SAFFiR Final Report

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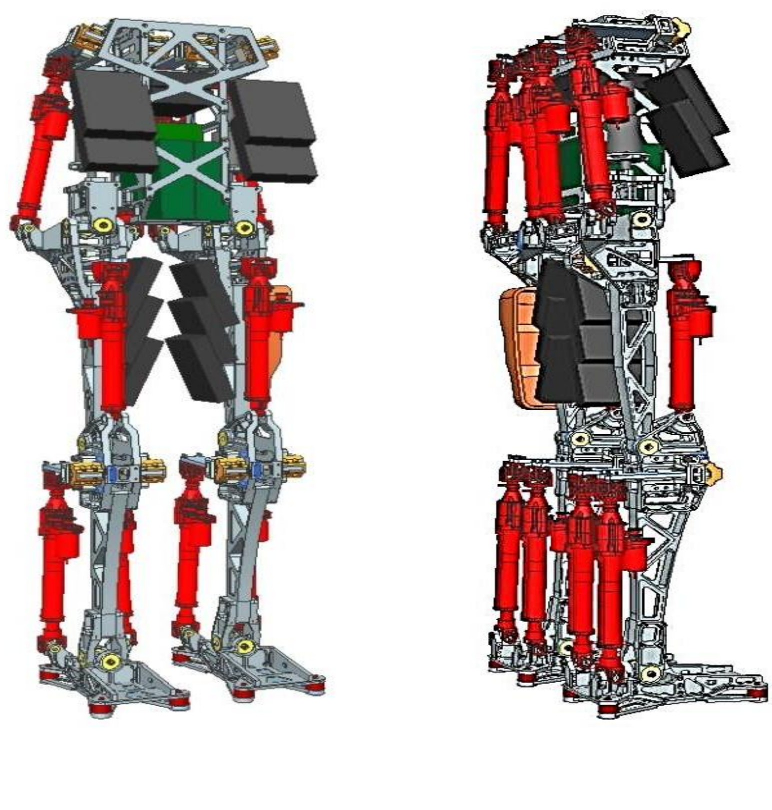

Executive Summary

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. More information detailing the background of this project is included in the “Background and Competitive Benchmarking” section of this report. 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 first two tasks of the senior design team are the development of external covers for SAFFiR’s joints and manufacturing a gantry to support SAFFiR during testing. The external covers need to protect the pinch points around the joints to keep the robot safe, and they need to aesthetically define and characterize SAFFiR, without inhibiting the movement of the robot. The gantry must prevent the prototypes from being damaged in the case of a fall while testing and should provide a way to suspend the robot for regular maintenance. More information concerning the requirements of the covers and gantry are included in the “Mission Statement and Team Composition” section of this report.

Both the covers and the gantry team have now generated and selected a final concept, completed manufacturing, and begun testing. The gantry and covers are have both been successful at meeting the customer’s deadlines. Now that the first tasks of concept design, selection, and manufacture are complete the team will be refocusing their efforts on new projects that will require the design process to start over. These new projects include a new design of the robot foot appendage and also a redesign of the current linear actuators for an increase in output force. The foot appendage design team will be an important design that will directly affect the walking dynamics of the robot. The linear actuator project is also critical in that the robot will eventually need to be strong enough to handle the payload to carry a fire suppressant. These new projects will be detailed in the “Plan for Spring Semester” section.

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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. This design team is tasked with designing, fabricating, and building a gantry that will prevent SAFFiR from sustaining damage due to accidental falls or trips during testing. This gantry should be easily adaptable to support future projects and not just SAFFiR. It also needs to be easy to assemble and disassemble, and small enough to pack into Pelican™ cases to be shipped to demonstrations across the globe. The gantry must not impede SAFFiR's walking motion or obscure an observer's view of the robot during testing. As an additional feature, it will also need to hoist and support SAFFiR off the ground so that its legs are easily accessible for maintenance and quick modifications without requiring a separate work bench. Several designs were considered, and by using the formal design process, the team designed a gantry with two A-frames joined at their points by a cross member. The cross member will implement two elastomeric die springs to absorb the impact and shock of a fall.

Personnel safety is a very important aspect of this project. Because students will frequently work on the fully assembled SAFFiR, all pinch points need to be covered to protect them from harm. A separate subteam was created to accomplish this task. In addition to providing safety, this subteam will be responsible for the overall aesthetics of the robot. They considered several design themes and agreed to follow the sapphire gem theme. This cover design focuses on recreating edges and angles that mimic facets of precious stones. These covers will be designed to both create an iconic look for SAFFiR and enclose pinch points. Additionally, all covers must mount to the existing frame and not inhibit or restrict any walking motion. The subteam decided that they will manufacture the covers by vacuum forming plastic, which will allow a smooth and polished surface while accommodating the desired contours of the facets.

The following sections of this report will further detail the project. The "Background and Competitive Benchmarking" section explains the purpose of this project and its advancement over the last year. The details of team objectives, leadership, management, and structure are included in the "Mission Statement and Team Organization" section. Following that, "Customer needs and Engineering Characteristics" identifies the customers of the project, their needs, and the derived target specifications. How the team will solve the problem is discussed at a low level in the "Work plan and schedule" section. "Conceptual Design Results" details the applied formal design process and presents many of the initial design concepts. Finally, "Conclusion and Future Work" provides a brief project over view and analysis of future work.

Background and Competitive Benchmarking

The SAFFiR Senior Design team focuses primarily on engineering solutions that support the needs of the SAFFiR project and the RoMeLa graduate students. SAFFiR (Shipboard Autonomous Fire Fighting Robot) is being designed and developed to autonomously navigate naval vessels and extinguish fires during an emergency to reduce ship damage. SAFFiR will be able to withstand the hazardous environment of a shipboard fire and work with human firefighters to extinguish the fire. This task is very difficult considering the constantly moving platform of a ship and the many human interfaces across Navy vessels. SAFFiR's humanoid approach will help it to address these issues as well as making it very adaptable to future applications. Right now the project has a complete leg and hip assembly. This milestone of the SAFFiR project will be demonstrated to the U.S. Navy on November 15th 2011.

Passive dynamic bipedal robotics is a new field of research. Passive dynamic walking is a type of robot control scheme based around the inverted pendulum model, and mimics natural human walking techniques. This control scheme involves the robot pivoting on a stance leg and falling forward onto the next leg; the robot falls forward and catches itself. This same continuously falling control scheme is what makes human walking so efficient. This area has not been previously fully developed due to the added complexity of controlling such a walking paradigm. Last year the senior design team working with this branch of RoMeLa created two working prototype robots to study the implications of such walking schemes. The first robot was SAFFiR 0.0 and this robot was designed to study the implications of passive dynamic walking. The second robot built was SAFFiR 0.5, this robot was designed to study the implications of series elastic actuator assemblies in passive dynamic walking. These assemblies place a compliant member in series with a linear actuator to mimic human muscles. The actuator provides an output force similar to a muscle, and the compliant member receives that force and transmits the force to the skeleton of the robot. The compliant member is designed to flex as a force is applied to it. This flexural strain can be measured and calibrated to the force output of the actuator. The force output of the actuator can then be used to create a force control scheme for the robot as opposed to the usual position control scheme. Force control schemes are similar to what humans use to walk. Creating such an actuator assembly is time consuming and expensive, necessitating the need for a safe testing environment utilizing covers for the robot and a testing support gantry.

Gantries from other robotics projects and industrial applications inspired some of the team's designs. The covers from earlier robots produced by RoMeLa stimulated the cover designs for SAFFiR. The covers on CHARLI do a good job of balancing the task of covering pinch points and having a unique look. That became a goal of the members of the Senior Design team. In order to get some ideas for unique covers, the team turned to characters such as Ironman and Robocop. These fictitious characters had a unique appearance that defined and identified them. The senior design team wanted SAFFiR's covers to have the same effect. With the completion of the gantry and covers, the Senior Design will have successfully completed its tasks in support of the RoMeLa team for their November 15th demonstration with the U.S. Navy.

Mission Statement and Team Composition

The goal of the undergraduate students is to aid the RoMeLa graduate students in the design and rapid prototyping of SAFFIR. This includes but is not limited to the design of support systems, external covers, and some of the appendage design. The undergraduate team has taken these projects and divided them into two major projects, the gantry, and the external covers, as seen in the following subsections. Early in the design process the undergraduate team developed a leadership system to help the coordination of tasks. The entire design team used a democratic system to vote on the leadership system that would lead the team through the tasks required. The system includes a single group leader who coordinates closely with the graduate students and professors to schedule milestones, coordinate tasks, and organize assignments. Under the group leader are the two team leaders. One team leader coordinates the tasks of the gantry team while the other team leader coordinates the tasks of the cover team. Manufacturing is organized and scheduled by our manufacturing lead. This individual helps coordinate with other RoMeLa members and team to guarantee efficient use of milling time and avoid conflicts. The team also has a scribe to provide reminders of upcoming milestones/ meetings and document the minutes of each meeting. 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 the gantry and external covers as described in the following subsections.

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 subteams are responsible for meeting as necessary to accomplish their deadlines.

Gantry

The SAFFiR Gantry will be a system that provides support to the robot during the testing and refinement steps of the design process. This system will consistently catch and support a robot before it can be damaged in the event of a fall or system failure. The Gantry will also be capable of raising the robot off the ground for storage and maintenance. This Gantry will serve as the structure by which the RoMeLa team will support the SAFFIR robot as they show its capabilities around the world. The Gantry will be designed for easy assembly and disassembly so it can be packed and moved with ease as the team travels.

External Covers

The goal of the external cover design team is to design covers for the external pinch points. Also, this team will be responsible for the aesthetic design and style that defines and characterizes SAFFIR. The aesthetic theme of the robot will follow it throughout its career. Just as the look and style of the CHARLI robot from the RoMeLa lab has its unique style the SAFFIR robot will be easily recognized. With this recognition the signature cover design will be the visually defining aspect of what will be one of the most technologically advanced, humanoid robots.

Customer Needs and Product Specifications

This section describes the customer needs and target specifications of the SAFFiR project. The first subsection 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. The second subsection defines the engineering characteristics and target specifications of the project. Connections between customer needs and engineering characteristics are identified, as is the importance of each target specification. Target design value ranges also included for each metric.

Identification of Customer Needs

Because the gantry and covers are safety structures that will be used to test SAFFiR prototypes, their 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 not a direct customer as they are only interested in the development of a bipedal autonomous robot, not the support structures used in testing.

The RoMeLa team is interested in gantry and covers solutions because they will provide a necessary platform for stable testing of SAFFiR prototypes. By preventing damage from the shock and/or impact of a potential fall, the gantry and covers will protect the time and monetary investments in developing each prototype. The gantry solution will also serve as a portable platform for demonstrations outside the lab, operable with minimal man power. The covers will also protect those who maintain the robot by covering pinch points, as well as visually define SAFFiR and characterize its style.

The RoMeLa graduate students 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 Tables A1 and A2.

The interpreted needs were then organized into a hierarchical list. This list identifies primary needs, characterized by a set of secondary needs. The primary needs represent our customer's most general needs, and identify important aspects that hold high priority. The secondary needs express these primary needs in greater detail and are individually ranked by importance. This hierarchical list of needs and importance is included as Figures A1 and A2.

Product Specifications

The customer needs were then translated to a set of precise, measurable specifications and metrics. The idea is that meeting these specifications will lead to satisfaction of the associated customer needs. Metrics were assigned by contemplating each need in turn and considering what precise, measurable characteristic of the product reflects the degree to which the product satisfies the need. Each metric was then assigned a marginal and ideal value based upon physical estimations and preliminary calculations. The importance of each metric is simply the average of those from the corresponding needs, rounded up. This information is tabulated below in Table 1.

Table 1. List of metrics for the SAFFiR gantry and marginal/ ideal values. The relative importance of each metric and the units for the metric are also shown. The marginal and ideal values for each metric are based upon physical estimations and preliminary calculations. The importance of each metric is simply the average of those from the corresponding needs, rounded to the nearest integer.

Metric No.	Need Nos.	Metric	Importance	Units	Marginal Value	Ideal Value
1	1, 4	Maximum supporting force provided by the gantry	5	kN	> 2.5	> 3
2	2	Support stiffness during fall	5	kN/m	> 150	> 200
3	3	Maximum support structure displacement	5	m	< 0.35	< 0.2
4	5	Time to assemble	4	minutes	< 30	< 15
5	6	Length of longest part	2	m	< 1.2	< 0.9
6	7	Total gantry weight	3	kg	< 14	< 9
7	8, 9, 11	Open space surrounding prototype	3	m^2	> 0.75	> 1.1
8	10	Modifiable height	2	m	> 0.6	> 1
9	12	Force to move gantry	4	N	<100	<75
10	13	Hoisting force	3	N	< 200	< 150
11	14	Minimum area from profile perspective	3	m^2	< 3	< 2
12	15, 16, 17	Aesthetic attractiveness	3	1 to 10	> 6	> 8
13	18	Thinnest width/ diameter	4	mm	> 50	> 75
14	19	Maximum part machine time	2	hours	< 12	< 8
15	20	Blank dimensions	1	m^2	< 1.2	< 1

Table 2. List of metrics for the SAFFiR covers and marginal/ ideal values. The relative importance of each metric and the units for the metric are also shown. The marginal and ideal values for each metric are based upon physical estimations and preliminary calculations. The importance of each metric is simply the average of those from the corresponding needs, rounded up.

Metric No.	Need Nos.	Metric	Importance	Units	Marginal Value	Ideal Value
1	1, 4	Safe operator control and capture of robot	5	injuries/test	< 1	0
2	6	Protect internal components	3	replaced parts/test	<2	0
3	5	Transparent covers	2	# parts/view	> 28	100
4	18,19	Time to assemble	3	minutes	< 30	< 15
5	8	Robot range of motion	5	%	>99	100
6	16,19	Total cover weight	3	lbm	< 4	<1.5
7	9,15	Aesthetic attractiveness	5	1 to 10	>7	10
8	16	Maximum part machine time	3	hours	<24	<12

Work Plan and Schedule

The SAFFIR project has rigorous deadlines established by the U.S. Navy. Because of this, the undergraduate team must be prepared to support initial testing by October 21st. This deadline leaves time to refine the gantry and covers by the November 15th U.S. Navy demonstration. In order to be prepared for that crucial milestone, the senior design team has developed a strict and detailed schedule to organize development and manufacturing of the SAFFiR gantry and covers. These two tasks will be detailed thoroughly in the following sections. After those initial tasks are completed, the senior design team has a lot of freedom in choosing the next set of tasks for this semester. Opportunities include redesigning the foot to implement magnetic latching, refining the articulation of SAFFiR's hands, refining the covers and designing additional ones, and reevaluating the controls system used for the current walking algorithm.

