses any addition of a fluid that changes the characteristics of the combustion. By changing the combustion on one side of the nozzle the thrust vector can be changed. The method of injection, as well as the fluid that is injected, are both topics of much debate and research. one of the biggest decisions when considering this method of thrust vectoring is the liquid that will be used the two main divisions are whether the liquid will inhibit the combustion or contribute to combustion. Combustion inhibitors will tend to cool one side of the nozzle while combustion contributors will add fuel or other additives to increase thrust on one side of the nozzle. Advantages of this method of thrust vectoring are that it has fast response capability and add to thrust by adding mass to the fluid stream. The disadvantages of this system are that they are heavy and the amount the valve opens is not linearly related to the rate of change of the thrust vector.

Gas injection

Gas injection is very similar to liquid injection the difference being that instead of new gas being added to the fluid stream combustion gasses are rerouted from behind the nozzle into the diverging section changing the flow through the nozzle itself. The advantages of this method are that additional fluids do not need to be stored onboard and so the system overall is lighter in weight. The downside to this method however, is that the hot combustion gasses

have to be routed through valves. In stationary tests the valves could never be made reliable enough to consider further testing.

Jet vane

The jet vane deflector is characterized by any fin or plate that is directly placed in the exiting flow of the nozzle. As the plate or fin moves it will cause the flow exiting the nozzle to deflect from the centerline of the rocket. Advantages of these systems are that the forces on actuators are low and thus they can be capable of quick response times. Since the blades are directly in the exhaust this causes the designer to make one of three choices, the propellant can burn relatively cool, the propellant can burn for relatively short period of time, or the vanes can be made of exotic heat resistant material. The other problem with this method is that a large deflection of the vane must be made in order to cause a change in the thrust vector. The large deflection and the inherent drag of fluid on the vanes reduce thrust.

Jetavator

The jetavator is a similar concept to the jet vane the difference being that instead of the vanes being in the flow the nozzle they are positioned around the perimeter of the nozzle and are parallel to the flow. This system has similar heat restrictions to the jet vane. Advantages include that the deflection of the jetavator is linearly related to the deflection of the thrust vector. The downsides of this design, besides the heat considerations mentioned in the jet vane section, are that the system can be heavy and that the jetavator restricts the exit diameter. Notable applications are F-16 and the Polaris A-1.

Fig 1. Jetavator Setup

Jet tab

The jet tab system involves a plate at the end of the nozzle that can be rotated into and out of the nozzle disrupting the flow. Initial advantages that the thrust deflection is proportional to the area of the tab that is exposed to the flow this makes controlling the system relatively easy. The downside of this system is that when the tab is in the fluid stream the flow stalls on the tab. The stalled flow causes lots of erosion on the inside of the nozzle. Testing was stopped on this method because of the material erosion problems.

Movable nozzle

Movable nozzles control the direction of the exiting flow by having the nozzle itself move. These are more recently developed technologies. The reason that they were developed more recently, and are now becoming more popular, is that it was difficult to support the thrust on the nozzle while sealing the gasses and remaining flexible. Moveable nozzle systems are broadly categorized into the type of flow inside the nozzle.

Flexible joint

The flexible joint system is the simplest design of the movable nozzle systems. The system uses a seal that attaches on the outside of the movable nozzle and the other end attaches to the rigid structure. The nozzle can now be designed without the concern of sealing the joint since the flexible seal will hold the nozzle pressure. The advantage of these systems is that there are no split lines and thrust loss is negligible. Disadvantages to this design are that the seal will be exposed to high temperatures

Rotatable

Initially rotatable nozzles were canted in a direction and needed to be used in groups to manage roll pitch and yaw these systems required large bearings and the movement is highly difficult to control as all three nozzles have to be in synchronization. Future developments resulted in a segmented nozzle that has three segments each attached by cuts that are not perpendicular to the axis of the rocket by moving the segments relative to each other the angle of the exiting flow is changed.

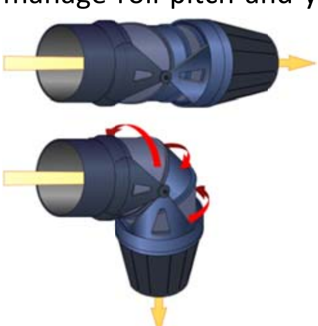


Fig 2. Rotating Segment Setup

The design of this nozzle is just as the name says it resembles the motion of a ball and socket with one inner ball connecting to the rigid frame and the outer ball remaining mobile as the flow transfers from the converging portion of the nozzle to the diverging nozzle it crosses the split line between the inner ball and outer ball.

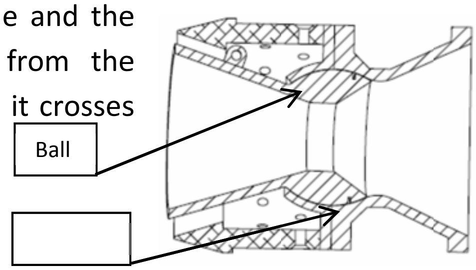


Fig 3. Ball and Socket Setup

Internal maneuvering vanes

Vanes are placed along the inside wall of the rocket nozzle. Being in the direct path of the hot thrust gases, the vanes are maneuvered by actuators to direct the thrust in order to better guide a rocket projectile. This type of system is common on surface-to-air missiles.

Fig 4. Internal Maneuvering Vanes

CHAPTER 3-Design Development

3.1-Objectives

This team seeks to develop a thrust vectoring system for the Sword Fish rocket built by Stellar Exploration. The thrust vectoring system will help steer the rocket through the fifteen second boost phase, and will go un-functional thereafter. As described in the background, many solutions currently exist to vector a rocket's thrust. However, since most of these solutions may not suit Stellar Exploration's requirements, we have put together a table of specifications using the Quality Function Deployment (QFD) method to translate customer requirements to engineering specifications. The solution(s) which best matches these specifications are further examined and given more consideration for development. The Appendices section provides a house of quality that this team used in the QFD method. This team also provides a specifications table in the Appendices section.

This team approximated the target values at the bottom of the house of quality, and intends to submit the target values for review and possible modification by Stellar Exploration. Each target value is assigned a relative weight. For example, the target value regarding heat requirements has a relative weight of 14.3%. This figure indicates the importance of heat requirements relative to other design specifications.

The derivation of relative weight proceeds as follows:

1. The user's qualitative requirements such as installation, safety, etc are listed in each row of the house of quality.
2. Each customer requirement is assigned an importance weight (i.e. 7.0 for durability).
3. The importance weights for all customer requirements are added up and the importance weight for each particular customer requirement is divided by this sum. The resulting figure is then multiplied by one hundred and called the relative weight for the particular customer requirement (i.e. 15.9% for durability).
4. Along each column are listed quantifiable technical requirements such as frequency response, weight, etc.
5. The intersecting cell between each column and row indicates how the respective customer requirement correlates with the respective technical

requirement. If there is no correlation, the cell is left blank. The cell is filled with a solid triangle if there is slight correlation, with a hollow circle if there is medium correlation, and with a symbol that resembles theta if there is strong correlation. For instance, heat requirement (quantitative) has light correlation with safety, medium correlation with response to angle change, strong correlation with durability, etc.

6. Each level of correlation is assigned a numerical value. A value of zero for no correlation, one for light correlation, three for medium correlation, and nine for strong correlation.
7. Take the relative weight for each customer requirement and multiply it by the correlation value in each cell of each respective row (i.e. 15.9*9 for durability and heat requirements).
8. Add up the resulting values along each column, and an importance weight is obtained for each technical requirement (i.e. 425 for heat requirements). This value is placed at the bottom of the house of quality.
9. Sum up the importance weights for all technical requirements, and divide into the importance weight for a particular technical requirement. Multiply the result by one hundred to obtain the relative weight for that technical requirement (i.e. 14.3% for heat requirements).

The relative weight indicates the importance of a particular technical requirement for our design. Having a relative weight of 14.3%, heat requirement has a higher relative weight than any other technical requirement. It also has strong correlation with the greatest amount of customer requirements. Therefore, this team should have the greatest concern regarding heat requirement throughout the design, build, and test process. Not satisfactorily meeting heat requirements will result in the greatest adverse impact on most customer requirements.

The following table of engineering specifications highlights from left to right, the type of technical parameter, this team’s target numerical value for that parameter, the tolerances it must meet, the risk of not meeting each target (High (H), Low (L), or Medium (M)), and how this

team will meet each parameter (analysis (A), test (T), similarity to existing designs (S), or inspection (I)).

Table 1

Spec. #	Parameter Description	Target Value (units)	Tolerance	Risk	Compliance
1	Frequency response	20 Hz	Min.	M	A, T, S
2	Weight	Adds <4 lbs on to system	Max.	M	A, T
3	Temperature	Withstand 1300 °F	±20 °F	L	A, T, S
4	Pressure	Withstand 600 psi	±50 psi	L	A, T, S
5	Thrust angle	±7 degrees from central axis	Max.	M	A, T
6	Size	< 5.75 in diameter[1]	Max.	L	A, I
7	Power usage	< 30 watts	Max.	L	A, S
8	Cycles till failure	5000 cycles ±150	Min.	L	A, T
9	Slew rate	0.5 seconds for half cycle	±0.001 second	H	A, T, S
10	Drag	Adds less than 1%	Max.	L	A, T
11	Actuation error	± 0.05 degrees	Max.	M	A, T

*For further reference see the bottom of the house of quality in Appendix A.

[1]See Appendix B

Frequency Response: Amount of cycles the actuators can achieve in one second.

Weight: Once installed on to the rocket, the system we design must not add more than 4 lbs. to the rocket's pre-installation weight.

Temperature: The system must withstand the high temperatures that result from fuel combustion and other factors.

Pressure: The system must withstand all pressures resulting from the rocket's thrust and other factors.

Thrust Angle: *See frequency response above.

Size: The system must be able to fit within a 5.75 in diameter. *Also see Appendix B.

Power usage: The system must use no more than 30 watts of power from the rocket's power supply.

Cycles till failure: The system must cycle thrust direction a minimum of 5000 cycles before failure.

Slew Rate: Amount of times in one second that the system can cycle direction of thrust between ± 7 degrees from the rocket's central axis. The risk of not being able to meet this requirement is high. The thrust vectoring system requires a high cycling speed because it must finish steering the rocket to the correct trajectory within 15 seconds of launch. This team is unsure whether it can design a system to achieve this speed within the given power and size restrictions. If the cycling speed is achieved, this team is unsure whether all components of the system will function properly at the desired slew rate for a full duration of 15 seconds.

Drag: Once installed on to the rocket, the system must add no more than 1% of the rocket's pre-installation drag.

Actuation Error: The actual thrust angle must not deviate more or less than 0.05 degrees from the intended thrust angle.

3.2-Concept Selection

This team used a decision matrix to select our top design. The four best designs were listed across the top of the matrix. These included the jetavator, internal maneuvering vanes, ball and socket, and cylinder-powered designs. Each design was then given a 1-10 rating (Table1.Column(s) 3, 5, 7, 9) relative to characteristics such as installation ease, durability, interface ease, etc. After the ratings for each design were summed, the ball and socket design was found to have the highest total rating of 83.5 out of 100 (Table1.Column7). Thus, this team found it to be the best design.

Table 2

		Jetavator		Vanes		Ball and Socket		Cylinders	
Column1	Column2	Column3	Column4	Column5	Column6	Column7	Column8	Column9	Column10
Criteria	Weight	Rating	Score	Rating	Score	Rating	Score	Rating	Score
installation ease	6.8	8	54.4	8.5	57.8	9	61.2	8.5	57.8
Safety	2.3	9	20.7	9	20.7	9	20.7	9	20.7
durability	15.9	6.5	103.35	8	127.2	8.5	135.15	9	143.1
interface ease	11.4	5	57	7	79.8	9	102.6	9	102.6
heat requirements	15.9	6.5	103.35	4	63.6	6.5	103.35	7.5	119.25
response to angle change	15.9	7	111.3	7.5	119.25	8.5	135.15	8	127.2
low weight	15.9	6.5	103.35	8	127.2	8	127.2	5	79.5
ease of manufacture	2.3	5	11.5	6	13.8	7	16.1	7	16.1
low drag	11.4	5	57	10	114	10	114	9.5	108.3
Cost	2.3	6	13.8	6	13.8	8	18.4	7	16.1
	100.1	64.5	6456.45	74	7407.4	83.5	8338.5	79.5	7957.95

*Refer to the following photos for reference:

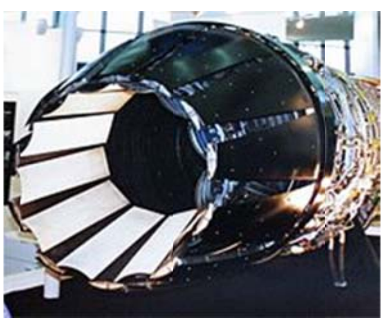


Fig 5. Jetavator

Fig 6. Maneuvering Vanes

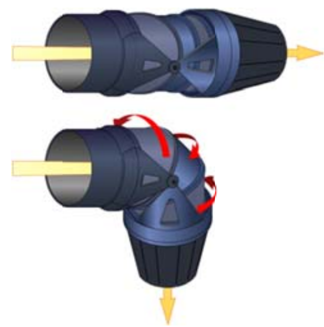


Fig 7. Rotating Segments

Installation

The ball and socket concept was easiest to install on to the Swordfish Rocket, thus receiving the highest rating of 9 for the 'installation ease' category. Unlike the jetavator design, which requires the installation of multiple maneuverable vanes and actuation mechanisms around the rocket's end (See Fig. a), the ball and socket design only requires one movable part, and two actuation mechanisms. Installation of vanes inside the nozzle or boat-tail would also be more challenging than installation of the ball and socket mechanism. It would require this team to do machine work on the nozzle or boat-tail in order to make room for at least three actuation mechanisms in tight space (See Fig. d). Although a cylinder mechanism is easier to install than the jetavator and internal vanes mechanisms, it still requires more moving parts than the ball and socket design.

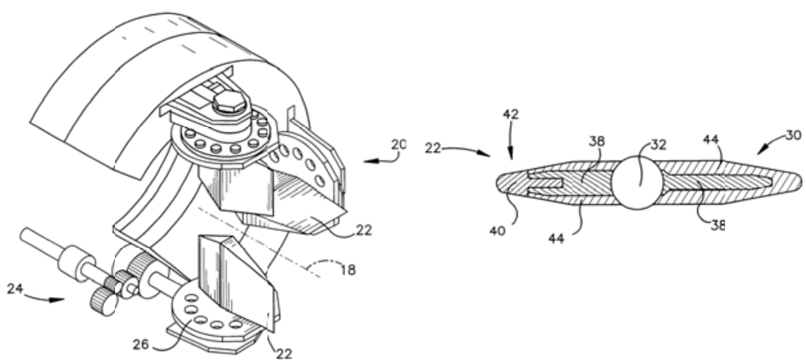


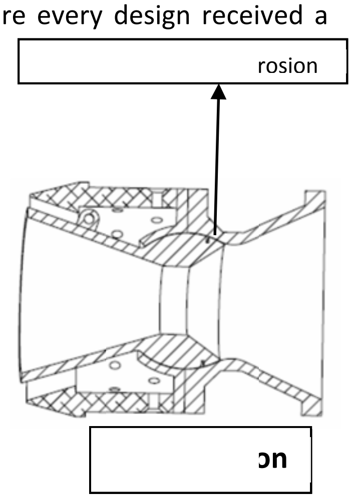
Fig 8. Vane Installation

Safety

Safety concerns are very low for each design concept, and therefore every design received a high rating of 9 in that category.

Durability

Since the bolts and flanges in the ball and socket design can uptake great loads, and the overall number of components in the design is relatively low, this design's implementation will provide a durable mechanism. However, this team's selected design still has a lower rating than the cylinder design in the 'durability' category. The reason being that the inlet of the rotating nozzle is susceptible to erosion around it edges. This issue could lead to a noticeable degradation in performance. The



jetavator and internal vane designs have lower ratings than both aforementioned designs. The greater number of small moving parts in the jetavator and internal vane mechanism increases the probability of failure.

Interfacing

Another selection parameter is how well each type of mechanism interfaces with the electronic control system on board the rocket. Again, the ball and socket design's low number of moving parts and simplicity of actuation gives it a high rating of 9.

Heat Requirements

The rating given to each mechanism in the 'heat requirements' category indicates how well each type of design would withstand heat from the rocket exhaust. The cylinder powered concept was given the highest rating due to the fact that the cylinders would maneuver the nozzle from outside of the flow regime. Thus, the system has the least percentage of its surface area exposed to heat. Internal vanes, which would be placed directly in the path of the flow regime (see Fig b), will have the greatest percentage of surface area exposed to exhaust heat. This is why the particular design was given the lowest rating in the 'heat requirements' category.

System Response

The 'response to angle change' category indicates how fast a particular mechanism responds to signals from the electronic control system. The mechanism with the least complicated manner of set up and motion is given the highest rating.

Weight

This team gave the ball and socket design the highest rating in the 'weight' category for two reasons. One reason is the low number of components required for the design. Secondly, the ball and socket design requires redesign of the outward nozzle shape. We expect the redesign to reduce the overall weight of the rocket.

Manufacturability

Out of the four possible designs we considered, the ball and socket design rated among the highest in ease of manufacturability. The jetavator and internal vane based designs have many small components to them. This makes it more difficult and time consuming to precisely manufacture them. The relatively large size and lower number of components in the cylinder and ball and socket based designs makes the components much easier to manufacture.

