SAFFiR Senior Design Team:

4016 Final Report

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Executive Summary

This report details the progress of the SAFFiR (Shipboard Autonomous Firefighting Robot) senior design team throughout the semester in their mission of assisting the Robotics and Mechanisms Laboratory (RoMeLa) in advancing the SAFFiR project. The Table of Contents on the next page maps out the sections of the report.

SAFFiR is a Shipboard Autonomous Fire Fighting Robot to be used on naval vessels to help personnel with damage control in the event of a fire. The graduate students have tasked the senior design team to help complete portions of the project. The advisors for this project are Dr. Dennis Hong, Derek Lahr, and Bryce Lee. The teams initial design challenges from last semester, the gantry and covers projects, have been completed. Details about these projects can be reviewed in the fall final report submitted in December 2011. The new projects, the actuator and foot redesign, will be the focus of this document. Both of these challenges have been successfully completed and delivered to the graduate students.

The linear actuator redesign team was able to successfully incorporate a second motor into the current linear actuator redesign. Additionally the team was able to fully enclose the ball screw by redesigning the limit switching mechanism to incorporate magnetic reed switches in the place of physical contact switches.

The foot redesign team has been tasked with developing a more advanced foot for the SAFFiR Project. The goal was to develop a foot that could conform to uneven terrain and provide a stable rectangular platform on which SAFFiR could place its weight. This team was able to successfully complete this design challenge and has now delivered two complete feet that are ready to be installed on the SAFFiR Robot.

The focus of this report is to present to the reader the products that have been developed, the process used to reach the end goal, and the future recommendations that we would make if the projects were to be taken to the next level. The old design challenges from last semester will not be addressed and information regarding those projects can be found in last semesters final report. Refer to the table of contents for a directory of the sections that this report contains.

Table of Contents

Introduction

The Robotics and Mechanisms Laboratory (RoMeLa) at Virginia Tech with sponsorship from the U.S. Navy is currently designing and constructing a Shipboard Autonomous Fire Fighting Robot (SAFFiR). SAFFiR is a bio-inspired, anthropomorphic, bipedal robot, whose actuations mimic those of human muscles and tendons. This is accomplished by using series elastic actuators coupled with compliant members, which are regulated through closed loop feedback from load cells. This unique design deviates from the typical use of series motors, providing a greater range of motion, more efficiently, while reducing the profile of the actuators. Because this is a revolutionary approach, the RoMeLa team anticipates encountering unexpected behavior and difficulties when testing SAFFiR's walking capabilities. Our senior design team has been assembled to assist the graduate students by tackling design challenges that can be separated from the main design challenge.

One sub-team has been tasked with designing, fabricating, and building a linear actuator that will have double the power output of the current design. This actuator must also be designed in such a way that they could be swapped out with the current design without any modifications to the main SAFFiR skeleton. Many designs were considered each contributing their own piece to the final design. The team has decided that a second motor in a side by side or "Disney" configuration will used to double the power output. The tensioning of the belt will be achieved by pivoting the second motor on a hinge that is incorporated into the main body of the actuator. The limit switches have also been improved so that the ball screw can be fully enclosed. The team is happy to say that the design is ready to be incorporated into the body of the SAFFiR project.

The second sub-team is tasked with designing, fabricating, and building a more advanced foot for SAFFiR. The main design objective is to create a foot that will be able to conform to the uneven floors of the test ship on which SAFFiR will have to walk during the FY13 Demonstration. The many concepts that have been generation will be presented in the foot specific section of this report. The report will then outline the final design that was selected and how it accomplishes the challenge of conforming to the ground. Recommendations on future design revisions will be made to assist any person who may decide to improve upon our design.

The following sections of this report will elaborate the details of the overall team structure and projects that have been introduced here. The Conclusions section will focus on future recommendations made for future revisions of our products. We have met the design goals that we set for the end of this semester and have been able to deliver four products to the graduate students that are ready to be incorporated into the main body of the SAFFiR project.

Team Composition

The goal of the undergraduate students is to aid the RoMeLa graduate students in the design and rapid prototyping of SAFFIR. The team consists of 9 members that have been divided among the sub teams. The team established a hierarchy with a team lead whose focus is work with the graduate students to establish milestones, keep the sub-teams on task, and oversee the completion of class assignments. Assisting the team lead is also a team scribe, a head of manufacturing, and individual sub-team leaders. The scribes role is to maintain minutes at all large group meetings and the manufacturing head is responsible for facilitating machine time scheduling and the ordering of all parts for the team. Each sub-team leader is responsible for effectively managing their team, splitting up design tasks evenly among team members, and keeping the team on schedule. Figure 1 shown below details the roles each member has. It should be noted that the gantry and covers teams will not be discussed in this report.

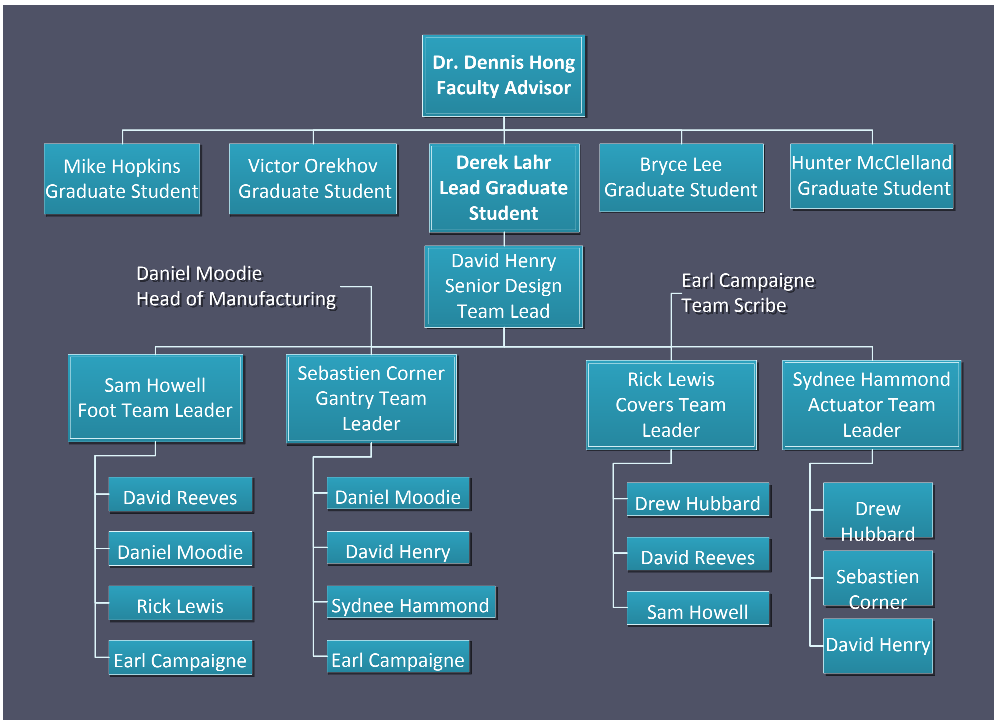


Figure 1. Team Organizational Chart. Note that this report will not discuss the covers or gantry teams as they are drawing to a close.

With this hierarchy, all of the tasks are organized in an easy to manage system where each leader ensures team efficiency and success.

The U.S. Navy is the only major stakeholder in this project and is the end customer for the RoMeLa graduate students. The RoMeLa graduate students are the end customer of this undergraduate design team. Therefore, the current primary tasks of this design team are now the foot and actuator design challenges.

The scheduled Tuesday and Thursday meetings are used to update the graduate students on the team's progress, solicit design feedback, ask design or manufacturing questions, and coordinate tasks. Outside of these meetings, the individual sub-teams are responsible for meeting as necessary to accomplish their deadlines.

Linear Actuator Redesign Project

Introduction

This section of the report will detail the progress made on the linear actuator project. This project consists of solving the design challenge of adding a second motor to the existing design. SAFFiR will have many tasks that it must accomplish to successfully fight fires, and the original output of 1kN of force per actuator will not be sufficient while under the load of fire suppressant equipment. Some major design requirements include achieving a power output of 2kN while remaining under 1.1kg in mass as well as not restricting SAFFiR's range of motion. The current design is also difficult to assemble with one person, and the machining is tedious. The team also worked to solve these issues in the new design.

The following sections will explain in detail the process used for multiple iterations of concept generation and selection. They will also delve into the details of the final design, manufacturing processes and lessons learned, as well as the testing and final results. The next sections will also detail the challenge that was presented in the limit switch redesign. The existing design requires that holes be cut into the carbon fiber outer tubes, and leaves the costly ball screw exposed. The challenge was to implement new limit switches that did not need such holes. The design process and detail design will be explained further in the subsequent sections.

Mission Statement and Team Composition

The actuator team was assembled in late 2011 in an attempt to increase the overall power output of the linear actuators used in SAFFiR. The SAFFiR graduate students are concerned that the current actuator design will be unable to provide enough force once the robot is completely assembled. The team that was assembled to tackle this challenge consists of Sydnee Hammond as the team lead with Drew Hubbard, Sebastien Corner, and David Henry as team members. Together these four people will focus on doubling the power of the current linear actuator design through the incorporation of a second motor.

The creation of a stronger linear actuator has the potential to increase SAFFiR's allowable payload. The direct benefactors from this design improvement will be the graduate students working on SAFFiR. The design will interface with the robot in exactly the same way as the current linear actuators. Additional constraints for the design team include keeping the system lightweight, simplifying manufacture, maintaining a compact design, and minimizing friction in the system.

The actuator team will deliver a completed actuator by the 1st of April 2012. This will allow for a month of testing so that on May 1st the design is ready to be integrated into SAFFiR. This design team's goal remains to assist the graduate students and ultimately help SAFFiR reach a state where it can be implemented into a shipboard environment.

Concept Generation

The linear actuator team generated many concepts for both motor configurations and tensioning systems that could be used to accomplish our primary design needs. The following sections will detail the four main concepts that were considered for motor configuration. It is also important to note that each incorporates a different form of tensioning. The simplest Disney design ended being the best concept but each other idea had important components that in some way contributed to the final design.

Disney Design

The Disney design features two motors mounted in the same orientation as one another, and parallel to the carbon fiber tube. The name is derived from the "Mickey Mouse" look of the aluminum that the motors are solidly mounted to, which can be seen below in Figure 2.

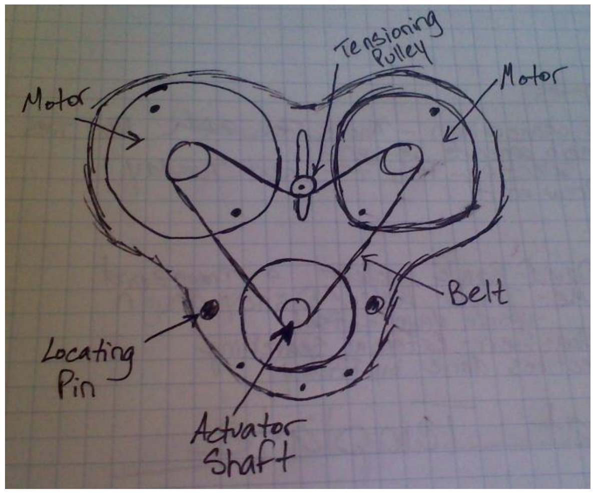


Figure 2. Sketch of the Disney design concept. The "Mickey Mouse" configuration of the metal is what gives this design its name. Both motors would be solid mounted with a sliding mechanism for tensioning.

This design would allow the motors to be solid mounted to the aluminum and decrease assembly time. With this motor configuration, there are many ways to achieve proper belt tensioning. Possible solutions include a sliding pulley or bushing, a wheel mechanism, or a pivoting member which will be explained in more detail in the "Concept Selection" section. One of the main advantages of this design is that the motors can be mounted in a single piece of aluminum. This allows the part to be lightweight and reduces the number of parts for manufacture.

The use of a single belt is also an advantage over other designs. One of the main customer needs is to reduce assembly time, so having fewer parts to put together is desirable. This configuration also does not interfere with the robots motion at any of the joints. The motors being side by side allows a joint such as the knee to be fully bent without a motor striking the back of the thigh. One concern, though, is that spacing across the back of the hip will be an issue. The team has designed a possible solution where the U-joint mount can be adjusted to swing the motors on the outer hip to a wider angle. This will allow all eight motors to fit across the back of SAFFiR without interfering.

Upside Down and Offset

The upside down and offset design features motors that face opposing directions and are on different sides of the carbon fiber tube. They would, though, both still be parallel to the actuator. This concept can be seen below in Figure 3.

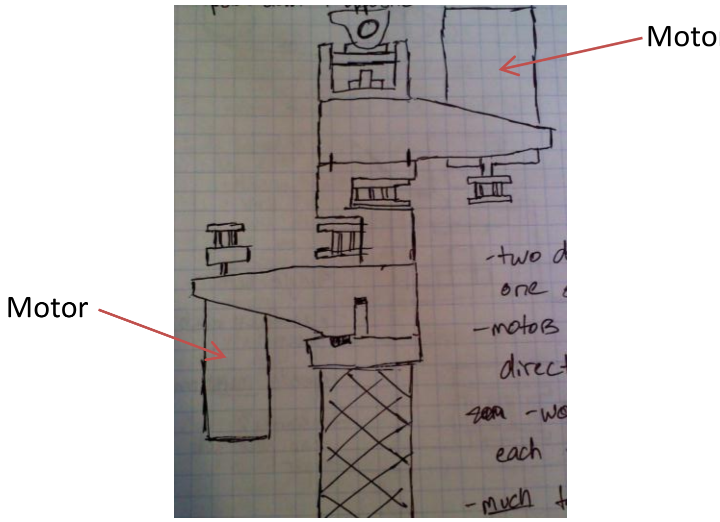


Figure 3. Upside down and offset concept. The motors would be on opposite sides of the actuator and face in different directions. This would also include two drive gears and belts.

Since the motors are not mounted together, the number of parts to manufacture would be increased as compared to some of the other design concepts. The use of two gears is also a disadvantage as it requires two of these tensioning systems and adds more parts to the overall assembly. The motors, though, could potentially be solid mounted for ease of assembly, with the tensioning system relying on a pivot of the mount or a sliding dowel. Another advantage is the way that these can be packaged, especially across the back of the hip. By staggering the actuators as shown in Figure 4, they can be placed close together without interference.

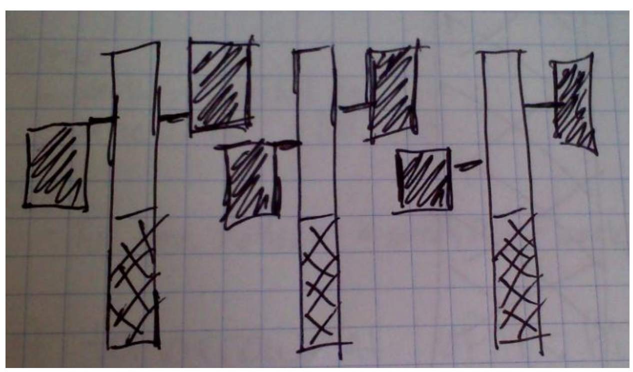


Figure 4. Staggered configuration across the back of this hip. This allows all eight motors to be mounted close to one another, though only six are shown above. The shaded black boxes represent the motors and the cross hatching shows the carbon fiber tubes.

Although this concept would be very applicable to the back of the hip, there are would be interference at other joints. The knee, for example, would not be able to bend all of the way without the top motor striking the back of the thigh. Since clearance is a crucial issue for the design, this concept may not be best for SAFFiR's application.

Bank Sucker Design

The bank sucker is the name given to a design concept that focuses on aligning the two required motors in an inline, facing configuration. The name was chosen because of the design's similarities to the transport tubes found at bank drive through teller stations. This concept can be better seen in Figure 5. In this drawing the upper cylindrical component would be the interface between the two motors. Each motor would mount to an end of the cylinder and their axles would be united in a single pulley. This motor assembly would then attach to the main body of the actuator through a tensioning system of some kind.

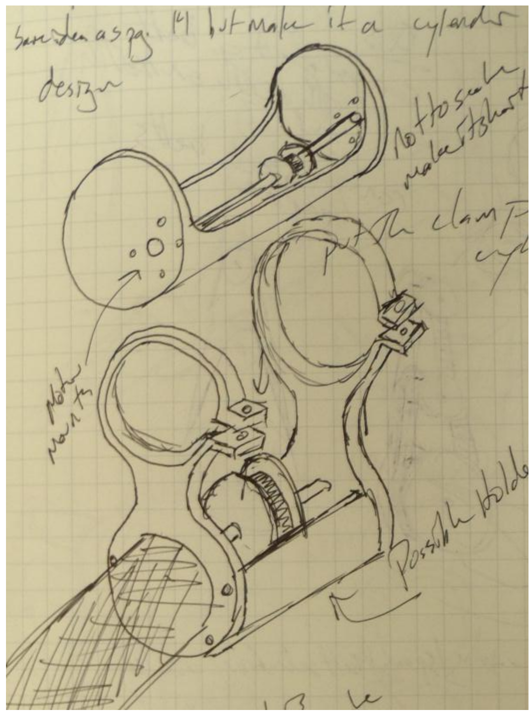


Figure 5. Initial sketch for the bank sucker concept. Note that the motors would mount on the upper assembly on both sides of the cylinder.