There are a plethora of resources available to the senior design team under the umbrella of RoMeLa. To begin we have the 9 members of the senior design team. Each member brings their own unique background and experiences to the group creating a diverse setting in which to generate and test ideas. In addition we have the assistance of two graduate advisors charged with the task of supervising the design team. They provide valuable instruction, advice, and directions on how to best design and manufacture our generated concepts. Perhaps the most valuable resource is the RoMeLa machine shop. This includes two milling machines, vacuum former, laser cutter, drill press and a variety of other, more typical manufacturing tools. We also have the PACE CAD laboratory, where we perform the majority of our CAD and CAM work. Other resources include U.S. Navy financial funding, a volunteer electrical engineer, two past members, two Industrial design volunteers, and the SAFFiR prototypes of the previous senior design team. Implementation of these resources will vary from project to project but all are incredibly valuable. The nine members have been divided into two sub-teams and each use the additional resources listed as they deem fit.

The Gantt chart for the SAFFIR team, included below as

Figure 1, shows the different tasks of the design project as well as due dates of each task. The chart also has a vertical status line that shows the current progress. The black line inside each task represents the percentage completion of that task. The SAFFIR project is broken down into two projects, one consists of making the cover of the robot (hip, knee, calf and thigh parts), while the other consists of building a gantry to support the robot in case it falls down. The schedule highlights two important due dates by which each design phase must be completed. By October 25 the gantry team should have the project done and the cover team should have the Hip covered. Then, both teams will work on the second iteration of the covers. The team tries to follow the timeline set at the beginning of the project. Nevertheless, the dates in the timeline were established at the beginning of the project and are more estimated than precise. As the team moves forward the Gant Chart is updated and new tasks are added. Following are detailed descriptions of the schedule of and resources used by each sub-team.

Gantry Team

The gantry team is made of Sebastien Corner, David Henry, Sydnee Hammond, Daniel Moodie, and Earl Campaigne. This subteam uses the PACE CAD lab and RoMeLa's three axes CNC extensively to design and manufacture aluminum components.

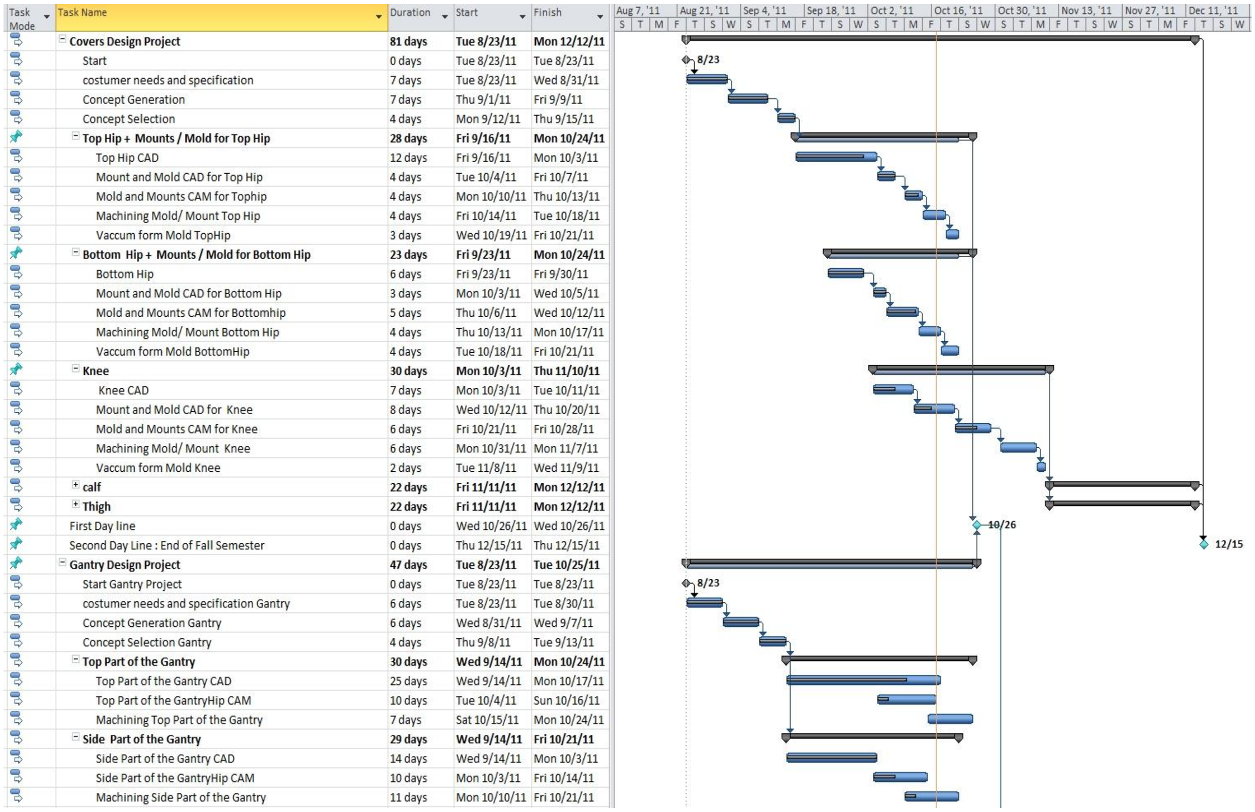
The side of the gantry was designed and made in CAD by October 3rd. The CAM was then prepared by October 17th. The top, supporting beam of the gantry was designed and made in CAD by October 16th and had complete CAM by the 17th. To meet the October 21st deadline, the team then has 4 days to machine the aluminum parts and assemble the gantry.

Covers Team

The covers team is made up of 4 members. Rick Lewis, Drew Hubbard, David Reeves, and Sam Howell. The PACE CAD lab is one of the most valuable resources available to the sub team. The PC's there are perfect for designing the covers in NX 7.0 and performing CAM for manufacture. The RoMeLa machine shop also provides the means by which to manufacture molds and vacuum form covers from the molds. Also two students from the Virginia Tech College of Architecture and Urban Studies have volunteered to help design the cover's appearance.

The covers team spent the first 2 weeks defining our needs for completion and initial design themes. On the week of August 29th through September 12th we began concept sketches and design. From September12th through 19th we confirmed the design and initial CAD of the upper hip design. From the Sept 26th through the 30th the CAD of the mold for the upper hip was completed and CAD for the

mounts of the upper hip were created. From Oct 3rd through 7th the CAM for the upper hip mold and mounts were completed along with designs for the lower hip. From Oct 10th through 25th manufacture of the top hip will be completed along with manufacture of top hip mounts. Also lower hip molds and mount CAD will be completed. In addition, design of the knee cover will be completed by Oct 21st. By Nov 10th manufacturing of the first iteration of covers and mounts will be completed.



Task Name	Duration	Start	Finish
Covers Design Project	**81 days**	**Tue 8/23/11**	**Mon 12/12/11**
Start	0 days	Tue 8/23/11	Tue 8/23/11
costumer needs and specification	7 days	Tue 8/23/11	Wed 8/31/11
Concept Generation	7 days	Thu 9/1/11	Fri 9/9/11
Concept Selection	4 days	Mon 9/12/11	Thu 9/15/11
Top Hip + Mounts / Mold for Top Hip	**28 days**	**Fri 9/16/11**	**Mon 10/24/11**
Top Hip CAD	12 days	Fri 9/16/11	Mon 10/3/11
Mount and Mold CAD for Top Hip	4 days	Tue 10/4/11	Fri 10/7/11
Mold and Mounts CAM for Tophip	4 days	Mon 10/10/11	Thu 10/13/11
Machining Mold/ Mount Top Hip	4 days	Fri 10/14/11	Tue 10/18/11
Vaccum form Mold TopHip	3 days	Wed 10/19/11	Fri 10/21/11
Bottom Hip + Mounts / Mold for Bottom Hip	**23 days**	**Fri 9/23/11**	**Mon 10/24/11**
Bottom Hip	6 days	Fri 9/23/11	Fri 9/30/11
Mount and Mold CAD for Bottom Hip	3 days	Mon 10/3/11	Wed 10/5/11
Mold and Mounts CAM for Bottomhip	5 days	Thu 10/6/11	Wed 10/12/11
Machining Mold/ Mount Bottom Hip	4 days	Thu 10/13/11	Mon 10/17/11
Vaccum form Mold BottomHip	4 days	Tue 10/18/11	Fri 10/21/11
Knee	**30 days**	**Mon 10/3/11**	**Thu 11/10/11**
Knee CAD	7 days	Mon 10/3/11	Tue 10/11/11
Mount and Mold CAD for Knee	8 days	Wed 10/12/11	Thu 10/20/11
Mold and Mounts CAM for Knee	6 days	Fri 10/21/11	Fri 10/28/11
Machining Mold/ Mount Knee	6 days	Mon 10/31/11	Mon 11/7/11
Vaccum form Mold Knee	2 days	Tue 11/8/11	Wed 11/9/11
calf	**22 days**	**Fri 11/11/11**	**Mon 12/12/11**
Thigh	**22 days**	**Fri 11/11/11**	**Mon 12/12/11**
First Day line	0 days	Wed 10/26/11	Wed 10/26/11
Second Day Line : End of Fall Semester	0 days	Thu 12/15/11	Thu 12/15/11
Gantry Design Project	**47 days**	**Tue 8/23/11**	**Tue 10/25/11**
Start Gantry Project	0 days	Tue 8/23/11	Tue 8/23/11
costumer needs and specification Gantry	6 days	Tue 8/23/11	Tue 8/30/11
Concept Generation Gantry	6 days	Wed 8/31/11	Wed 9/7/11
Concept Selection Gantry	4 days	Thu 9/8/11	Tue 9/13/11
Top Part of the Gantry	**30 days**	**Wed 9/14/11**	**Mon 10/24/11**
Top Part of the Gantry CAD	25 days	Wed 9/14/11	Mon 10/17/11
Top Part of the GantryHip CAM	10 days	Tue 10/4/11	Sun 10/16/11
Machining Top Part of the Gantry	7 days	Sat 10/15/11	Mon 10/24/11
Side Part of the Gantry	**29 days**	**Wed 9/14/11**	**Fri 10/21/11**
Side Part of the Gantry CAD	14 days	Wed 9/14/11	Mon 10/3/11
Side Part of the GantryHip CAM	10 days	Mon 10/3/11	Fri 10/14/11
Machining Side Part of the Gantry	11 days	Mon 10/10/11	Fri 10/21/11

Figure 1. Gantt chart of the SAFFiR senior design team. The different tasks with their deadlines are listed along the left. This is only the schedule for the Fall semester. The Spring schedule will be discussed in further detail later.

Concept Generation, Gantry

This section describes how the concepts were generated. It will begin by discussing the concept generation architecture used by our team. Next the exact process used to generate ideas as well as the ideas generated in a chronological order will be presented. Lastly the current concept being explored will be discussed, the pros and cons of it, and the challenges ahead.

Team Architecture.

For concept generation, our team split into two groups; one for designing the gantry system and one for designing the covers. Concept generation for each team was initially done through individual brainstorming. After the initial brainstorming, the team met for an initial design meeting and presented each idea. Each team member then built off each idea individually, generating more detailed concepts. Afterwards, a detailed design meeting took place where each member presented their more detailed design ideas. This meeting allowed for all the other members to provide their input and hash out any fundamental design flaws. The final design meeting allowed each member of the group to present their most promising design idea and determine the final design. Each individual utilized various design tools such as concept filtering and scoring matrices. This overall architecture was similar to the 6-3-5 method combined with many poster sessions.

Initial Design meeting

The gantry design team held a meeting after the initial brainstorming. The meeting started with clarification of the problem. Each member then presented what they had already brainstormed on our own, from this the team identified four different broad design categories to further investigate. These design categories were the following: Tent (Figure 2), uni-cycle (Figure 3basket (Figure 4), single support crane (Figure 5), double support crane (Figure 6). The tent design category relies on similar mechanics to a small camping tent; this category has several supporting members with anchors between the bases to prevent the members from splaying outwards. The basket design category consists of a rolling base with vertical posts. Between the posts would be netting that surrounds the robot, thus catching it upon falling. The uni-cycle design category consists of a roll-able platform with a protrusion that creates a catching mechanism below the robot. The single legged crane design category consists of a single supporting column that can rotate around a moving base. The last design category is the two legged crane. This category consists of two supporting columns on rolling bases, tethered to the robot via a cross brace. Upon leaving this meeting, we were assigned the task of external search and moderately detailed design. The goal of this assignment was to generate more concepts and hash out fundamental flaws in the ones already presented, for the following meeting.

Detailed Design Meeting

The second design meeting was held to hash out the details of feasibility and commence concept generation/ filtering. Since each concept was feasible, we wanted to look deeper into what would be required of each. At this meeting team members took turns presenting the potential challenges of each design concept from initial design meeting. The beginning of this meeting was an internal search and establishment of design feasible design boundaries.

Detailed Design Concepts

The arched tent design as seen in Figure 2 garnered a large amount of attention due to the potential simplicity, strength, and low weight. The arched tent design concept is currently in use due to the high strength to weight ratio. The RoMeLa graduate students recommended that carbon fiber tubing is very well suited for the gantry's design. Because of carbon fiber tubes possess limiting flexibility, two tent sub-categories were investigated: the jointed tent and the arched tent. The jointed tent design would alleviate the limitations of carbon fiber by using straight carbon fiber tubes between bent aluminum joints. This allows for the overall arched design while leveraging (injecting) the strength of carbon fiber tubes, seen in Figure 2. The arched tent concept would not necessarily use carbon fiber tubes. This concept would use many small poles that would combine together exactly like tent poles, seen in Figure 2. The arched tent concept would require small tubes that can bend as needed and still support the dynamic load of the robot falling. These tent designs would require a tensioning member to prevent the legs from spreading flat upon loading.

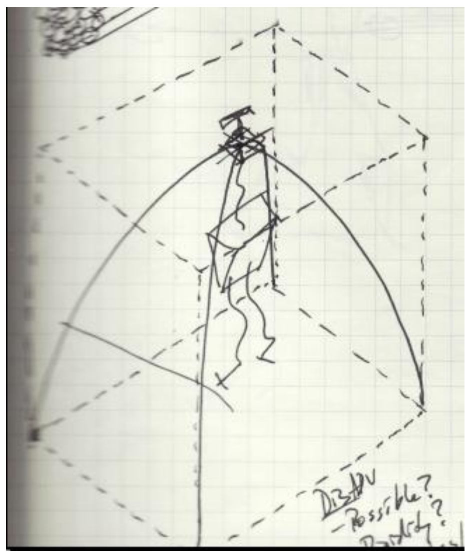


Figure 2. Arched tent design concept. Arched poles allow for large loads compared to structural size.