Drag

The design that provides the lowest amount of drag is one that results in the least amount of surface area exposed to air flow around the rocket. Since most components of the jetavator design are located around the outer edge of the rocket's back end (Fig. a), this particular design results in the

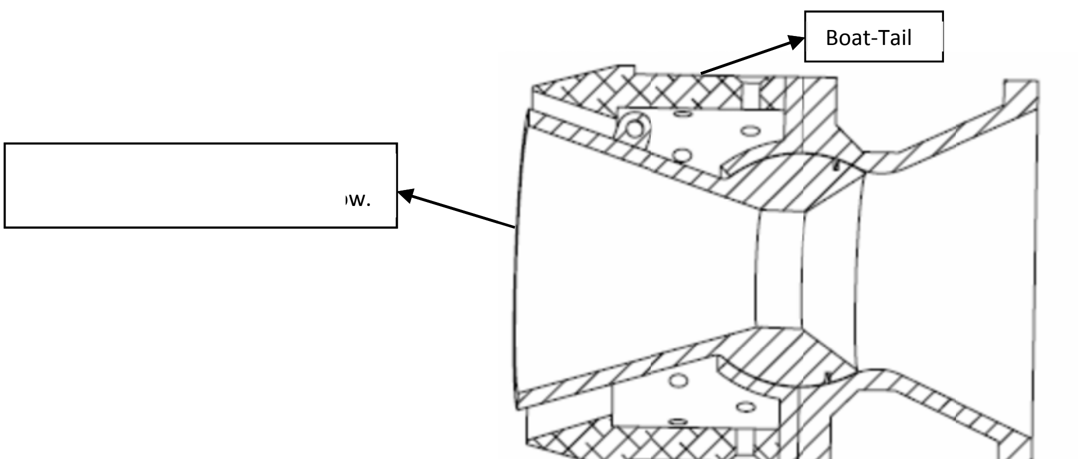
greatest amount of surface area exposed to air flow. This consideration resulted in the lowest rating of 5 for the 'drag' category. The internal vane based design results in all mechanisms of the thrust vectoring system being placed inside the rocket nozzle or boat-tail (Fig. b). Thus, zero area is exposed to air flow, and a highest rating of 10 is assigned.

Cost

For the 'cost' category the ball and socket design is assigned the highest rating. The ball and socket design will cost the least to prototype due to the lower number of components and relative ease of manufacture.

Further Concept Development

Our next steps involve the resolution of some design issues, as well as further modifications to improve our design. First this team needs to decide whether or not our nozzle should extend outside of the boat-tail. If it does extend outside, this team predicts lower back pressure, possibly greater speed and acceleration, more room to maneuver the nozzle, but increased drag.



ncept

If the entire length of the nozzle in Fig. f is shortened and made to stay inside the boat-tail, this team predicts very low drag, greater back pressure, and very little space to maneuver the nozzle for effective operation of the entire system. One adverse possibility of the shortened nozzle being rotated to a certain angle is the flow of gases partially thrusting against the walls of the boat-tail before exiting through the back.

Another issue is whether to round the edges of the nozzle inlet to prevent erosion along the edges and improve flow performance (See Fig e). In addition, this team is considering coating the outside of the nozzle's rotating end with a material that will prevent friction and make actuation easier. Coating the inside walls of the nozzle with light heat resistant material is another option under consideration. This team predicts that the heat resistant coating will help minimize performance degradation due to heat effects.

Linear actuator analysis and selection is discussed further on in this report under “Analysis and “Material/Component Selection”

CHAPTER 4-Final Design

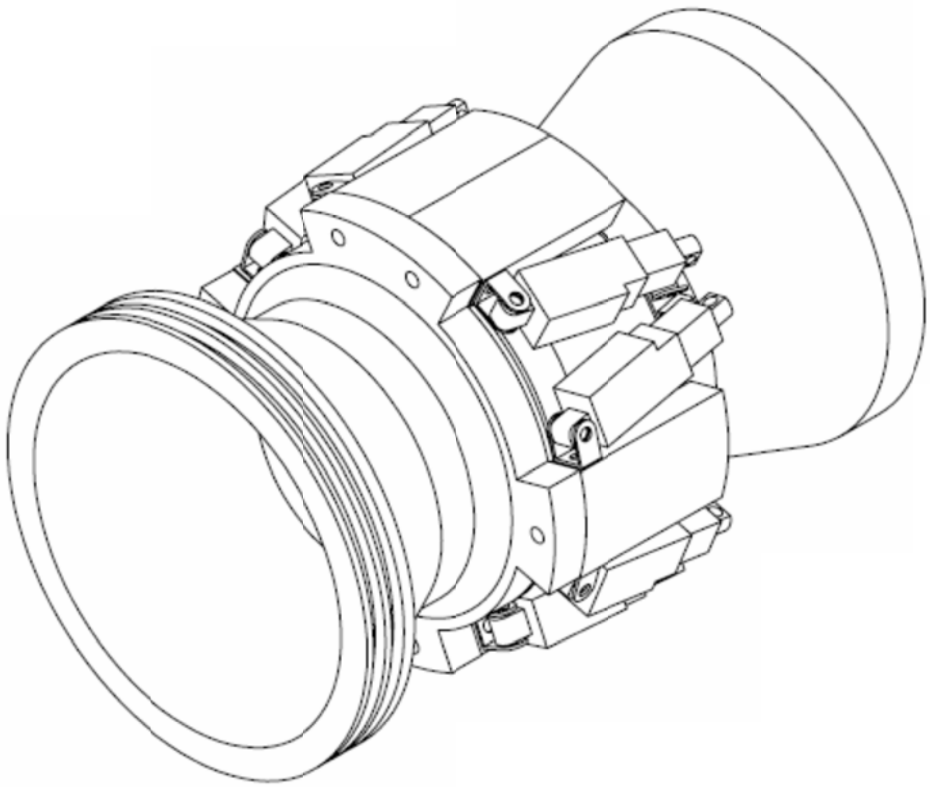
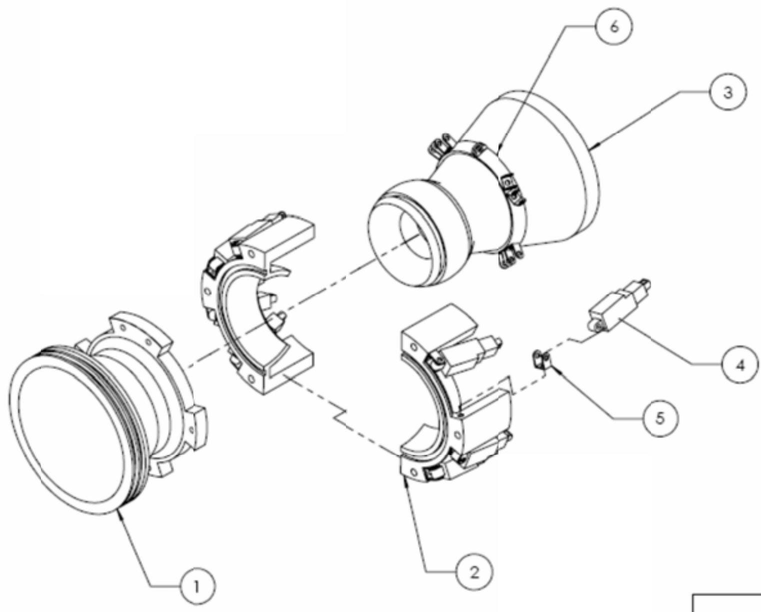


Fig 11

Isometric View of the Final Solid Model Design

***NOTE: Actuator setup and prototype requirements have changed.**

See Chapter 8 for further details



ITEM NO.	PART NUMBER	QTY.
1	socket	1
2	flange	2
3	ball	1
4	actuatorAssem	8
5	actuator mount	16
6	collar	1

Fig 12

Exploded and Labeled View of the Final Design Solid Model

4.1-Design Description

Item No. 1-Socket: The socket holds the converging and throat sections of the nozzle (Item No. 3; also referred to as the ball). This ball and socket setup allows the nozzle to rotate in different directions with the help of actuators. This item will be made of graphite.

Item No.2-Flange: Flanges serve a two tier purpose. They hold together the ball-and-socket setup against the pressure produced by hot gas flow through the nozzle, and serve platforms for mounting the actuators (Item No. 4).

These items will be made of Inconel 718. It was decided that in addition to the required ductility, the flanges would need to demonstrate superior strength at high temperatures. Thus, Inconel is assumed to be a good choice for these requirements.

Item No.3-Ball (interchangeably called nozzle from this point on): This component is a converging-diverging nozzle which accelerates hot gas flow from subsonic to supersonic. The outside of the converging section is shaped like a sphere to allow rotation via the ball-and-socket setup for the sake of vectoring thrust in different directions.

This item will be made of graphite. Graphite was chosen for its resistance to oxidation and suitable thermal properties. These thermal properties included low conduction and thermal expansion coefficients. The ball's outside diameter was made small enough to make up for thermal expansion due to high temperatures during operation.

Item No.4-Actuator Assembly: Actuators push and pull against the diverging section of the nozzle, causing rotation all along the converging spherical section.

Actuators were mainly chosen based on how much force each could supply. Analysis revealed that each actuator would need to put out 20 pounds of force. This takes into account that each actuator would be working against both the weight of the nozzle and the pressure built up inside the nozzle.

Item No.5-Actuator Mount: Holds the actuator in place and connects the actuators to the diverging section of the nozzle.

Item No.6-Collar: Mounts onto the diverging section of the nozzle and serves as a mount for the actuator mounts. This item will be made of Inconel 718.

A major design consideration was making this collar thick enough so that it didn't pop out of its slot once thermal expansion took effect.

4.2- Engineering Analysis

Heat Transfer Analysis

The high temperatures in the nozzle warrant a heat transfer analysis of key areas in the nozzle. These include the beginning of the converging section where there is a thin wall between the 4000 degree combustion gasses and the electronics that will power and control the rocket.

<u>System Sketch</u>

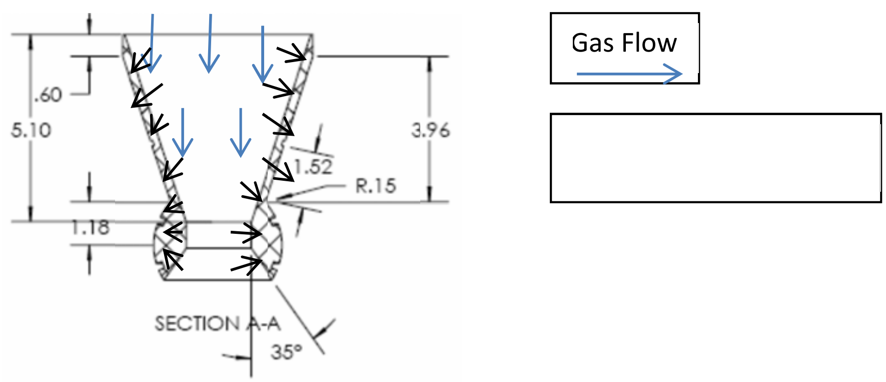


Fig 13. Heat transfer in nozzle

<u>Objective</u>

To compute the temperature(s) inside the nozzle walls and at the nozzle surfaces.

<u>Assumptions</u>

The heat transfer was simplified as one dimensional conduction through a wall.

<u>Method/Approach</u>

1. Start out by looking up what typical convection coefficients for forced convection flow of gasses. These values range from 25- 250 depending on how turbulent the flow is.

2. Use a value of 200 w/mK because the electronics need to last through the extent of the burn time. Analysis is done for a duration of fifteen seconds and using a .2inch thick pyrolytic carbon.

Results

Analysis results gave a relatively constant temperature through the wall right around 3400 degrees. This temperature analysis really gave a starting point to be able to start choosing materials.

Thermal Expansion Analysis on the Nozzle

Due to temperatures of up to 3400 degrees Fahrenheit, this team expects the nozzle to undergo thermal expansion. The contact stresses between the nozzle and flanges upon thermal expansion of the nozzle may generate more friction than the solenoid actuators used to rotate the nozzle can actually overcome.

System Sketch

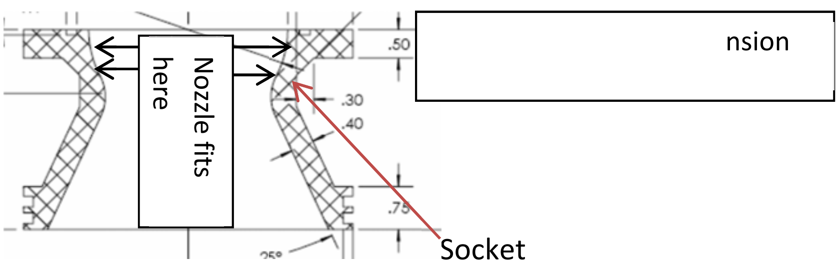


Fig 14. Thermal expansion of nozzle

Objective

The purpose of this analysis is to find the point of maximum expansion along the outside surface of the nozzle. Doing so will allow this team to take thermal expansion into account during dimension specification.

Assumptions

1. The thermal expansion at each cross section of the nozzle will be approximately the same as the thermal expansion for a hollow cylinder with the same inner and outer diameters as the given cross section.

Approach/Method

1. The nozzle converges on the inside and has a spherical outside surface. Due to the varying inner and outer diameters, thermal expansion analysis had to be conducted at more than one point along the nozzle length to see where the greatest amount of expansion would occur.

2. Thermal expansion analysis was conducted at the thinnest cross section of the nozzle (the entrance) as well as the thickest cross section (the throat).

Results

*See Appendix E for more detailed Analysis

Table 3

Cross Section	Radial Expansion due to thermal expansion
At nozzle entrance	0.00434 inches
At throat	0.008112 inches

Conclusions/Recommendations

We recommend a 0.008112 inch tolerance between the nozzle and the flanges. Mounting O-rings on the nozzle is suggested in order to make up for the loss in rotational stability resulting from the tolerance. This is discussed in more detail later in the report.

Thermal Expansion Analysis on Inconel Collar

A calculation of the thermal expansion for the Inconel collar mounted on the diverging section of the nozzle was required. The collar is about 0.15 inches thick, and we had to confirm that it would not expand enough to overcome the depth of its mounting slot. The mounting slot is 0.06 inches deep.

System Sketch

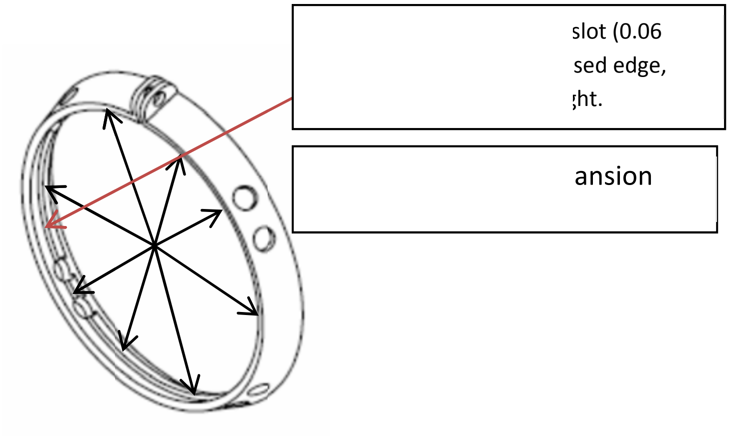


Fig 15. Thermal expansion of collar

Objective

The objective of this analysis is to compute the radial expansion of the collar, and confirm that it is not greater than the depth of the collar's mounting slot.

Assumptions

1. Approximate collar to be a hollow cylinder.

Method/Approach

1. Apply a basic thermal expansion equation to the collar using advanced mechanics of materials principles.

Results

Radial Expansion on Collar: 5.3038*10^-3 inches

Depth of Slot: 0.06 inches

Conclusions/Recommendations

The thermal expansion of the collar does not clear the slot depth. It is good to use as is.

Force Analysis

Actuator selection requires an analysis of the force required to rotate the nozzle.

<u>System Sketch</u>

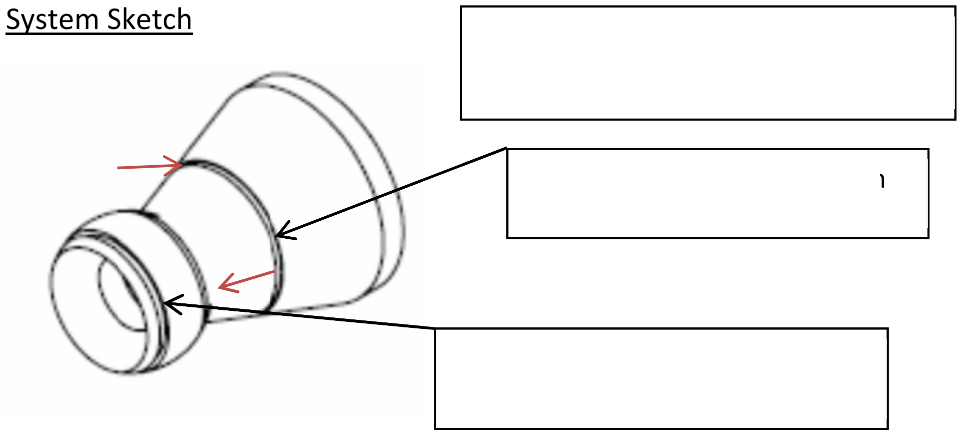


Fig 16. Forces on nozzle

<u>Assumptions</u>

In this analysis it was realized that the seals mounted over the ball-shaped section of the nozzle would be the main friction component to provide resistance to motion.

<u>Method/Approach</u>

The maximum pressure difference across the nozzle was used to approximate the normal force that would be on the seals.

<u>Results</u>

The results of this analysis told us that the force required to break the friction would be around 40lbs.

4.3-Cost Analysis

The price of Inconel components varies depending on the grade of Inconel the sponsor wants used. The lowest price is for Inconel 600 (i.e. bar price. Cell #8), while the highest price is for

Inconel 718 (i.e. bar price. Cell #8). Inconel 718 is mainly used in aerospace and gas nozzle applications, but Inconel 600 may suffice due to the very small operating time.

Inconel fasteners have a lead time of 1-2 weeks to manufacture. The cost of the finished parts can be seen in the table below (Fasteners. Cell #8).

Table 4

Material	Component(s)	Quantity	Price
Graphite 1	Nozzle 2	1,6” Diameter,12” Long, Solid Graphite Rod 3	$256 4
Inconel 5	Fasteners, Flanges, Collar 6	8 readymade fasteners, 6” Diameter; 6” long solid bar; Hex Head 4mm diameter, 12 mm long fasteners 7	Fasteners:$34-$44 each Bar: $1450-$2400 each Hex Head Fasteners: Quote Requested 8
Grafoil 9	O-Ring Seals 10	4 11	$90 each 12
Carbon Felt 13	Insulation 14	N/A 15	N/A 16
Aluminum 17	Linear Actuators 18	8 19	$80 each 20
			Total: ~$1910-$2870 21

4.4-Material/Component Selection

Nozzle We chose to make the nozzle out of graphite. Metals such as aluminum and steel were not selected for this application due to their thermal and oxidation properties.

zzle

Regarding oxidation properties, the solid fuel used to power the rocket is highly oxidative. Since metals oxidize easily, fuel flow through an aluminum or steal nozzle will have a highly adverse impact on the system's performance. However, graphite does not oxidize easily, and the oxidative nature of the fuel will have a negligible impact during the 17 seconds of operation.