This sketch shows a tensioning system very similar to the old actuators tensioning system. The main focus of this design however is the motor configuration. Several different tensioning systems for this configuration could have been designed. Some advantages of this design include that it is minimalistic. Only one belt is needed to transmit power to the ball screw and very little aluminum would be needed. This will help keep the actuator lightweight and cut down on the number of parts required for assembly. Some disadvantages of the design include the overall alignment of the motors. It is possible that the upper motor would interfere with the joint at the top of the actuator. As will be discussed in later sections this design was not chosen as our final concept.

Trapezoid Design

This design, while named after a possible tensioning system, is focused on the motor configuration of inline, stacked motors. With this configuration it is possible to reduce the width of the actuator to help prevent interference in the hip region where four actuators will be installed side by side. In Figure 6 you can see what a possible design in this configuration would look like.

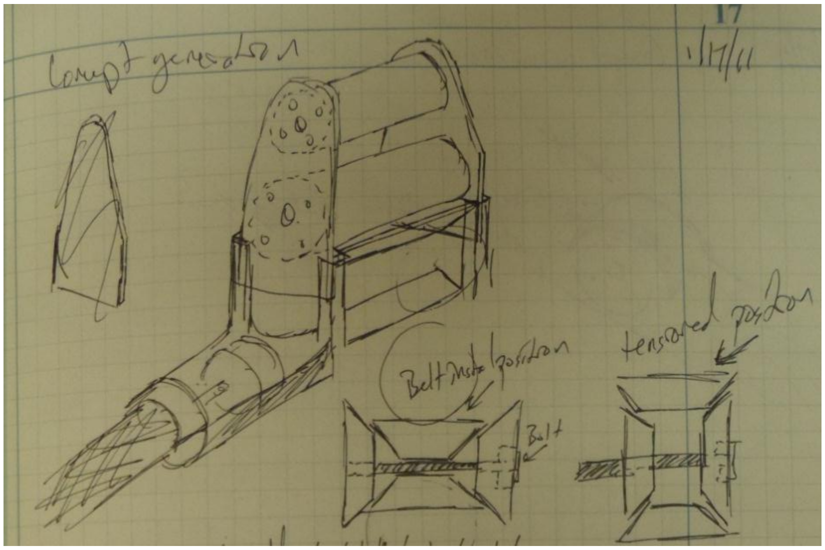


Figure 6. Possible design configuration for the Trapezoid design concept. The two schematics in the lower right describe a tensioning system from which this concept got its name.

Major advantages of this design include its slim profile. As mentioned above, this design will ensure that interference does not become a problem in the hip region. If designed correctly this concept would only require a single tensioning system. Part of this concept is an idea of stacking the belts so that only one pulley would be needed on the ball screw. More research would need to be done to determine if this is a reliable way to transmit power. Some disadvantages of this design include the depth that comes as a trade off to a slim design. There was also some concern that motors in this configuration might create interference problems between the calf motors and thigh. All ideas considered for the tensioning system also required more parts that the current design. As will be discussed in the next section this design was not chosen as our final concept.

Limit Switching.

This section consists of the concept generation of the limit switch project the actuator design team had to complete. This design challenge was to redesign the current limit switching technique to fully enclose the actuator ball screw. This design will accomplish the tasks of the current limit switch design while enclosing the outer carbon fiber tube that houses the ball screw. The switching mechanism was the first concept to be generated. Currently the actuator uses toggle switches that have cutouts in the outer carbon fiber tube. Multiple concepts were generated to account for the switching operation. The next concept to be finalized was the sealing of the entire actuator. There were multiple solutions to this problem but only one proved to be low friction and still eliminate contamination of the ball screw. The following section will cover the multiple concepts generated for both design challenges.

The first idea generated to solve the switching mechanism issue was a laser light curtain idea. This idea included the lasers inside the carbon fiber tube that would switch whenever the light curtain was broken. The issue that arose that kept this idea from being selected was the fact that the wires would still have to go inside the tube making the sealing problem even harder.

The second idea generated was the cable tension idea. This idea was a cable attached to the inner carbon fiber tube and the outer carbon fiber tube. This cable would be tensioned as the inner carbon tube would actuate in and out of the outer carbon fiber tube. A switch would be attached to this cable and the measure of the tension by the switch could locate the actuator. This would increase the friction of the system therefore it was not a good solution for the switching mechanism.

The final concept generated was the reed switch design. This design uses the reed switch shown in Figure 2. Three of these reed switches would be placed in homing locations just as the current system's toggle switches are located. These switches would be activated by a magnet that would be mounted to the inner carbon fiber tube. Therefore, as the inner carbon fiber tube actuates inside the outer carbon fiber tube the magnet would pass by the reed switches located on the outer carbon fiber tube. This system would operate identical to the current limit switch system with two extremity switches and one central homing switch. However, with these reed switches no holes would have to be cut into the outer carbon fiber tube.

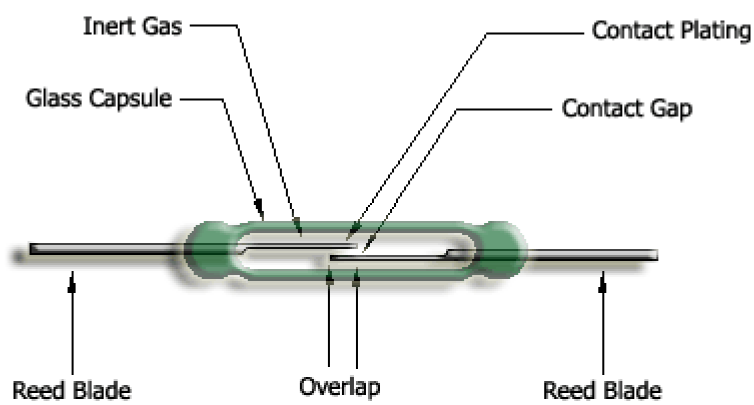


Figure 7. Image of the design of the reed switches that will be used on the PCB board to limit the motion of the actuator.

Sealing:

The second design challenge was to fully enclose the outer carbon fiber tube of the linear actuator design. The main design constraints were to fully enclose the actuator to eliminate dust and smoke from contaminating the ball screw and maintain low friction in the system. The first concept developed to seal the actuator was a gasket/o-ring idea. This idea was to seal the bottom of the outer carbon fiber tube with a gasket that is wide enough to fill the gap between the inner and outer carbon fiber tube.

However, this design with a good seal would increase the friction of the system as the rubber gasket created suction to the inner carbon fiber tube.

The second concept generated for the sealing design challenge was to use a solid foam block to seal the gap between the two carbon fiber tubes. This foam would keep smoke and dirt out of the carbon fiber tube and if made from the right material would maintain a low friction. However, the availability of foam thin enough to fit between the carbon fiber tubes was very unlikely.

The third and final solution of the sealing design challenge was to use a brush. This idea was first sparked by the idea of an arrow rest that helps silence the shot of a bow and arrow. The idea transformed into the use of an inverted coil brush to brush off debris and keep smoke from getting into the outer carbon fiber tube. This idea became the best result because it was easily obtainable, it met the design criteria, and it maintained the low friction. The inverted coil brushes that will be attached to the bottom of the outer carbon fiber tube are shown in Figure 3 below.

Figure 8. Inverted coil brushes that will wipe the debris off the inner carbon fiber tube and seal the outer carbon fiber tube.

Concept Selection

In the concept selection phase of the linear actuator redesign the team used multiple methods to narrow down the ideas generated to a few possible solution. Once the concept generation was complete there were fifteen different designs to choose from. The following concept selection criteria were used to narrow these ideas down to four possible candidates. This was accomplished using the concept screening matrix seen in Table 1: Selection Matrix for actuator design ideas. Once these ideas were narrowed down then a scoring matrix was used to select the final design to be used for the actuator redesign.

Table 1: Selection Matrix for actuator design ideas

Actuator Ideas	Motor Config	Mfg.	Compact	Efficiency	Lightweight	Assembly	Force Sensor	Final Score
Piggy Back	X	-	-	-	0	+	0	-2
Mated Gears	X	-	-	0	-	-	0	-5
Triangle/Angle Mount	X	-	-	0	+	+	0	0
Track Pulley **(BASE)**	X	0	0	0	0	0	0	0
Slotted box	X	-	0	+	-	+	0	0
Bank Sucker	X	-	0	+	+	0	0	2
Trapezoid	X	-	0	+	-	+	0	0
ZigZag	X	-	0	+	-	-	0	-2
Upside Down Offset	X	-	+	+	-	0	0	0
Mated Motors	X	-	0	+	-	-	0	-2

(yellow)	Motors Facing Each other
(blue)	Base design used for scoring
(red)	Design to go to scoring matrix
(orange)	Design to go to scoring matrix

Table 2: Scoring Matrix for final four actuator design ideas

	Assy	Low Friction	Manufacture	Compact	Lightweight	Looks	Interference	Total
Weight	10	10	5	15	15	5	40	100
Upside Down	3	5	2	2	2	5	1	215
Bank Sucker	2	5	3	3	4	5	1	255
Disney	4	5	4	3	3	3	5	415
Trapezoid	3	5	2	3	3	2	5	390

Once the selection matrix was complete the four designs selected then moved to the scoring matrix. The scoring matrix allowed the team to finalize the design that would best meet all of the criteria by adding extra criteria that would eliminate those designs that were less feasible to complete. Each of the four designs was compared to the criteria shown in Table 2 and the design that recorded the highest score was the design the team pursued. The scoring system was based on the customer needs and the importance the customer had on each of the categories. Therefore each category corresponds to a certain percentage of the total as you can see that the Assembly category accounts for ten percent of the total design weight. Once the designs passed through the scoring matrix the final design called the Disney design was selected.

Once the final design was selected the team continued to produce ideas to add more detail to the final design. One last brainstorming session allowed the team to finalize the "Disney" motor configuration and also incorporating part of a hinge design from another idea. All of the details of this design will be explained in more detail in the Detail Design section of this report. It is important to note that the final concept selection of this motor configuration paved the way to the addition of elements from other design ideas to create the final design that will be seen later in this report.

Detailed Design

With the team currently involved in the detailed design process this section is still only partially complete. The following section addresses the calculations that have been performed to ensure that the linear actuators design will be able to withstand the forces associated with doubling the power output.

Calculations

The calculations for the linear actuator redesign project consisted of shear calculations of the trunion, the carbon fiber tube buckling, belt minimum friction angle, and shear of the cross sectional area of the belt entryway. All of these calculations will be discussed in more detail in this section.

The first calculation performed to allow the design process to continue on schedule was the belt friction angle calculation. This calculation consisted of the decision of the pulley arrangement with the Disney design and the type of belt to be used. It was decided that sixteen tooth pulleys were to be used because they were currently in stock and to maintain a mesh factor of one at least six teeth had to be in contact with the belt at all times. This allowed the team to calculate the minimum angle that the belt would have to maintain to hold that mesh factor. The minimum angle was calculated using the equation shown below to be one hundred and thirty five degrees.

Min Angle=Number of Teeth X Degrees per Tooth

The second calculation performed was the minimum allowable area for the belt entryway part. This was a simple shear calculation using the equation shown below.

Min Area=Max Force/Material Yield Strength

Knowing that the yield strength of the Al 6061T6 aluminum used and knowing the maximum force seen by each actuator will be approximately two thousand newtons the minimum area calculation was easily found to be 7.246 mm^2.

The third calculation performed was the U-Joint tensile failure. It was assumed that the 2 kN load would be transferred equally throughout the U-Joint member. This would apply 1kN of force on each arm of the joint. Knowing that the area of one of the two sections of the joint was 9.5 mm^2 the stress in one arm of the joint could be calculated using the equation below.

Stress in member= Force in the member/ (2 times the Area)

The stress was calculated to be 52.63 MPa. Knowing the stress in the U-Joint allowed the factor of safety of the part to be calculated. This factor of safety was calculated to be 5.24 using the equation seen below.

Factor of Safety= Yield Strength/Stress in Member

The final calculation performed was the buckling load of the carbon fiber tube connecting the ball screw to the connection points of the robot. This load was calculated by first finding the moment of inertia of the cylinder. This moment of inertia was found to be 1.791x10^-3 mm^4 using the equation seen below.

I=Pi/4(R2^4-R1^4)

The modulus of elasticity was known to be 128.931 GPa and the length L was known to be 0.128m. Using this known data and the moment of inertia previously calculated the final critical load was easily calculated to be 34.775 kN using the critical buckling load equation seen below.

*Pcr=((Pi^2)*E*I)/L*

Once the critical load for the carbon fiber tube was found the factor of safety was then calculated to be 17.39 using the following equation. Where the critical load is the Pcr calculated before and the actual load is the 2kN load seen by the actuator.

Factor of Safety=Critical Load (Pcr)/Actual Load

All of these calculations were beneficial to the detail design process allowing the design engineers to swiftly move forward with their designs. Now that these numbers have been calculated they will be a reference point to any additional features the detail design process may add. Having calculated these numbers will allow the team to design more quickly and will allow the team to move into the manufacturing realm of the project at a faster pace.

Gear Ratio Background

To accomplish this project it is important to understand the principal concepts of how gears affect parameters such as torque and velocity. In this section we will talk about the basics of gears and illustrate the equations related to the mechanism.

The input power provided by the motor is equal to the provided torque time its rotational velocity. These two variables are usually determined by looking at the motor datasheet. But unfortunately, motors commercially available do not normally have a desirable speed to torque ratio. With gears, you will exchange the actual torque/ velocity ration to the desired one. This exchange happens with a very simple equation that you can calculate.

$$Torque_{act} * Ang\_Velocty_{act} = Torque_{des} * Ang\_Velocty_{des} \qquad (1)$$

$$InputPower = OutputPower$$

Nevertheless, this equation supposes that the input power provided by the motor is equal to the output power of the system. This may be erroneous due to lost energy caused by gear frictions or the tension of the belt in a belt and gear system. By looking at this equation, we determine that torque and angular velocity are balancing between each other. If one wants to increase the velocity of the system, he has to decrease the amount of torque.

Concretely, to swap torque and velocity you use two (or more) gears. One is connected to the motor while the second is used to determine the desire torque and velocity. In any pair of gears, the larger gear will move more slowly than the smaller gear, but it will move with more torque. Indeed, in a belt and gear mechanism the velocity of the belt remains constant at any point of the belt. Thus the angular velocity time the radius of gear one is equal the angular velocity time the radius of gear two which is equal to the belt velocity.

$$Velocty_{belt} = R1 * \omega 1 = R2 * \omega 2 \qquad (2)$$

Gear_ratio=R1/R2

Thus, the bigger the size difference, the gearing ratio, between two gears, the lower the output velocity will be and using equation (1) the greater output torque will be obtained.

Motor Configuration

The linear actuator team decided to pursue the “Mickey mouse design “ as the structural basis of the motor housing. The architecture of this design is based on two identical motor mounts positioned symmetrically according to the median plan that cross the lower bearing support (figure1). This gives the structure to equally distributed mass adding a sense of equilibrium to the design. The symmetrical architecture allows the belt to obtain equal surface contact with the two small pulleys and the principal pulley.

This connection between the belt and the pulleys is really important since it transmits power from the motors to the linear motion. Not enough surface contact between these components would weaken the transmission and thus would reducing the efficiency of the linear actuator. According to the datasheet of the pulleys and the power transmission analysis, the team decided to separate the two motors by an angle of 40 degrees. At this angle the belt rotates the pulleys with a maximum of efficiency and thus avoids any loss or frictions.

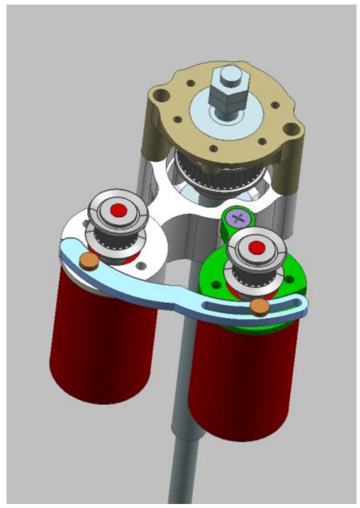


Figure 1. Final photos of the new linear actuator CAD design. The mobile motor mount (green) rotates around the pivot point (purple bolt). The arm is used to fixed that motor mount on the fixed one by screwing down the bolts.