The uni-cycle design category, shown below in Figure 3, consists of the various designs that could support the robot from below. The initial design concept was a single wheel, pinned at the top joint with the robot. This would prevent the robot from fully falling over but would likely hinder the robots motion. The potential for hindering the robot necessitated the concept of an operator propelled hand cart that would be placed under the robot with a support and cradle system to catch the robot. This system would be less likely to hinder the robot, and more stable.

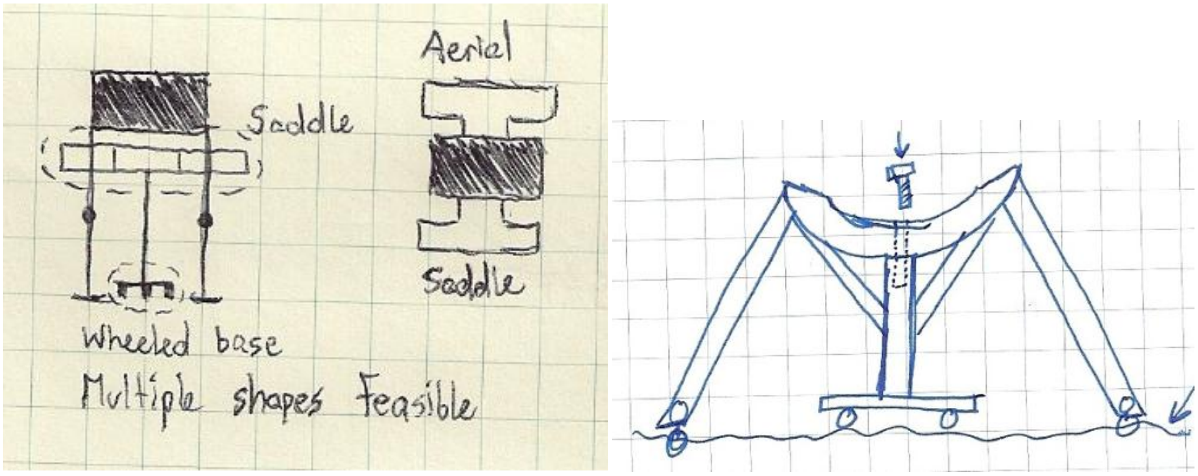


Figure 3. Example of the unicycle design. Both concepts would require an operator to push them and follow the robot's motion.

The basket design category consists of a rolling cage that surrounds the robot shown in Figure 4. This cage could be multi-tiered with railings with a continuous mesh that would catch the robot, much like the safety net on a trampoline.

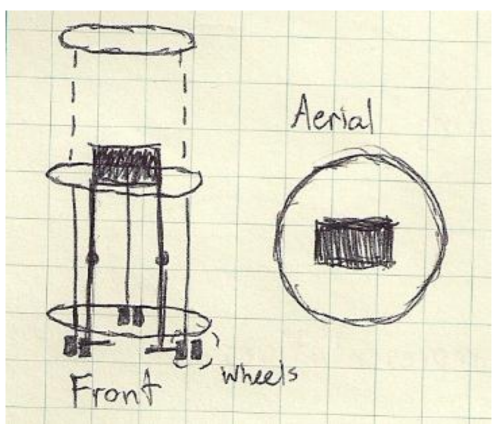


Figure 4. Example basket design. Basket would surround the robot with protective guards to prevent falls.

The single support crane system as shown in Figure 5 was initially inspired by hospital IV stands. This system would have a rolling base and a pivoting column. The top of the column would have an extension that would reach over the robot and a supporting cable down from the extension. This system had much promise due to its low profile and simplicity. The need to catch the robot upon falling means the system would have to be stable under a high dynamic load. To facilitate this, the system would require a large wheel base or a heavy weight at the base to increase stability.

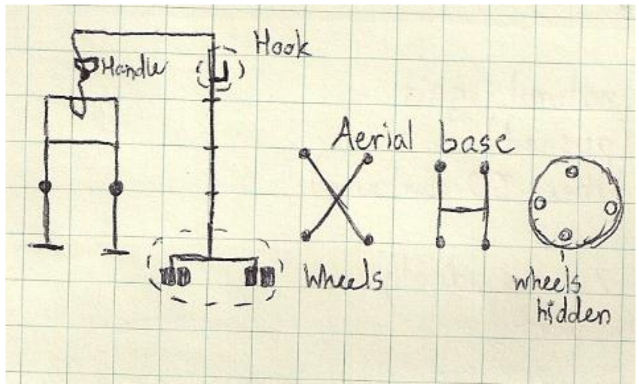


Figure 5. Example single support crane system design. Single base and support column rotate and roll to allow robot motion.

The double support crane shown in Figure 6 is most similar to large industrial cranes and gantries used today. This would give it the innate advantage of current widespread use and thus a large knowledge base for proper design. Conversely this removes from some of the appeal because it is so common and similar to what is used in many other robotics labs.

Figure 6. Double jointed support crane. This design is inspired by industrial cranes and gantries.

This design consists of two supporting legs on either side of the robot, with a single cross brace at the top. The legs would allow linear motion along the floor. The cross brace would create rigidity in between the two legs and a mounting point for attachment to the robot. This design is also very open and would not inhibit the view of the robot during a demonstration.

Gantry Concept Selection

This section describes the concept selection phase. Each different design has been discussed, and now it is time to explain the process in which we decide which design to follow through with. The previously mentioned designs were the Arched Tent, Jointed Tent, Unicycle, and Crane. These designs can be reviewed in the concept generation section. This section will go over what the team saw as an advantage and disadvantage to each design; then it will discuss the scoring criteria and the methodology behind it.

Scoring Criteria

The scoring criteria for the gantry design needed to reflect our customer needs. We determined that we would score each gantry concept on a scale of zero to five with regards to the following criteria: Support, modifiable, walk freely, pick up robot, coolness factor, visibility, safety, weight, manufacturing, and assembly. These criteria were chosen to reflect the engineering metrics associated with the customer needs presented. Each criteria was weighted on a scale of zero to five as well, to indicate the importance of that metric.

Each metric was carefully chosen and weighted to allow for the optimal final gantry design. The weighting system starts at zero and ends at five, thus determining the highest importance with five and lowest with zero. Any criteria that were determined to have a zero weighting were removed due to its null effect on the end result.

The criteria that were most important were given a weight of five, they consist of support, walk freely, coolness factor, visibility, and safety. Support describes how well the concept could catch the robot and prevent damaging of the robot in a time of failure, it is important since this is the purpose of the gantry. Walk freely describes how little force is transmitted to the robot through the gantry, since the purpose of the gantry is to prevent falls, we determined it would be necessary for the gantry to not cause any falls. The coolness factor of the concept describes how aesthetically pleasing the gantry is, and how it reflects RoMeLa as a whole, this was so we could be a good representation of the lab. Visibility describes the visibility of the robot while operating in the gantry; this is so the robot can be demonstrated without distraction. Safety describes how well the gantry will prevent the robot from injuring the user in the case of a failure, since an injured graduate student cannot repair a broken robot.

The criteria that were weighted second highest, were the ability to pick up the robot and the ability to manufacture the gantry; these were given a weight of four. A desired feature of our customer was the ability to pick up the robot through the natural support mechanisms in the gantry, thus one criterion is to pick up robot. The manufacturability of the gantry was of second level importance due to the need to finish the gantry in time for testing of the robot, a gantry that would be too hard to manufacture might not be made at all.

The third highest weighted criteria would be weighted with a three; these criteria were modifiable, and assembly. We were told that it was desired but not necessary to be able to accommodate robots larger than the current one, thus a feature to modify the height of the gantry was desired. The gantry needed to be assembled and disassembled at every demonstration, thus we created an assembly criterion.

The lowest criterion was given a weight of two. We determined that this criterion would be the weight of the gantry. We determined this would be least important due to all other criteria being essential for proper functionality of the gantry, whereas this would only determine what else could be packed with the gantry in a pelican case.

Concept Rating

This section will discuss how each of the designs were rated against one another.

The Crane design was determined to be the best gantry concept. We gave this design a four for support due to it definitely catching the robot upon a fall, but having the potential to fall forwards or backwards due to having a smaller base than the tented designs. The crane maxes out the modifiability rating due to only needing to replace two poles to change the height. This design also maxes out the walk freely category due to very little force being transmitted through a hanging tether. It would be very easy to pick up the robot with the crane, thus a score of five. The coolness factor of the crane is a high four due to carbon fiber construction, but not a maximum of five due to the similarity to other gantry designs. The visibility of the robot with this design would be high due to the wide width of the frame and large area around the robot that would be easily visible, thus a score of five. This design would put the user far enough away from the robot to receive a safety score of five. The weight of this design would become a factor due to the large structure needed to create such an apparatus as well as the rigidity needed to account for the square design, thus a three rating. The many right angles of this design as well as the extensive use of carbon fiber, give a high manufacturability rating of four. Lastly the assembly of this design would be moderate given the many different pieces to assemble, thus a rating of three.

The Arched Tent design was determined to be the second best gantry concept. We gave this design a three for support due to it definitely catching the robot upon a fall, but having the potential of the legs splaying or skewing. The arched tent would require a total redesign for different heights, thus a rating of one for modifiability. This design also maxes out the walk freely category due to very little force being transmitted through a hanging tether. It would be relatively easy to pick up the robot with the tent, given a hanging tether, the concern was securing the rope could be difficult, thus we gave it a four. The coolness factor of the arched tent is a high five due to carbon fiber construction, and its uniqueness from any other design. The visibility of the robot with this design would be lower than the crane due to having four legs, thus a score of three. This design would put the user far enough away from the robot to receive a safety score of five. We thought the weight of this design would be minimal due to tents being design for high strength to weight ratios, thus weight was given a five. The tent would be manufactured out of many small carbon fiber tubes, thus theoretically giving a high manufacturability rating of five. Lastly the assembly of this design would high due to the ease in aligning and setting up tent poles.

The Jointed Tent design was determined to be the third best gantry concept. We gave this design a five for support due to it definitely catching the robot upon a fall. The jointed tent would require a tube swap different heights, thus a rating of four for modifiability. This design also maxes out the walk freely category due to very little force being transmitted through a hanging tether. It would be relatively easy to pick up the robot with the jointed tent, given a hanging tether, it would likely be easier than the arched tent due to possible mounting points for rope tie-downs. The coolness factor of the jointed tent is a high five due to carbon fiber construction, and its uniqueness from any other design. The visibility of the robot with this design would be higher than the arched due to the joints moving the poles further away from the robot, thus a score of four. This design would put the user far enough away from the robot to receive a safety score of five. We thought the weight of this design would be higher due to joints adding weight to the tent concept, thus weight was given a five. The jointed tent would be harder to manufacture than the arched tent due to the need for joints and strange angles to be milled. Lastly the assembly of this design would be difficult due to the many joints and poles to keep track of.

The Unicycle design was determined to be the worst gantry concept. We gave this design a one for support due to it the likelihood of the robot falling off of the unicycle upon failure. The unicycle would potentially need a redesign to catch different types of robots, thus a rating of three for modifiability. This design also would likely hinder the robot while walking, thus it is given a one for walk freely. It would be relatively easy to pick up the robot with the unicycle, given a hydraulic jack type of mechanism. The coolness factor of the unicycle is a high four its uniqueness from any other design. The visibility of the robot with this design would be relatively low due to the close proximity to the robot, thus scoring a three. This design would put the user far enough away from the robot to receive a safety score of five. We thought the weight of this design would be low due to its small size, thus weight was given a five. The unicycle would be hard to manufacture due to the strange shapes needed to catch the robot properly. Lastly the assembly of this design would be difficult due to the many different pieces needed to create a large wheelbase, thus it would score a three.

Concept selection matrix

We took all of the different concept criteria and created a matrix of all of the scores along with weighted scores, the sum of the weighted scores determines the total score of a design. The highest total score determines the best design. This matrix can be seen in Table 3.

Table 3. Concept Selection Matrix. Compilation of scores and their associated weights.

		Tent Arched		Tent Jointed		Unicycle		Crane	
Selection Criteria	Weight (0-5)	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Support	5	3	15	5	25	1	5	4	20
Modifiable	3	1	3	4	12	3	9	5	15
Walk Freely	5	5	25	5	25	1	5	5	25
Pick up Robot	4	5	20	5	20	1	4	5	20
Coolness Factor	5	5	25	5	25	4	20	4	20
Visibility	5	3	15	4	20	3	15	5	25
Safety	5	5	25	5	25	5	25	5	25
Weight	2	5	10	3	6	5	10	3	6
Mfg.	4	5	20	3	12	3	12	4	16
Assembly	3	5	15	2	6	3	9	3	9
Total Score			**173**		**176**		**114**		**181**
Rank			2		3		4		1

Based on this concept selection matrix the team decided to pursue the detailed design and implementation of a crane style gantry. Detail design and testing will be discussed in depth in the following sections.

Detailed Design and Concept Refinement

To obtain maximum efficiency for the team, the project design was divided into small projects. Each member of the team was responsible for completing their individual tasks within the specified deadline. This section of this paper will present each different component and detail the constraints, initial design, challenges of the design and the final design of each section of the project. The completed assembly can be seen in Figure 7.

Figure 7. Final photos of the gantry. A rigid, balanced and light architectural design that is easy to store. The picture on the left shows the configuration of the gantry as it will be used with the robot while the photo on the right shows how the A frames can be twisted for storage against a wall.

The following sections will detail the process by which the individual components were created.

Gantry Joints

The gantry joints are the interfacing pieces between the different tube plugs. These joints allow for different angles to be used to create the overall shape of the legs of the gantry.

Constraints

We determined that these joints needed to fulfill the following constraints: Low weight, adjustable enough to compensate for tolerances at glued interfaces, rigidity at high loads, and modularity to allow for adjustments to the frame. We determined that since these parts would travel internationally, and that weight is always an issue due to airline fees, that weight reduction was essential, this helps satisfy constraint number 7. We found that our methods for cutting carbon fiber and gluing to the ends of carbon fiber tubes was insufficient to produce the accuracies we needed for creating a level gantry. Thus we determined that the design would have to allow for these tolerances, this is associated with constraint number 19. The rigidity of our system is essential in supporting our robot since the spring system depends on the support of the rest of the gantry. This necessitated there to be very little give in the joints. This requirement also has the added benefit of protecting the carbon fiber from excessive deformation. This constraint satisfies overall system constraints 2 and 4. Lastly, our customer expressed a desire to be able to adjust the height of the gantry for different robots in the future; in order to do this, interchangeability with the joints is essential, this satisfies constraint 10.