In addition, graphite has a coefficient of expansion of 2.2 in/in °F compared to 12.3 in/in °F for aluminum and a minimum of 5.5 in/in °F for steel. A lower thermal expansion for the nozzle requires a smaller tolerance between the nozzle and flange. This poses less risk to rotational stability during operation.

<u>Flanges</u>

Our team chose to have flanges and fasteners of the system made out of Inconel. Although Inconel 718 is most suitable for gas nozzle applications, we may go with a lower grade of Inconel due to the small operation time of 17 seconds. Inconel was selected for its superior yield and rupture strengths at extreme temperatures.

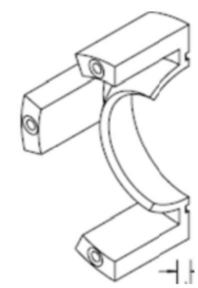


Fig 18. Inconel Flange

However, one important thing to note is that we will only use Inconel in our prototype design if Stellar Exploration specifies that the prototype needs to be tested under extreme temperature conditions.

<u>Fasteners</u>

This team chose Inconel ¼-20X3 slotted flat head socket cap fasteners. We felt flat head screws to be appropriate, as they would negate the risk of interference between fastener heads and other components of the system.

Actuator selection

The selection of actuators was difficult due to force and space requirements. Initially solenoids were thought more suitable because of their ability to produce very quick movements. The problem with solenoids is that for the force desired the lightest ones are around thirty pounds. This weight would not be reasonable to add to the rocket.

Due to the stated reasons, linear actuators were then decided upon. Many actuators that could provide the desired force were very large. After a long search, two actuators that would be suitable were found. One was the T-NA series made by Zaber. These actuators are 3 inches long and can produce a peak thrust of 14.6lbs. However, they sell this actuator for one thousand dollars apiece. The actuator chosen was the Frigelli L12 series actuator. These actuators come in a range of options with different gearing and lengths of stroke. The 10mm (.394in) stroke option with a 210 to 1 gear ratio that with a 12 volt battery will produce a peak force of 45N(10.1lbf) at 2.5mm/s(.0984in/s). Four of these actuators will be required in each direction to produce the 40lbf. Each actuator is equipped with its own feedback potentiometer that will give the length of each actuator so they can be controlled more accurately. The cost of these actuators is 80 dollars. The 12-volt model will draw around 130mA at peak force. That means that the system will use 12.48 watts maximum.

Grafoil

Grafoil seals were selected due to their good combination of rigidity and flexibility under the given circumstances. These characteristics will help the system to maintain stable rotation. In addition, this material can withstand up to 6000 degrees Fahrenheit.

Carbon Felt

Carbon felt provided the lowest thermal conductivity of any material we could find. Hence, it was the best choice for insulation. In addition, it can be used in low enough amounts for it to not have a big effect on the system's weight specifications.

CHAPTER 5-Manufacturing/Assembly

Manufacturing/Assembly

Nozzle Parts

This team plans to manufacture the nozzle on a CNC lathe machine. Facilities on the Cal Poly campus have machines which are capable of following the shape profile of our nozzle design. After obtaining the overall shape of the nozzle, slots for O-rings and collar will be made on a lathe machine.

Flanges

The flanges will be manufactured in a similar fashion as the nozzle parts. However, in addition, boring and threading is required for where the bolts will be placed.

Further Fabrication and Assembly Instructions

The boat tail will need to be modified from its current design to provide more space for the components of the system to move. What needs to be done first is the inside rear section that is currently a continuation of the nozzle must be lathed so that the new nozzle will have room to maneuver inside it. The other thing that must be done is to cut notches so that the actuators will have room to move. This can be accomplished using the chop saw first to create the angled cuts and then a rotary cutting blade to finish the bottom part of the trapezoid shaped cuts.

The collar that is placed around the nozzle to provide attachment points for the actuators will be manufactured by taking a ring of the metal (either steel or inconel) being used for the flanges and lathing the circular portion then the ring will be cut and tabs will be welded to the ends of the ring. These tabs will be used to clamp the collar onto the nozzle. The last step will be to drill holes for the screws that will hold the actuator brackets. *For further detail, see the "Manufacturing section" in Chapter 8.

Assembly of the entire system starts with inspection of the parts all dimensions should be checked so that problems will not be encountered later. After all the dimensions have been checked the first parts that can be put together are the actuator brackets and the collar. The brackets can be attached using hex head screws coming from the inside of the collar and holding the brackets on with one washer and a nut at this stage they can just be tightened by hand and be tightened down later. Once all the brackets are attached the collar can be slipped down over the small end of the ball/nozzle and fitted into the locating slot a bolt can be slipped through the hole in the tabs and finger tightened. Take the grafoil seals and cut two lengths that will fit into the slots on the round part of the ball. This piece can now be put aside. Now measure another length of grafoil for the slot in the carbon socket. Place the socket down on a bench so that the slot with the seal is pointing up. Now the ball can be placed into the socket. Take the two flanges and the remaining actuator brackets and attach them to their corresponding holes in the flanges with provided bolts. Now the flanges can be placed on the socket around the ball aligned with the bolt holes. Care should be taken to place the grafoil seals into the slots in the flanges without damaging them. The ¼ 20x3in bolts can be placed in the holes in the flange and through the socket. Washers and nuts can be tightened onto the bolts securing the ball and flanges to the socket. The next thing is to fit the actuators into the brackets place the actuator in the brackets using the M4 bolts provided. These bolts can be tightened next you can tighten the bolts holding the actuator brackets down and move on to the next actuator until all eight have been attached. Once all the actuators are in place the bolt for the collar should be tightened. The next step is to flip the hole assembly over and insulate the chamber where the batteries and controller will be kept. Care should be taken with the assembly in this position since it may be unstable. Taking the insulating carbon felt loosely wrap this section with long strips overlapping the previous end with each successive pass until there is just enough room to place the batteries and other electrical components directly up against the aluminum fuselage. Once the electronics have been hooked up the entire assembly can be inserted into the fuselage and assembly is complete.

This rocket nozzle is designed to be used once so no maintenance schedule or repair is recommended.

CHAPTER 6-Project Planning

6.1-Project Management Plan

This team has completed the final design phase of the product. The original plan was to have this final design report completed by February 1, 2011(Gantt Chart, Row 34). However, we have been delayed by a few days, and this report is now complete on February 5, 2011.

The first milestone was the Project Requirements Document (Gantt Chart, Row 14). This document showed a translation of all customer requirements to engineering specifications. Requirements such as durability (QFD, Row 3) were translated to requirements such as ability to withstand a specified high temperature.

Milestones including the Preliminary Design Presentation (Gantt Chart, Row 20), creation of the solid model (Gantt Chart, Row 25), Conceptual Design Report (Gantt Chart, Row 28), and Conceptual Design Review (Gantt Chart, Row 29) served to present the basic workings of the system. The Conceptual Design Report included everything from the Project Requirements Document, a finalized design concept, a project management plan, etc. The Conceptual Design Review consisted of a presentation of the Conceptual Design Report’s main parts to the project sponsor.

The current report is a more detailed version of the Conceptual Design Report. The content takes into account detailed analysis used to finalize system dimensions. It also expands on additional subsystems such as the actuators.

For the final design phase of the project, Harsimran Singh handled the thermal expansion analysis and contact stress analysis. This is in addition to taking charge in acquisition of materials such as graphite, Inconel bars, and Inconel fasteners. Dane Larkin so far handled the digital solid modeling of the design and analysis relating to actuation of the system. This is in addition to taking charge in acquisition of materials/components such as linear actuators, graph foil O-rings and carbon felt insulation.

From this point on, this team will be concerned with manufacturing and testing the system. A lead time of 1-2.5 weeks for acquisition of all materials (Gantt Chart, Rows 36 & 37), and 8-10 weeks to build and fully test the system (Gantt Chart, Rows 37-39) is expected. However, this is only the case if this team builds the prototype itself. If a third party is chosen to manufacture some components, the building time will differ from what is previously stated. A visual model of the management plan is available in Appendix F along with a summary. A summary of testing and design verification plans is provided below.

6.2-Design Verification/Testing Plan

Plans to validate the concept will begin by measuring general attributes of the assembly such as overall weight size and clearance between moving parts and range of motion of the nozzle. After general attributes have been measured the assembly will be fitted into a test fixture that resembles the back end of the rocket. The actuators can then be hooked up to function generators that will produce voltage to move the nozzle. With the function generators hooked up, measurement of the actuation speed can be obtained. The next test would be to set the function generators up so that they would be able to cycle the nozzle through the two degrees of freedom for 5 thousand cycles. During the previous tests the power requirements will be measured by oscilloscopes. These tests will be able to show that our design meets the requirements that were set out at the beginning of the project.

In addition, the system prototype must undergo the required gas flow testing. This will verify that the system reacts as desired to operational temperatures and pressures.

CHAPTER 7-Conclusions and Recommendations

The outside diameter of the nozzle's converging and throat sections is designed a specific amount smaller than the inside diameter on each flange cross section to take thermal expansion during operation into account. The O-rings mounted on top of the nozzle are specifically dimensioned to make up for the difference in diameter. These O-rings reestablish the rotational stability of the nozzle, which would otherwise be compromised by the nozzle not being flush with the flanges. Any careless changing of these dimensions will have an adverse impact on system performance.

This team has left it up to the sponsor to decide which grade of Inconel should be used. Although industry generally uses 718 grade for aerospace and gas nozzle applications, we recommend the use of a lower grade such as Inconel 600 or 625. Systems in industry are expected to operate for much longer durations than the 17 second operating time of our system. In addition, Inconel 718 is a much more expensive grade. The use of Inconel 600 will be a cheaper financial alternative for Stellar Exploration. Even if Stellar Exploration decides to use Inconel 718 for future applications, the use of a lower grade would be more practical at least for the current testing purposes.

Unless overall system dimensions are increased, we recommend continued use of flat head fasteners to negate the possibility of interference between the fastener heads and other parts of the system.

The Inconel collar mounted on the diverging section of the nozzle is predicted to expand 0.0032 inches under the given conditions. We recommend not making its mounting slot shallower than a depth of 0.0032 inches.

Chapter 8-Final Project Updates

The preceding written materials and the materials in the Appendices regard a prototype which will undergo full testing. That is to say, the prototype will undergo both hot gas tests and actuation tests. However, for the purposes of this senior project Stellar Exploration decided to limit the project requirements to a prototype that will only need to undergo actuation testing. Thus, the prototype has not been built using materials such as graphite and Inconel. The current model uses standard steel nuts and bolts, a steel collar connecting the actuators to the nozzle, and rapid prototyping materials.

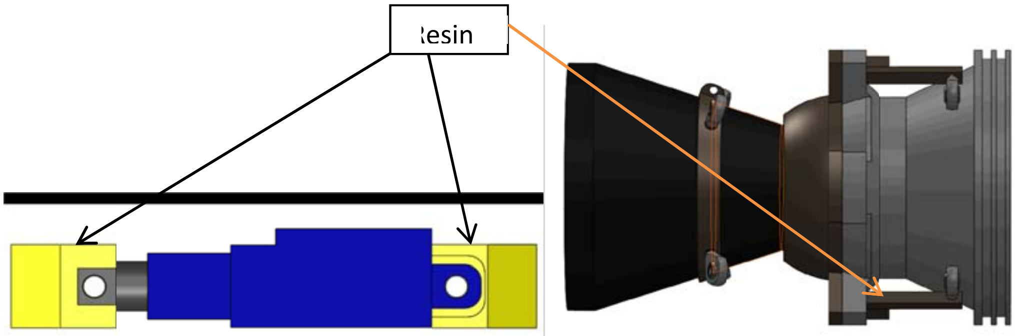
Written and visual material presented from here on until the Appendices section concerns the current prototype model.

8.1-Materials

The nozzle, flanges and socket are rapid prototype models made entirely out of a thermoplastic called Acrylonitrile butadiene styrene (ABS). All actuator mounting brackets and couplers are also rapid prototype models, but are made of resin-based rapid prototype material instead.

Socket Nozzle Flange

Fig 19. Rapid Prototyped Components



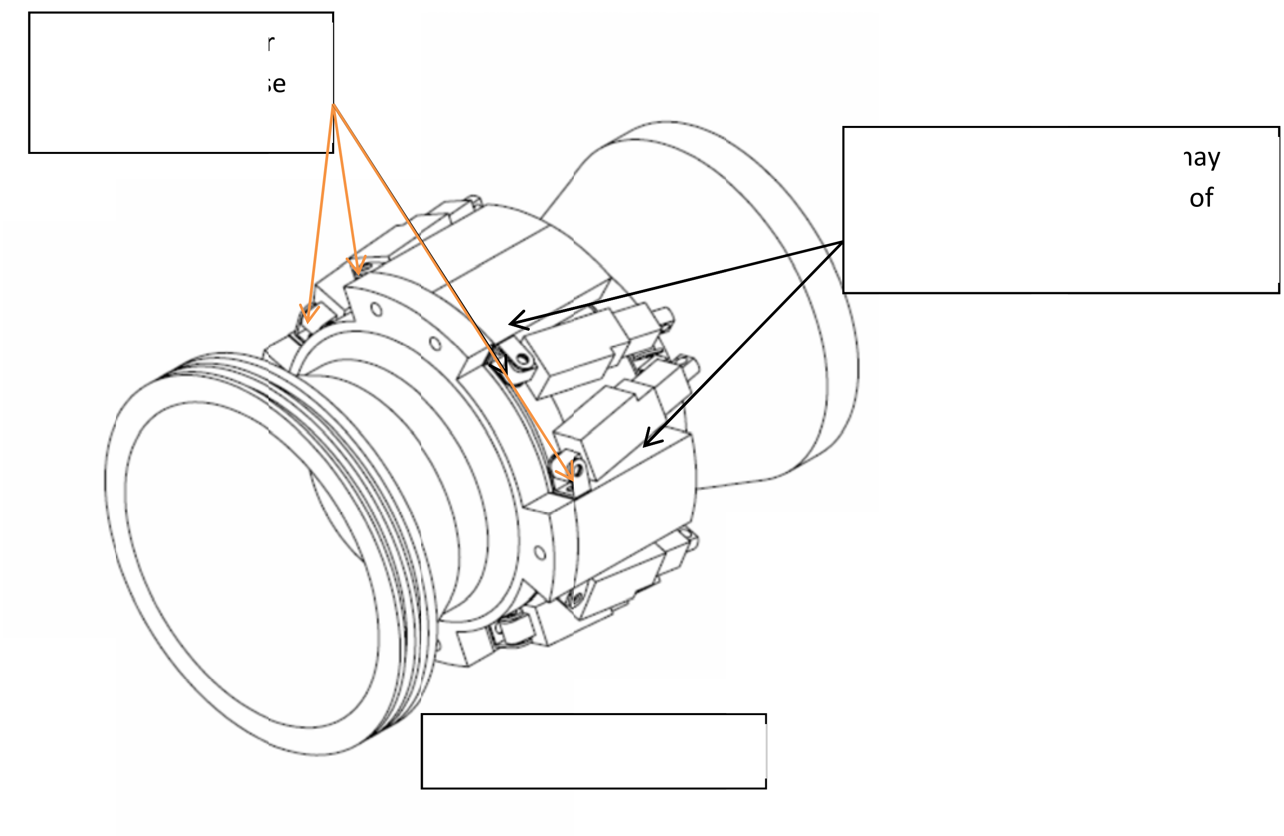
Actuator couplers and mounting brackets

Fig 20

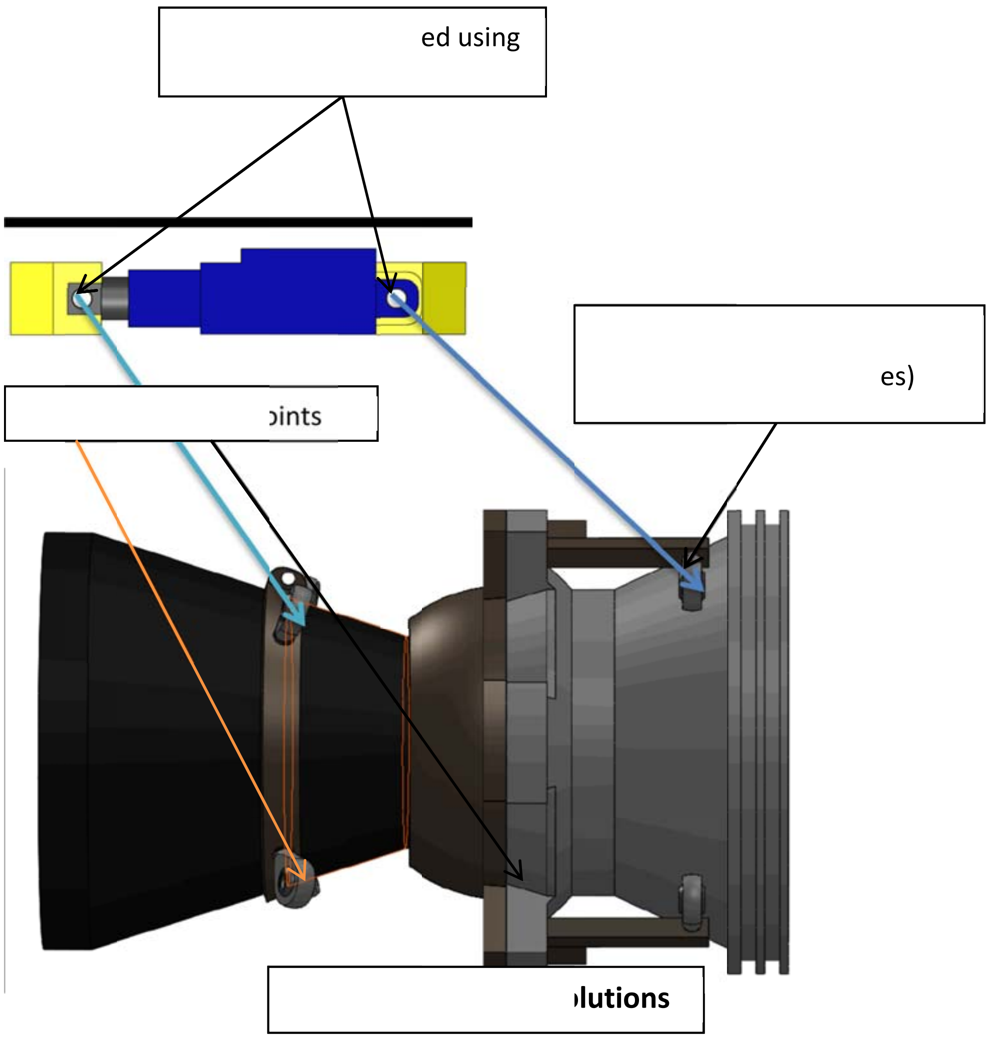
All bolts and threaded stock are standard steel parts bought from a hardware store.