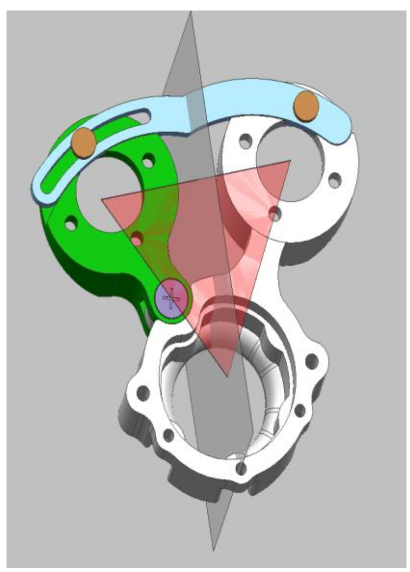


Figure 2. Top view of the bearing support connected to the motor mounts. The grey plan is used for symmetry. The red triangle is used to position the motors at same distance from the axis of rotation translation and at an angle of 40 degrees. Furthermore, the two motors mounts are positioned the

closest possible to the bottom bearing support in order to minimize the inertia relating to the axis of rotation-translation of the linear actuator and also to minimize the weight (figure2).

Nevertheless, the two motors mounts differs by their roles. The right motor mount remains fixed on the bottom bearing support while the left motor mount is free to rotate around a pivot point. This rotation is beneficial since it help the user to assemble the belt on the pulleys really easily. By moving the mobile motor mount on the left or right side the user can move the motors to a position that gives the desired tension to the belt. This tension or the position of the motor mount may differ according to the size of the pulleys due to their dimensions. After finding the right position the user can lock in place the mobile motor mount by screwing down the arm on it.

All in all that design integrates all the solution that thoroughly answers the needs from our customers. It is really easy to assemble. The motor mounts match properly the shape of the motor and few screws are needed to locked them on their respective fixtures. As explained before, the design is made in order for the belt to come together easily with the pulleys. This ease enables also to find the right belt tension and thus minimizes any friction between the belt and the pulleys. It also allows the user, who desires to modify the pulley ration, to change any pulley on the motor without any constrains. It is a compact design. After screwing down the arm on the motor mounts, the overall design is really rigid. It's symmetric structure also gives the design a sense of simplicity that makes it look good. The design is really light. The bearing support connected with the two motors mounts have a weight a 65g which is below the recommended 100 g. Finally, the design is compact enough to fit 4 actuators across SAFFiR's hip.

Limit Switching

This section consists of the detail design of the limit switches, from the purchased components to the board layout and design. Most of the design layout remained the same but the wiring and components changed significantly. The first task was to calculate the proper resistors needed to incorporate the reed switch circuit. The second task was to lay out the location of the reed switches and design the board that would incorporate all of the purchased components.

Purchased Components

The purchased components necessary to accomplish the reed switch limit switching mechanism were the reed switches, resistors, brushes, and LEDs. The reed switches were one of the main components because the reed switches had to be able to be activated easily but be small enough to fit on the carbon fiber tube. The final components chosen to be used on the limit switch prototype were Hamlin 5mm reed switches. These switches shown in Figure 9. Hamlin Reed switches used on the PCB limit switching board below are 10mm long and 1mm in diameter. These dimensions make this switch small enough to fit to the carbon fiber tube while also maintaining the minimum 3mm activation distance necessary. This activation distance is necessary because the reed switches will be located at least 3mm away from the internal magnet due to the thickness of the outer carbon fiber tube and the outer diameter of the magnet.

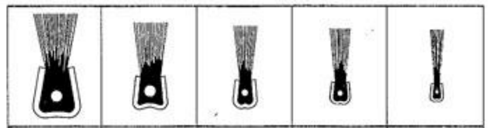
Figure 9. Hamlin Reed switches used on the PCB limit switching board

The second major component purchased for the reed switches were the two different surface film resistors used to complete the circuit. One resistor was a 470 ohm and the other was a 10kOhm surface film resistor. These resistors are very small in comparison to average sized resistors. The two resistors used in the design were Vishay model 1206 resistors that have dimensions of 1.6mm wide and 3.2 mm long. These small resistors will allow the board to be as compact as possible. All ordering information can be found in the purchase orders and the vendor used was mouser electronics.

The third component used was a small LED manufactured by Kingbright. Two LEDs were used at each switching location to visually show power on and switch on. These LEDs will aid in the troubleshooting and overall operation of the robot making things more visual. The LEDs used were two different colors in order to distinguish between the two different signals of power on and switch on. The green LEDs were used to signal power on while the blue LEDs were used to signal switch on.

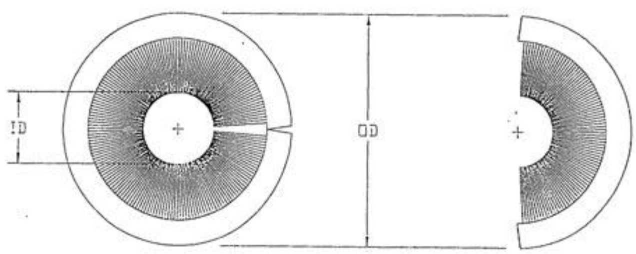
The final component ordered was the inverted coil brush that is to be mounted to the bottom of the carbon fiber tube. This brush was ordered from CarolinaBrush and was made custom for this application. The brush has an outer diameter of 1.42 inches and an inner diameter of 0.7 inches. The inner diameter is the minimum outer diameter of the inner carbon fiber tube to ensure proper cleaning of the inner tube. The specifications sheet shown in Figure 10 shows the #3 brush chosen for the design. This style brush uses the least amount of bristles to maintain low friction while also allowing for a large enough metal backing to mount to the outer carbon fiber tube.

CHANNEL BACKING DESIGN DATA



	#10	#7	#5	#4	#3
Strip Backing Sizes Before Forming					
	1¼" x .050	⅞" x .035	⅝" x .037	½" x .030	.425 x .025
Strip Backing Sizes After Forming					
Approximate Width	7/16" (.437)	5/16" (.312)	7/32" (.218)	3/16" (.187)	5/32" (.156)
Approximate Height	½" (.500)	5/16" (.312)	¼" (.25)	7/32" (.218)	5/32" (.156)
Minimum O/A Height*	¾"	½"	7/16"	⅜"	⅜"
Maximum O/A Height*	14"	12"	10"	8"	6"
Filament Size Range	.003–.072	.003–.050	.003–.040	.003–.032	.003–.024

*Depends upon filament size
Metal Backing Material: Electro–Galvanized steel or stainless steel
Fill Materials: Synthetics: Nylon 6, 6.6, 6.12; Polypropylene; Polystyrene.
Or Tampico; Horsehair; Wire
Other Fills Are Available Upon Request.



Minimum Inverted Disc/Coil O.D.'s

#10 = 8'' #7 = 6'' #5 = 4'' #4 = 2'' #3 = 1-1/4''

Figure 10. Spec sheet of the inverted disk coil brush with brush fiber sizes and metal backing sizes.

Redesigned Components

The two components that had to be redesigned were the two limit switch to carbon fiber tube interfaces. These components were simple rings that attached to the top and bottom of the carbon fiber tube with holes in them for the PCB board to mount on to. The redesign of these parts consisted of widening the flats to which the board mounted to in order for the board to lay as a tangent to the outer circumference of the outer carbon fiber tube. The inner diameters of these parts remained unchanged from the previous design because the outer carbon fiber tube had not changed.

The bottom carbon fiber tube interface ring shown in Figure 11 has the new board inter face where the board will lay flat against the side of the tube instead of perpendicular. This makes the application of the reed switches more practical and effective. The countersink shown in the top of the part in the figure will allow for the incorporation of the inverted disk brush mentioned in the previous paragraph.

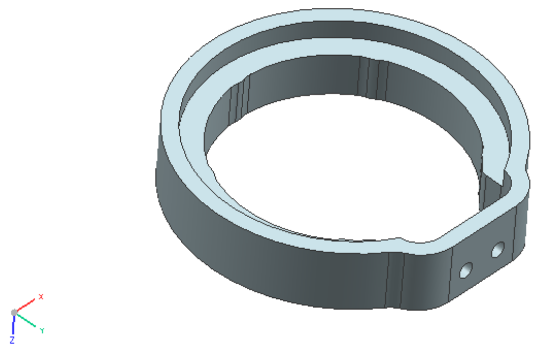


Figure 11. The CAD model of the bottom carbon fiber tube interface with countersink for the brush application and the new board connection.

The top carbon fiber tube interface ring is similar to the bottom ring except that it does not incorporate the countersink for the brush, and it is not a solid piece. The top carbon tube interface ring is a semi-circle that can flex with the varying outer carbon fiber tube outer dimension to still be able to mount to the actuator's upper housing. This top ring is what holds the outer carbon fiber tube in place by mounting to the bottom side of the upper actuator housing. The top carbon fiber tube interface ring can be seen in Figure 12.

Figure 12. The top carbon fiber tube interface ring with extended flats to incorporate the new PCB board

Linear Actuator Manufacturing

This section consists of all the necessary tools, stock sizes, and procedures necessary to produce all of the linear actuator parts. In brief no manufacturing operation should be performed without the proper training especially any special operations requiring special tooling. Most of the actuator parts were simple in nature and could be easily machined with a .375 inch or 0.25 inch roughing end mill. However, there were two operations that required some special tooling and training. One part required a boring bar operation. All boring bar operations require boring operation training before they can be performed. Also, a part required a thread milling operation which once again requires special training. The final tool requirements to fully manufacture a linear actuator are 0.375 inch rougher, 0.25 inch rougher, 0.375 finishing end mill, 0.25 finishing end mill, boring bar, thread mill, and a cobalt steel 0.25 inch end mill to cut the bushings. Lastly, the final manufacturing time for all operations is 1.5 weeks. This manufacturing time is to complete all the parts for one actuator.

Conclusions and Future Recommendations

Even though we are very satisfied with the product that we are delivering, there are still some future recommendations in hindsight. One of the things that we could have done more in depth was a tolerance study. The motors did not fit in the original mounts that we cut, and significant work had to be done with a Dremel to get them to sit properly. This was also the case with the pivoting joint. When first cut it was almost impossible to pivot, and also difficult to remove until materials was shaved off with sandpaper. It would also be worth looking into some of the ergonomics and manufacturing issues above the U-joint. Since we were bolting on at this location, we did not have to manufacture any of these parts, so they did not get redesigned even though they might have benefitted from it.

For the limit switches the locations of the reed switches may need to be modified to ensure that they are triggering at the right point. A recommendation is to be careful when machining the components that glue to the outer carbon fiber tube they are thin and proper tab placement is essential in preventing the parts from warping during the manufacturing process.

In conclusion, the linear actuator team was very satisfied with their final product after a semester of hard work. The use of the 6-3-5 method and extensive mind map led to in-depth concept generation, and the team completed several phases while deciding on a motor configuration and subsequently a tensioning system. Once this was chosen, the team moved on to detailed design which included belt and load calculations as well as CAD modeling. The design was then prototyped using the Makerbot in the DREAMS lab to check the design for assembly, manufacturability, and clearance. Once the design was proved by the prototype, manufacturing was able to begin. After the new designs were cut into reality, several tests were run. First, the team made sure that everything fit properly and was easy to tension. Satisfied that the part worked as planned, the team used EPOS Studio to program the motor controllers and run both motors off of one signal. The team is extremely happy to exceed the customer's original expectations and deliver a high quality product to be implemented on SAFFiR.

Foot Redesign Project

Introduction

This section of the report will detail the progress made on the foot project. This project's aim was to design a foot for SAFFiR that can maneuver across the uneven terrain of the test ship for the Navy demonstration in the fall 2012. The current foot is a flat plate and could hinder the walking abilities of SAFFiR so a new foot that can conform to the ground was needed. Other major design criteria that must be met are to maintain four points of contact with the floor, keep the total weight below 550 grams, and ensure that all forces from the floor are directed through the force-torque sensor. The team has designed a new foot to meet these challenges and has a functional foot ready to be implemented on the robot to help prepare for the Navy demonstration.

The sections below will outline the process used to generate concepts and come to a conclusion on the final concept. All major designs that were generated will be discussed with an emphasis on their contribution to the final design. To conclude this section of the report a brief future recommendations section will outline problems with the current design and potential solutions for those design challenges.

Mission Statement.

RoMeLa assigned the SAFFiR senior design group to redesign the foot apparatus to solve a few issues they foresee when the robot becomes operational. The robot will be tested on the Navy's firefighting training ship where fires are started and put out regularly. Over time this has warped the decks of the training ship. Therefore a rigid and flat robotic foot would be unstable on the ship's deck. RoMeLa needs a foot with some compliance to allow for more stability in this unsure environment. Also, the robot would significantly benefit from having more grip on the deck as it walked to ensure a stable walking base. However whatever engineering solution the team develops for the added grip would have to leave the load cell that takes measurements for the walking algorithm unaffected.

The goal for the foot redesign team is to produce a compliant foot for SAFFiR that can safely and effectively interface with the surface of the Navy's firefighting test ship. The device will safely hold the weight of the robot and be compatible with the walking algorithm. The device will also secure the robot to the metal deck of a ship. The team members associated with this project are Daniel Moodie, David Reeves, Earl Campaigne, Rick Lewis, and Sam Howell. The final product will be delivered by 03 MAY 2012. The primary market for the team's product is RoMeLa to be used on the SAFFiR project. The secondary market includes the United States Navy since SAFFiR is being developed to fight fires on Navy ships.

Customer Needs and Product Specifications

This section describes the customer needs and target specifications of the SAFFiR project. The first section addresses who the customers are, why they are interested in a solution to the problem, and presents their surveyed needs. These needs are then categorized according to their perceived importance/ priority. Connections between customer needs and engineering characteristics are identified, as is the importance of each target specification.

Identification of Customer Needs

The foot being designed by the group will be used as a functional part of SAFFiR so the primary customers are the RoMeLa graduate students leading the project: Derek Lahr and Bryce Lee. As the head of RoMeLa, Dr. Dennis Hong is another customer. The US Navy is also a customer because the foot of the robot will have an effect on the robot's ability to perform at the next demonstration.

The RoMeLa team is interested in a new foot design because the current foot will not perform well under the conditions of the first demonstration. The floors of the Navy test ship are uneven so a flat plate foot will be unstable. The RoMeLa team needs a foot on SAFFiR that can maneuver across warped metal floors in order to perform well at the demonstration.

Members of the RoMeLa team were interviewed by the team to elicit customer data. These conversations were transcribed into engineering log books for reference. The customer statements were then interpreted in terms of customer needs. Special attention was given to identifying critical, secondary, and latent needs. The interview statements and interpreted needs are included as Figure 13

Customer:	Derek Lahr	
Interviewers:	SAFFiR Senior Design Team	
Date:	02 DEC 2011	
Question/ Prompt	Customer Statement	Interpreted Need
Size	Sole can be bigger. Bigger is better. Weight should not be much more than the current foot. The feet should not look like clown feet.	The foot sole should be larger than the current design. The weight of the foot. should not significantly increase. The size of the foot should aesthetically match the size of SAFFiR
Operation	Foot must be solid when engaged with floor. Compliance is more important than magnetism. Investigate the use of magnets. Your budget it $5,000.	The foot must be a rigid platform to support SAFFiR. The foot should apply compliance before magnetism. The team will research magnetism. The foot must be made for less than $5,000.
Environment	There is +/- 5 degrees between each footstep. There can be a change in height of .25 inches between the toe and heel.	The foot should account for +/- 5 degrees between each footstep. The foot should account for a change in height of .25 inches between the toe and heel.
Manufacturability	We have a three degree of freedom CNC. You (all) need to machine your designed parts.	Each part of the foot is manufacturable on the CNC. (!) Each part of the foot is machinable by its designer.

Figure 13: Customer needs statement and interpreted needs for the SAFFiR foot. This information was obtained from an interview by the design team.

Concept Generation

In order to conduct our concept generation we each developed a series of concepts and developed the most promising of those into workable concepts. Each member refined their ideas and shared the most promising of those ideas with the group. The major ideas developed by our team are listed below.

Four Toe Design Concept

This concept features three toes that independently rotate on a hinge, a fourth toe that forms the heel,, a gear chain that locks all four toes in place, and rubber soles to increase surface friction (Figure 14). As SAFFiR steps onto a surface, the heel will contact the ground first. As in a human foot, a large impulse force in generated when the heel strikes the ground. A rotational spring/ dampener system, attached to the heel and the rear axis of rotation, can be used to absorb much of the impulse force.