These joints needed to interface between the tube plugs for each different tube. These tube plugs had an identical interface for all tubes, thus the joints only needed to have one type of interface.

Initial Design Concepts

Our initial design concept for a joint was to mill a six or more sided shape out of aluminum in such a fashion as to allow for easy side operations. This would allow drilling and tapping, and thus subsequent threading of the tube plugs into the ends. This is seen in Figure 8, where the joint has a single through hole going down the middle of the part, and two blind holes at angles on the bottom.

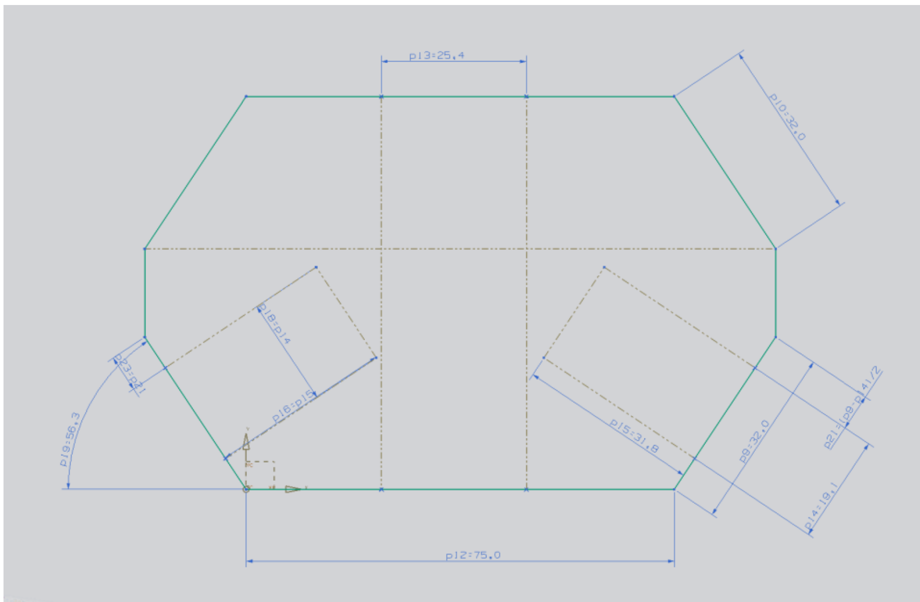


Figure 8: Example of the first revision of a 6 sided gantry joint.

The first revision design had some fundamental flaws to it. Such flaws include the ability to screw the legs of a triangle together. It is fundamentally impossible to assemble a triangle due to the fact that once two of the legs are assembled; the third would require two rotating members to attach to, which would be impossible.

Design Challenges.

The primary design challenge is creating a part that is easy to assemble. Our initial ideas included using pre-milled plugs and holes as locating devices for each part. This would allow for quick assembly without the need for a level to create a balanced assembly. Also since the clamping force is not essential, we only needed one bolt per joint and a locating pin to aid in force transmission. An example of this design is seen in Figure 9.

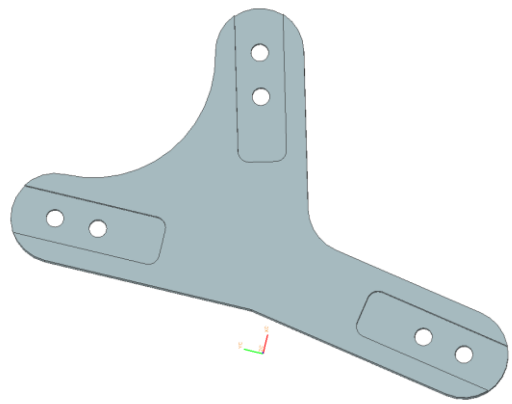


Figure 9. Second revision of a tube plug joint. Locating done by locating pins and bolts.

As can be seen, the overall shape of the joint defines the geometry of the gantry. Then the slots hold the tube plugs in place while transmitting force. The holes then lock the plugs into place and aid in force transmission. The issue with this design was the fact that each tube still had two bolts associated with it. It would be preferable to only have one bolt per tube or even better, one bolt per joint.

The third revision of the joint design brought the needed bolts per joint down to one by using pre-milled locating pins within the slots. This allowed for the locating pins to locate the tube plugs and transmit force properly. This design can be seen in Figure 10.

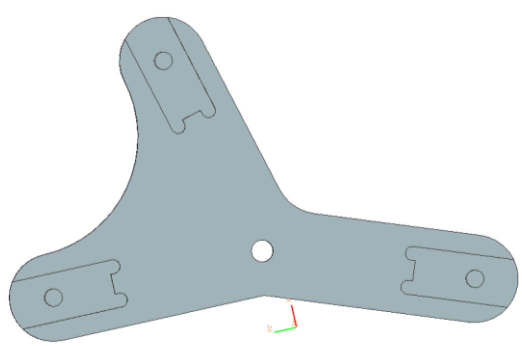


Figure 10. Third revision of the tube plug joint design. Pre-milled locating pins used.

The locating pins allow for easy and quick assembly of the gantry while securing the tube plugs in place. The fundamental issue with this design is the need for high tolerances when cutting and gluing the carbon fiber tubes. If the tubes were not cut to the correct length, it would be impossible to later fix that issue, and thus the gantry would be crooked. Another issue with this design is the need for aligning the tube plugs rotationally in the carbon fiber tubes while being glued. If these tube plugs were not aligned, the gantry would again be irreversibly crooked.

The aforementioned issued with revision three of the gantry joints, necessitated the fourth and final major revision to the joint design. This revision removes the square tube plugs previously used and replaces them with round plugs. These round plugs are then held with friction as the two halves of the joint are clamped together. This design iteration can be seen in Figure 11.

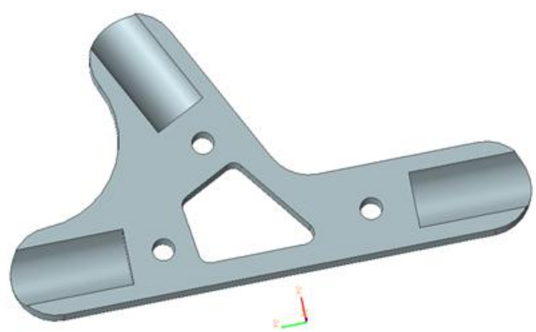


Figure 11: Semi-final design of the gantry tube plug joints. Rounded ends allow for rotational misalignment and deep slots allow adjustment to effective length.

Figure 11 shows the semifinal design of our gantry joints. This design vastly improves the flexibility of our tube plug manufacturing tolerances. Since the tube plug can be at any rotation within the joint, it is less necessary to align the plugs relative to each other, in the carbon fiber tube. The slot in the joint is now cut deeper, so if the carbon fiber tubes are too long or too short, we can adjust where the tube plugs sit in the slot to compensate.

Final Design

The final design takes all of the advantages of the design shown in Figure 11, while removing unnecessary weight and creating a more compact package. This design simply took the slotted portions of the joints, and brought them in to reduce the overall profile. This design can be seen in Figure 12.

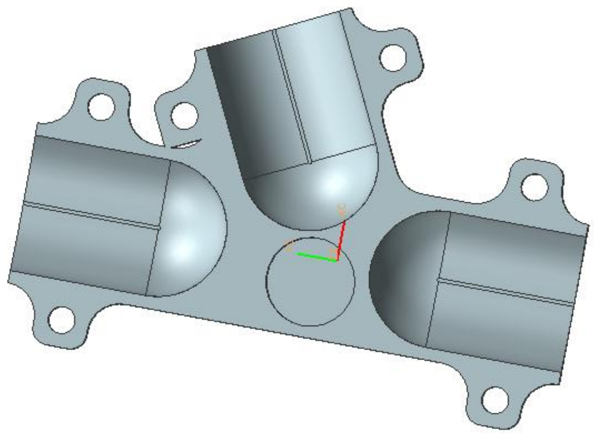


Figure 12. Final gantry mount design, reduced weight and profile.

The through holes are drilled to 5mm on one part, and tapped to 5mm on the mating part. This produces the clamping force needed for the assembly. The middle pocket is done for weight reduction, but further iterations increased the size of this pocket to reduce weight even further.

Future Recommendations

It is recommended to look into a clamping method that reduces the total number of bolts that need to be used. The current assembly is easy to assemble, but the task of completely removing all of the screws is rather bothersome. A method that could reduce the number of screws necessary would be appreciated.

Tube plugs

The tube plugs interface between the carbon fiber tubes and the joints of the gantry. The tube plugs prevent crushing of the carbon fiber tubes and in some cases provides the interface to other parts.

Constraints

This part interfaces between the carbon fiber tube and the joint. This piece prevents direct clamping onto the carbon fiber tube. Directly clamping onto the carbon fiber tubes runs the risk of crushing the tube due to over tightening. As well, the size of our carbon fiber tubes would require very large joints to properly clamp to the tube; this would increase the overall weight and size of the joints. These tube plugs step down the size of the carbon fiber tubes to something more manageable for the joints. Since the size of the carbon fiber tube is no longer coupled with the joints, it is as well possible to use different sized tubes interchangeably while using the same joints.

Initial Design Concepts

The tube plugs had two different design phases. The first phase was created a square ended plug that allowed interfacing with the square slotted joints. The second design was a change to allow for interfacing with the round slotted joints.

Final Design

The final design of the tube plug consisted of a round body, with round protrusion. This allowed interfacing with the inside of the carbon fiber tube, as well as, a method of being clamped by the joints. The inside of the tube plug is hollowed out to reduce the weight of the plugs. The final design can be seen in Figure 13.

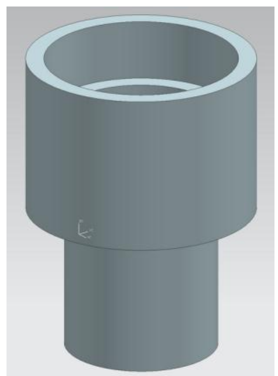


Figure 13. CAD model of the final tube plug design.

Future Recommendations

Given the current design and the requirements for the tube plug, it is difficult to see anything that should be changed. Possibly more weight reduction or reducing the overall size. But, since there are currently issues with glue de-bonding from the tube plugs, the overall internal surface area should remain the same.

Carbon Fiber Tubes

The carbon fiber tubes connect aluminum joints in order to form the frame of the gantry. They are designed to support the weight, bending and buckling of the weight of the robot.

Constraints and Manufacture

The most important constraint that influenced cutting the carbon fibers tubes was that they must be cut very precisely to ensure that both A frames are the same size. Each carbon fiber tube was cut to 50 cm and all of them were aligned at same level as shown in Figure 14. The three sections of the "A" sides, the top, middle and bottom, are each equal to 1/3 of the total height respectively. The top of the gantry consists of aligning two of these tubes to support the pulley and spring system at each part. We note that the team had design constrains such as the total height of the gantry that should not be over 2 m. Therefore the top vertical tube is shorter than the others, 47 cm which is the same for the horizontal tubes . To cut the carbon fiber tubes, a specialty tool was necessary so as to not damage the tubes and cut very quickly. Another constrain consisted on having the cross section of the tube flat. This was done by sanding the tube using a sand belt. This operation should be done slowly and smoothly to avoid removing too much material. Once cut, the tubes are glued with their respective plugs. The requirement of this process was to clean and to sand the interior of the tubes over 10 cm before gluing

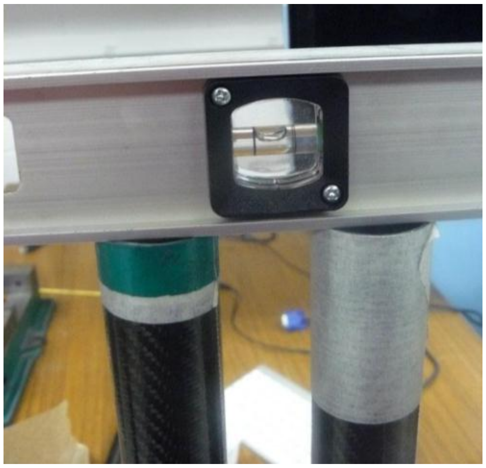


Figure 14. Photos cutting process for the carbon fiber tubes. All the tubes should be at the same level to ensure the symmetric balance of the overall design.

Final Design

When ordering carbon fiber tubes, it was critical to choose the right dimension of the tubes in order to prevent failure and increase safety (need 1 to need5). Therefore, the team conducted a stress analysis of the gantry and found the appropriate tubes that fulfill the safety and design requirements. The team chose a large factor of safety to ensure success of the product when testing.

Table 4 shows the results of stress calculations due compressive stress, bending stress and buckling.

Table 4. .Results of stress calculations from bending and buckling.

Material Properties				**Bending**		**Eccentric Buckling**	
ID (In)	Thickness (In)	OD (In)	Second Moment of Inertia (in^4)	Beam Deflection (in)	Max Bending Stress (PSI)	Max compressive stress at midspan (PSI)	Max compressive stress at base (PSI)
0.4	0.13	0.53	0.002615	16.36	8376.67	21402.78	11537.67
1	0.12	1.12	0.028138	1.52	8412.45	2089.88	9914.67
1.25	0.12	1.37	0.053054	0.81	8326.45	1464.33	9541.98
1.5	**0.12**	**1.62**	**0.089538**	**0.48**	**8268.01**	**1143.77**	**9288.75**
1.75	0.12	1.87	0.139799	0.31	8225.71	947.45	9105.47

2	0.12	2.12	0.206044	0.21	8193.68	813.27	8966.67

To prevent from buckling failure it is important to choose the correct inside and outside diameter of the tubes. The higher is the outside diameter and the thicker is the tube, the lower is the deflection from buckling. This is due to the second moment of inertia which is related to the diameters of the tubes. In addition, carbon fiber tubes have the remarkable function of being strong with a tensile modulus of 33 MSI and lightweight with a density of 0.065 lbs/in^3. Therefore, stress due to bending and compression were low compared to the limits of 230,000 psi. Thus, the team chose tubes with an inside and outside diameter of 1.5 in and 1.62 in respectively. These calculation were done using a load of 300 lb(4 times the weight of the robot). At this worst case scenario, the tube should flex a maximum of 0.48 inches, which is acceptable. We chose a load of 300 lb because that is the load induced by dropping 80 lb over 20 cm which is discussed in detail in the “Spring Assembly” detailed design section. The dynamic load is much higher than the static load, therefore, the team decided that it was judicious to determine the stress calculation using a load four times higher than the robot load. This corresponds to a factor of safety of four. Also, the spring system attached on the top of the gantry should absorb a large amount of energy from the robot load. So we assumed that the factor of safety is even higher than 4 in real test condition. A detailed explanation of the methods used for these calculations can be found in the design binder under the gantry resource folder.