8.2-Design Changes

The original design called for the actuator mounts provided by the supplier to be installed at the collar and flanges. However, mounting actuators close to the flanges, and mounting one actuator per mount posed risks of over constraining the system.



In order to resolve these issues, the number of mounting points was first decreased from 16 to 8 by coupling two actuators at each point. The couplers (see yellow blocks in Fig 22) increased the length of the assembly, thus allowing mounting points to be moved further back from the flanges. This prevented any sort of interference during nozzle rotation. The couplers are fixed to the rest of the assembly with off the shelf rod ends.



8.3-Manufacturing

As previously stated, most parts of the prototype such as ball, socket, flanges and mounts were rapid prototyped. The only machined component is the collar. The collar was manufactured using a lathe. The manufacturing process is as follows:

1. Machine a section of round solid steel bar at an angle.

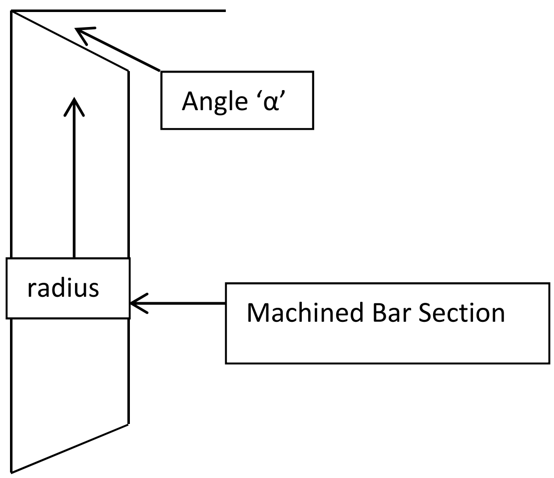


Fig 23. Machined Section of Solid bar

2. Hollow out the machined bar section to desired thickness. Take care to leave raised edge along collar's inside surface. This edge must fit into the collar's mounting slot.
3. Drill holes where actuator mounts must be placed
4. Make a cut down the collar. This cut must be half way between two actuator mounts
5. Weld tabs onto edges of the discontinuity.

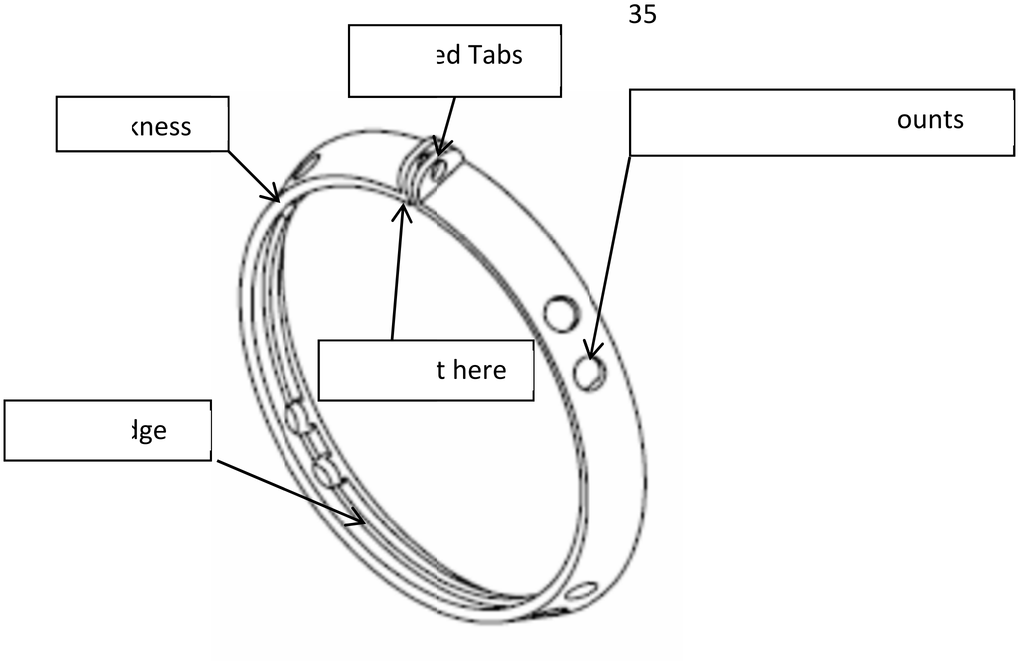


Fig 24. Fabricated features of collar

Chapter 9-Testing

9.1-Testing Apparatus

The nozzle's rotation to an angle of +/- 7 degrees was the only test objective which required fulfillment. The test apparatus was set up as follows:

1. Construct an Isosceles triangle with a total vertex angle of 14 degrees

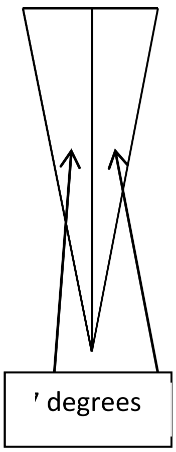


Fig 25. Test Apparatus

2. Place the triangle inside the nozzle with vertex facing down.
3. Align a weighted string along triangle's vertex.

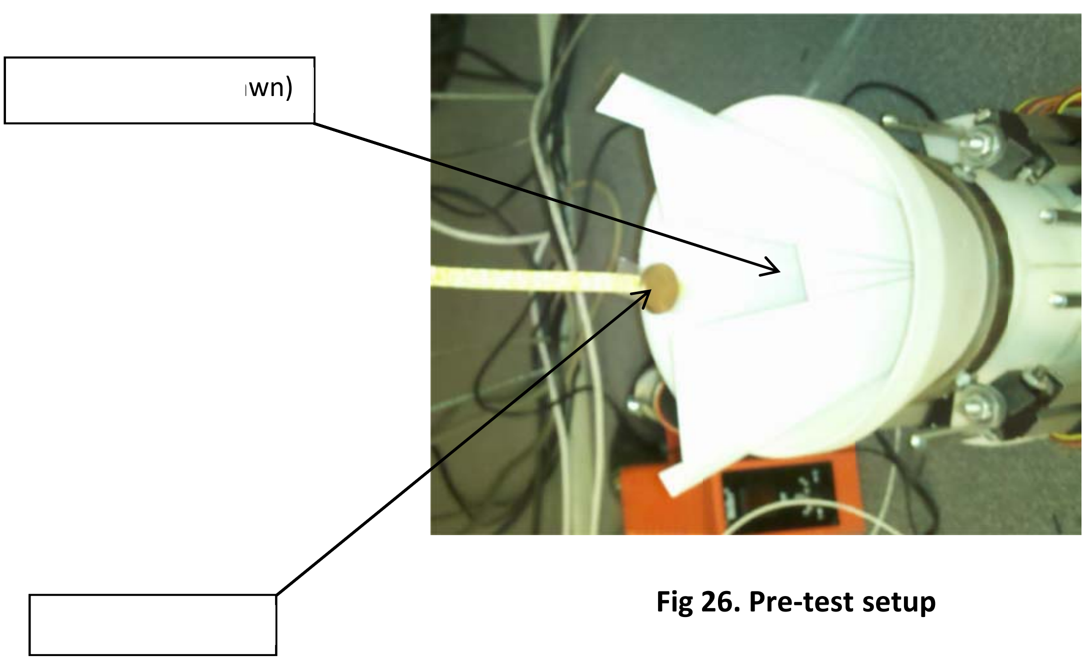


Fig 26. Pre-test setup

4. Actuate nozzle motion. If weighted string aligns with a triangle side, objective has been met.

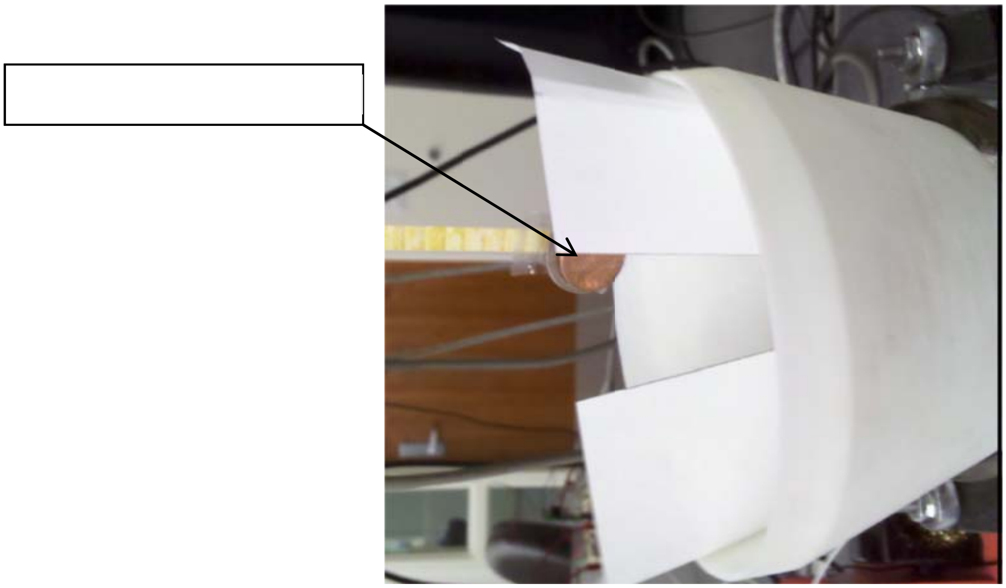
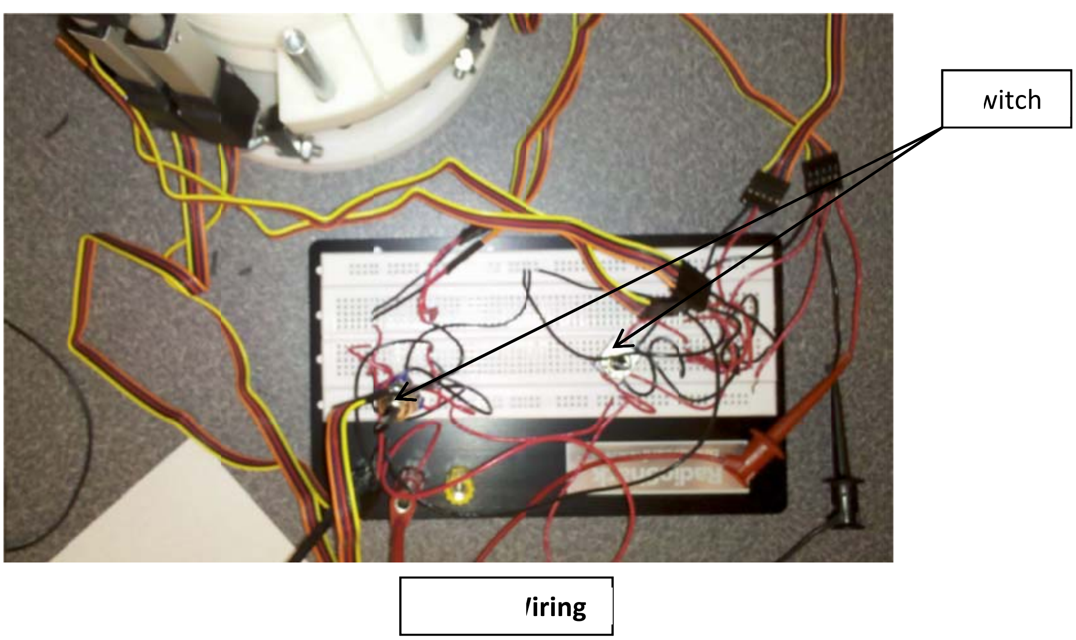


Fig 27. Test objective verification

9.2-Wiring Setup

Motion control for testing is done with switches hooked up to a bread board.



Each actuation point on an axis of rotation has a polarity opposite to the point at the other end of the axis. Thus, as one pair of actuators extends the pair on the other end of the axis contracts. These motions rotate the nozzle.

APPENDIX A

		Jetavator		Vanes		Ball and Socket		Cylinders	
Column1	Column2	Column3	Column4	Column5	Column6	Column7	Column8	Column9	Column10
Criteria	Weight	Rating	Score	Rating	Score	Rating	Score	Rating	Score
installation ease	6.8	8	54.4	8.5	57.8	9	61.2	8.5	57.8
Safety	2.3	9	20.7	9	20.7	9	20.7	9	20.7
durability	15.9	6.5	103.35	8	127.2	8.5	135.15	9	143.1
interface ease	11.4	5	57	7	79.8	9	102.6	9	102.6
heat requirements	15.9	6.5	103.35	4	63.6	6.5	103.35	7.5	119.25
response to angle change	15.9	7	111.3	7.5	119.25	8.5	135.15	8	127.2
low weight	15.9	6.5	103.35	8	127.2	8	127.2	5	79.5
ease of manufacture	2.3	5	11.5	6	13.8	7	16.1	7	16.1
low drag	11.4	5	57	10	114	10	114	9.5	108.3
Cost	2.3	6	13.8	6	13.8	8	18.4	7	16.1
	100.1	64.5	6456.45	74	7407.4	83.5	8338.5	79.5	7957.95

Title: ______________________

Author: ______________________

Date: ______________________

Notes: ______________________

Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1
++	Strong Positive Correlation	
+	Positive Correlation	
−	Negative Correlation	
▼	Strong Negative Correlation	
▼	Objective Is To Minimize	
▲	Objective Is To Maximize	
x	Objective Is To Hit Target	

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Direction of Improvement: Minimize (▼), Maximize (▲), or Target (x)																									

Quality Characteristics (a.k.a. "Functional Requirements" or "Hows")

Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	frequency response	weight	heat requirements	pressure	angle of thrust	size	power	number of cycles till failure	slew rate	drag measured	actuation error
1	3	15.6	7.0	installation ease		▲		O		O					O
2	3	2.2	1.0	safety			▲	O			▲				
3	9	15.6	7.0	durabillity		▲	Θ	Θ	O	O		Θ			O
4	9	11.1	5.0	interface ease	Θ				Θ				Θ		Θ
5	9	15.6	7.0	heat requirements	▲	▲	Θ		O	O		O			O
6	9	20.0	9.0	response to angle chage	Θ	O	O	O	Θ	▲	Θ		Θ		Θ
7	9	8.9	4.0	low weight		Θ	O	O		O	O	▲			
8	9	2.2	1.0	ease of manufacture		O	Θ	O	▲	Θ		▲			▲
9	9	6.7	3.0	low drag					O	O				Θ	
10	9	2.2	1.0	cost	Θ	O	Θ	▲		O		O			O
11															
12															
13															
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15															
16															
17															
18															
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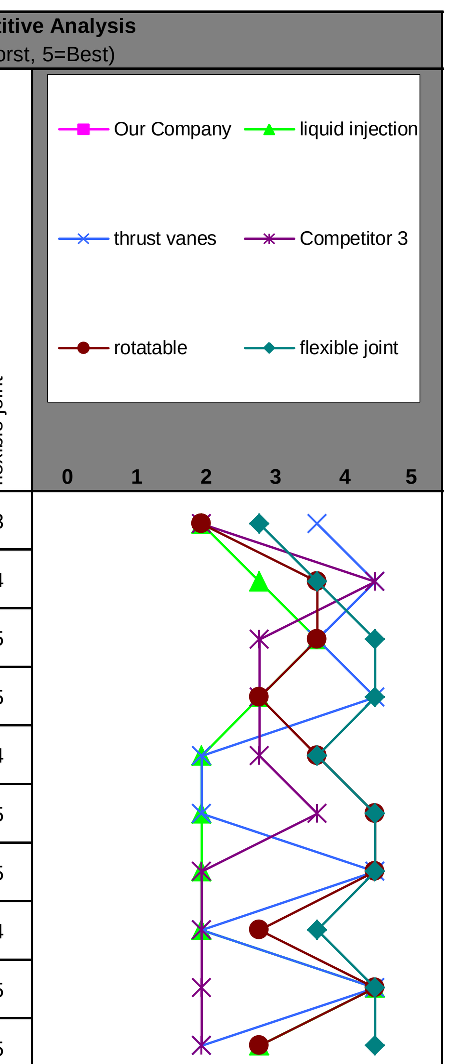
20															
21															
22															
23															
24															
25															

	1	2	3	4	5	6	7	8	9	10	11
Target or Limit Value	20 hz	4lb over existing	withstand 1300 for 15 sec	600 psi	7 degree resultant vector	less than5.75 d	less than 30watts	5k cycles before failure	.5 sec half cycle	adds less than 1% to drag	less than .05 degree
Difficulty (0=Easy to Accomplish, 10=Extremely Difficult)	9	4	5	4	7	3	2	5	5	5	5
Max Relationship Value in Column	9	9	9	9	9	9	9	9	9	9	9
Weight / Importance	315.6	200.0	408.9	288.9	395.6	233.3	208.9	204.4	280.0	60.0	428.9
Relative Weight	10.4	6.6	13.5	9.6	13.1	7.7	6.9	6.8	9.3	2.0	14.2

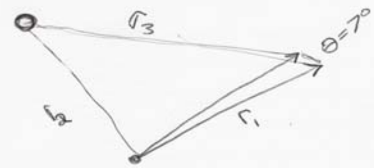
Competitive Analysis (0=Worst, 5=Best)