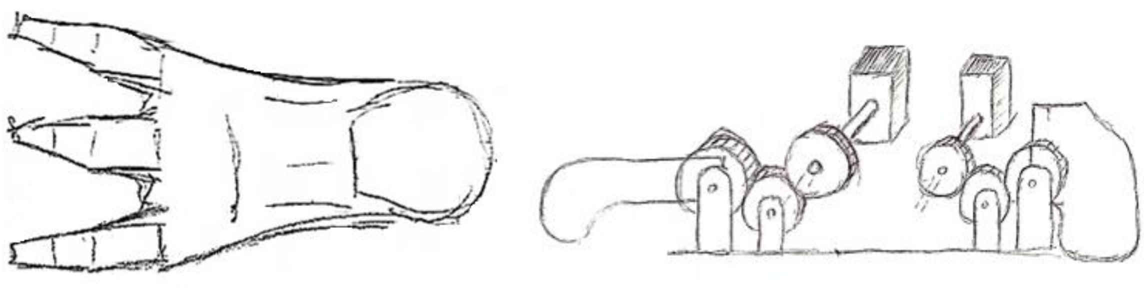


Figure 14: Bottom profile (left) and internal mechanisms (right) of the 4 Toe Design Concept.

Mid-stride, the three toes will be angled downward by a rotational spring along their axis of rotation. As the foot contacts the ground under SAFFiR's weight, the three forward toes will freely rotate so that they conform to irregularities on the surface. After all four points of contact are made, a digital signal will be sent from SAFFiR's walking algorithm to activate the locking mechanism of all four toes. This triggering mechanism is hard coded into the walking algorithm and avoids many problems introduced by mechanical switches, namely accidently or premature triggering.

This design utilizes a series of gears attached to each toe as a locking mechanism (Figure 14). When the circuitry of the foot receives the digital signal from the walking control algorithm, a rotational DC motor is powered. This motor then uses an internal control system to maintain the position of the gear chain by providing counter torque. Because the gears can no longer rotate and are connected directly to the toe, the four toes are locked into place and provide four stable and versatile points of contact.

The most challenging aspects of this concept will be designing and integrating a rotational spring/ dampener system for the heel that can absorb the impulse force, conform to surface irregularities, and not extend itself. Choosing reliable gears for the locking mechanism is another design challenge. The gear teeth must be large enough to transfer high torques without breaking, but still small enough to fit within the desired profile of SAFFiR's foot.

Locking Mechanisms

Because SAFFiR must walk across surfaces warped by fire, the foot for SAFFiR must be redesigned with at least three degrees of freedom so that multiple points of contact can be maintained across those warped surfaces. The additional degrees of freedom are obtained by adding independently moving supports (toes) to the foot. This addition will provide SAFFiR with more versatile, reliable, and stable ground contact. If the new foot design is to do this and still conform to the $\pm 5°$ floor difference due to warping, then the toes must possess a locking mechanism to ensure that they do displace after conforming to an uneven surface. The locking mechanism will ensure a stable platform for the passive dynamic walking on uneven ground.

Figure 15 below shows generated concepts to handle this locking feature. Illustration (a) shows how gears may be used to achieve locking: A system of gears can spin freely to allow unrestricted placement of a toe. When the foot and toes have achieved the desired stance, a counter torque can be applied to the gear to lock the toe in position. Similarly, an additional gear that does not spin freely could be added to the chain to achieve locking without applying a constant torque. Illustration (b) shows how toothed tracks and gears can be combined to achieve locking. A further refined version of this concept involves a ratcheting system in which the track is lowered onto the gear or a second track. Illustration (c) shows how locking can be achieve by manipulating the track that permits the degree of freedom. This solves the movement discretization problem introduced by gears and tracks. Other ideas that were investigated included clamping mechanisms with a rotation axis, brake lines to control tension and compression, and spring/ lever systems.

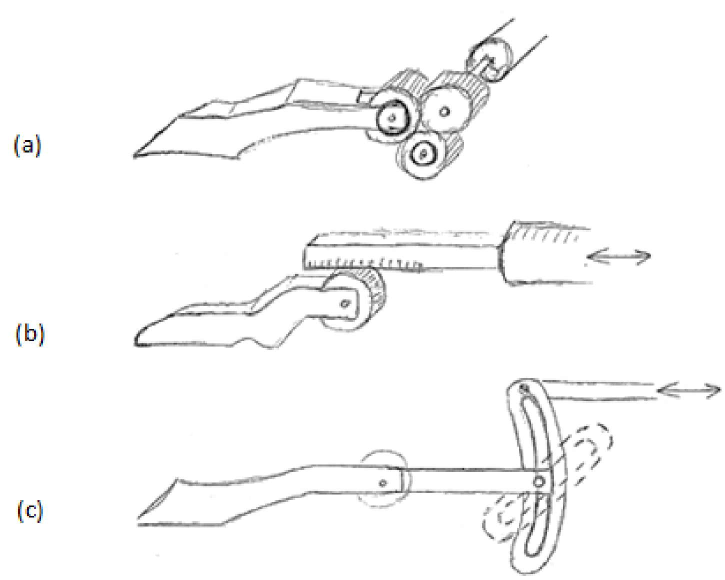


Figure 15: Preliminary concept generation results to provide a locking mechanism for supports (toes).

Triggering Mechanisms

The locking mechanisms must be activated/ deactivated by a triggering mechanism. This triggering mechanism may be mechanical, electronic, or digital signals from the control algorithm.

We considered various mechanical trigger concepts, the primary once being a contact ring. The sole of SAFFiR's foot could possess a protruding ring. As the sole contacted the ground, the ring would depress into the foot. An attached lever or spring system would then trigger the appendage locking mechanism. The contact ring design simplifies the SAFFiR foot into a purely mechanical system. For some surfaces however, the contact ring may lock the appendages too early or not at all.

We also considered a variety of electrical signals. For examples, two points on the sole of the foot could serve as a voltage supply and circuit ground. When the foot makes complete contact with the metallic ship deck, electricity will travel through the floor and complete the circuit. This voltage drop could be used to power the triggering mechanism. Similar electronic systems could be designed using IR sensors, pressure sensors, or digital buttons. These designs are generally more reliable, but introduce electronic components to the foot design.

Third, we considered using digital signals to trigger the locking mechanism. After SAFFiR completes a step, the walking algorithm would send a digital signal to the foot's circuitry. Upon receiving the signal, the circuitry would provide power to the locking mechanism, and secure the appendages in place. This approach is more reliable, as the signal would be hardcoded. In the future the algorithm can send the signal based on sensor feedback, allowing SAFFiR to "feel" the floor.

Heel Mechanisms

When SAFFiR steps the heel of the foot will strike the ground first. This initial impact will generate a large impulse force on the heel that travels up into the leg. Following the concept of bio inspired design, the heel of SAFFiR's foot can be designed to absorb much of the impact force, as does the heel of human. Unlike, the heel of a human however, SAFFiR' heel can also be jointed to provide a conforming point of contact and provide further stability.

We investigated using mechanical springs as the heel of the foot. By choosing materials with the correct stiffness, the heel can allow the desired level of compliance and absorb a large percentage of the impulse force. However, choosing this stiffness and finding a suitable material spring may be difficult, although set screws and overlapping plates may be used to provide some adjustment.

We also considered making the heel mechanisms identical to those of the toes, but with a different shape. A radial spring and dampener system would be integrated to absorb some of the impact force. This approach would simplify the design because only one locking mechanism is required. However, it may prove difficult to design a system that absorbs the impulse force and provides the desired conformity, yet does not over extend.

We have also considered not changing the current heel, leaving it a flat plate. This does not take advantage of previously mentioned design opportunities, but it would reduce the design complexity of the foot.

Actuation Mechanisms

After SAFFiR steps and the triggering mechanism activates, an actuator must produce work to engage the locking mechanism. We primarily considered solenoids, dc motors, and springs/ levers. However, it is easy to translate the force from any of these actuators to match that of another. Because of this and because SAFFiR must strictly ration power consumption, the primary criteria for choosing an actuator is its high power efficient or low power consumption.

Grip Mechanisms

The metallic surfaces present on navy ships, alone, do not provide sufficient surface friction to provide a stable stance for SAFFiR's feet. The risk of slipping is too dangerous. To create more friction, the sole of SAFFiR's feet must be coated with rubber. Another solution involves using non-Newtonian fluids as the interface between SAFFiR's feet and the ground. These fluids increase in viscosity as they receive more pressure. So as SAFFiR initially steps, the fluid will be non-viscous and conform to the surface. But as SAFFiR balances its weight on either foot, the non-Newtonian fluid would become incredibly stiff and provide a high amount of surface friction. Unfortunately, non-Newtonian fluids are still experimental and incredibly expensive. Rubber soles are therefore the simpler, more available solution.

Toe Motion

We investigated many toe motions: up/down, rotational, hinged springs, and mechanical springs. All of these design solutions provide adequate conformity to surface irregularities. And each option is adequate for a variety of different situations. The most appropriate toe motion is determined largely by the implemented locking mechanism, actuator, and trigger.

Active Gripping Foot

One concern of our group was the ability of the foot to make a strong connection with the ground. In order to address this concern our group investigated the use of a mechanism that moves additional stabilizing digits onto the floor following the initial contact with the floor. This mechanism would also avoid the tendency of the contact points to shift position until they reach their final position. Our group explored this design concept further by creating a conceptual design of the entire foot. This design would create an initial platform using three semi conforming digits that arrest the momentum of the foot. The walking algorithm of the robot would trigger a single motor in the foot that would draw the foot's digits into place. The initial mechanism we intended to use to draw the digits into place was a cable that slide through guides on each digit. By tightening the cable the digits would be pulled toward the ground. The cable will pull each digit until it is engaging the ground. If one digit engages the ground before the others the cable will continue to affect the position of the other digits until they all engage the ground. When tension on the cable is released the spring loaded digits will return to their standard position. The method we would use to apply tension to the cable was a motor. Some potential benefits of this platform are very high stability and excellent contact with the ground. Some potential shortcomings of this design are higher weight and a large power requirement.

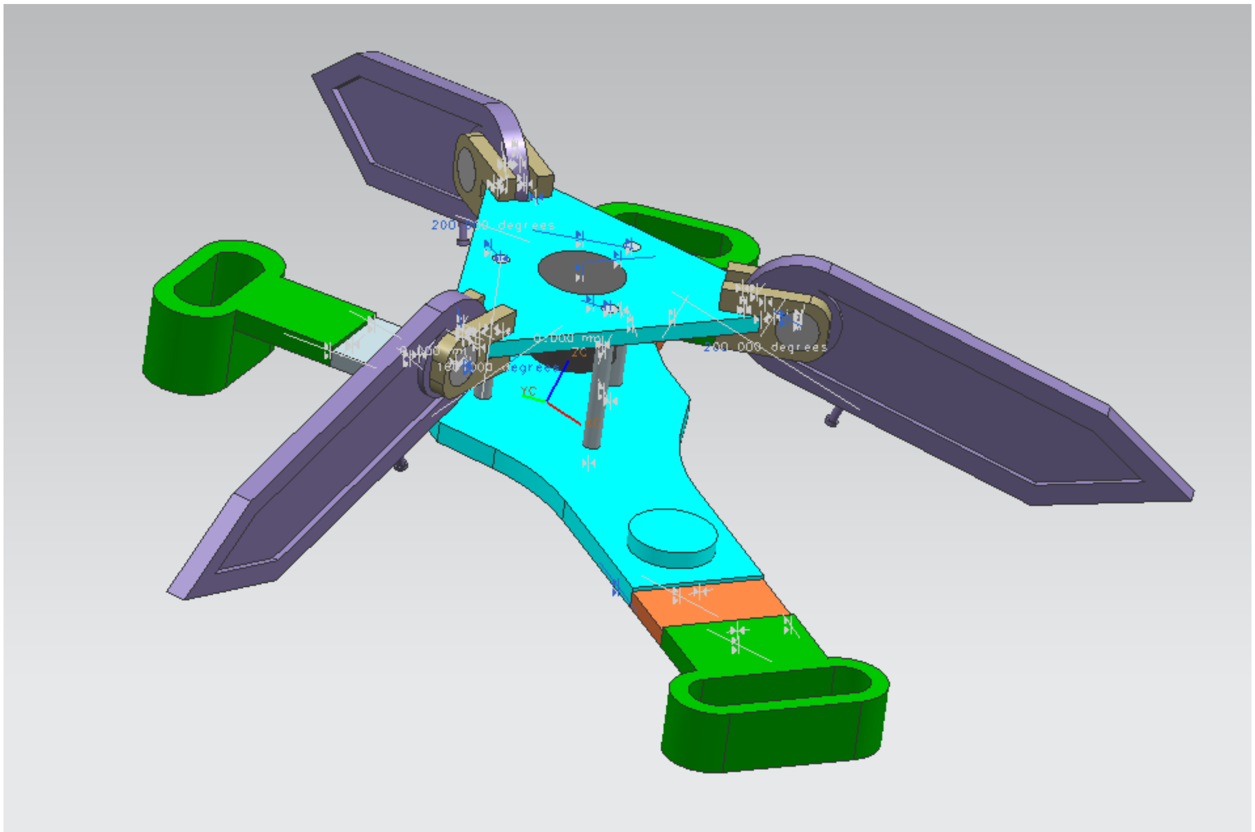


Figure 16: Active gripping concept for foot.

Rotational Toe, friction lock

The rotational toe with a friction lock concept depicts spring loaded toe members that rotate downwards towards the ground, as the foot contacts the ground, a frictional lock will engage which locks the toes rotation. The toe mechanism can be seen in Figure 17.

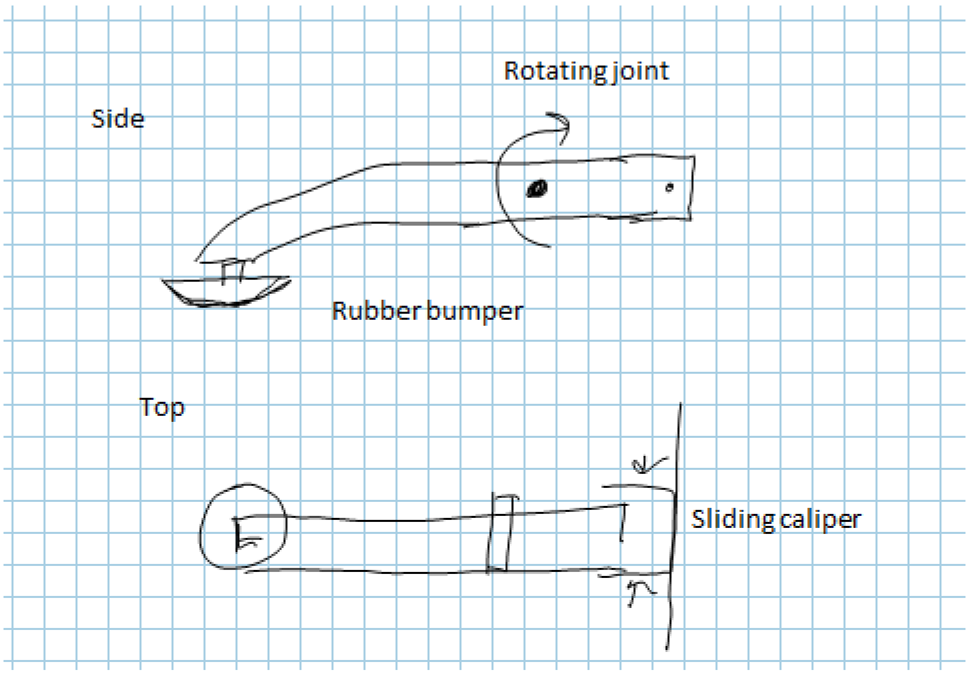


Figure 17: Toe rotation and locking mechanism

As can be seen, the toe rotates around a joint, one end of the toe contacts the ground, while the end on the other side of the joint slides in a caliper. As the foot contacts the ground, or as signaled by the walking algorithm, the caliper closes on the toe and locks the joint location in place. A mechanical locking mechanism will be described next.

There are various methods of mechanical locking that can be implemented; a fully passive method would require the force of the robot standing on the foot to actuate the calipers. To do so, the contact ring was invented. The contact ring sits inside the foot and makes contact with the ground, as the contact with the ground is made; the contact ring transmits a force that actuates the brake caliper. This mechanism can be seen in Figure 18. This figure depicts a side cutaway of this mechanism. The contact ring would be the lowest point of the foot, aside from the toes. Thus it would contact the ground and transmit force through a brake cable, similar to that of a bicycle, which would then actuate the caliper brake.