Future Recommendations

Several safety measure must be taken when cutting carbon fiber tubes. While cut, carbon fiber tubes reject a lot of carbon dust, which is really unhealthy and dangerous. Exposure to this dust may cause cancer. Therefore, it was necessary to use a mask filter to remove all carbon particles when breathing. We also make use of personal protective equipment including gloves to protect the hand when cutting and sanding the tubes and protective glasses to protect eyes from any impact.

Gantry Caster Interfaces and Mating Plugs (“Feet”)

The gantry caster interfaces or “feet” are joints that attach casters to the four legs of the gantry A-frame. These four casters permit mobility and support the weight of the gantry. Accordingly, the feet are designed to transmit angled loads in the A-frame legs into vertical loads through the caster to the floor. First, this section details the design constraints for the feet: quick assembly, low weight, unrestricted mobility, and minimalistic profile. Second, the initial design concept is presented and analyzed. Third, the design challenges of the initial design are discussed. Fourth, the final design is described in relation to how it solves the design challenges. A final section provides future recommendations for designing and manufacturing the gantry caster interface and mating plugs.

Constraints

The design constraints for the gantry feet are derived from product specifications for the entire gantry assembly, included in Appendix A. We identified these product specifications by performing customer interviews and needs-metrics analyses. First, the gantry needs to allow for assembly and disassembly, each in less than 30 minutes (Appendix A, metric 4). The feet, therefore, need to attach and detach from the A-frame legs quickly. The casters should also attach and detach from the feet quickly. Second, the entire gantry must weigh less than 30 lbm. The feet should accordingly weigh as little as possible (metric 6). Third, the interface design must promote unrestricted gantry movement (metric 7). Because of this, the casters cannot be obstructed or restricted in any degree of freedom. Fourth, the feet should have a small profile. This means they should be aesthetically minimalistic, with a low visual profile (metrics 12,13). We interpreted this as meaning that the feet should be no thicker than the 1.5” outer diameter of the carbon fiber tubes. With these constraints identified, we created the initial foot design.

Initial Design Concepts

The gantry foot has to be designed around the caster it interfaces with. So we had to first select a caster that best meets our design constraints. We chose a stemmed, thread, polyurethane caster of a 3.5” diameter with a lock. Compared to casters with a plate attachment interface, stemmed casters allow for easy attachment as they require no screws/ bolts and occupy minimal surface area of a part face. Stem options included friction-grips, grip-necks, and expanding stems, but threaded stems were chosen for their familiarity in design, manufacturing, and operation. We chose casters with locks so the gantry can become a fixed structure. Polyurethane wheels were chosen because they work best on asphalt, linoleum, concrete and steel floors. We decided to use a 3.5” diameter wheel that supports up to 250 lbs to support the weight of the gantry and the additional load induced by SAFFiR falling.

Initially, the foot was an aluminum block approximately 45 x 45 x 20 mm weighing 0.23 kg, shown in Figure 15. It featured one tapped ½” hole for the caster stems and two 4mm through holes to bolt with the plugs of our carbon fiber tubes. During the time frame of this design, these plugs were the standard jointing strategy used throughout the gantry. Each plug possessed a squared edge with two tapped 4 mm holes.

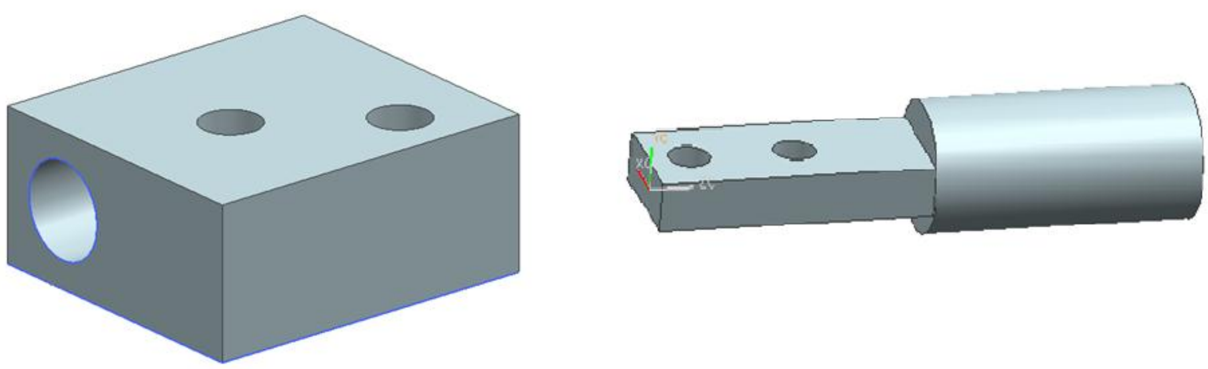


Figure 15. Initial design concept for the gantry caster interface and mating plug or “feet.” The block of aluminum is approximately 45 x 45 x 20 mm and weighs 0.23 kg. There is one tapped ½” hole for the caster stems and two 4 mm through holes to bolt with a plug. This design used the standard jointing strategy used throughout the gantry, squared carbon fiber tube plugs.

Design Revisions

Because of its simplicity, the initial foot design was easy to manufacture but not aesthetically pleasing. The feet looked like anchors on an otherwise minimalistic and elegant gantry. The feet were redesigned to have slimmer profile that fits within the diameter of the carbon fiber tubes, just like the redesign of the other gantry joints. This redesign also decreased the weight of the part tremendously. The design also had to be revised to accommodate a new standard jointing strategy for the gantry, round plugs instead of squared plugs.

Final Design

The final foot design uses the same caster detailed in the initial design section but is significantly smaller and lighter than in previous design. Where the original design weighed 0.23 kg, the final design weighs only 0.14 kg while the overall profile dimensions remained the same, 45 x 45 x 20 mm. However, the new shape includes a 64˚ angle such that the width and angle of the foot match and align with those of the 1.5” carbon fiber gantry legs. The same three holes are featured: one ½” tapped hole for a caster stem and two 4 mm holes to interface with the plug. This interface is recessed into the foot so that the plug can fit within the profile of the foot, appearing as a single part. The new interfacing plugs are made by modifying the cylindrical gantry plugs. A profile cut is required to square the protruding end. Two 4 mm holes also need to be drilled through the plug and tapped.

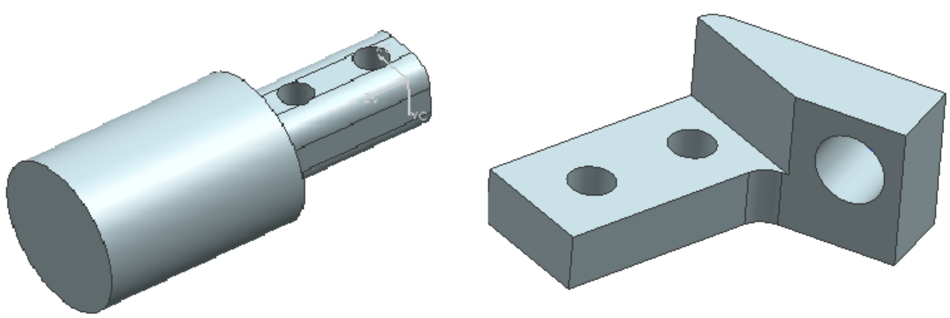


Figure 16. Final design of the gantry caster interface and mating plug or “feet.” The foot on the right has a rectangular profile approximately 45 x 45 x 20 mm and weighs 0.14 kg. The foot also has a 64˚ angle to match the angle of the gantry legs. There is one tapped ½” hole for the caster stems and two 4 mm through holes to bolt with a plug. This design uses interfacing plugs modified from the standard cylindrical plugs.

Figure 17. Manufactured feet interfacing a caster and carbon fiber leg of the gantry. One of four.

Future Recommendations

A future redesign of the gantry caster interface should include a lip along the interfacing edge. This lip would help ensure that there is no play between the interfacing parts, allowing for an even stiffer joint. This would help relax the need for tightly tolerance and concentric bolt holes shared by the caster interface and mating plugs. Otherwise, manufacturing and assembly of the gantry feet is easy and ideal.

To summarize, the gantry foot has evolved to accommodate a number of design constraints for the gantry: weight, maneuverability, assembly, and aesthetic appeal. The foot was initially designed as an aluminum block 45 x 45 x 20 mm for easy manufacturing with three holes, one ½" hole for the caster stem and two 4 mm holes for the plug interface. However, this design was aesthetically unpleasant and used excessive material. Design emphasis was switched to creating a minimalistic foot that continued the profile of the carbon fibers tubes for a more elegant look. The final design reduced the mass of each foot from 0.23 kg to 0.14 kg and included a 64˚ angle to align with the gantry legs and better compliment it visually. This redesign does require minor modifications to the standard cylindrical plugs for attachment. The plug profiles need to be flattened and two threaded 4 mm holes drilled. A future redesign should include a lip to ensure proper alignment of the caster interface and tube plugs. This would remove any chance for play between the parts due to low tolerance between the concentric holes.

Corner Braces (F-Block)

The main function of the corner brace is to connect the vertical components of the legs to the horizontal cross member. It also needed to mate with carbon fiber tubing in both directions and provide stiffness at the joint. The following sections will discuss the constraints that the blocks were designed around, concept generation, detail design, and future recommendations.

Constraints

One of the main constraints of the braces is that it needed to interface with both vertical and horizontal carbon fiber tubes. It also needed to be lightweight but stiff. This is where all of the bending induced by the load of SAFFiR would be translated down the legs, and a crucial location limited compliance. It also needed to follow the overall goal of being aesthetically pleasing. It had to accommodate a mechanism on which to secure the rope, which would also induce another load on the member. Since assembly time is also very important, it was necessary that this part be easy to assemble and not include too many components.

Initial Design Concepts

The first design to come out of sketches included a large rectangular block with holes cut into it in which to slide the carbon tubes. This design was bulky and would be very heavy and overbearing, and it was decided to permanently affix the tubes to the F block. To accomplish this, plugs would be machined on the side of the main body and the tubes would be epoxied to this surface which can be seen in Figure 18.

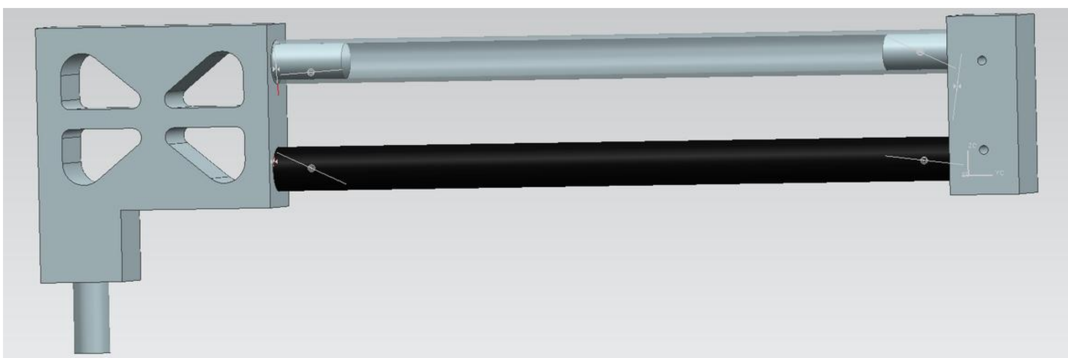


Figure 18. First CAD model of a design concept. This is very overdesigned and heavy, and would require machining on many faces and waste a significant amount of material.

This version would be very heavy and excessively large. It did not need to be that wide since the tubes were not going to slide inside of the aluminum. It would also waste a significant amount of material to but the plug on the bottom to slide

Design Challenges

One of the most challenging designs was the interface with the carbon tubes. As shown above, we went through several iterations before we chose a final way to make this connection. Weight was also a major issue. Since the part is solid aluminum it was originally very heavy. It took many machining sessions to reduce this weight. We eventually cut out pockets and recesses into the faces to reduce the overall weight of the part. We also hollowed out the plugs that the carbon glues on to. Machining was very difficult with a part this large. It was so thick that clamping and machining was hard to figure out how to accomplish, and was something we did not consider while designing.

Final Design

The final design of the corner brackets was only about 1.4 pounds each and can be seen below in Figure 19.

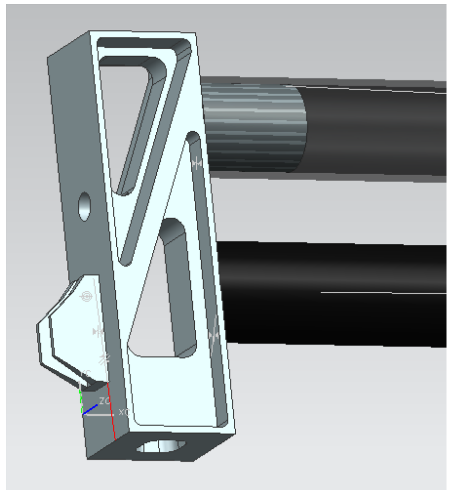


Figure 19. Final design of the top corner brackets. This includes recessed pockets for weight reductions, a clam cleat to secure the rope, plugs to provide stiffness to the carbon fibers tubes, and a through hole for the rope.

This low weight was accomplished with pockets cut all of the way through the front of the block, as well as recesses that followed this pocket that were 15 mm deep on both sides. The plugs had a 1.5” OD and were supposed to be 2” long. One of them is shorter due to a machining mishap. A ½” through hole is cut between the plugs for the rope to feed though. The rope would go out to a CL-222 clam cleat, which uses two M4 screws to attach to the back side of the component. This cleat is typically used in sailing applications, and holds the rope securely on the side of the bracket. The bottom of the block has a rectangular hole to accept a plug that is glued to the vertical carbon fiber tube. This rectangular pocket is 1/5” deep and limits the size and depth of the pockets on the other face.

Future Recommendations

One of the main things to more seriously consider during the design process is weight. It was not originally taken in to account which resulted in about 4 or 5 additional milling operations to reduce the overall weight. Both the through pockets and recesses could have been cut at the same time as the outside profile, the plugs could have been cut out when at that time as well. It would have also made a large difference to have a thinner part. The size was limited by the tube ID of 1.5” but we could have used smaller tubes or left less material on either side of the plugs. It would have also been beneficial to have changed the bottom plug design that connects to the legs. In order to twist the legs, the whole top has to be removed and clear the top of the plug. If these had a circular opening in which the rectangular plug could rotate, the top would not have to be pulled completely clear. This would mean that if it accidentally slipped out of someone’s hands it would fall back on to the plug and not fall to the ground. Most important would be to follow careful machining practice. Lack of tightening a crucial member of the mill resulted in a ½" roughing endmill plowing through one of the plugs which could have been avoided.