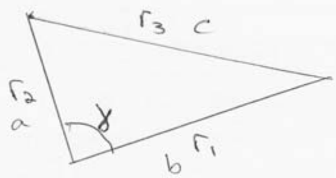
Row #	Our Company	liquid injection	thrust vanes	Competitor 3	rotatable	flexible joint
1		2	4	2	2	3
2		3	5	5	4	4
3		4	4	3	4	5
4		3	5	3	3	5
5		2	2	3	4	4
6		2	2	4	5	5
7		2	5	2	5	5
8		2	2	2	3	4
9		5	5	2	5	5
10		3	2	2	3	5

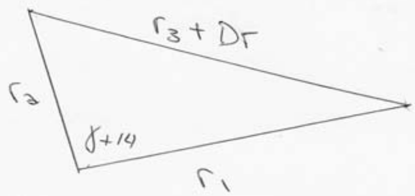


Powered by QFD Online (http://www.QFDOnline.com)

Motion of the nozzle:







$$c_1^2 = a^2 + b^2 - 2ab\cos\gamma$$

$$c_2^2 = a^2 + b^2 - 2ab\cos(\gamma+14)$$

$$c_2 - c_1 = \sqrt{a^2+b^2-2ab\cos(\gamma+14)} - \sqrt{a^2+b^2-2ab\cos(\gamma)}$$

Force required to move nozzle

$r_1 = 1.75$ $r_2 = 2.54\text{in}$

$$\Sigma M_o = -\mu F_N r_1 + F_s r_2 = 0$$

$$= (-.05)(1043.5\text{lb}_f)(1.75\text{in}) + F_s(2.54\text{in})$$

$$F_S = .05(1043.5\text{ lb}_f)(1.75/2.54) = 35.947\text{ lb}_f$$

Woops forgot to break FS into componons

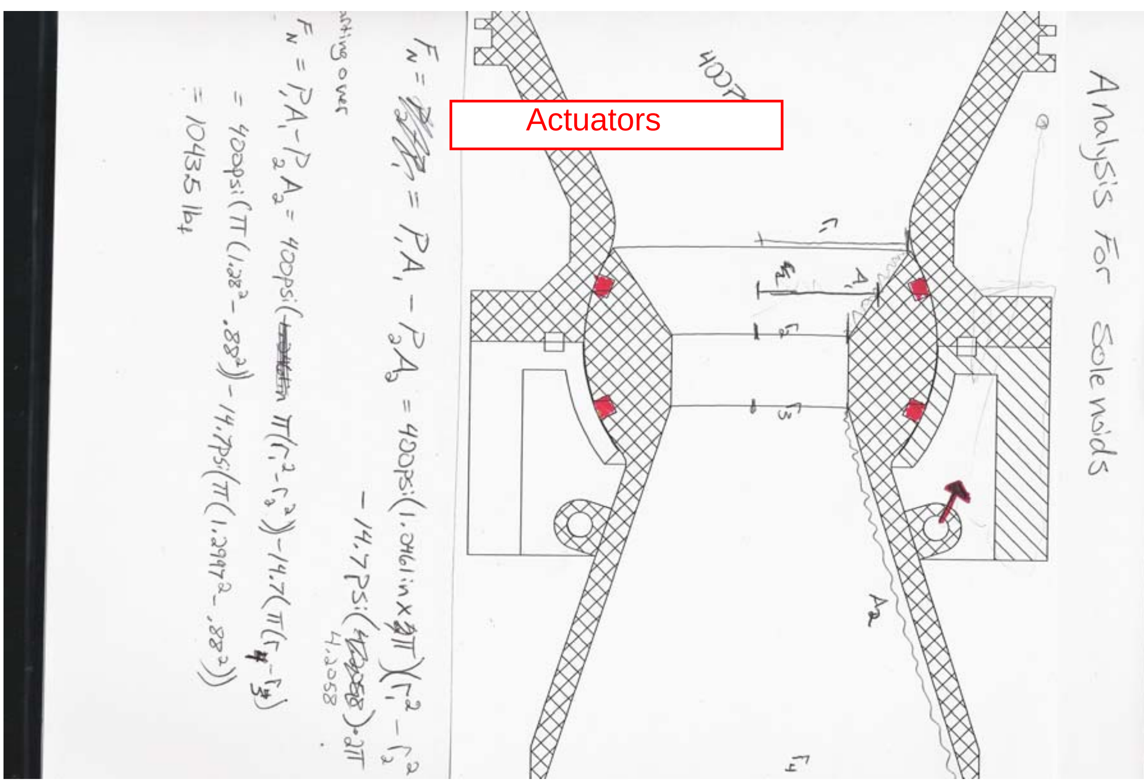
$$\Sigma M_o = -\mu F_N r_1 + F_s\cos(18) r_2 \sin(44.2) + F_s \sin(18) r_2 \cos(44.2)$$

$$-.05(1043.5)(1.75) + F_s(1.6841) + F_s(.5627)$$

$$F_s = 40.638\text{ lb}_f$$

So we need more room for solenoids!

Actuators



Heat Transfer Analysis

Approximate Solution

$F_o = \frac{\alpha t}{L^2} = \frac{(1.02\times10^{-6})(155 sec)}{(.0178 m)^2} = .0483 \quad \alpha = \frac{k}{\rho c_p} = \frac{1.6}{(2210)(709)} = 1.($

using $L = .7$ in or 1.78 cm
none of the approximate solutions apply
~~so θ*~~ must use the exact solution method

where
$$\theta^* = \sum_{n=1}^{\infty} C_n \exp(-\zeta_n^2 F_o)\cos(\zeta_n x^*)$$

where $C_n = \frac{4\sin\zeta_n}{2\zeta_n + \sin(2\zeta_n)}$

from appendix B.3

$Bi = 3.75 \quad \zeta_1 = 1.2466 \quad \zeta_2 = 3.9036 \quad \zeta_3 = 6.7865 \quad \zeta_4 = 9.7$

$C_1 = .03431 \quad C_2 = .03428 \quad C_3 = .03423 \quad C_4 = .03$

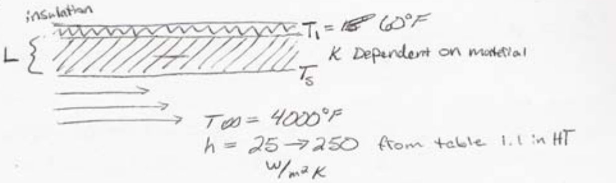
$x^* = \frac{x}{L} = \frac{x}{1.78 cm}$

$$\theta^* = C_1 \exp(-\zeta_1^2 F_o)\cos\left(\zeta_1\left(\frac{x}{1.78cm}\right)\right) + C_2\exp(-\zeta_2^2 F_o)\cos\zeta_2\left(\frac{x}{1.78cm}\right) + C_3\exp(-\zeta_3^2 F_o)\cos\zeta_3\left(\frac{x}{1.78cm}\right) + C_4\exp(-\zeta_4^2 F_o)\cos\zeta_4\left(\frac{x}{1.78cm}\right)$$

$= .03431\, e^{(-1.585\times10^{-5})}\cos(.00222x)$
$+ .03428\, e^{(-1.5543\times10^{-5})}\cos(.00695x)$
$+ .03423\, e^{(-4.697\times10^{-5})}\cos(.01208x)$
$+ .03415\, e^{(-9.776\times10^{-5})}\cos(.01743x)$

$= .03431\cos(.00222x) + .03428\cos(.00695x) + .03423\cos(.01208x) + .03415\cos(.01743x)$

if we consider a simplified Heat transfer model

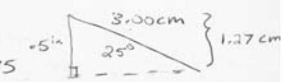


first known initial conditions $T_i = 60°F = 15.5°C$
typical materials being considered

	melting point	ρ	C_p	K		
Aluminum	933	2702	903	~~226~~ 186		
				K@ 600K	1000K	1500K
~~Carbon~~ Graphite, Pyrolytic ⊥ to layers	2273	2210	709	2.68	~~2.01~~ 1.60	1.08

for this material layers need to be ∥ to center of nozzle

$Bi = \frac{h_o L}{k} = \frac{(200\frac{W}{m^2K})(.03m)}{1.6} = 3.75$



lumped capacitance method is not recomended
the most general form of the heat ~~transfer~~ diffusion equation is

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + \dot{q} = \rho c_p\frac{\partial T}{\partial t}$$

for one dimension with no internal heat generation

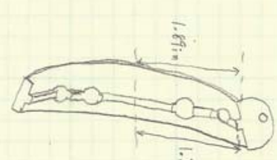
29

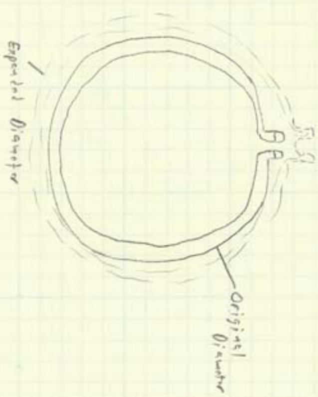
Thermal Expansion of Collar

3-0137 — 200 SHEETS — FILLER

Expansion of Inconel Collar

* Treat collar as a hollow cylinder





$$u = (1+\nu)\frac{\alpha}{r}\int_s^r T\, r\, dr$$

u = radial expansion; ν = Poisson's Ratio
α = Thermal Expansion coefficient r = outside diameter s = inside diameter
T: Temperature (°F)

$$u = (1+0.315)\left(\frac{7\times10^{-6}}{1.89}\right)\int_{1.74}^{1.89} 4220\, r\, dr$$

$u = 5.338\times10^{-3}$ in

Thermal Expansion of Graphite Nozzle

* Expansion will be greatest @ highest thickness

$$u = (1+\nu)\frac{\alpha}{r}\int_b^r T r_r \, dr_r$$

u = radial expansion; ν = Poisson's Ratio; α = Thermal Expansion Coefficient; r = outside diameter; b = inside diameter; T = Temperature °F

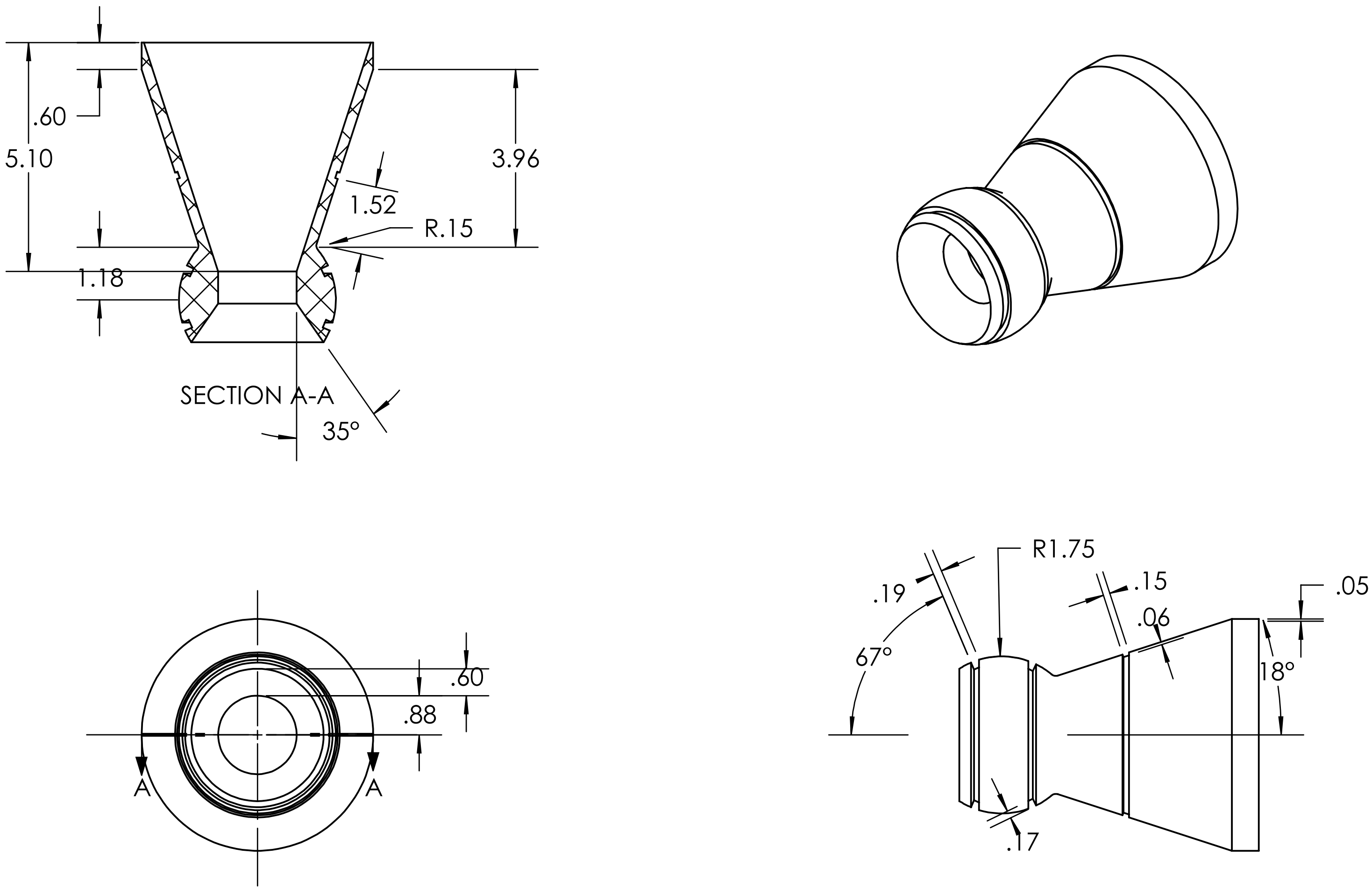
$$u = (1+0.2)\left(\frac{2.6\times10^{-6}}{1.74}\right)\int_{0.875}^{1.74} 4000\, r_r \, dr_r$$

$$u = 0.008112 \text{ in}$$

Thermal Expansion of Nozzle

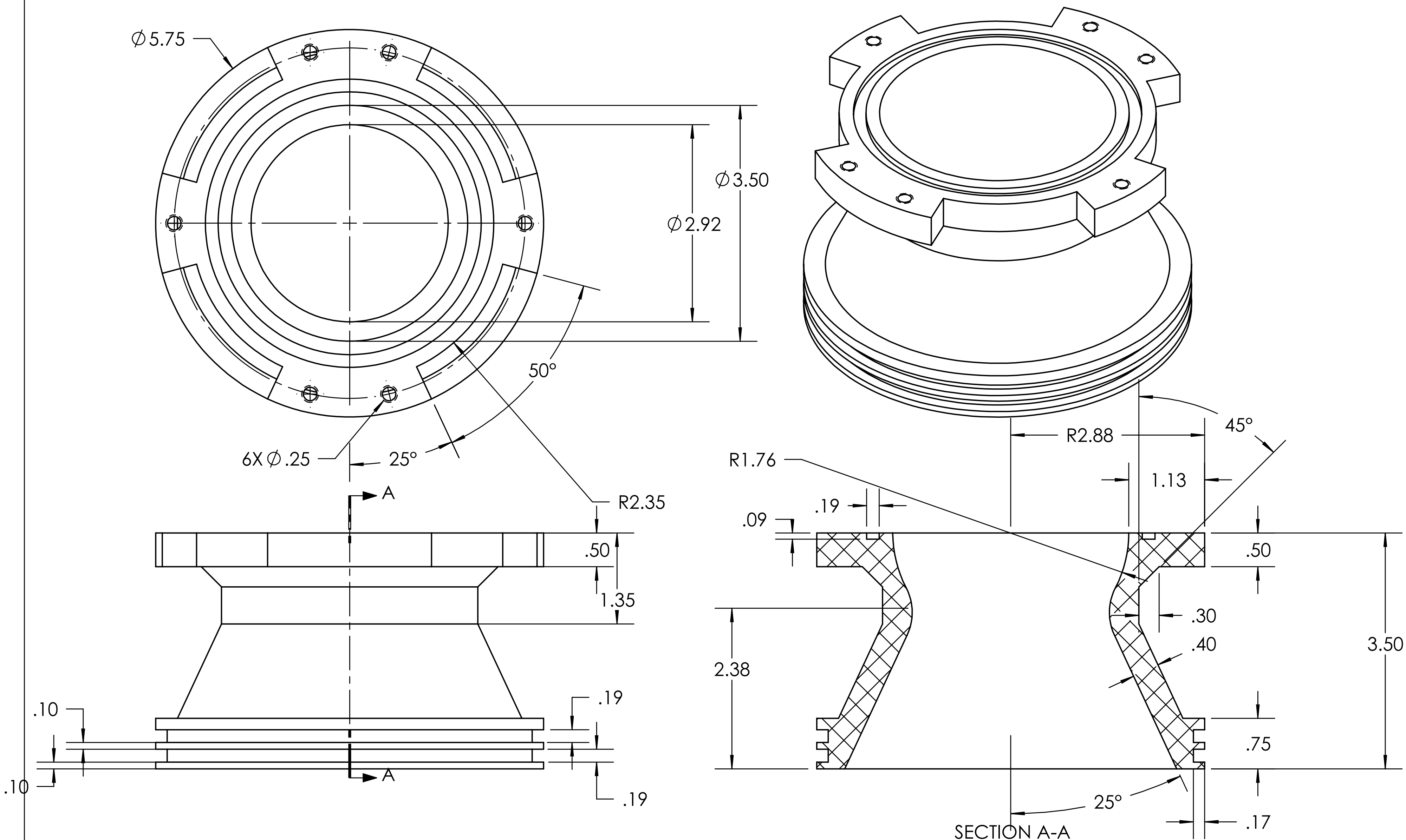
APPENDIX C

Material/Component	Vendor	Price	Contact
Graphite	www.GraphiteStore.com	$256 for one graphite rod	Address: GraphiteStore.com, Inc. 1348 Busch Parkway Buffalo Grove, IL 60089 US Phone: 800-305-1664 (Toll Free US only) 847-279-1925 Fax: 847-279-1926 E-mail: support@graphitestore.com
Fasteners	Fastener Solutions, Inc.	$34-$44 for each fastener Quote Requested on Smaller Dimension Fasteners	Name: Matt Bridges Office:866 463 2910 ext. 242F Cell: 225-200-7909 Fax: 225-927-9292 http://www.fastenersolutions.com
Inconel Rods	California Metal and Supply, Inc.	$1450-$2400 for each bar	Phone: 800 707 6061 Fax: 800 707 3439 http://californiametal.com
Linear Actuators	Firgelli Technologies	$80 each	Phone: 206-347-9684 Fax: 206-347-9684 sales@firgelli.com, www.firgelli.com
Graf Foil	www.sealsales.com	$90 each	Phone: 714-361-1435
Carbon Felt	ChemShine	N/A	Tel:0086-592-5530176 Fax:0086-592-5531751 MSN:guoxingyw@hotmail.com Email:info@chemshine-group.com