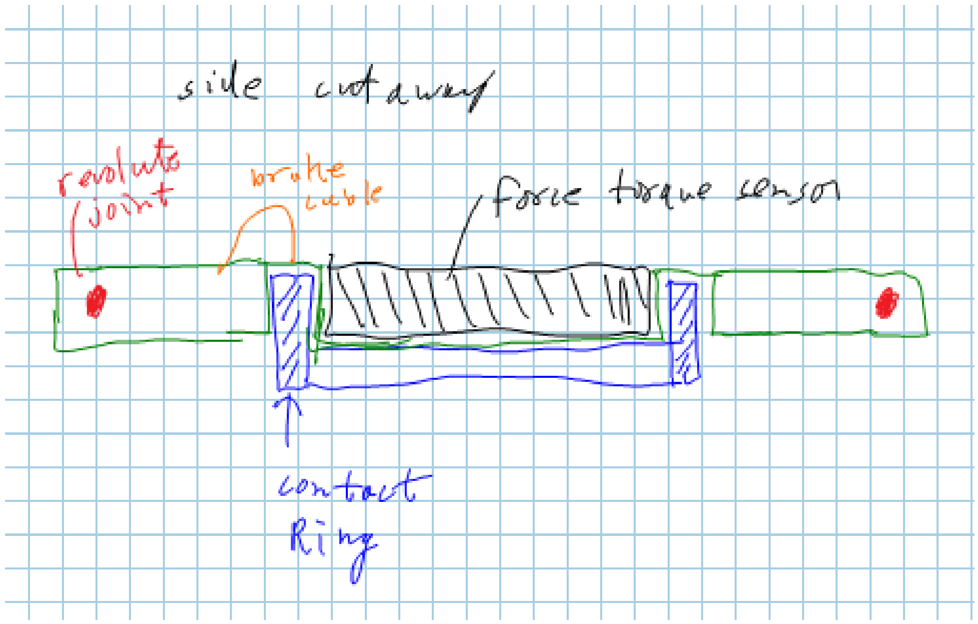


Figure 18: Foot baseplate cutaway

Ratcheting Toes and Compliant Heel

This concept features 2-4 toes that would compose the front half of the foot that conform to the ground by the use of ratchets. These toes would be spring loaded so that the toes were always pressed below the base of the foot so that the toes would conform individually to the terrain. As each toe would deform it would be pressed up into the ratchet stopping it from moving down any more. After the foot as been placed, a mechanism would lock the ratchets in place providing a steady platform for the foot to press off of while still conforming to the terrain underfoot. As the foot is pressed off of, or lifted, the mechanism would release the lock and the ratchet allowing it to go back to its springed position ready for the next step. Additionally this concept would employ the use of a compliant heel to absorb the force of a heel strike and allow for a small degree of give. This heel would be basically a large mechanical spring that could be adjusted by tightening or releasing a bolt that would adjust its stiffness. This would act much like the mechanism in a compound bow for adjusting the draw. Figure 19 and Figure 20 below illustrate early design concepts of the ratcheting mechanism for the toes and for the compliant heel.

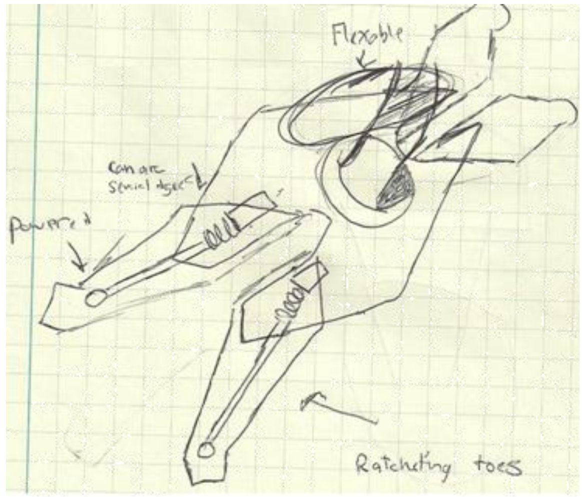


Figure 19: Featuring 2 toes with the Ratchet, and a winged heel that would allow for 2 points of contact on the back heel in the case of an obstruction.

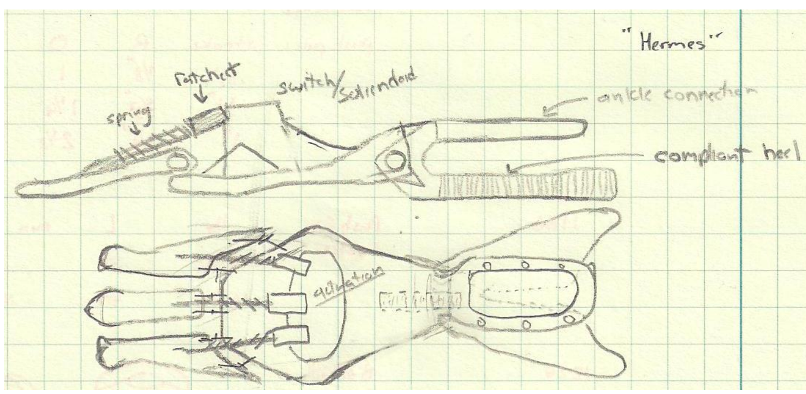


Figure 20: Featuring 3 toes with a ratcheting mechanism and winged heel. This illustration features a sleeker design.

The most challenging parts of this concept will be refining the ratcheting system for efficient locking and determining the mechanism for release of the Ratchet. In addition the refinement of the mechanical spring for the heel would take some time but is within an achievable scope.

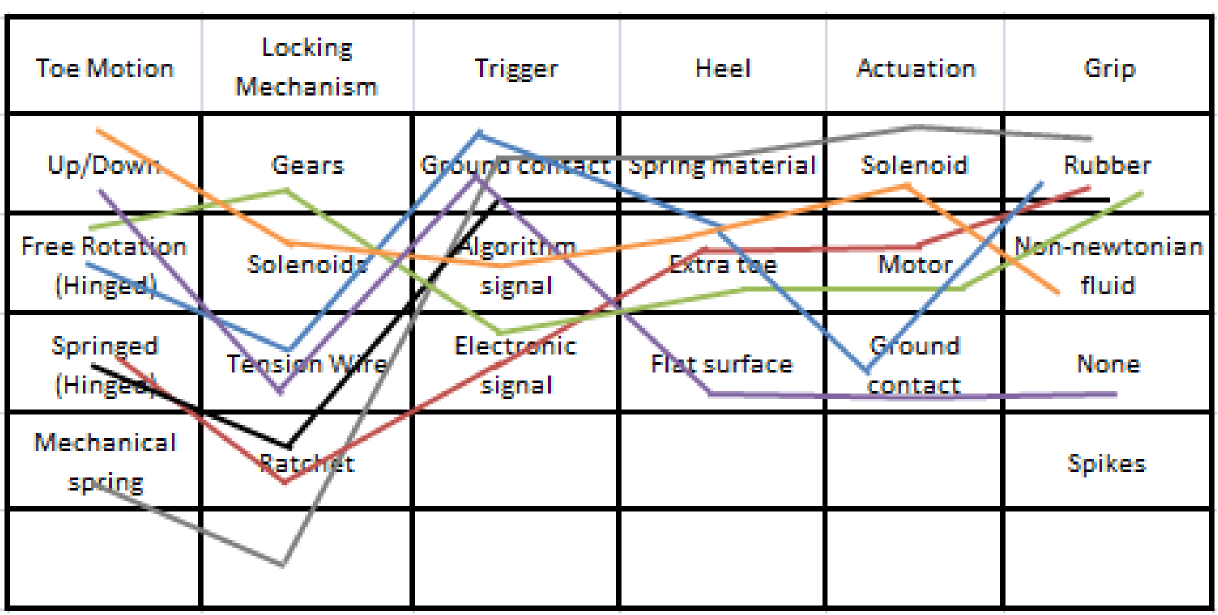
Spring-Locking Concept

This concept centers on the goal to quickly and simply be able to handle the variations in the floor on the test ship that SAFFiR will have to walk across in demonstrations. The concept uses springs similar to leaf springs on a truck suspension. A small spring would be placed at the four corners of the basic foot in place currently (a flat aluminum plate). One end of the spring would be fixed and the other would be on a slider. To lock the foot in place a stopper would engage the springs using a DC motor to prevent them from changing while the foot is in complete contact with the ground to provide a stable standing/walking platform. Once the foot lifted off the ground the spring would return to original height and the stopper would disengage. The stopper would be controlled by a command in the walking algorithm to tell the motor when to provide force and when to release. The benefits of this concept are as follows. The design is fairly simple and could be quickly adapted to the current foot. The concept adds only a few parts so it could be quickly manufactured. Finally, since it using the same basic footprint of the current foot, it should have no effect on the walking algorithm other than to engage the stopper. The main issues with this design are as follows. This design would only benefit SAFFiR on the first demonstration. After that, a much more intricate foot would be needed to walk on anything other than the test ship floor. The spring system is simple but not tested. Without having much background information on moving springs as shown in this concept, it could be nearly impossible to have it function properly. Since there was much the group did not know about trying to lock the foot in this manner and because the design lacked potential to be used on later demonstrations, the concept was not chosen for initial prototyping.

Concept Selection

Morphological Chart

The morphological chart is a tool used by the team to help generate additional solutions. This is done by pulling the key concepts from each idea presented by the team and categorizing them into associated groups. We identified these groups to be; Toe motion, Locking Mechanism, Grip mechanism, Heel, Trigger, and Actuation. From there we travel across the chart creating different combinations of the presented concepts. The Individual subheading topics are described in the following sections. It can be seen below in Figure 9.



Toe Motion	Locking Mechanism	Trigger	Heel	Actuation	Grip
Up/Down	Gears	Ground contact	Spring material	Solenoid	Rubber
Free Rotation (Hinged)	Solenoids	Algorithm signal	Extra toe	Motor	Non-newtonian fluid
Springed (Hinged)	Tension Wire	Electronic signal	Flat surface	Ground contact	None
Mechanical spring	Ratchet				Spikes

Figure 21: Morphological Chart used for Concept Selection

This chart was created by pulling from 6 initially presented ideas; from these we identified 6 key areas that defined each idea. Using this we recreated our initial ideas by breaking them down and came up with an additional concept that was chosen to maximize the strengths of each concept. Also we were able to identify what sub topics we described that we did not want to use.

Decision Matrix

To complete our first round of concept selection after presenting each member's idea to the sub team we decided to use a selection tool to better focus our areas of design. First we identified our design requirements and decided on appropriate weighting value based on the importance of each. The total weighted max then becoming a value of 470. The completed matrix can be found in Table 3.

Table 3. Decision matrix detailing the concept selection process

	Weight	Sam	David	Earl	Dan	Rick
Stability Provided	**5**	5	8	8	7	7
Movement Hinderance	**5**	9	7	8	7.5	8
Load Cell Incorporation	**5**	10	10	10	10	10
Contact Points (4 min)	**5**	8	9	8	7	6.5
Verticle Height	**2**	9	4	7	9	7
Manufacturability	**3**	7	2	2	5	5
Weight	**4**	8	5	4	7	8
Cost	**1**	7	4	4	6	6
Aesthetics	**3**	2	8	9	6.5	8.5
Design Integration	**4**	9	7	8	7	6
Design Simplicity	**2**	9	2	5	6	4.5
Design Novelty	**3**	1	8	7	9	9
Future Usability	**5**	2	5.5	7	6	6
Sum:	**47**	86	79.5	87	93	91.5
Weighted Total	**470**	311	315.5	335	341	340

The requirements identified as the most important were identified by our customer (the graduate students of Romela) and the conversations among the team. The most important requirements identified were Stability provided to the Robot, Lack of movement hindrances, load cell incorporation, future usability to incorporate to the future iterations, and a minimum of 4 contact points on the ground.

From the information in Table 3 we can see that the two highest scored concepts were only 1 weighted point apart. Signaling that the two concepts are very close in viability for implementation. The detailed concepts can be found in the previous sections detailing the first round of concept generation from the members of the foot sub team.

Foot Prototypes

This section will discuss the various foot designs that were prototyped for further study. Primarily these designs revolve around different locking mechanisms. First is the Revolute joint with extra degree of freedom for locking, this design uses two forces from the ground to create a clamping force that locks the whole toe. Second is the chain toe design, this design uses motorcycle chain as the main pivot points and a track for the chain to move through, locking is achieved through braking the chain. Third is the linear translation design, this design uses a linkage mechanism to transform the rotational motion of the toe into translational, which can be locked via a clamp. The fourth design is that of the translational parallel locking toes, this design uses a hinged brake to clamp down on a set of spring loaded toes that extend down into the ground. These designs are discussed in further detail below as well as any preliminary analysis done up to this point.

Foot Prototype – Revolute joint with extra degree of freedom for locking

The deformation based self-locking foot design stems from the idea of adding a degree of freedom to the foot in order to create a locking mechanism based on the weight of the robot. This design hinges around the idea of a straight line of contact with the ground at each digit. By allowing each digit to rotate freely, the digits are allowed to find a line of contact, with two points defining that line of contact; by having two separate digits, it is possible to have four points of contact. The first revision of this design can be seen in Figure 22.

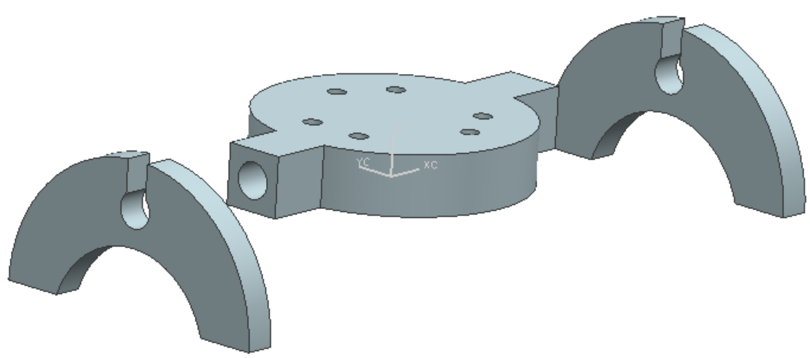


Figure 22: First revision of the self-locking multi degree of freedom foot design

As can be seen, each digit can rotate freely about a collinear axis that interfaces with the baseplate of the foot. This design relied on metal deformation to clamp a central rod when a force is applied to each side of the toe. This design relied on tight tolerances to allow for a pre-clamping which would resist motion and aid in the locking of the mechanism. Because of the need for tight tolerances and material deformation, it was deemed unfeasible.

To improve the initial design idea, I added an extra degree of freedom in each toe; this would allow a clamping on the central rod without relying on material deformation.   This can best be seen in Figure 23.

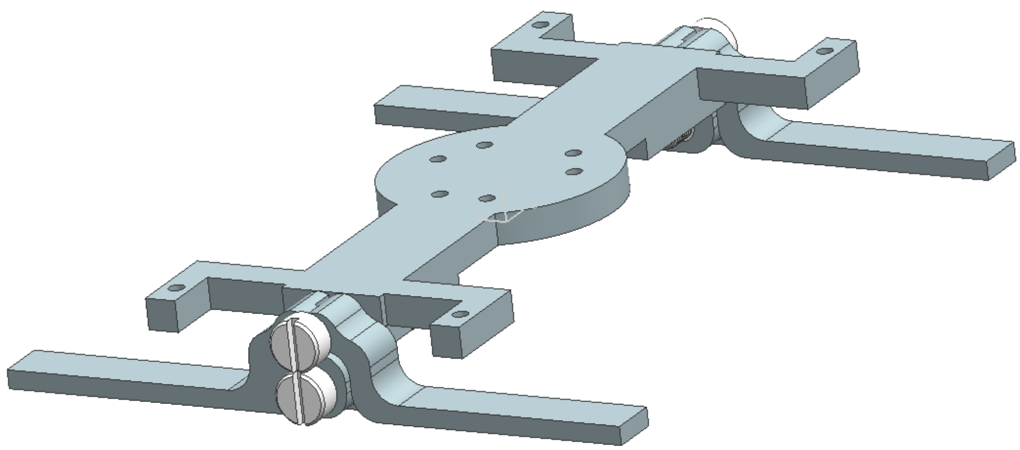


Figure 23: Second revision of the self-locking multi degree of freedom foot design, this design relies on an extra pivot point instead of material deformation.

This design relies on two degrees of freedom, the first is the top pivot point which allows the toes to rotate relative to the body of the robot. This pivot is the rod which will be clamped when the toes need to lock. The second degree of freedom is the pivot directly below the clamping rod; this pivot creates force amplification as the toes contact the ground.

This design has the advantages of force amplification through a pivot point, and lack of reliance on material deformation; an unfortunate downside to this is the difficulty in creating a pre-load force, as that would require external springs. This design also has an issue with a force being applied in the middle, if the toe were to contact the ground at the pivot point; no locking force would be applied to the above rod.