Spring Assembly

The spring assembly is the section of the gantry that connects both upper support members and absorbs shock from the robot during a fall. The system will need to be lightweight, attractively designed, and easy to use.

This section is going to describe the process of taking the spring assembly from design concept to manufactured product. The discussion will begin with identifying the constraints that pertain to this particular component of the gantry. Then talk about the process of transforming initial concepts into a final model. This will be followed by final recommendations for future revisions of this part.

Constraints

The spring assembly is a crucial component of the gantry that will needs to fulfill the gantry's customer needs. Need number 2, the gantry absorbs shock from falling, and need number 13, the gantry is capable of hoisting and supporting the robot, were the two main needs addressed with this component. In addition, the spring assembly system has to interface with the Pulley Side Mounts and have a method of attaching to the robot while maintaining enough slack to prevent interference with the robots motion. These constraints helped to define the problem that needed to be solved and helped to shape the design of the final concept through every revision.

Initial Concepts

The spring assembly's design evolved along with the other components of the gantry that it needed to interface with. The initial design concepts centered on trying to identify a method for shock absorption and a method for connecting to the rest of the gantry. One of the first designs discussed simply attached to the support members of upper cross beam. By iterating the design process, the spring assembly became a part of the upper support structure. It also incorporated a spring and pulley system to absorb the shock of impact. Figure 20 shows some of the intermediate steps taken to get from the initial concept to final idea.

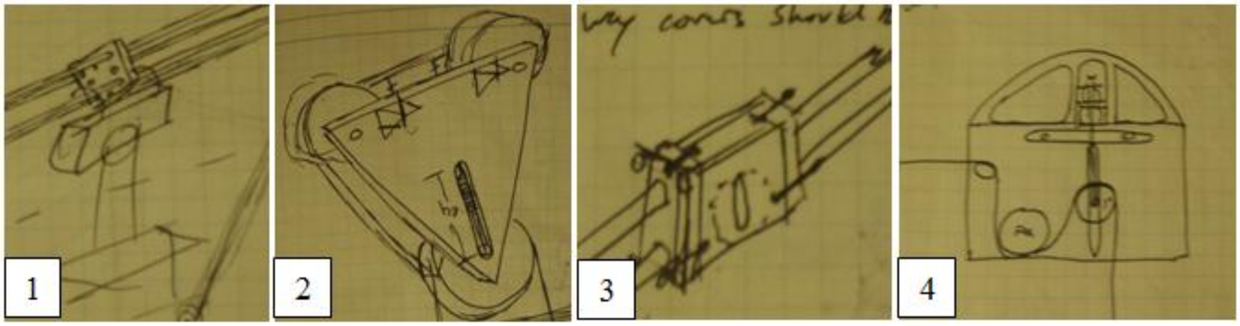


Figure 20. The iterative design process from initial concept to final idea. Item 1 shows the first design which would only function as a shock absorber and hook onto the frame. Item 2 incorporates an internal spring and pulley system that will support the robot. Item 3 places the spring assembly between the two support struts. Item 4 was one of the first sketches that captured the idea of the final concept.

The final sketch presented in Figure 20 still needed a lot of improvement but it presented a design that utilized compressive springs, integrated into the upper support assembly, and used a pulley system to transfer the load from the robot to the springs. The challenges that were presented by this design will be addressed in the next section.

Design Challenges

The challenges that surfaced during the design process of the spring assembly were tackled as they arose. They helped to shape the design of the spring assembly. Some of the larger ones which will be discussed in this section included spring selection, ease of assembly, and weight reduction.

Spring Selection.

In order to protect the robot during a fall, it was crucial that the shock absorption system be tuned to the expected loads. The robot weighs 35 kilograms and will be tethered by a line with 20 cm of slack. Two types of falls were considered for the analysis. The first is a worst case scenario where the full 35 kg of the robot falls 20 cm. The fall was modeled using the energy method and equation (1.1) was found to describe the peak dynamic force or force experienced at the bottom of the decompression zone.

$$F_{\max} = \frac{2mg\left(h_1 + h_2\right)}{h_2} \tag{0.1}$$

In this equation F_{max} stands for the peak dynamic load experienced at the bottom of the compression zone. The weight of the robot is expressed by mg. h_1 represents the distance the weight is in free fall and h_2 represents the decompression zone. Details on how this equation was determined can be found in David Henry's logbook on pages 29-30 and 62. Table 5, shown below, was used to identify possible springs that would fit our design criteria.

Table 5. Various Peak Dynamic Loads at varying decompression distances. An important design consideration is that by doubling the decompression distance the Peak Dynamic Load is almost cut in half.

h_2, decompression height (cm)	Fmax, Peak Dynamic Load (N)	K, Spring Constant (N/cm)
1.27	11566	9107
2.54	6128	2413
3.81	4316	1133
5.08	3409	671

A decompression distance of 3.81 centimeters was selected as the ideal distance to balance shock absorption and compact design. A type of rubber spring called an elastomeric die spring was identified that best fit our needs of high load and small compression distance in a compact package. The two different types of springs offered in this category are shown in Figure 21.

Figure 21. Elastomeric Die Springs. The picture on the left represents the heavy and medium loading design. The picture on the right represents the light loading design. One of each type is implemented in the final design to achieve a variable spring curve.

These springs also provided the solution to our second, milder loading situation. Here we considered the forces created when stopping a 35 kg 1 meter high pendulum from tipping with a 20 cm tether. It was identified that a shock absorption system that is designed for the worst case scenario may not be able to provide much shock absorption in a more typical situation. In order to account for this it was decided that a two spring system operating in series would be implemented. The first spring would provide the absorption for the mild loading cases the second would absorb the shock should the system be severely loaded. This system results in an overall spring curve that has two regions. As shown in Figure 22 these regions each have their own distinct spring constant.

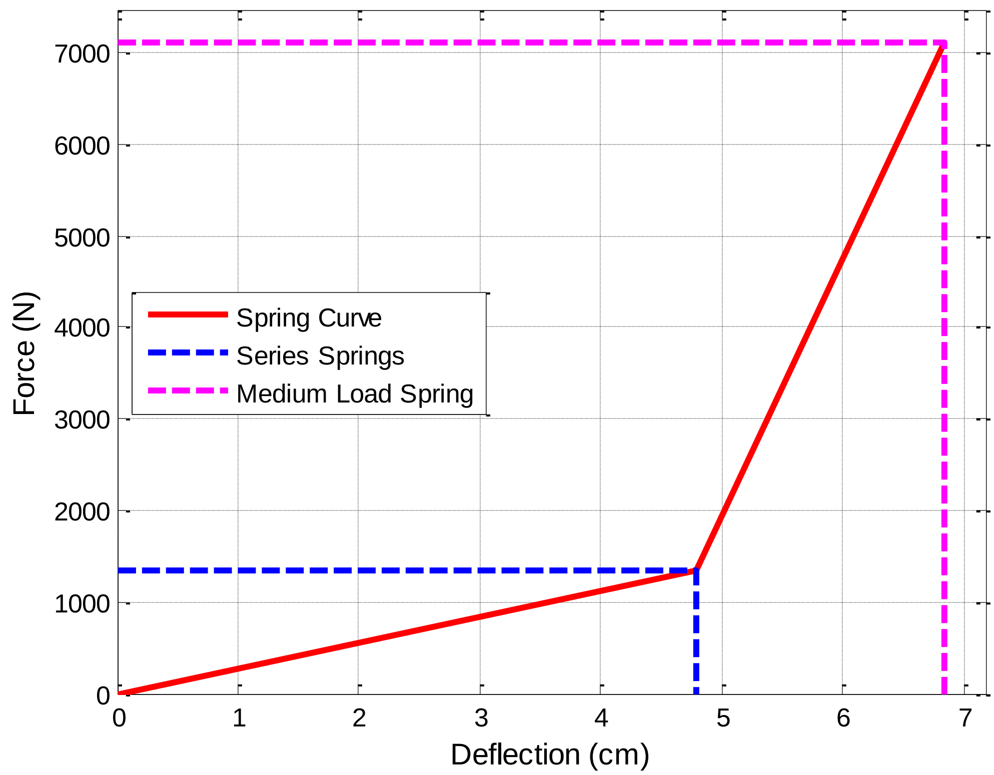


Figure 22. Spring Curve for the gantry's shock absorption system. The region identified by the blue dashed line represents where both springs are acting in series. The region identified by the pink dashed line represents where the light duty spring has been fully compressed and only the medium duty spring is absorbing load.

The spring constant for each region was determined by using the properties of the selected springs and a MatLab code that can be found in Appendix B. In region 1 both springs act in series until the maximum defection of the light duty spring is reached. At this point a stopper prevents the light duty spring from being overloaded and the heavy or medium duty spring takes any additional load. This code can be reiterated using any set of springs to better tune this curve to the expected loading situation. The final springs that were selected are shown in Table 6 along with the details of each compression region.

Table 6. Selected Spring Details. Also shown in this table are the region details that correspond to Figure 22. Note that the peak dynamic loads of each region are governed by their limiting springs but the spring constant and deflection are different in region 1 when the springs are acting in series.

McMaster Part Spring Type, Part Number	F_{max}, Peak Dynamic Load (N)	δ_{max}, Deflection max (cm)	K, Spring Constant (N/cm)
Light Duty, 9724K19	1334	4.3	309
Medium Duty, 9732K22	7117	2.5	2830
Region 1	1334	4.8	279
Region 2	7117	2.0	2830

The spring design was a challenge but the team was confident that the selected springs would be able to absorb the expected load for the gantry. It is possible that our estimations are on the high end and the selected springs will provide absorption for cases that exhibit loads 2000N higher than estimated. Because of this overdesign it may be beneficial for future teams to explore the spring selection further when more accurate loading information can be obtained. Despite our uncertainties in the calculations testing showed that both spring engage during a worst case loading scenario as planned.

Ease of Assembly

Another challenge presented by this design was meeting the required needs of the spring assembly with as few components as possible and packaging them in a way that makes assembly easy. The final idea that was developed had two pulleys, a rope guide, and several spacers that would make assembly of the final unit a complex operation. In order to simplify the design, the function of the second pulley and rope guide were incorporated into a component called the pulley side mount. This added to the complexity of machining the pulley side mount but removed three components from the assembly and got rid of the second pulley saving the team 40 dollars. The original sketch from which this idea sprang from is messy and complex but is depicted to indicate how these ideas come up through collaboration with teammates and iterative design and can be seen in Figure 23.

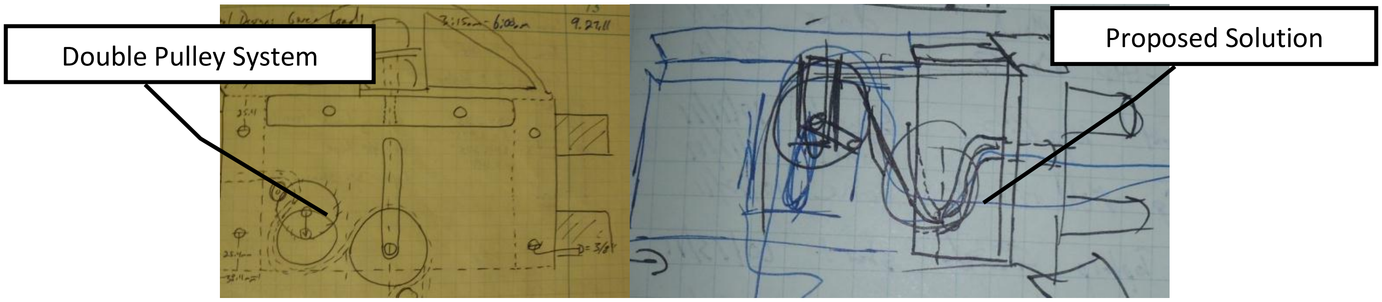


Figure 23. The initial concept drawing for incorporating the pulley and rope guide functions into the pulley side mount. On the left you can see the design that included two pulleys and the rope guide. The drawing on the right roughly shows how the rope can be guided with a machined slot in the pulley side mount.

The effects of this quick sketch can be seen in the final design and is a result of a single question posed by Derek Lahr during a meeting, “How are you going to assemble this?”. Many small modifications were made to the design throughout the month of concept development and detailed design. The continuous feedback and criticisms of the team members were what made these modifications possible. Even when their advice was not directly applicable it often sparked a thought that would lead to a meaningful design modification.

Weight Reduction

One of the more interesting aspects of this design was trying to make the spring assembly as light as possible. This process was very aesthetic in nature but also highly technical. When this issue was brought up it was also identified as a way to make the inner workings of the spring assembly visible. Following this design idea patterns were drawn around all the crucial components and as much material as could be safely removed was extruded out of the cad model. Figure 24 shows the initial concept sketch that lead to the final design.

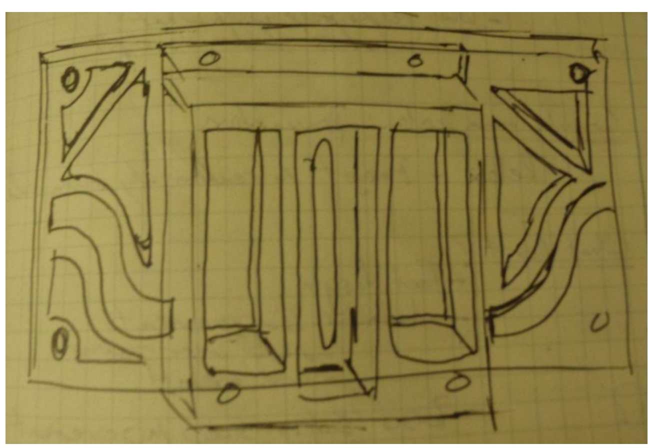


Figure 24. Weight Reduction Concept Generation. Note that most of the aluminum removed reflects the inner workings of the spring assembly.

This evolution in the design added greatly to the milling time of the part but also reduced the weight considerably. The change also brought up another concern. Would rope jams in all of the new open space become a problem? To solve this issue each pocket that had a moving component near it had a slightly larger pocket recessed into the part. This allowed for plastic inserts, made on the laser cutter, to be placed into each pocket. These components minimally increased the weight and prevented possible rope jams and also stop operators from accidentally putting their fingers in dangerous locations during handling.

Final Design

The final design of the spring assembly is one of the more complex parts on the gantry. It accomplished the required customer needs and is also lightweight and integral to the structural integrity of the gantry. Figure 25 shows a series of pictures that should provide all the necessary detail for understanding this section.