Stellar Thrust Control	DRAWN BY: DANE LARKIN	INIT:	CKD BY: SIMRAN SINGH	INIT:
Mechanical Engineering CAL POLY	TOLERANCE: .001	UNITS: INCHES	MATERIAL: CARBON	
	NEXT ASSY:	SCALE: 1/4	TITLE: BALL	
	DWG #: 001	DATE: 2/5/11	GROUP:	

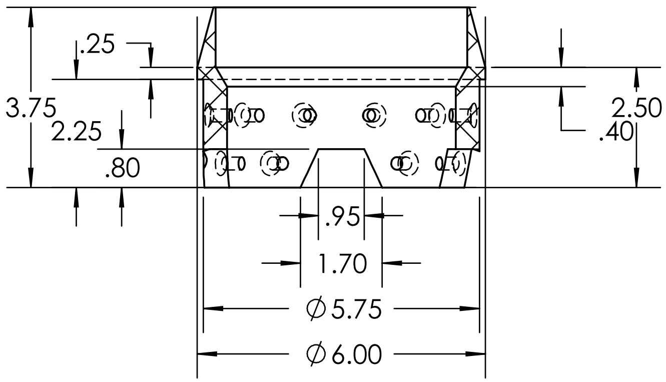
5 4 3 2 1

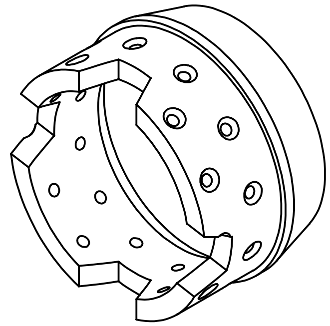


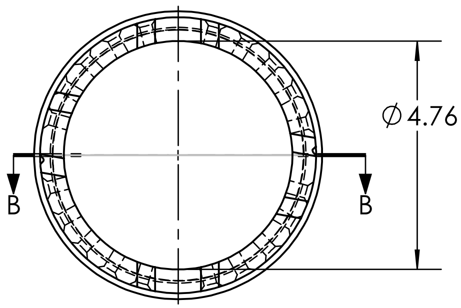
Stellar Thrust Control Mechanical Engineering CAL POLY	DRAWN BY:DANE LARKIN	INIT:	CKD BY:SIMRAN SINGH	INIT:
	TOLERANCE: .001	UNITS:INCHES	MATERIAL: CARBON	
	NEXT ASSY:	SCALE:2:1	TITLE: SOCKET	
	DWG #: 004	DATE: 2/5/11	GROUP:	

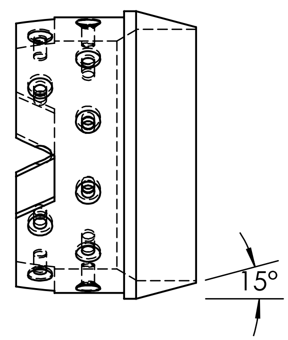
5 4 3 2 1

SECTION B-B



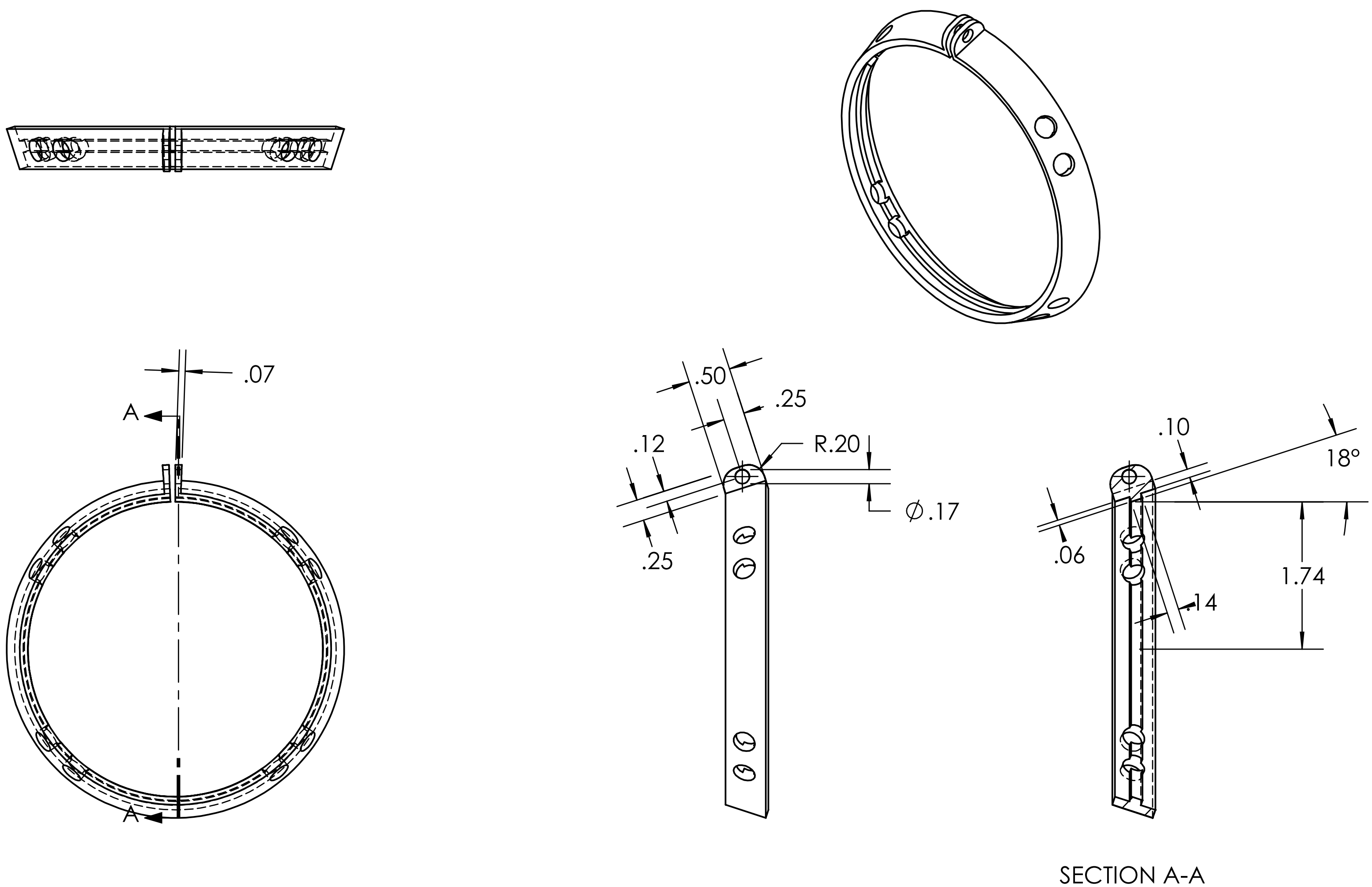






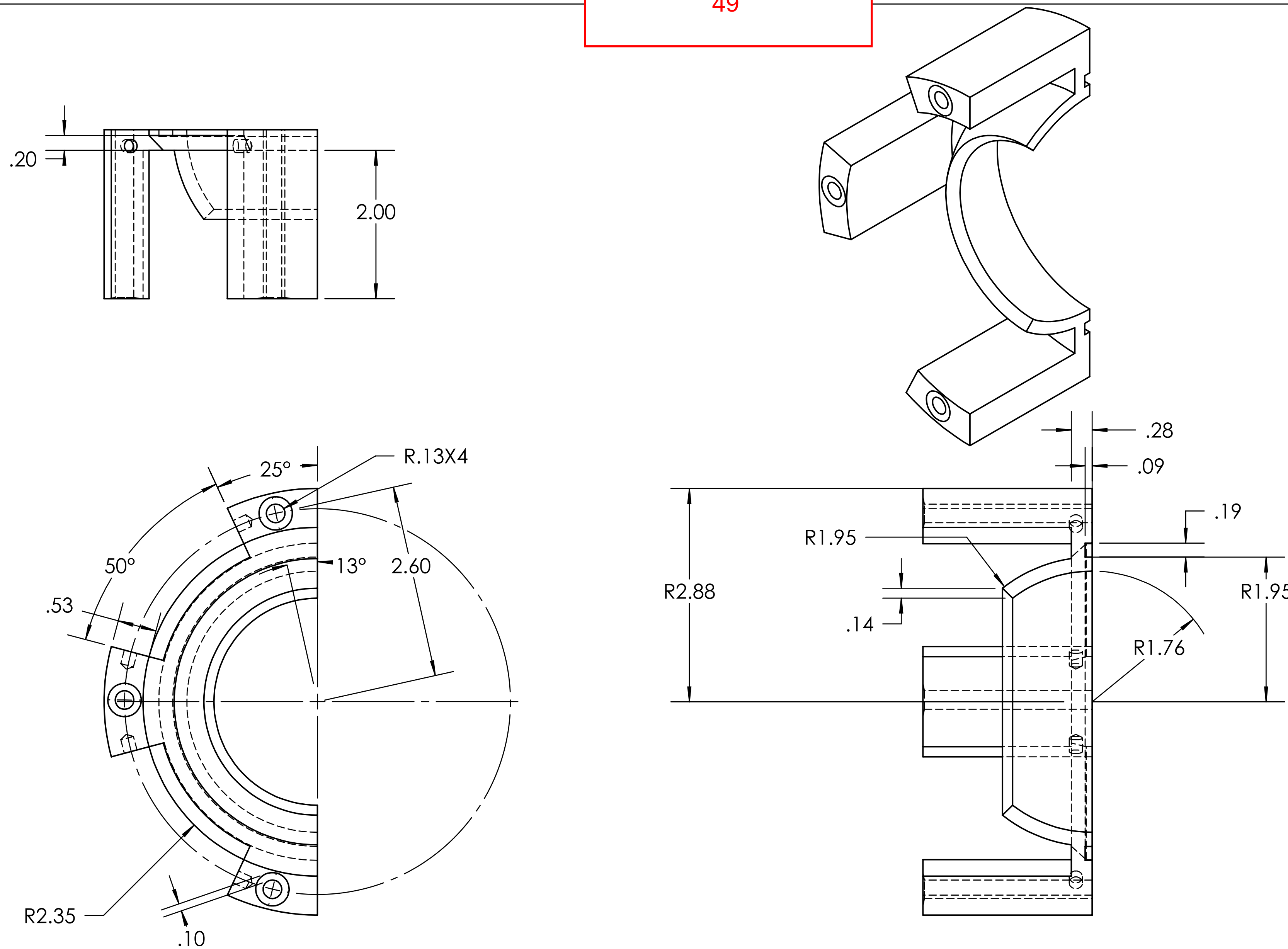
Stellar thrust control	DRAWN BY: DANE LARKIN	INIT:	CKD BY: SIMRAN SINGH	INIT:
Mechanical Engineering CAL POLY	TOLERANCE: .001	UNITS:INCHES	MATERIAL: ALUMINUM	
	NEXT ASSY:	SCALE:1:4	TITLE: MODIFIED BOAT TAIL	
	DWG #: 002	DATE: 2/5/11	GROUP:	

5 4 3 2 1



Stellar Thrust Control	DRAWN BY: DANE LARKIN	INIT:	CKD BY: SIMRAN SINGH	INIT:
Mechanical Engineering CAL POLY	TOLERANCE: .001	UNITS: INCHES	MATERIAL: STEEL OR INCONEL	
	NEXT ASSY:	SCALE: 2:1	TITLE: COLLAR	
	DWG #:003	DATE:2/5/11	GROUP:	

5 4 3 2 1

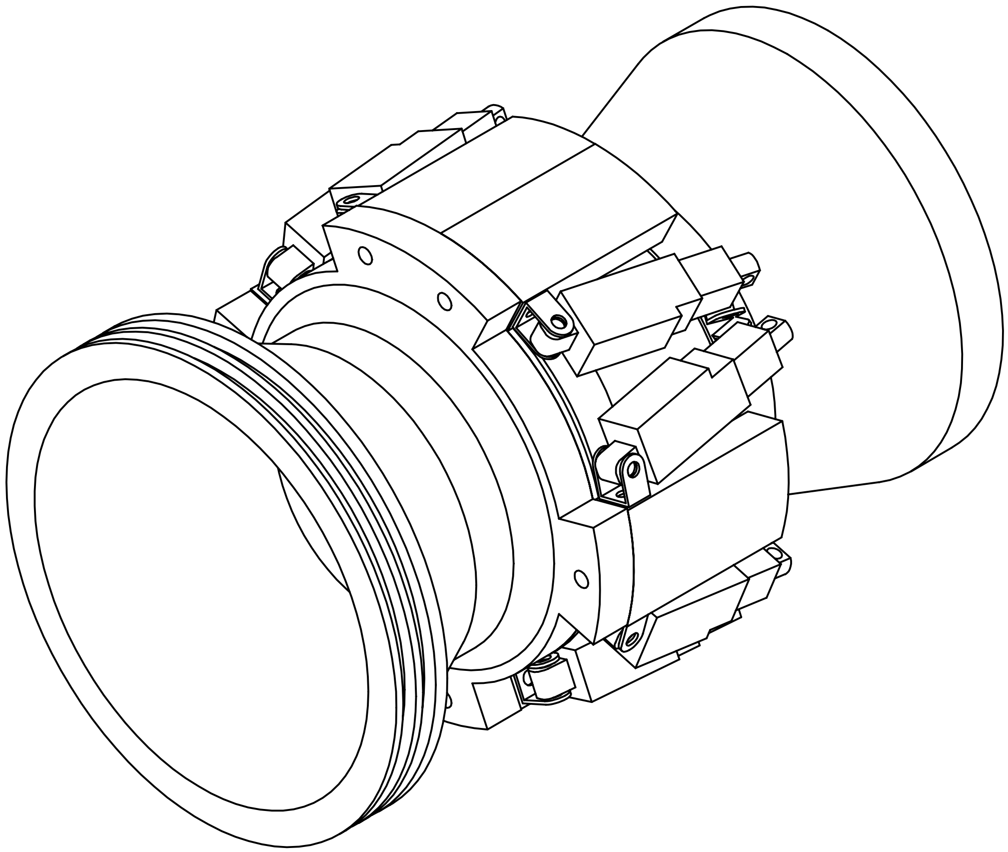


Stellar Thrust Control

Mechanical Engineering
CAL POLY

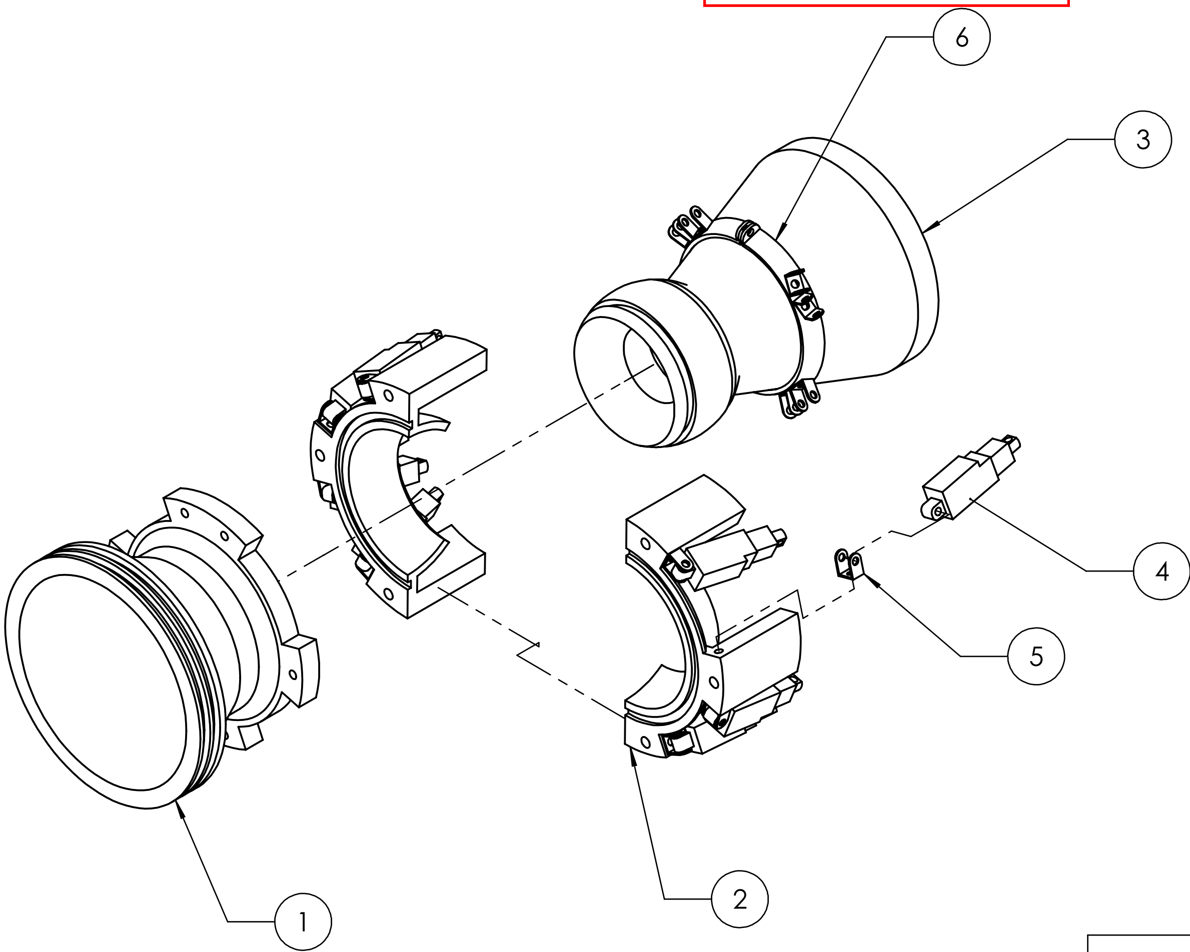
DRAWN BY: DANE LARKIN	INIT:	CKD BY: SIMRAN SINGH	INIT:
TOLERANCE: .001	UNITS: INCHES	MATERIAL: ALUMINUM OR INCONEL	
NEXT ASSY:	SCALE: 2:1	TITLE: FLANGE	
DWG #: 005	DATE:2/5/11	GROUP:	