To overcome the terrain issues with the second revision, a third revision was made; this third revision creates a slightly higher profile, but at the same time it alleviates the issue of contacting the ground in line with the pivot. This design can be seen in Figure 24

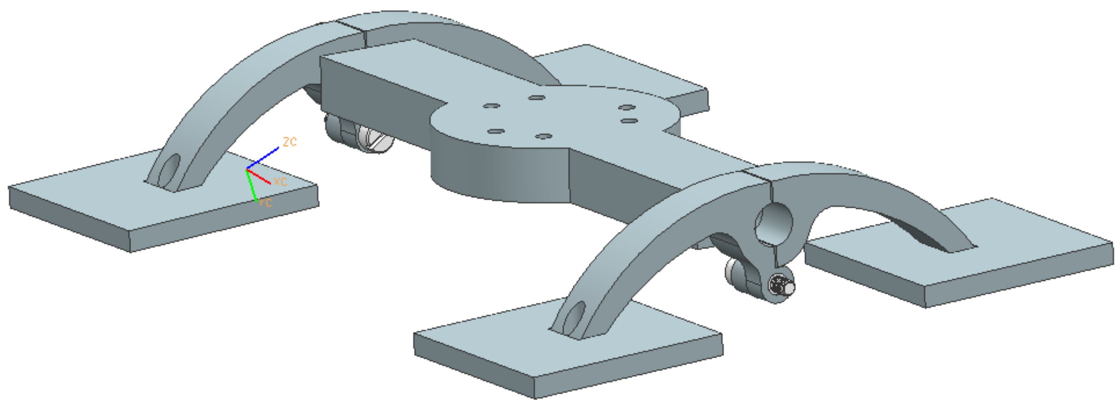


Figure 24: Third revision of a self-locking multi degree of freedom foot.

This revision was designed into the most detail, thus the most explanation will go into it; as the supporting material is available.

The features of this design concept include the following: a novel auto-locking mechanism that remains locked only when needed, a potential for a fully passive solution, and a locking mechanism that increases holding torque as needed. A diagram of the joints can be seen in Figure 25.

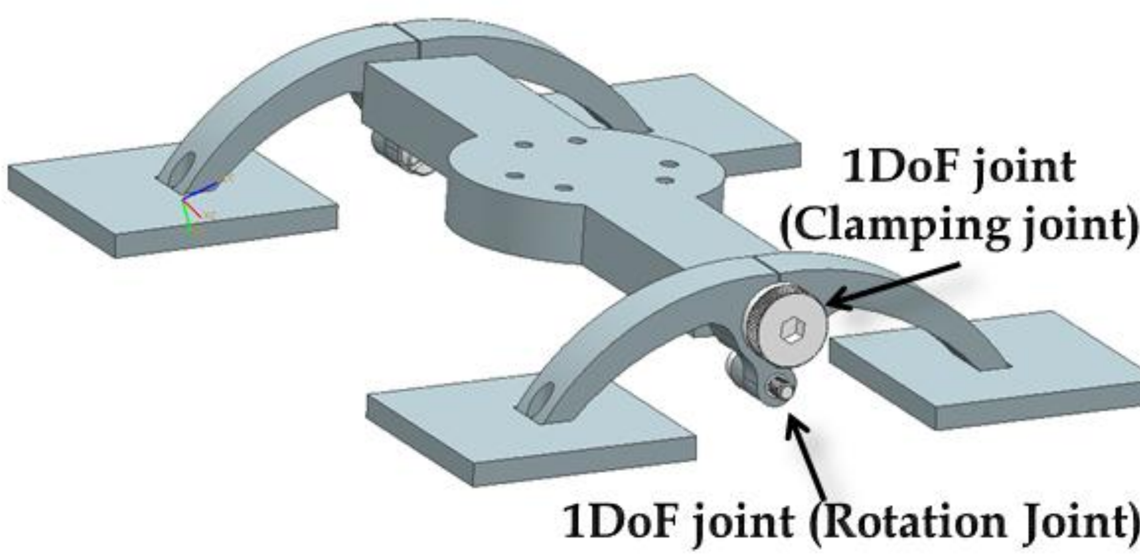


Figure 25: Diagram of locking mechanism

This design conforms to different ground conditions by the rotation of the toes relative to the clamping joint.

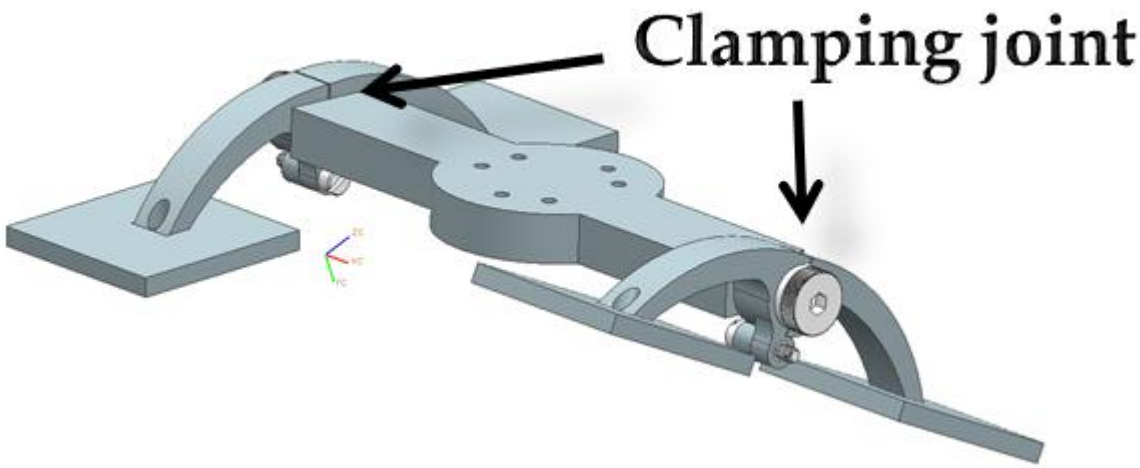


Figure 26: Toes rotated about clamping joint to conform to the floor

Thus, by the toe rotating around the clamping joint, the toes can find a single line of contact. This line of contact should exist for all configurations and two toes creating two lines creates four points of contact.

The locking mechanism of this toe relies on a rotation about the Rotation Joint.

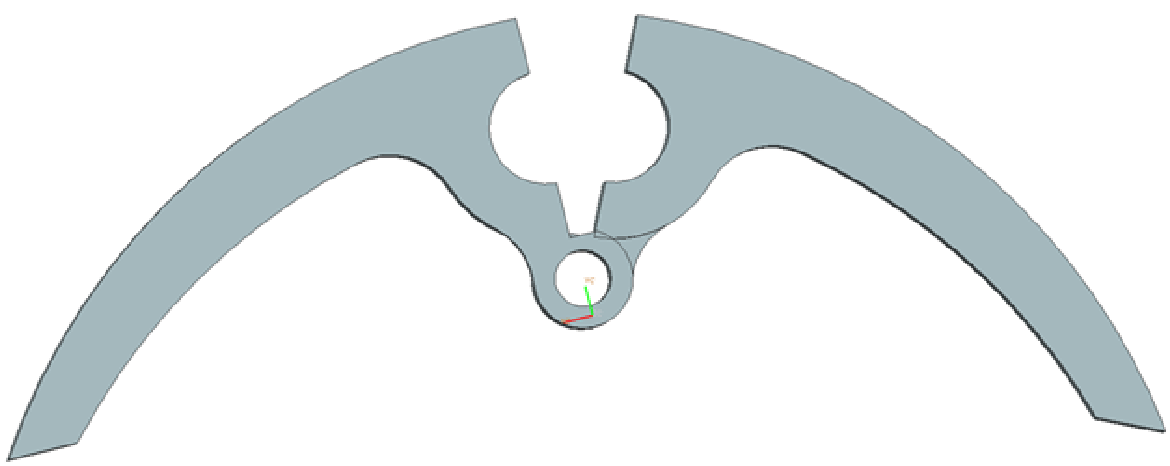


Figure 27: Locking mechanism opened up

By having a degree of freedom in the rotation joint, the sides of the toe can reach down to the ground and as the weight of the robot pushes down through the clamping joint, the reaction from the ground causes a pivot about the rotation joint and thus a clamping on the above rod, as seen in Figure 28.

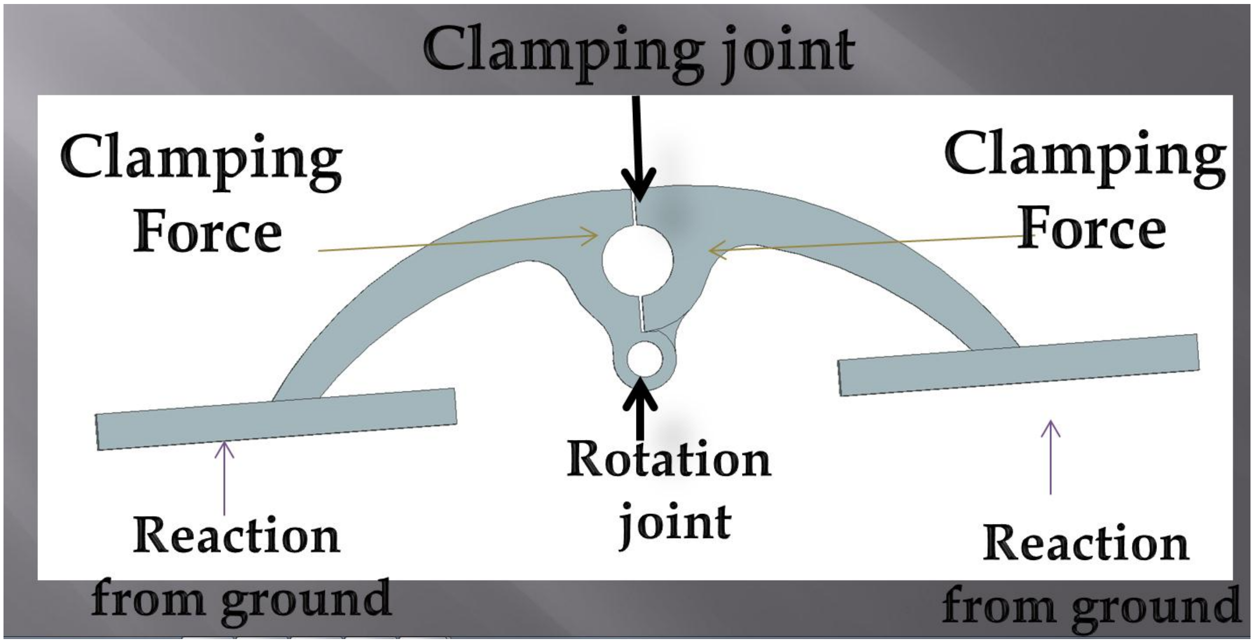


Figure 28: Free body diagram of clamping action.

Foot Prototype – Chain Toe

The chained toe prototype was a proof of concept prototype that demonstrated the motion of a toe mechanism using repurposed motorcycle or bike chain. The concept is essentially a complicated linkage that would transfer linear motion into rotational. The initial design sketches can be found in Figure 29 and Figure 30 below. The use of the repurposed chain provides a reliable and strong transmission of motion. By attaching a flat surface to the base of one of the bottom links of chain one can create a toe by pushing or pulling on the remaining links to the right while constraining the motion of the links on the front of the toes. This motion is seen in Figure 31 and Figure 32 using real chain which proves the use of this concept. A stationary image is shown in Figure 29 and an extended image is shown in Figure 30.

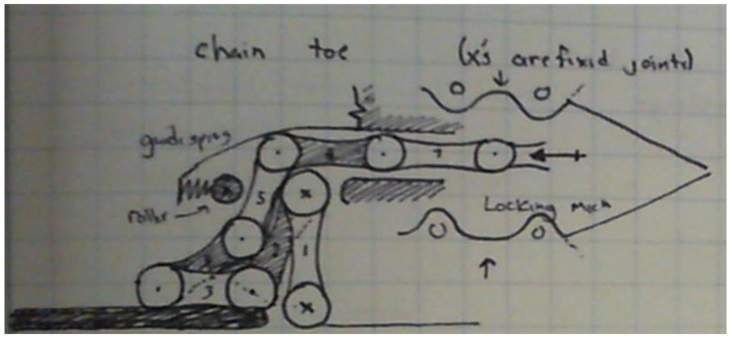


Figure 29. Illustrated here is the layout of the links where x's in the links indicate fixed points. The ball in front of link 5 constrains the motion of the links to ensure reliable placement of toes

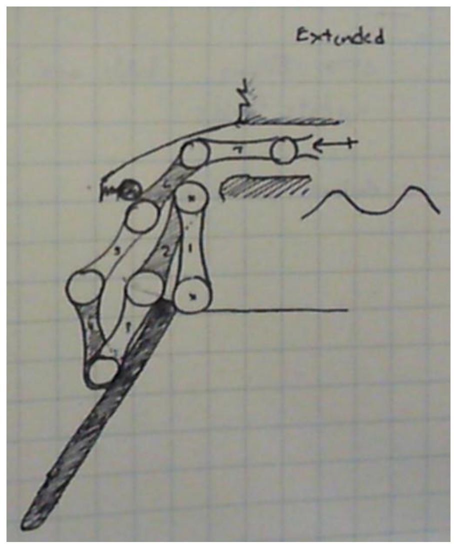


Figure 30. Illustrated here is the layout of the toes when the links inside the channel are pushed forward making the bottom links rotate downward muck like an actual toe

Figure 31. Real image of chain in base orientation, Illustrates how well the chain fits together which optimizes space.

Figure 32. Real image of chain in extended orientation. Illustrates how the toe would extend when links are pressed forward.

A CADD model was created to demonstrate how the base of the toe platform would attach to the links of chain in Figure 33.

Figure 33. CADD drawing of toe plate attached to the floor links that would transmit the motion to the toe.

Constraints: The best way to lock the motion of the toes would be a simple matter of inserting a block into the chain inside the guide channel. The makeup of the chain provides for an easy locking mechanism with lots of places to stop the motion.

Foot Prototype – Linear Translation

The linear translation prototype's goal was to prove that a toe could be linked to a linear shaft or rod that could be clamped. This prototype had a rotational toe mounted on the front of the foot linked by a bar to a sliding shaft. This shaft could slide both forward and backward as the toe rotated up and down. By placing a high normal force on the sliding shaft the toe could be clamped into place. This showed that the idea could be applied to a braking system that could lock SAFFiR's toe in place once it had adapted to uneven terrain. This prototype suggested a high success rate based on its simplicity. This model also resembled a human toe, which could later be used for a more human-like stride by stepping off from the toe. This design displayed several ways to be adapted to our final design since more than one toe-shaft assembly could be rigged to the foot, and it could be placed in several different types of configurations. The unknowns for this type of setup are how much friction force would actually be needed to brake the sliding shaft and how the foot could sense when to lock without being tied into the walking algorithm. The wooden prototype can be seen in Figure 34.

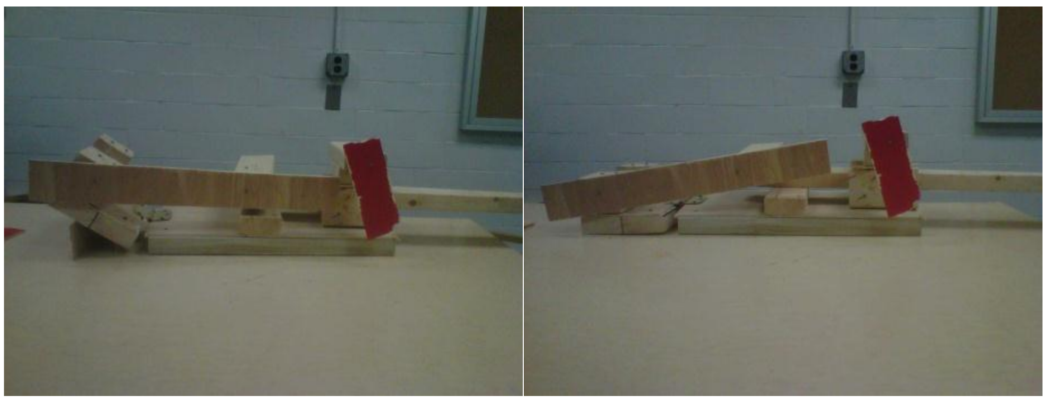


Figure 34: Photos of the linear translation prototype. Note the difference in location of the sliding shaft when the toe is placed in the two different locations.

Foot Prototype – Translational Parallel Locking Toes

One of the ideas that our group identified for further exploration was a toe that slid and was stopped by friction surfaces or gear teeth. Our group explored the utility of using translational toes that slid along constraining bearings that eliminate all but one degree of freedom. Ideally our design can be locked by a single actuator. The simplest way for our team to lock the toes with a single actuator was through the use of a common rotational axel that locked parallel toes. An additional concern shared by our group was the torque resistance needed to provide sufficient locking force, in this iteration of the design the force can be amplified using a lever. The completed assembly can be seen in Figure 35.