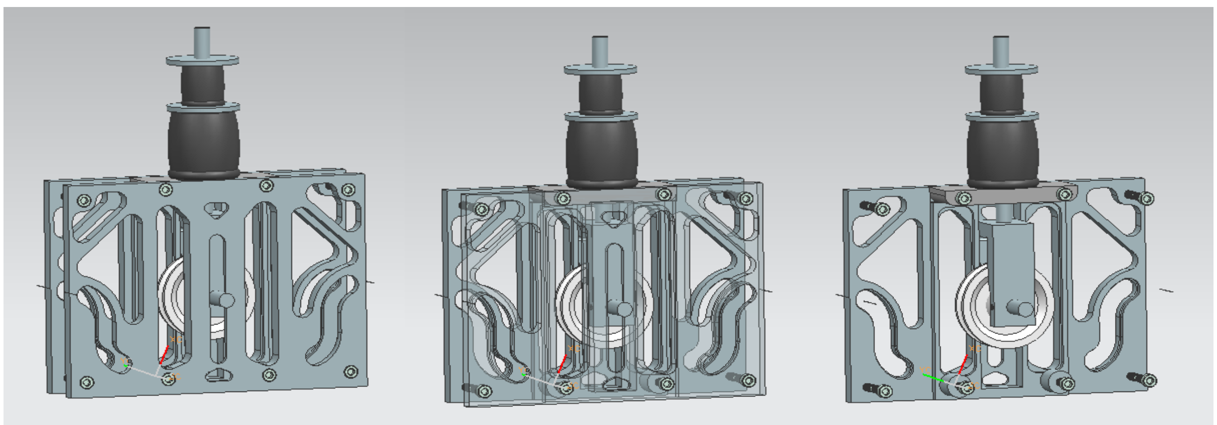


Figure 25. The final spring assembly CAD model. The picture on the left shows all components where the picture on the right has had the front pulley side plate removed so that you can see the inner workings of the spring assembly better.

Each component of this design can be viewed in detail in the gantry cad folder found in the teams electronic design binder. Refer to Figure 26 for the locations of all the following parts. The pulley side plates provide the structural support for the upper gantry while guiding the spring assembly and providing attachment points for the pulley side mounts. The pulley holder houses the pulley and can be seen best on the right most picture in Figure 25. The pulley shaft, running through the pulley mount, is held in place with two set screws. The spring support rod enters the pulley mount from above. The support rod transfers the force of any fall directly to the springs so that they can compress and provide the necessary shock absorption. Three spacers ensure that the pulley side plates are spaced appropriately and that the pulley support rod is in line with the pulley holder.

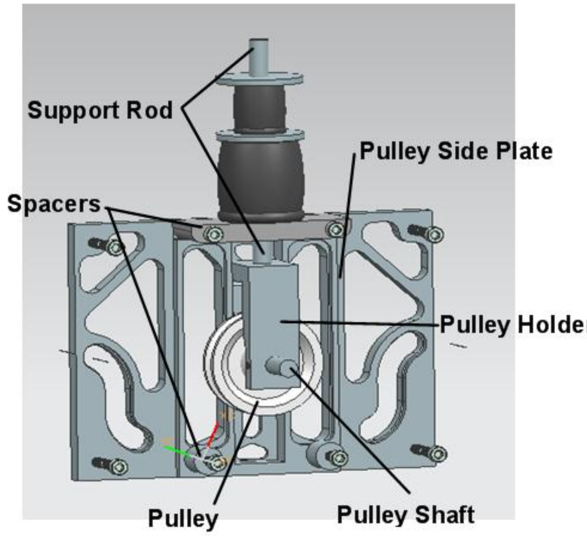


Figure 26. Detailed and Labeled Drawing of the Spring Assembly. Note that in this picture the front Pulley Side Plate has been removed so that the internal parts can be seen.

Important aspects of the design include how the pulley mount rides inside a guide machined into the pulley side plate. This provides an emergency stop should either the springs or attachments fail in the assembly. The guiding system for the rope is designed to prevent the possibility of rope jams. It also minimizes rope wear while transferring the force of any fall directly to the pulley holder and indirectly to the springs. The springs are modular in the sense that replacements can be tuned for different load types and swapped out for the existing ones with no major changes to any other components. The final assembly after manufacturing and finishing can be seen in Figure 27.

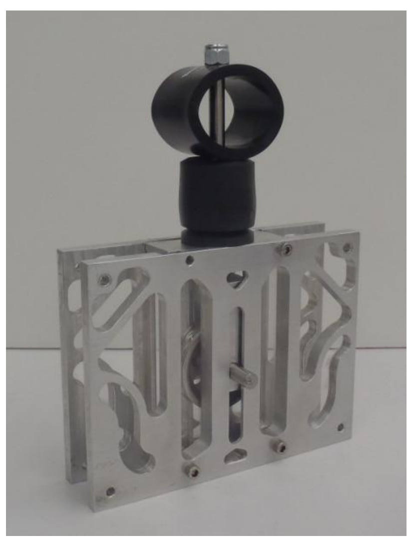


Figure 27. Final Spring Assembly. Note that spring spacers are not depicted in this picture but are installed in the final assembly.

The creation of such a complex part this early in the semester has taught the team lessons in machining, assembly, tolerances, and ordering parts. In future projects, these lessons will help the team move smoothly through the more challenging problems. Overall the spring assembly interfaces well with the rest of the gantry. With the exception of some recommendations that are outlined in the next section, the team is happy with the final product and excited that the gantry performs as expected.

Future Recommendations

This section is going to detail some lessons that were learned while designing, machining, and assembling this part of the gantry and will offer some recommendations for any future design revisions.

Many of the recommendations stem from mistakes made during the manufacturing process. One major recommendation for future designs is to communicate as much as possible with any people whose designs you are planning to interface with. Close inspection of the final assembly shows that the pulley side mount and pulley side plate designs do not line up perfectly. It is recommend to complete all of the CAM of the parts that you are going to interface with and verify that the final designs are identical. Another way to fix this problem is to simply not design components that need to line up perfectly for aesthetic reasons. Designing something that is intentionally mismatched would be easier and any small imperfections will not be as easily noticed. Several other mistakes were made due to zeroing errors that yielded a 0.1 in gap between one pulley side mount and the pulley side plate. Inspection also shows that the top of one pulley side plate has a gouge on the inner face that does not jeopardize the part but is really close to ruining the outer surface finish. There is also an error with one of the pulley shaft guides. One side was machined with a 3/8in end mill when it should have been machined with a ¼ in end mill this means that it is wider than it should be and doesn't match the opposite side.

Another problem can be found in alignment of the bolt holes. The top spacer was a part whose holes were drilled using the drill press and this resulted in some drill bit drift and therefore one hole that doesn't line up in the final assembly. This error was fixed by remaking the top spacer and being more careful when machining the bolt holes.

In conclusion almost all of the mistakes that were made in the design and manufacturing process happened because not enough care was taken when completing crucial tasks. In the future always double checking the zeros and starting earlier should help to minimize future mistakes. The process of designing, manufacturing, and assembling the spring assembly was challenging but exciting. It is the only part of the gantry that has moving parts and there is lots of room for improvement. However, the team is confident that the final design and product has accomplished the needs we set out to fulfill.

Overall Gantry

Each of the above mentioned sub-components fit together to create the final gantry. This structure is strong enough to support over 700 pounds of dynamic load, which was proven in testing that will be discussed in the following section. All of the individual parts were created with weight in mind, and this resulted in a final overall with of 28 pounds which is lower than the customer request of 30 pounds. Many lessons were learned throughout the process, and though some were specific to parts, some such as manufacturing time, scheduling, and weight applied to all components. Many people found that manufacturing takes about three times longer than typically planned, and thus needs to be scheduled as such. It was also hard to take deadlines seriously in the beginning of the project, as it seemed like the whole semester was plenty of time to complete our tasks. It was a hard lesson learned that this can be detrimental and cause panic as a hard deadlines, such as a Navy review, approach and find the team unprepared. Weight also was not originally at the forefront of the design, and features such as pockets and recesses were an afterthought. This caused excessive machining time and set the schedule back further. Overall, though, the team is very pleased with the final product, and hope that the gantry will remain in the RoMeLa lab for years to come and can serve as a testing fixture for future robots as well as SAFFiR.

Testing the Gantry

After designing, manufacturing, and assembling the gantry one final step remained to prepare for use. The Gantry needed to be put through a series of tests that verified it could hold up to the loads it was designed for. These tests included an assembly speed test, a static load test, and a dynamic load test.

Assembly Speed Test

One of the design constraints for the Gantry's design was metric number four, time to assemble. This metric states that the two people must be able to assemble the Gantry in less than 30 minutes. Ideally they would be able to assemble the Gantry in less than 15 minutes.

This test was done by first packaging the gantry in its carrying case. The timer was started and two team members assembled the gantry as if they were preparing for an offsite demonstration. Assembly was done with the use of hand tools and an electric Allen wrench.

From start to finish our team members were able to assemble the gantry in 25 minutes, which is within our design goals. It is predicted that until the graduate students are familiarized with the set-up procedure it is likely that their set-up time will be slightly longer but with practice any team of two people should be able to replicate our beat our team's assembly time.

Static Load Test

Another design constraint for the gantry was that the system must support the robot during a fall. The loads expected in the event of a fall were approximated as a point mass of 35 kg falling a maximum distance of 20 cm. When this situation is decelerated over a distance of 5 cm a maximum dynamic force of 3100N can be expected.

In order to determine if the gantry can support loads of this magnitude the first step was to perform a static load test. A length of rope that could be strung through plate weights was used to attach masses to the gantry. In increments of ten plate weights were attached to the gantry until a maximum load of 80 pounds hung from the center pulley assembly.

One major problem was uncovered during this test. During loading several glue joints between the carbon fiber support members and their aluminum plugs failed. This failure was not catastrophic because the weights were added slowly. This failure's root cause was determined to be a problem in the gluing procedure that resulted in poor bonding of the carbon fiber aluminum joints. In order to fix this problem the gluing procedure was modified and a cleaning step was added between the sanding and gluing steps of the procedure.

Dynamic Load Test

After modifying the weak glue joints in the assembly the team preformed another static test which was a success. The next step in the testing process was to simulate the maximum dynamic load that could be expected during a worst case fall. This load was determined to be 3100N and will be simulated by dropping 35 kilograms of plate weights a distance of 20 centimeters and letting the gantry completely catch the fall.

The test was performed and captured on video which can be seen in the teams design binder under the Gantry/Pictures and Video folder. This test proved that that the gantry is capable of withstanding the loads expected during a worst case scenario fall. It was also determined that the two tier spring design system which was designed to engage in the event of a serious fall functions as expected. Close examination of the side view video footage in slow motion reveals that the medium duty spring compresses the expected distance during the peak compression.

Conclusion, Gantry

The Gantry team was assembled to tackle the challenge of creating a support for the robot when walking. The team diligently accomplished this task by 15th November, which was the requested deadline from the graduate students. The gantry meticulously fulfilled all the customer needs with the respect of structure, manufacture, appearance and safety needs.

Testing showed that the gantry is capable of supporting a 36.4 kg (~ 80) pound load dropped 20 cm which is equivalent to a 712 lb dynamic load. This ensures that the SAFFiR robot will be safely held during a fall. The support system of the gantry is made of a multi-spring and rope assembly. The rope has 20 cm of slack in the support rope that allows the robot to move freely. This will prevent the system from interfering with the robot when walking. Then, two springs operating in series are implemented. The first spring absorbs the weight of the robot as a break, the robot slow down. While the second spring absorbs the shock, the robot is stopped. However, it is impossible today to determine precisely how the robot will react during a fall and how the robot, attached to the gantry, will withstand the impact. SAFFiR is not completely built yet, so it is difficult for the team to determine a precise solution. Nevertheless, convenient solutions are proposed by the team for future test. First, it is possible to change the robustness of the first spring , if a better energy absorption is required to slow down the robot. The second solution is to tighten the rope, if it is desired for the robot to fall down over 10 cm instead of 20 cm.

Not only is the gantry strong to support the weight of the robot, it is also very light. This is really convenient while traveling. The grades student will have to travel with the gantry and the robot around the world for demonstration. Therefore, each section of the gantry has been made in order to maximize strength and to minimize weight. All the joints were made in aluminum, which is a really light and strength material. Using the CNC machine, the team minimizes weight by removing maximum of extra weight without interfering on the strength of the joint. To connect these joints, the team used carbon fiber tubes, which is one of the most remarkable material. It can support really high stress and be really light. The total weight of the gantry is 13 kg (~28 pounds) which is really low compare to the 35 kg robot weight that it has to support, which is approximately three time of its own weight.

In addition, the team will buy a pelican case that will be used to transport the gantry. This pelican case will be chosen in order to match all the weight and dimension restrictions of the airplane companies. Also, one of the most sophisticated utilities of this gantry refers to the fact that it is designed to be easy to store. The “A” side of the gantry can be rotated 90° that allows the gantry to be stored along any wall.

Future recommendation for improvement, when designing a structure such as a gantry, will be based on the connection interface between projects and team communication. The team decided to pursue a “project management” where each person was champion of his own task. Each member made his own design of his piece and tried to interface with other projects by communicating with their owners. However, designs evolved with time and a lot of modifications were made for improvement. Thus, mistakes happened during assembly because people did not communicate efficiently about their modifications. Therefore, one major recommendation for future designs would be to have a connection interface document where all sensitive dimensions will be carefully listed. The team also decided to meet once a week to update all the team about the work of each team members. Each person explains to the team his accomplishments and future plan about his own project.

Another constraint was the deadline and the time to accomplish the entire gantry. The team tried to respect it but the little experience in CAD, CAM and manufacturing pieces leaded the team to accomplish tasks in hurry. Nevertheless, the team is confident about the work accomplished and looks forward to seeing the SAFFiR robot attached to the gantry.

Concept Generation, Covers

In order to generate solutions for the covers design problem the five step design process outlined in the text “Product design and development” was utilized [1]. This process provided the flexibility to explore a wide selection of solutions but also the structure to select optimal solutions and identify key parts of the problem. The five step design process consists of a clarification of the problem, internal and external search for ideas, and a reflection on the concepts generated.

Clarification of the problem

The team developing the covers established that the primary roles are to promote safety, protect the robot, and make the robot aesthetically pleasing. Upon further deliberation it was decided that to keep the user safe, the covers should prevent the user from having their digits crushed in the robots joints. The covers should protect the vulnerable joints of the robot in the event of a fall or catastrophic malfunction. Because the U.S. Navy is investing a lot of money in this project, the covers should be aesthetically appealing so that they complement/ highlight the advanced technology that runs SAFFiR, enhancing its presentation. Clarification of the design problem revealed that the covers must be elegant and protect the vulnerable joints of the robot and prevent users from being injured by the pinch points of the joint.