5 4 3 2 1



Stellar Thrust Control	DRAWN BY:DANE LARKIN	INIT:	CKD BY: SIMRAN SINGH	INIT:
Mechanical Engineering CAL POLY	TOLERANCE: .001	UNITS:INCHES	MATERIAL:	
	NEXT ASSY:	SCALE: 1:2	TITLE: FULL ASSEMBLY	
	DWG #: 006	DATE: 2/5/11	GROUP:	

5 4 3 2 1



ITEM NO.	PART NUMBER	QTY.
1	socket	1
2	flange	2
3	ball	1
4	actuatorAssem	8
5	actuator mount	16
6	collar	1

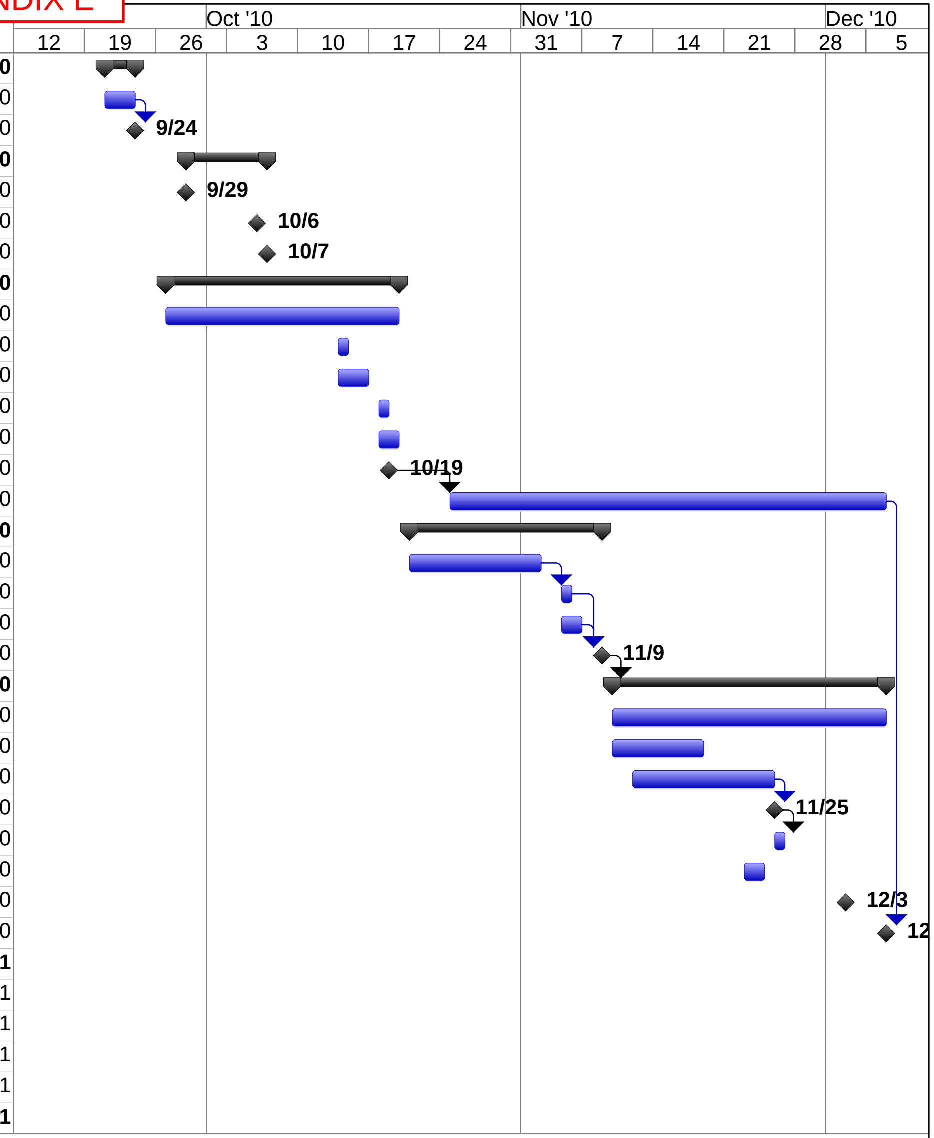
Stellar Thrust Control

Mechanical Engineering CAL POLY

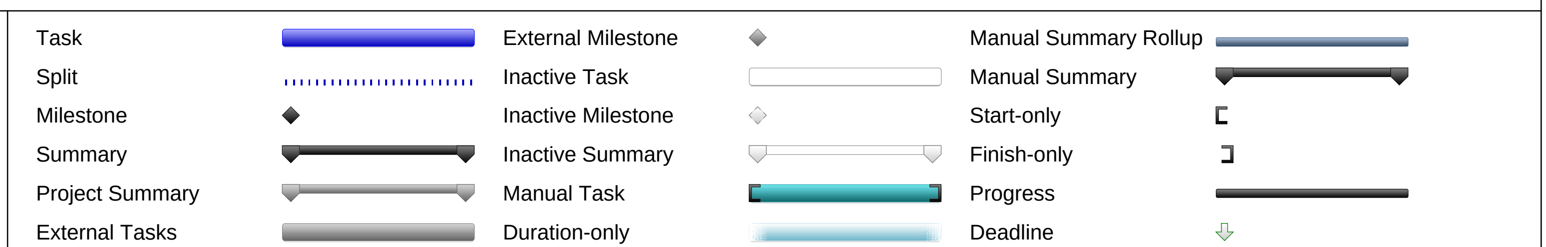
DRAWN BY:DANE LARKIN	INIT:	CKD BY: SIMRAN SINGH	INIT:
TOLERANCE: .001	UNITS: INCHES	MATERIAL:	
NEXT ASSY:	SCALE: 1:4	TITLE: EXPLODED ASSEMBLY	
DWG #: 007	DATE: 2/5/11	GROUP:	

5 4 3 2 1

ID		Task Name	Duration	Start	Finish
1		**selecting projects**	**3 days?**	**Tue 9/21/10**	**Fri 9/24/10**
2		project presentations	3 days?	Tue 9/21/10	Thu 9/23/10
3		project preference form	0 days	Fri 9/24/10	Fri 9/24/10
4		**sponsor communication**	**6 days**	**Wed 9/29/10**	**Thu 10/7/10**
5		team introduction to sponsor	0 days	Wed 9/29/10	Wed 9/29/10
6		visit the sponsor	0 days	Wed 10/6/10	Wed 10/6/10
7		team contract	0 days	Thu 10/7/10	Thu 10/7/10
8		**projects requirement Doc**	**17 days?**	**Mon 9/27/10**	**Tue 10/19/10**
9		background research	17 days?	Mon 9/27/10	Tue 10/19/10
10		QFD development	1 day?	Thu 10/14/10	Thu 10/14/10
11		specification Development	2 days?	Thu 10/14/10	Sat 10/16/10
12		method of approach	1 day?	Mon 10/18/10	Mon 10/18/10
13		management plan	2 days?	Mon 10/18/10	Tue 10/19/10
14		project Requirements Doc	0 days	Tue 10/19/10	Tue 10/19/10
15		Correct Requirements Doc	31 days	Mon 10/25/10	Mon 12/6/10
16		**Idea Generation**	**13 days?**	**Thu 10/21/10**	**Tue 11/9/10**
17		brain storming	9 days?	Thu 10/21/10	Tue 11/2/10
18		PEW diagram	1 day?	Fri 11/5/10	Fri 11/5/10
19		conceptual model	1 day	Fri 11/5/10	Sat 11/6/10
20		preliminary design presentation	0 days	Tue 11/9/10	Tue 11/9/10
21		**Conceptual Design**	**19 days?**	**Wed 11/10/10**	**Mon 12/6/10**
22		Enhance design requirements doc	19 days?	Wed 11/10/10	Mon 12/6/10
23		priliminary calculations	7 days	Wed 11/10/10	Thu 11/18/10
24		initial drawings	10 days	Fri 11/12/10	Thu 11/25/10
25		solid model	0 days	Thu 11/25/10	Thu 11/25/10
26		proto type	1 day?	Fri 11/26/10	Fri 11/26/10
27		preliminary plans for constructioon and te	2 days?	Tue 11/23/10	Wed 11/24/10
28		conceptual design report	0 days	Fri 12/3/10	Fri 12/3/10
29		conceptual design review	0 days	Mon 12/6/10	Mon 12/6/10
30		**Design finalization**	**18 days?**	**Thu 1/6/11**	**Tue 2/1/11**
31		reanalyze certain design aspects	5 days	Thu 1/6/11	Wed 1/12/11
32		make changes to concept	1 day?	Thu 1/13/11	Thu 1/13/11
33		student presentations	0 days	Tue 1/18/11	Tue 1/18/11
34		Design Report Doc	0 days	Tue 2/1/11	Tue 2/1/11
35		**manufacturing**	**42 days?**	**Mon 2/7/11**	**Tue 4/5/11**



Project: senior Project.mpp
Date: Fri 2/4/11



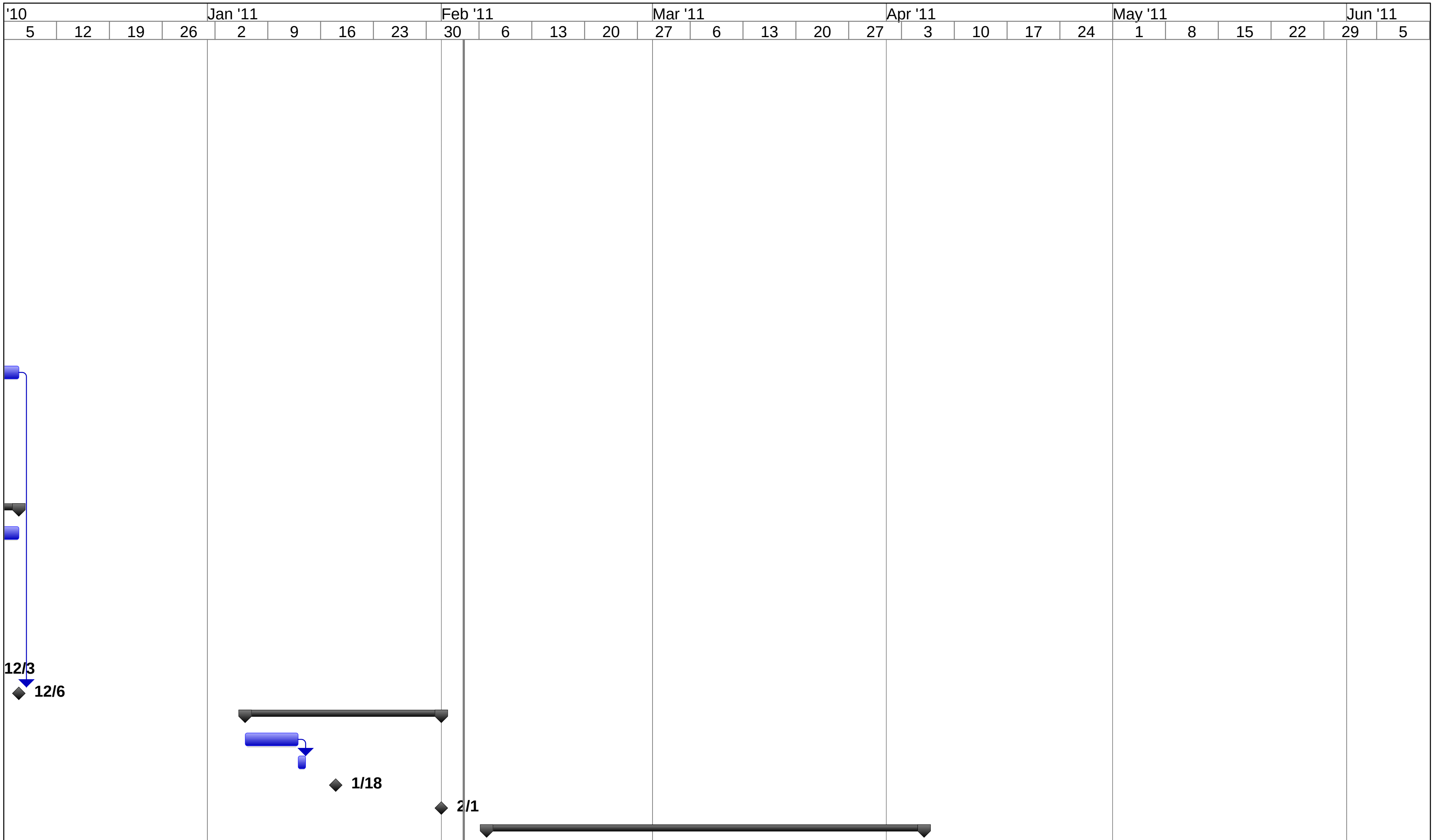
ID		Task Name	Duration	Start	Finish
36		contact sponsor about materials	5 days?	Mon 2/7/11	Fri 2/11/11
37		machineing and assembly	21 days?	Fri 2/11/11	Sat 3/12/11
38		testing	11 days?	Mon 3/14/11	Mon 3/28/11
39		fixing anything that is broken	6 days?	Tue 3/29/11	Tue 4/5/11
40		final project design report	0 days	Fri 6/3/11	Fri 6/3/11

Oct '10 | Nov '10 | Dec '10
12 | 19 | 26 | 3 | 10 | 17 | 24 | 31 | 7 | 14 | 21 | 28 | 5

Project: senior Project.mpp
Date: Fri 2/4/11

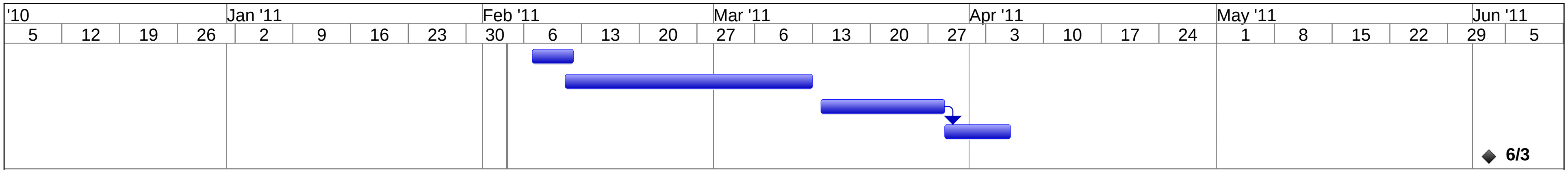
Task
Split
Milestone
Summary
Project Summary
External Tasks
External Milestone
Inactive Task
Inactive Milestone
Inactive Summary
Manual Task
Duration-only
Manual Summary Rollup
Manual Summary
Start-only
Finish-only
Progress
Deadline

54



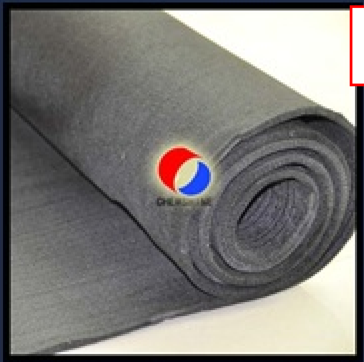
Project: senior Project.mpp
Date: Fri 2/4/11

Task	External Milestone	Manual Summary Rollup
Split	Inactive Task	Manual Summary
Milestone	Inactive Milestone	Start-only
Summary	Inactive Summary	Finish-only
Project Summary	Manual Task	Progress
External Tasks	Duration-only	Deadline



Project: senior Project.mpp
Date: Fri 2/4/11

Task	External Milestone	Manual Summary Rollup
Split	Inactive Task	Manual Summary
Milestone	Inactive Milestone	Start-only
Summary	Inactive Summary	Finish-only
Project Summary	Manual Task	Progress
External Tasks	Duration-only	Deadline



Chemshine carbon felt has PAN based carbon Felt and Rayon based carbon felt.

1, Technical Specifications:

- Volume Density (g/cm3): 0.11-0.13
- Tensile Strength (Mpa): 0.12-0.30
- Thermal Conductivity (W/m.k): 0.09-0.13(25℃) 0.20-0.27(1000℃)
- Specific Resistance (Ohm.cm): 0.18-0.22
- Carbon Content (%): ≥99
- Ash Content (%): ≤0.5
- Moisture Absorption (%): ≤2
- Processing Temperature (℃): 1000-1450

2, Available Size:

- Length (mm): 3000-12000
- Width (mm): 1000-1250
- Thickness (mm): 3-25
- Applicative Temperature Range (℃): 1300-1850

Other size can be tailored after confirmation.