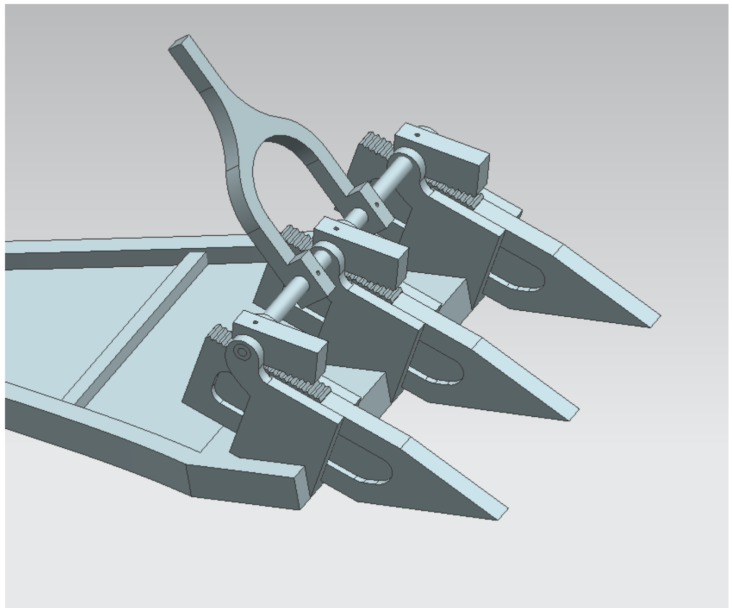


Figure 35. Translational Parallel Locking Toes Prototype Design. A simple elegant way to constrain and lock the motion of multiple toes, the picture above shows the vision of a foot that utilizes translational toes and a simple locking mechanism.

The following sections will explain the ideas for each section of the design.

Translational Toes: As mentioned before the team explored the use of toes that were constrained to one degree of translational freedom. Benefits of this idea include a stable interface with the floor that does not need to change position in the XY plane in order to change position in the Z direction. Another benefit of a purely translational toe is a uniform distribution of force regardless of the position of the toe. In order to understand these benefits you must explore the alternatives. The primary alternative to a translational toe is a rotational toe. A rotational toe must always move in two directions in order for the interface point to adjust to the contours of the ground. This additional movement requires that the toe be able to slide along the floor. Our team was concerned that a toe that was designed to slide along the floor would not provide a stable platform as it could slide when the robot experiences a lateral force. Also as anyone versed in statics will understand, as the position of the toe changes the torque applied to the toe also changes as a result of the changing moment arm.

Locking Mechanism: The method used to lock our designs is a primary concern among our group. The factors that must be balanced by our group include the effectiveness of the locking mechanism against the weight, power consumption, and control input required. In an effort to limit the power consumption, weight, and control input required by our system our group explored the use of a common braking system that utilized the mechanical advantage of a lever. Many actuators have a high range of motion but limited torque. A lever will take advantage of the low range of motion required by our braking mechanism and the high range of motion delivered by the available actuators.

Summary

After developing the previous prototypes, the team combined a linear translated toe with a clutch locking system. We began detail design and found that acquiring the correct parts was too difficult so we chose a modification of the prototype with the passive mechanical locking design. From this point the team began detail designing. The team's design has one degree of freedom in the front that is locked into place by a friction force caused by the normal force of SAFFiR's weight pushed against the rotating toe. Once SAFFiR picks up its foot the toe is unlocked and is prepared to reengage at a different angle. As the team stands now there is a CAD model as seen in Figure 36 that is being adjusted to the detail design as the process continues. The team will deliver a functional foot to the SAFFiR team on May 02, 2012.

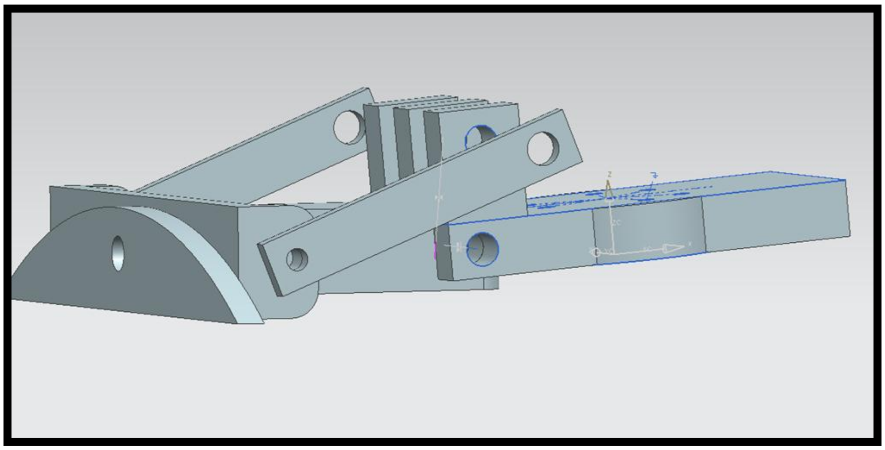
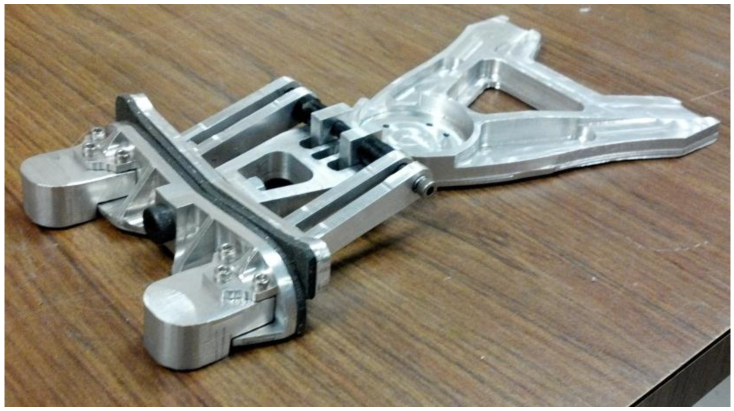


Figure 36. Latest CAD model of the passive mechanical locking design.

Detailed Design for Final Foot Design

After selecting the design concept we wished to pursue our team set to work developing the overall design into a solution that best meet the criteria of our customer. Our customer's primary focus was on functionality, the foot is required to conform reliably and lock and unlock quickly. A stipulation added to functionality was durability, it is critical that this design survives numerous actuations. A malfunction in the foot could cause the robot to fall and damage itself critically. Durability and functionality were the focuses of our detailed design refinement. Our customer also required a foot that was low mass. Small changes in the mass of the foot have large impacts in the moment of inertia of the leg and thus greatly affect the dynamics of the robot. Our team's goal was to keep the mass of the foot as close to the existing foot as possible. A minor concern of our design team was the aesthetics of the design, the robots our lab builds are highly publicized and it is important that the parts of the robot are visually compelling. The design of the foot required a significant number of revisions. Primarily once the initial architecture was found, a method of force amplification was needed to create a friction lock that was sturdy enough to support the weight of the robot when fully extended to the extremities of the foot. Each designed needed extensive modeling to approximate the amount of friction necessary to lock the joint, these calculations were done to find the friction necessary to lock with the weight of the robot at the extreme edge of the toe. Interestingly enough, since the weight of the robot is used as the force to engage the lock, the weight of the robot cancels out of the calculation to find the friction force.



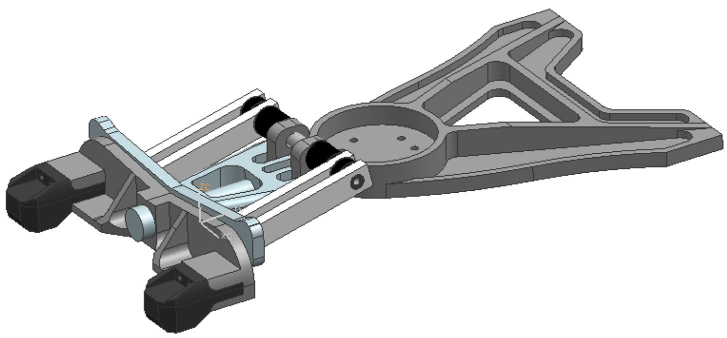


Figure 37. Picture of manufactured foot and semi-final cad model.

Functional Constraints

The primary functional constraint was conformance to the ground. Our initial design constraint was to account for a +/- 5 degree warping of the floor, thus a worst case scenario is that of a peak in the middle of the foot with a 5 degree decline on both sides. The height of the arch of the foot thus needs to be high enough to account for this. To be safe, we used a +/- 10 degree warping for the final foot design. This worst case scenario sets the needed arch height of the foot based on the length profile of the current foot. This constraint also means that the rotational member of the foot needs to be able to rotate freely through that range. Pared with the conforming constraint is the locking constraint. The locking mechanism must be strong enough the prevent the position of the foot from shifting across a wide range of weight distributions. Our goal was for the foot not to shift when the center of the robots weight is at the edge of the profile of the foot.   Another constraint is the overall size of the foot, it was necessary to produce a foot that maintained a similar profile to the current foot, so that when the robot is toeing off the ground, the force from that toe off does not exceed what the force torque sensor can measure. With respect to the force torque sensor, it was a requirement to be used and placed at a location close to the middle of the foot.

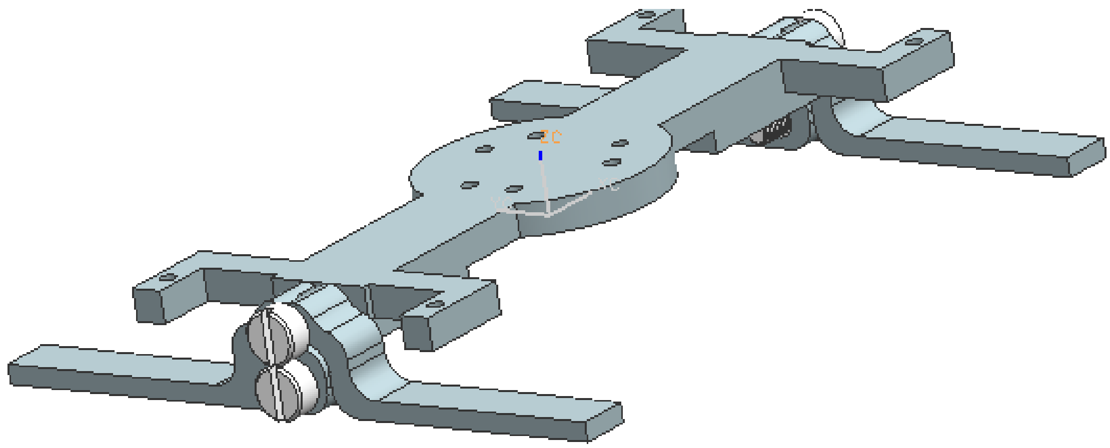


Figure 38. Initial Design Concept

The initial design concept, seen above, is the beginning of the theme used in all future design concepts. The theme is to use an axis of rotation to allow for a rotating member to rotate as necessary to accommodate for the floor. Then for a separate axis of rotation to engage when both ends of the previous member contact, this second axis of rotation would engage the locking mechanism. This particular design only uses two axles to create this locking mechanism, and since the two axles are in the same plane, it is difficult to find the

The next design revision of this was primarily to address ground contact issues. The previous foot concept did not necessarily contact the ground on the furthest extremities, whereas this design would contact further out.

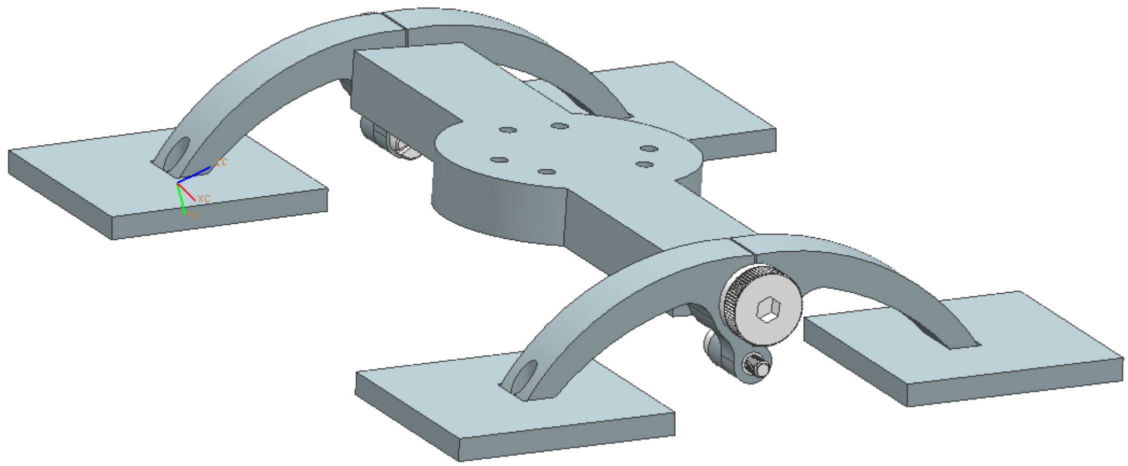


Figure 39. Overall architecture of the V4 foot. Ground contact occurs at the toes, force torque sensor is mounted in the middle, rotation of the toes occurs at the large bolt interface, rotation of each individual member occurs around the lower bolt interface.

Conformance of this design relies on rotation about the top bolt joint, as seen in the following figure. This design requires wide toes to provide sufficient braking force to arrest the rotation of the toe.

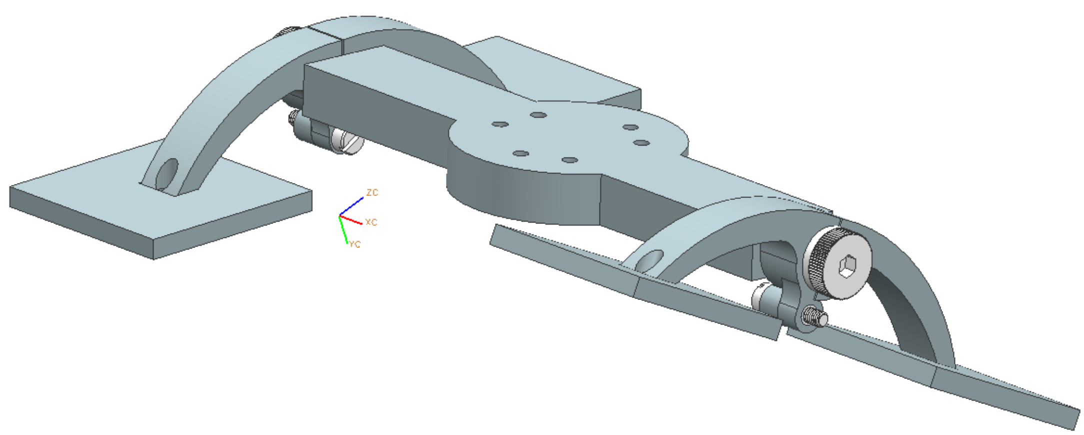


Figure 40. V4 foot concept, conforming to uneven surface.

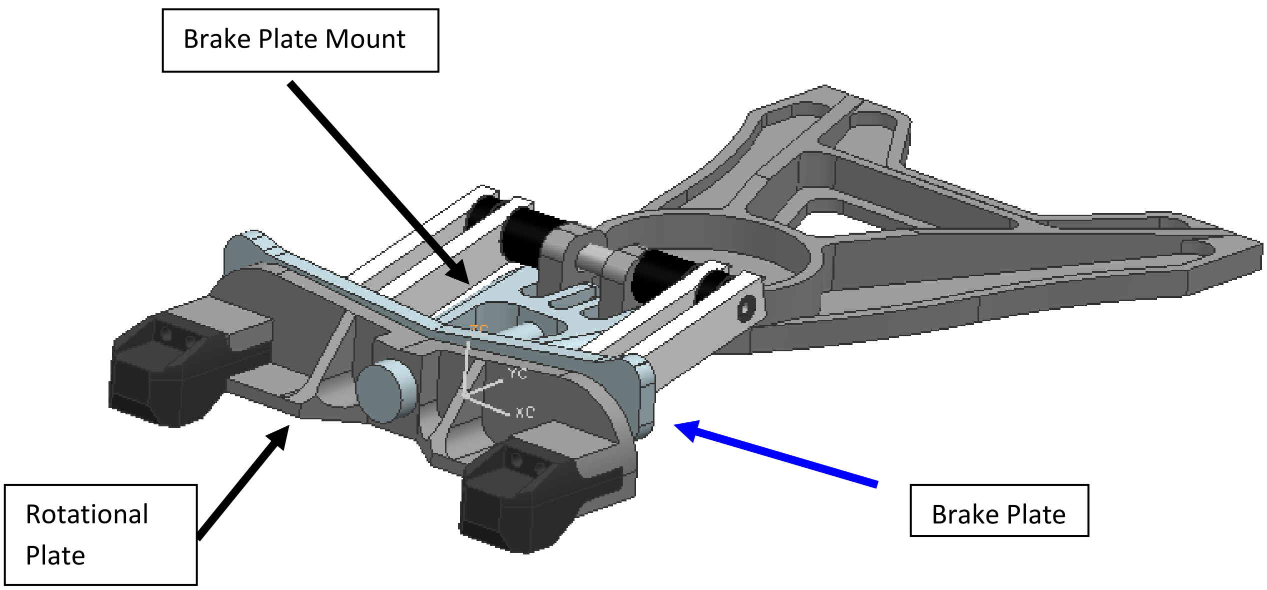
As can be seen, the front toe section rotates about the top joint, thus allowing for conformance to uneven surfaces. This concept relies on “line of contact” where the toe member will rotate until two points of contact are made, as well the rear does the same creating a second “line of contact” two lines of contact guarantee four points of contact.

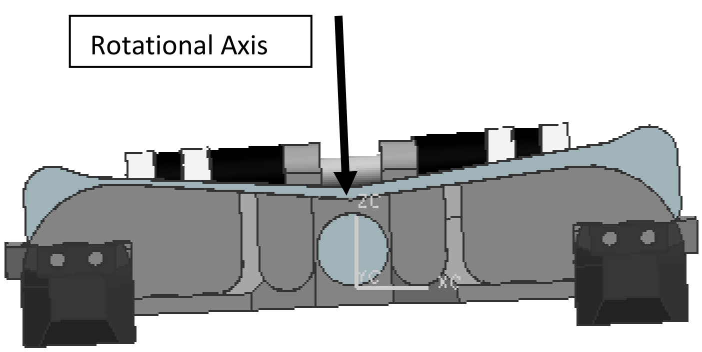
The fourth design concept was unacceptable due to the limitation of locking force. The locking force is proportional to the ratios of the distances between the bolts and the width profile of the foot. Unfortunately for the robot to extend its weight over the toes, this locking force would be insufficient. Thus it was necessary to increase the force amplification.

Another design concept including gears was studied, but discarded due to weight and complexity issues.

Final Design Concept

The final design concept can be seen in the following figure, as it moves the locking axis far away from the rotational axis, thus allowing for a much larger locking force.





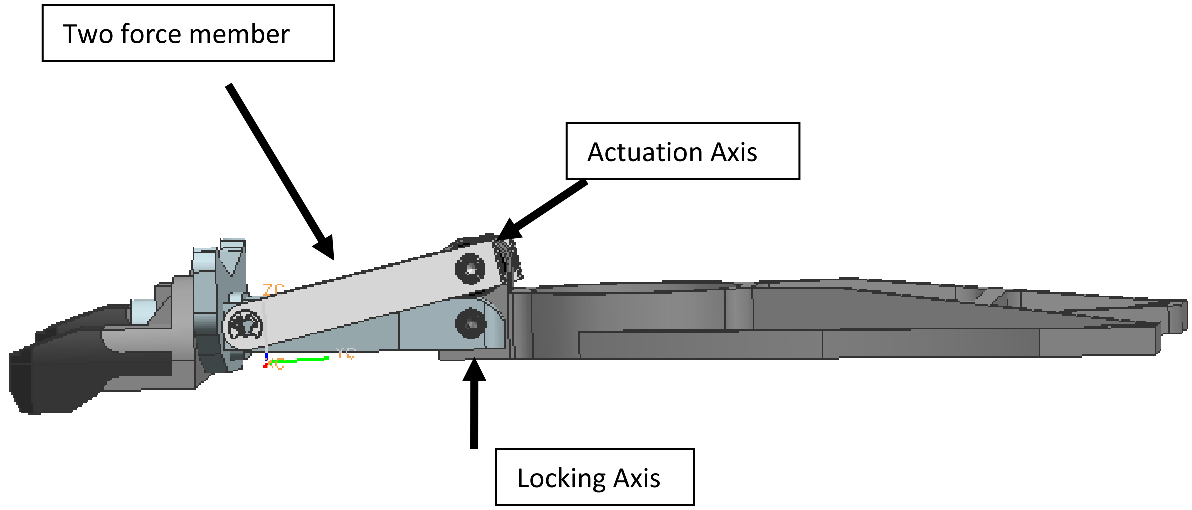


Figure 41. CAD overview of the semi-final foot design.

As can be seen above, the locking axis has been rotated out of the plane of the rotational axis which thus allows movement and an increase in the length of the moment arm, relative to the length of the rotational moment arm. Because of this, we can effectively increase the length of the locking moment arm as much as we would like, thus allowing for the creation of nearly any width profile of the foot.

Actuation of this foot initially occurs as the ground contacts the two black toes at the front. The sum of the forces on these toes applies a force to the bolt going through the rotational axis. This rotational axis is what allows the foot to conform to the ground. The force on the bolt through the rotational axis pushes the Brake plate and brake mount plate up as it causes the locking axis to rotate. As these rotate upwards, the actuation axis rotates causing the two force members to push the brake plate outwards. As the brake plate pushes against the rotational plate, a friction force occurs that prevents further rotation. Our team was very happy with this design solution, we decided to continue forward and detail design of the individual components.

Detail design of individual components

In order the create the most reliable products our team isolated individual components and optimized them to best meet our design goals. The parts that optimized were the brake plate mount, the brake plate, the rotational plate, and modular toes.

Brake Plate Mount

The role of the brake plate mount is to locate and constrain the brake plate relative to the rear foot assembly. The design requires that the brake plate is constrained to only one direction of translation and no direction of rotation. This is accomplished with a locating slot and pin shown in the figure below. The brake plate mount also holds the bolt that connects the rotational plate to the brake plate; this bolt bears the tension generated in the locking. The brake plate mount must be able to effectively translate this tension. The brake plate mount was designed to effectively transmit these forces, material that was not essential in this mission was removed where possible.

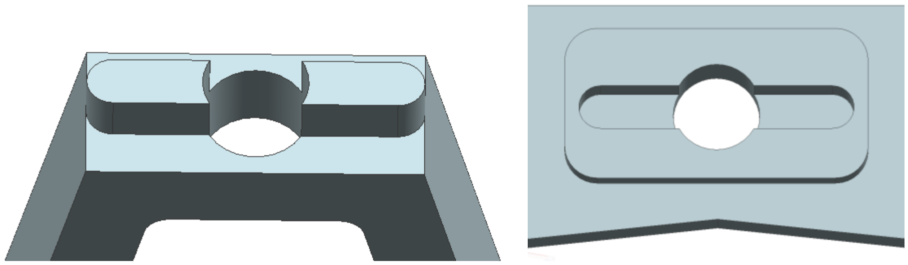


Figure 42. detail of locating slot.

Brake plate

The brake plate was designed to stop the rotational plate from rotating when the brake force is applied. It must be constrained not to rotate and to only translate in one direction; this is accomplished by its interface with the brake mount shown in the figure above. A high friction interface with the rotational plate is critical to the function of the foot. In order to increase the friction we utilized a friction material commonly used in brakes. The shape of the brake plate insured that the force of the braking can be transmitted as far from the center of rotation as possible to utilize a torque advantage that prevents the plate from slipping.

Rotational Plate

The rotational plate of the new SAFFiR foot design provides a rotational degree of freedom. This axis of rotation allows the toes to displace against a warped or even surface, while ensuring two points of stable contact in the front. These toes attach to the rotational plate using three screws and a slot. For ease of machining, the slot was made to be just slightly larger than 3/8ths inches across. The mating part of the toe slides into the slight. Three screws are secured through the holes that align between the toe and rotational plate. Because the toe's holes are threaded, the width of the screws increase the mechanical strength of the design and prevents loading on the threads. This standardized method of attachment allows the rotational plate to easily mate with alternative toe designs. To help achieve weight requirements, the rotational toe is designed to be as thin as possible. Even so, the rotational plate possesses contoured ribs that prevent the slot walls from deforming under a load, further ensuring reliable mechanical design despite weight reduction.

The back face of the rotational toe is epoxied to a matching section of break plating. This breaking surface contacts another to create a friction lock under the weight of SAFFiR. Because of this, the toes (which have conformed to the uneven ground) are locked and held in place. Once the weight of SAFFiR is moved off the foot, the friction between brake pads decreases and the toes are again free to conform.

Removable Toes

Our team decided that detachable toes would help support the mission of the robot by enabling the graduate students to easily adapt and test different solutions. Our team focused on a reliable interface with the rotational Plate that would transmit force with minimal deformation. One consideration our team was asked to explore was collecting data on when the foot has contacted the ground. Our first interchangeable toe design incorporates a Large top face that can easily be machined as a location to incorporate a touch sensor. Another design consideration is the ground clearance. The middle of the foot must not contact the ground and bypass the rotating surface. The initial toe is tall enough to prevent actuating assembly from interfering with the ground. Our design requires a precision fit to properly transmit forces. In the first manufactured toe we did cut the toe larger that the hole and used a lot of post processing to fit. For future toes, our team will be more accurate with machining on both sides to ensure accuracy along with an additional finishing pass.

Final Product

The results of the detail design and manufacture can be seen in the figure below. The locking mechanism preformed just as we thought it would. The foot has a high enough clearance to meet and exceed the metrics given to us by our customers. The profile is only slightly larger than the original foot and well within the dimensions our customer requires. Overall our customer is very satisfied with our product.

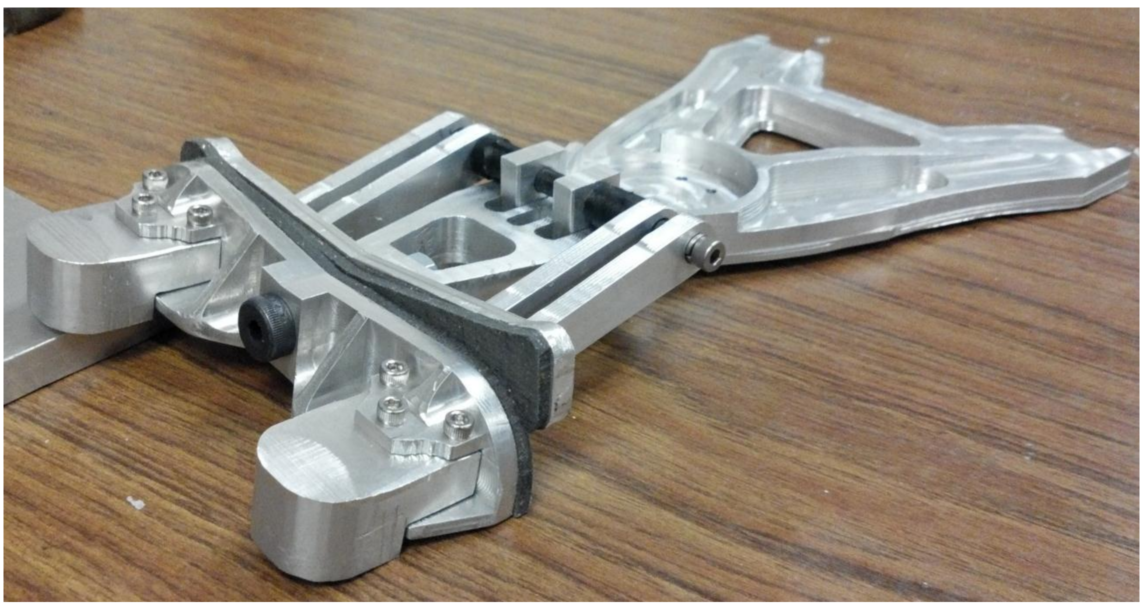


Figure 43. Semi-Final manufactured foot.

As can be seen above, this design accounts for ground contact by allowing the front toes to rotate, and it locks via the sum of the forces on these toes causing rotation about the locking axis.

Future Design Concept

Our final design was very successful; however our team always seeks improvement. The our future design concept resolves a few potential issues with the final design concept. The interface slot that joins the brake plate mount and the brake plate requires additional strength to ensure that it preforms reliably with its dynamic load. The slot was made much thicker and longer to better support forces in the horizontal axis perpendicular to the rotational axis. The flat sole of the final design could make contact in the middle of the foot instead of the rear of the foot. This contact would create a less stable platform and potentially cause the position of the foot to slip when the robot shifts its weight. Ou future design concept uses thin slanted members to reduce the potential for interference. The brake plate could come into contact with the ground instead of the rotational plate, given certain floor curvatures. To address this potential issue our team designed toes that mounted to the bottom of the rotational plate and provided additional clearance. The existing sole of the foot requires an a large amount of time and material to manufacture due to the amount of material that needs to be removed around the vertical mounts for the two force members. A more efficient way to design the sole breaks the sole into three easier to manufacture pieces. The proposed future design is shown below, our team plans to manufacture this part during the exam period.

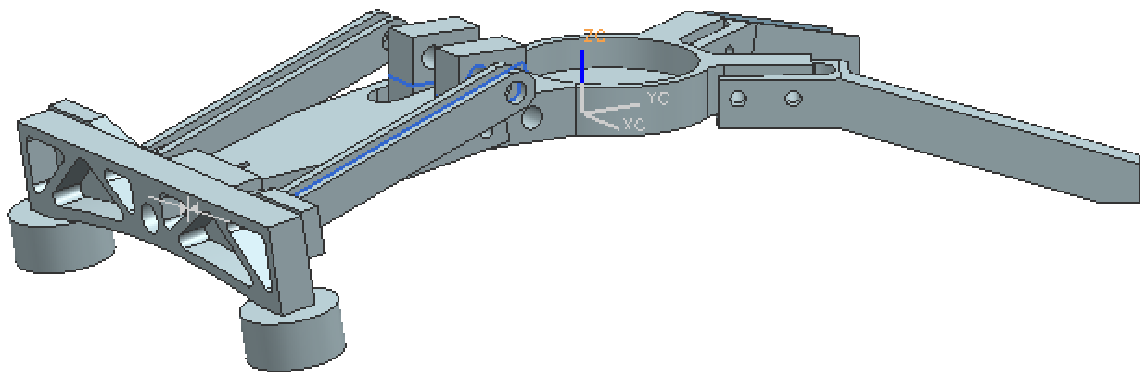


Figure 44. Finalized design concept.

As seen above, is a nearly finished final design concept. This concept sacrifices the low profile of the previous concept, for the ability to properly span the variation in the floor. As well, it has increased the size of several interfaces for robustness and ease of manufacture.

Conclusion and Future Recommendations

Over the duration of the spring semester, the foot team managed to deliver a functional foot for SAFFiR that met all of our customer needs and exceeded expectations. The team worked together fairly well to manage work load and develop ideas. For future work on the foot, the team has the following recommendations in addition to the proposed next revision. First, allow more time for manufacturing when dealing with more complicated parts. Though this may sound simple, when manufacturing difficult parts there are many areas to make mistakes so plan ahead for them to happen. Also, look more into weight reduction because there are areas where material is unnecessary where the foot could shed some grams. Finally, strive to keep the foot passively actuated to that it can be mounted on future robots with little to worry about with interfacing.

Conclusion

The nine members of the SAFFiR senior design team have put in a great effort this year. As the focus of this paper has shown the actuator and foot teams have completed two great products. This compounds the success seen by the gantry and covers teams last semester.

The best way to describe our projects role in the SAFFiR Project is to relate it to the role an engineering consulting firm would have. The graduate students and Dr. Dennis Hong realized that they lacked sufficient resources to complete the design challenges on hand. In order to remedy this situation the senior design team was formed. From the beginning of the year, when the team was presented with our initial design challenges, we assumed full ownership of the projects. The graduate students functioned as a customer would throughout the design process providing the funding and feedback necessary to deliver the desired product by the specified deadline.

The design process has been used throughout the year to help uncover the most effective solutions for the four challenges we were presented with. From project planning and brainstorming to concept refinement each step helped to further develop our design ideas.

The team is excited to have delivered both a Gantry and set of covers to the graduate students and happy that they are being used during the testing stages of the SAFFiR project. Additionally the team is excited that this semesters projects ended so well. The foot is a great platform that conforms to uneven terrain while providing a stable walking platform. The actuator has successfully enclosed the ball screw and incorporated a second motor and tensioning system into the actuator design. These products are with minor modifications ready for implementation in to the main SAFFiR project. Details of these minor modifications are made clear in each teams respective sections.

The team as a whole has learned an incredible amount this semester and has on the whole done a great job at working together. When looking back on the first several meetings team it is shocking to see how much we have improved. Not only in our ability to solve complex challenges but also in our ability to work effectively as a team. From the feedback we have received so far we are glad to be delivering four effective products to the graduate students and hope that they are effective solutions to the design challenges that we were presented with.