Grafoil® Pump / Valve Stem Packing

Grafoil® Thermabraid Pump/Valve Stem Packing

Braided Grafoil® flexible graphite Packing, with encapsulated E-Glass. Suitable for high temperatures to **1200 F in steam** service, 850 F in an oxygen rich atmosphere and 5400 F in a reducing or non-oxygen atmosphere. Speed 4000 FPM (Feet per Minute)

Pressure: 3000 PSI (200 bar)

pH 0-14 *may require end rings - Ideal choices are style 4500 or style 90

Construction: Interlock Braid

	Item#	Size Packing	Size Box	Price
1	2300-1250-G	1/8"	1 lb	$ 90.00
Quantity			Apprx. Ft. 150	

Add to Cart

Print

Close

Grade: GR001CC

Manufacturer: Graphtek LLC

Method of Manufacturing: Isostatically Pressed

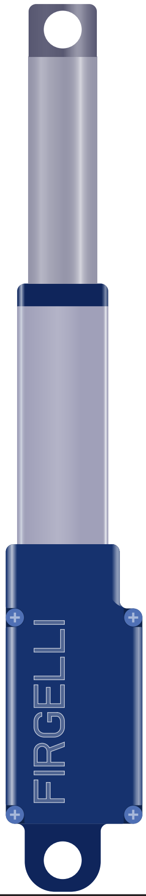
Description: High strength, wear resistant graphite

PROPERTY	US VALUE		METRIC VALUE	
Density	**0.065**	lb/in ^{3}	**1.81**	gr/cm ^{3}
Shore Hardness	**76**			
Flexural Strength	**7250**	psi	**50**	mpa
Oxidizing Atmosphere	**801**	°F	**427**	°C
Neutral Atmosphere	**5000**	°F	**2760**	°C
Porosity	**12**	%		
Electrical Resistivity	**0.00055**	ohm/inch		ohm/cm
Thermal Conductivity	**49**	BTU/(h.ft ^{2} °F/ft)	**85**	W/(m ^{2} . K/m)
Ash Content	**100**	ppm		
CTE	**2.6**	in/in °F x 10 $^{-6}$	**4.6**	Microns/m °C

Print

Close

Miniature Linear Motion Series • L12



Firgelli Technologies' unique line of Miniature Linear Actuators enables a new generation of motion-enabled product designs, with capabilities that have never before been combined in a device of this size. These small linear actuators are a superior alternative to designing with awkward gears, motors, servos and linkages.

Firgelli's L series of micro linear actuators combine the best features of our existing micro actuator families into a highly flexible, configurable and compact platform with an optional sophisticated on-board microcontroller. The first member of the L series, the L12, is an axial design with a powerful drivetrain and a rectangular cross section for increased rigidity. But by far the most attractive feature of this actuator is the broad spectrum of available configurations.

Benefits

- → **Compact miniature size**
- → **Simple control using industry standard interfaces**
- → **Low voltage**
- → **Equal push / pull force**
- → **Easy mounting**

Applications

- → **Robotics**
- → **Consumer appliances**
- → **Toys**
- → **Automotive**
- → **Industrial automation**

L12 Specifications

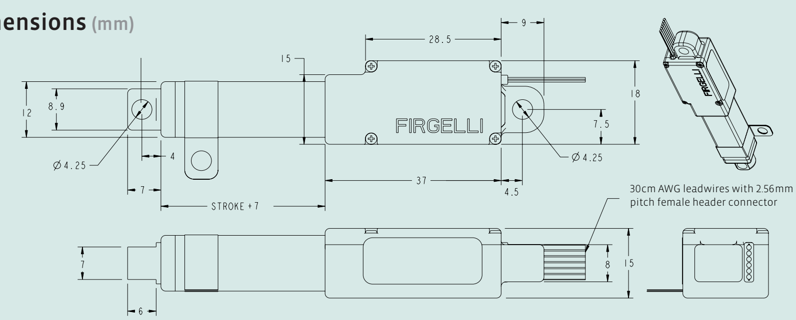
Gearing Option	50	100	210
Peak Power Point [1]	12 N @ 11 mm/s	23 N @ 6 mm/s	45 N @ 2.5 mm/s
Peak Efficiency Point	6 N @ 16 mm/s	12 N @ 8 mm/s	18 N @ 4 mm/s
Max Speed (no load)	23 mm/s	12 mm/s	5 mm/s
Backdrive Force [2]	43 N	80 N	150 N

Stroke Option	10 mm	30 mm	50 mm	100 mm
Weight	28 g	34 g	40 g	56 g
Positional Accuracy	0.1 mm	0.2 mm	0.2 mm	0.3 mm
Max Side Force (fully extended)	50 N	40 N	30 N	15 N

Mechanical Backlash	0.1 mm
Feedback Potentiometer	2.75 kΩ/mm ± 30%, 1% linearity
Duty Cycle	20 %
Lifetime	1000 hours at rated duty cycle
Operating Temperature	–10°C to +50°C
Storage Temperature	–30°C to +70°C
Ingress Protection Rating	IP–54
Audible Noise	55 dB at 45 cm
Stall Current	450 mA at 5 V & 6 V, 200 mA at 12 V

[1] 1 N (Newton) = 0.225 lb_f (pound-force)
[2] a powered-off actuator will statically hold a force up to the Backdrive Force

Dimensions (mm)



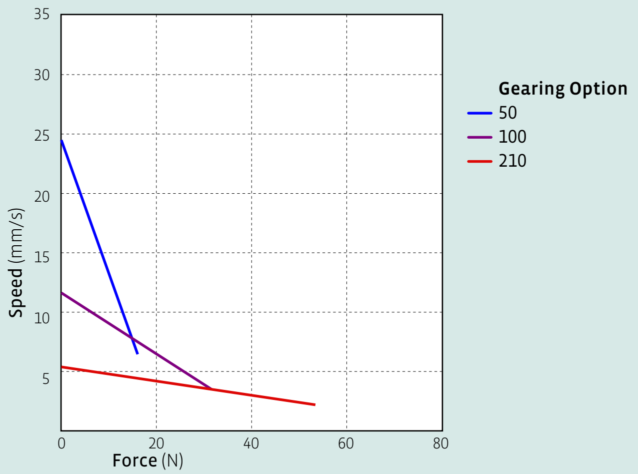
Firgelli Technologies Inc.
4585 Seawood Tce.
Victoria, BC V8N 3W1
Canada

1 (206) 347-9684 *phone*
1 (888) 225-9198 *toll-free*
1 (206) 347-9684 *fax*

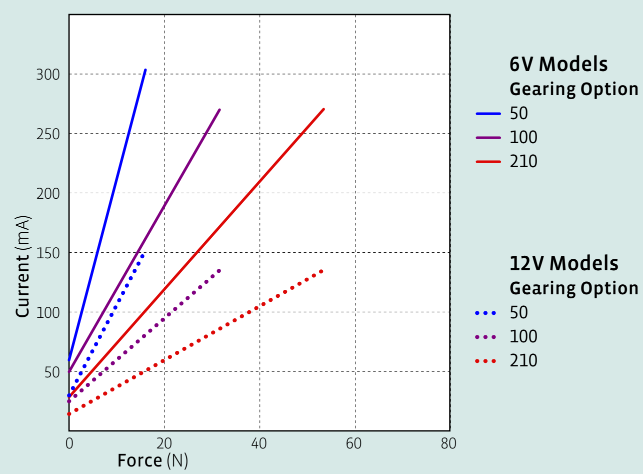
sales@firgelli.com
www.firgelli.com

L12 Specifications

Load Curves



Current Curves



Model Selection

The L12 has five configurable features. L12 configurations are identified according to the following scheme:

L12-SS-GG-VV-C-L

feature	*options*
SS: Stroke Length (in mm)	**10, 30, 50, 100** Any stroke length between 10 and 100 mm is available on custom orders, in 2 mm increments.
GG: Gear reduction ratio (refer to force/speed plots)	**50, 100, 210** Other gearing options may be possible on custom orders.
VV: Voltage	**06** 6 V (5 V power for Controller options B and P) **12** 12 V
C: Controller	**B** Basic 2-wire open-loop interface, no position feedback, control, or limit switching. Positive voltage extends, negative retracts. **S** 2-wire open-loop interface (like B option) with limit switching at stroke endpoints. **P** Simple analog position feedback signal, no on-board controller. **I** Integrated controller with Industrial and RC servo interfaces (see L12 Controller Options section). Not available with 10mm stroke length configurations. **R** RC Linear Servo. Not available with 10mm stroke or 12 volts.
L: Mechanical or electrical interface customizations	Custom option codes will be issued by Firgelli for custom builds when applicable.

Basis of Operation

The L12 actuator is designed to move push or pull loads along its full stroke length. The speed of travel is determined by the gearing of the actuator and the load or force the actuator is working against at a given point in time (see Load Curves chart on this datasheet). When power is removed, the actuator stops moving and holds its position, unless the applied load exceeds the backdrive force, in which case the actuator will backdrive. Stalling the actuator under power for short periods of time (several seconds) will not damage the actuator. Do not reverse the supply voltage polarity to actuators containing an integrated controller (I controller option).

Each L12 actuator ships with two mounting clamps, two mounting brackets and two rod end options: a clevis end and a threaded end with nut (see drawing on page 4). When changing rod ends, extend the actuator completely and hold the round shaft while unscrewing the rod end. Standard lead wires are 28 AWG, 30 cm long with 2.56 mm (0.1") pitch female header connector (Hi-Tec™ and Futaba™ compatible). Actuators are a sealed unit (IP–54 rating, resistant to dust and water ingress but not fully waterproof).

Ordering information

Sample quantities may be ordered with a credit card directly from www.firgelli.com.

Please contact Firgelli at sales@firgelli.com for volume pricing or custom configurations.

Note that not all configuration combinations are stocked as standard products. Please refer to www.firgelli.com/orders for current inventory.

L12 Controller options

Option B—Basic 2-wire interface

WIRING:

1 (red)	**Motor V+** (5 V or 12 V)
2 (black)	**Motor ground**

The –B actuators offer no control or feedback mechanisms. While voltage is applied to the motor V+ and ground leads, the actuator extends. If the polarity of this voltage is reversed, the actuator retracts. The 5 V actuator is rated for 5 V but can operate at 6 V.

Option S—Basic 2-wire interface

WIRING:

1 (red)	**Motor V+** (5 V or 12 V)
2 (black)	**Motor ground**

When the actuator moves to a position within 0.5mm of its fully-retracted or fully-extended stroke endpoint, a limit switch will stop power to the motor. When this occurs, the actuator can only be reversed away from the stroke endpoint. Once the actuator is positioned away from it's stroke endpoint, normal operation resumes. For custom orders, limit switch trigger positions can be modified at the time of manufacture, in 0.5mm increments.

Option P—Position feedback signal

WIRING:

1 (orange)	**Feedback potentiometer negative reference rail**
2 (purple)	**Feedback potentiometer wiper** (position signal)
3 (red)	**Motor V+** (5 V or 12 V)
4 (black)	**Motor ground**
5 (yellow)	**Feedback potentiometer positive reference rail**

The –P actuators offer no built-in controller, but do provide an analog position feedback signal that can be input to an external controller. While voltage is applied to the motor V+ and ground leads, the actuator extends. If the polarity of this voltage is reversed, the actuator retracts. Actuator stroke position may be monitored by providing any stable low and high reference voltages on leads 1 and 5, and then reading the position signal on lead 2. The voltage on lead 2 will vary linearly between the two reference voltages in proportion to the position of the actuator stroke.

Option I—Integrated controller with industrial and RC servo interfaces

WIRING:

1 (green)	**Current input signal** (used for 4–20 mA interface mode)
2 (blue)	**Voltage input signal** (used for the 0–5V interface mode and PWM interface modes)
3 (purple)	**Position Feedback signal** (0–3.3 V, linearly proportional to actuator position)
4 (white)	**RC input signal** (used for RC-servo compatible interface mode)
5 (red)	**Motor V+** (+6 Vdc for 6 V models, +12 Vdc for 12 V models)
6 (black)	**Ground**

The –I actuator models feature an on-board software-based digital microcontroller. The microcontroller is not user-programmable

The six lead wires are split into two connectors. Leads 4, 5 and 6 terminate at a universal RC servo three-pin connector (Hi-Tec™ and Futaba™ compatible). Leads 1, 2 and 3 terminate at a separate, similarly sized connector.

When the actuator is powered up, it will repeatedly scan leads 1, 2, 4 for an input signal that is valid under any of the four supported interface modes. When a valid signal is detected, the actuator will self-configure to the corresponding interface mode, and all other interface modes and input leads are disabled until the actuator is next powered on.

0–5 V Interface Mode: This mode allows the actuator to be controlled with just a battery, and a potentiometer to signal the desired position to the actuator – a simple interface for prototypes or home automation projects. The desired actuator position (setpoint) is input to the actuator on lead 2 as a voltage between ground and 5V. The setpoint voltage must be held on lead 2 until the desired actuator stroke position is reached. Lead 2 is a high impedance input.

4–20 mA Interface Mode: This mode is compatible with PLC devices typically used in industrial control applications. The desired actuator position (setpoint) is input to the actuator on lead 1 as a current between 4 mA and 20 mA. The setpoint current must be held on lead 1 until the desired actuator stroke position is reached.

RC Servo Interface Mode: This is a standard hobby-type remote-control digital servo interface (CMOS logic), compatible with servos and receivers from manufacturers like Futaba™ and Hi-Tec™. The desired actuator position is input to the actuator on lead 4 as a positive 5 Volt pulse width signal. A 1.0 ms pulse commands the controller to fully retract the actuator, and a 2.0 ms pulse signals full extension. If the motion of the actuator, or of other servos in your system, seems erratic, place a 1–4Ω resistor in series with the actuator's red V+ leadwire.

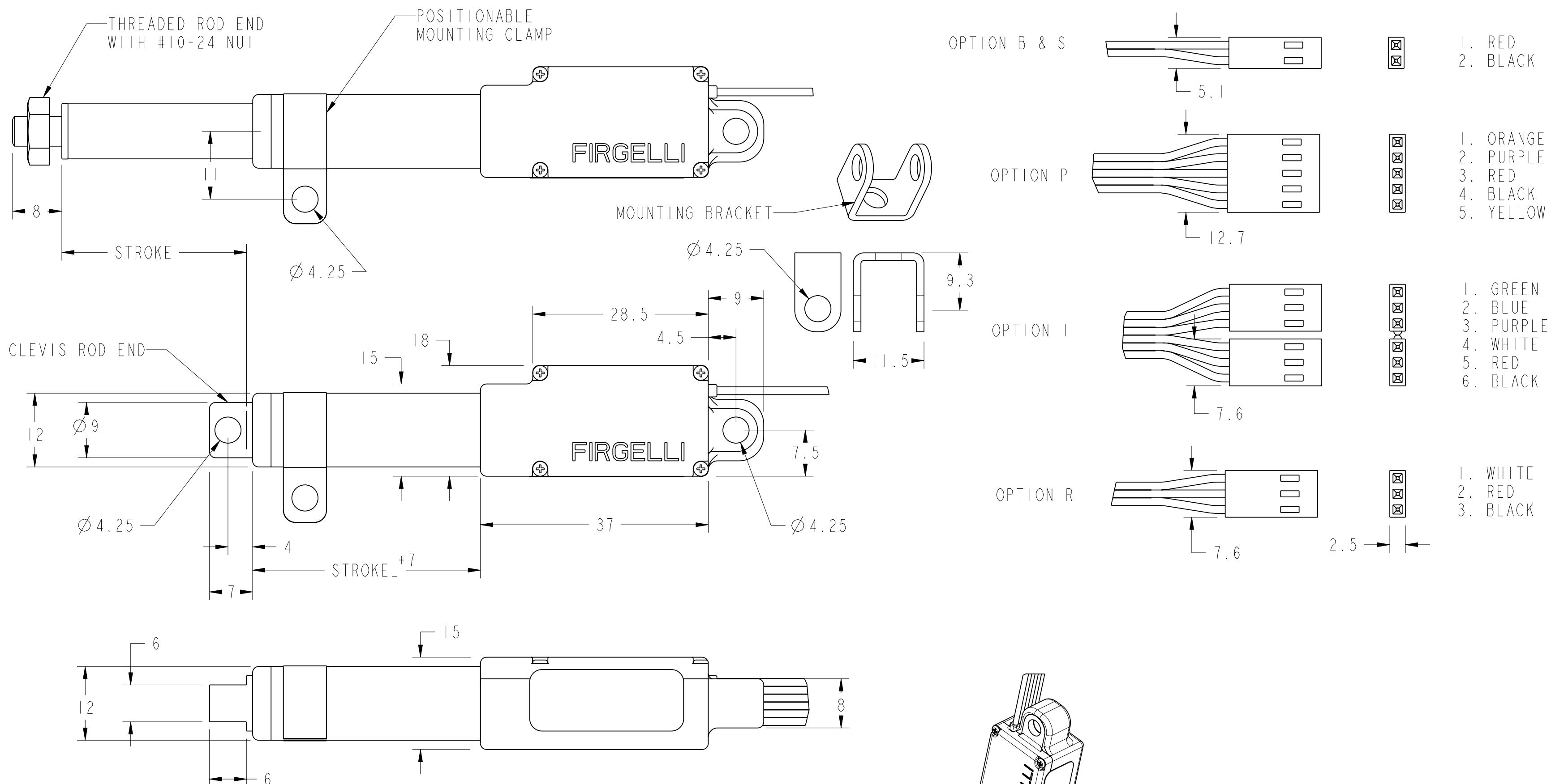
PWM Mode: This mode allows control of the actuator using a single digital output pin from an external microcontroller. The desired actuator position is encoded as the duty cycle of a 5 Volt 1 kHz square wave on actuator lead 2, where the % duty cycle sets the actuator position to the same % of full stroke extension. The waveform must be 0V to +5V in order to access the full stroke range of the actuator.

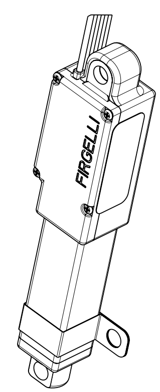
Option R—RC Linear Servo

WIRING:

1 (white)	**RC input signal**
2 (red)	**Motor V+** (6 VOC)
3 (black)	**Ground**

The –R actuators or 'linear servos' are a direct replacement for regular radio controlled hobby servos. Operation is as above in RC servo interface mode (option I). The –R actuators are available in 6 volt and 30, 50 and 100 mm strokes only.





SCALE 1:1

NOTES:

1) WHEN CHANGING ROD ENDS, EXTEND ACTUATOR COMPLETELY AND HOLD THE ROUND SHAFT WHILE UNSCREWING THE ROD END PLUG

2) Ø4.25 MOUNTING HOLES WILL FIT M4 OR UN #8 SIZE SCREWS

3) TWO MOUNTING CLAMPS, TWO MOUNTING BRACKETS, ONE EXTRA THREADED ROD END WITH NUT AND #8-32 HARDWARE, IS INCLUDED WITH EACH ACTUATOR.

4) STANDARD LEAD WIRE LENGTH IS 300mm. 28AWG STRANDED RIBBON WIRE. CONNECTORS ARE 2.54mm PITCH FEMALE HEADER CONNECTORS

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L12 ACTUATOR FAMILY INTERFACE DIMENSIONS	SCALE 3:2