Internal and external search

In order to find design concepts that meet the design specifications, internal and external searches were performed to analyze ideas already implemented by other groups and the covers subteam. This search started with the covers designed by the team last year that were implemented on the CHARLI project which won the Robo-Cup award in 2010 for best humanoid. Figure 28 identifies some of the visual references analyzed for inspiration. The smooth contours of the covers on the CHARLI robot were identified as a potential solution this year. Inspiration from movies and science fiction was also prevalent, particularly Iron Man and IRobot. From these resources several potential ideas were developed. When brainstorming as a group the formal 6-3-5 method was utilized. Each member of the team created six design ideas before the members must pass their ideas to the adjacent member. The next member then created three new ideas or modifications of existing ideas. The team conducted a total of four rotations yielding up to 18 ideas per member. Upon completion of the 6-3-5 concept generation, all ideas were gathered and repeated ideas were eliminated. The remaining ideas formed the foundation upon which the team began concept selection. One particularly promising idea is that which follows the SAFFiR theme: a clear blue faceted design that resembles sapphire crystals.

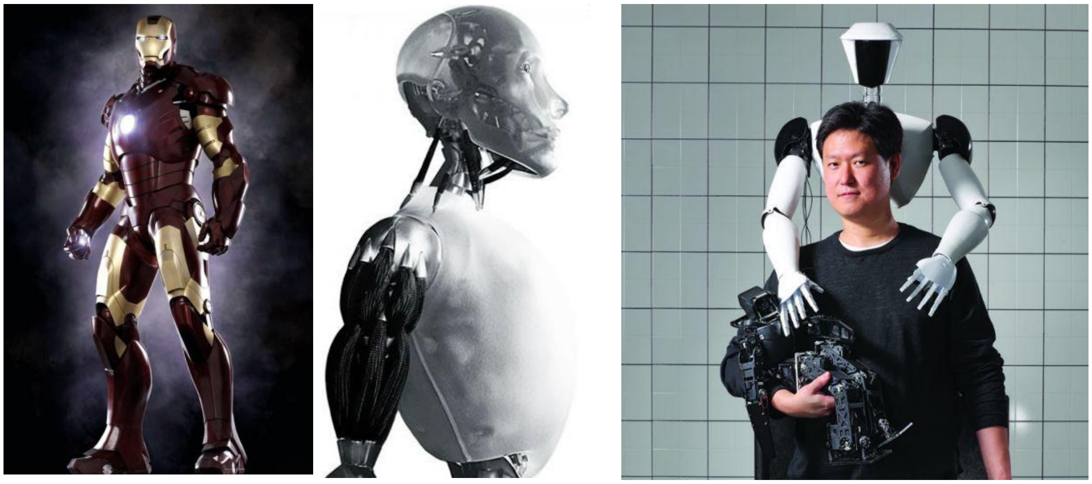


Figure 28. Example sources of external exploration. The team explored external ideas from science fiction as well as previous generations of our existing project. The left image is of the exoskeleton of the film Iron Man. The centermost image is the NS-5 robot from the film I, Robot. The right image is the predecessor to our existing robot, CHARLI with our host professor Dr. Hong.

Systematic Exploration

In order to organize our concepts classification trees and combination matrices were used. The team first organized the ideas into a classification chart, lumping like ideas into groups. Several different categories were identified: minimalist covers, interlocking plates, angular covers, smooth contours, and full coverage. This simplified the selection process and made it easier to identify the promising and difficult design concepts. A combination chart was also used to examine whether parts of multiple ideas could be restructured more efficiently by breaking up each concept into its basic elements. Some of the key principles that arose included the amount of the joint that was covered by the cover, as well as the degree to which the cover matched the contour of the leg. Some primary limitations included the obstructing motor controllers that are mounted on the side of the leg as well as the protruding compliant members that alter the shape of the leg. The team decided that rather than cover up the compliant members, they should be showcased instead. The covers should highlight the features that make the SAFFiR robot unique rather than simply dressing it up to look like a prop from a science fiction film. In this way the inspirations from external and internal searching were modified to match SAFFiR and highlight its fundamental beauty, form and technology. The most promising solutions are included as Figure 29 and Figure 30.

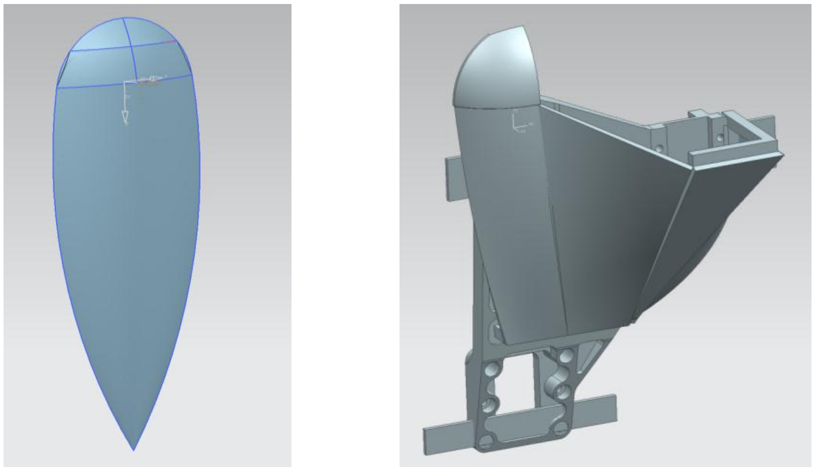


Figure 29. Simple contour shape design can be seen on the left. This is an initial contour concept for a simple cover. On the right is a simple full coverage design. This hides the compliant member from view.

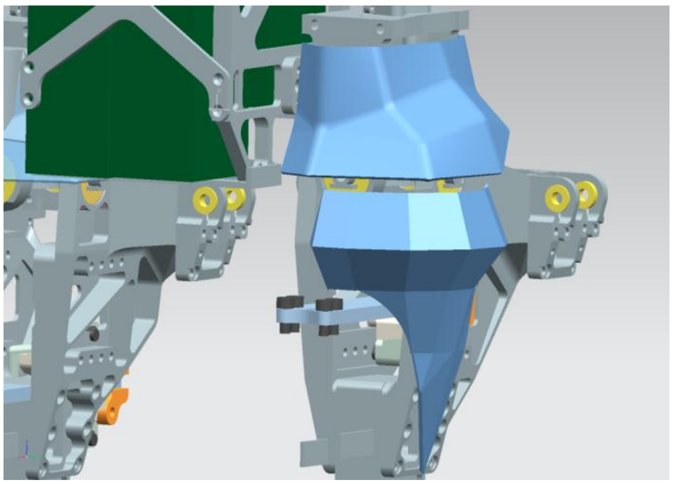


Figure 30. Complex faceted cover design for the upper and lower hip. This features faceted angles and conforms to the form of SAFFiR.

Reflection on the solutions

In order to refine the ideas from systematic exploration the team reflected on its ideas through constructive criticism and an iterative process. As ideas were developed, the team periodically switched gears and made observations, criticisms, and suggestions. The mood for this reflection was always respectful and the focus was on improving ideas not demonstrating personal worth. The important part of the reflection was the incorporation of the feedback into the next round of concept generation. Using the five step process for concept generation proved to be effective.

Covers Concept Selection

This section describes the concept selection phase. We have discussed the process for generating concepts, and this section discusses how we decided which concept to develop and manufacture. The previously mentioned designs were the smooth contoured shapes, interlocking *Ironman* plates, faceted sapphire Plates, and large bulky *Robocop* plates. This section will discuss assets and detriments to each design, followed by the scoring criteria and the methodology of selection.

Scoring Criteria

The scoring criteria for the covers design reflected our customer needs. We determined that we would score each gantry concept on a scale of zero to five with regards to the following criteria: operator safety, structure/operation, manufacturing, and appearance. These criteria were chosen to reflect the engineering metrics associated with the customer needs presented. Each criterion was weighted on a scale of zero to five to indicate the importance of that metric. Metrics were chosen and weighted carefully to optimize final cover performance. The weighting system starts at zero and ends at five, thus determining the highest importance with five and lowest with zero.

The criteria that were most important were given a weight of five, and they consist of operator safety, operation, and appearance. Operator safety quantifies how well the concept could protect the user from personal injury, this is important because the users value their safety. Operation describes how little covers impede the motion of the robot, since the robot is designed for high performance we determined the covers should impede the motion as little as possible. The appearance of the robot is always very important to the RoMeLa team as the covers will help to create the image of the robot.

The criterion that was rated the second most important was the structure of the covers which was given a weight of four. A desired feature of our customer was the ability to see the functionality of the robot, which is separate from aesthetics because the aesthetics related mostly to the shape of the covers. Also included in the structure criteria was the ability of the cover to protect the joint. If the other safety functions perform correctly this protection the covers offer will not be important; however any added protection is welcomed to protect the robot. The manufacturability of the gantry was of second level importance due to the need to finish the gantry in time for testing of the robot, a gantry that would be too hard to manufacture might not be made at all.

The lowest criterion was given a weight of two. We determined that this criterion would be the manufacturability of the gantry. We determined this would be least important due to low volume of parts that needed to be manufactured, this would only determine how many iterations we could make on our designs.

Concept Rating

The **Faceted faces** design was determined to be the best covers concept. We gave this design a four for operator safety due to its complete coverage; however the angles of the facets might facilitate injury. This design receives five points out of five for structure because it can be constructed out of high strength transparent polycarbonate. This design receives the maximum score in manufacturability because we can use computer controlled milling and vacuum forming techniques. This design receives a four out of five in the category of appearance because the projected designs were visually pleasing, however other designs looked better. Finally this design received a five out of five in operation because our rough design did not hinder the movement of the robot at all. The overall score for this design was 95 out of 105.

The **Contoured Shapes** design was determined to be the second best covers concept. We gave this design a four for operator safety due to its complete coverage; however the lack of distinct edges reduced the strength of the contact faces and thus reduces the overall safety. This design receives four points out of five for structure because it can be constructed out of high strength transparent polycarbonate; however the shape is not as rigid as other alternatives. This design receives the maximum score in manufacturability because we can use computer controlled milling and vacuum forming techniques. This design receives a five out of five in the category of appearance because the projected designs were visually pleasing and matched the style of the predecessor. Finally this design received a four out of five in operation because our rough design did not hinder the movement of the robot except in extreme scenarios. The overall score for this design was 89 out of 105.

The **Interlocking Plates** design was determined to be the third best covers concept. We gave this design a five for operator safety due to its complete coverage; the interlocking plates leave no gaps that could pinch a user. This design receives four points out of five for structure because it can be constructed out of high strength transparent polycarbonate; however the need for more sturdy mounts could cause problems with the motor control mounts. This design receives the low score of 2 in manufacturability of the tight tolerances and many small interacting parts. This design receives a five out of five in the category of appearance because the integration of the plates would be captivating and inspirational. Finally this design received a three out of five in operation because the interlocking plates would constantly impede the motion of the joints. The overall score for this design was 87 out of 105.

The **Heavy Plates** design was determined to be the least desired covers concept. We gave this design a five for operator safety due to its complete coverage; the rigid plates also help the user handle the robot. This design receives three points out of five for structure because it will be constructed out of carbon fiber; this would impair the vision of the robot; however the strength would protect the robot from damage. This design receives score of three out of five in manufacturability because of the difficulty of using carbon fiber. This design receives a four out of five in the category of appearance because the projected designs were pretty cool; however ultimately drab. Finally this design received a three out of five in operation because the bulky plates could hinder the movement of the robot. The overall score for this design was 89 out of 105.

Concept selection matrix

We took all of the different concept criteria and created a matrix of all of the scores along with weighted scores, the sum of the weighted scores determines the total score of a design. The highest total score determines the best design. This matrix can be seen in Table 7.

Table 7. Concept Selection Matrix for the cover design. A compilation of scores and their associated weights shows that faceted faces will best meet the desired criteria.

		Contoured shapes		Interlocking Plates		Faceted faces		Heavy Plates	
Selection Criteria	Weight (0-5)	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Operator Safety	5	4	20	5	25	4	20	5	25
Structure	4	4	16	4	16	5	20	3	12
Mfg	2	5	10	3	6	5	10	3	6
Aesthetics	5	4	20	5	25	4	20	4	20
Operation	5	4	20	3	15	5	25	2	10
Total Score			**89**		**87**		**95**		**61**
Rank			2		4		1		3

Covers detailed design documents

For the purposes of the detailed design documents for the covers portion of our project this document illustrating the process for the design of the upper hip cover was used also for creating covers for the lower hip and knee. As the upper hip cover was the first part made we used the recommendations listed at the end of this document to supplement the process for the remaining covers

Upper Hip Cover

The Upper hip cover functions to secure and provide safety to the large pinch point formed by the three degree of freedom joint found in the hip. It also serves to help define the image of the robot and as its design was the first one finished it served as a template for the aesthetic design aspects of the remaining covers. This section will cover the process of creating the design of the cover, designing the mold for the cover, and the manufacturing process for the mold.

Constraints

The two main design constraints that this part was built around were that of providing safety for the pinch point and that of creating an image of the robot. In order to safely cover the pinch points we decided to attach this cover to the vertical hip mounts to reduce the need to design around moving parts. This placement allowed us to determine the range of motion of all potentially intersecting parts and design around it, to allow it to pass but cover the pinch point. Close angles and corners on vacuum formed pieces have greater rigidity; thus, we picked a faceted aesthetic design.

Initial Design Concepts

The initial concept was to use a simple rounded piece that was less than 180 degrees to allow us to create a mold that could be used on the vacuum former. An early design can be seen below in Figure 31.

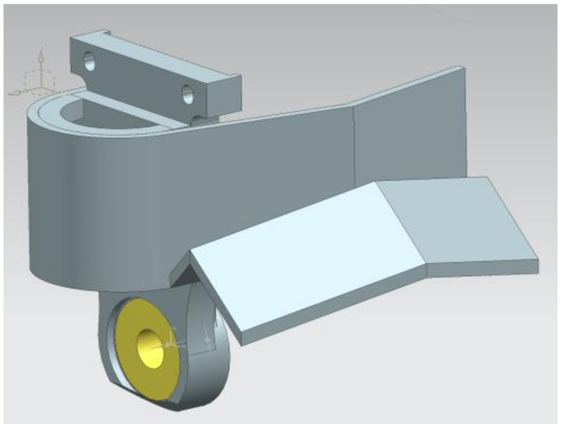


Figure 31. Initial design concept for Upper hip cover before vacuum forming education took place

From this design we realized that, if we were to go around the entire hip that, the cover would be over 180 degree in one direction. But it was realized that, since we were not using the top portion of the hip area on the cover, we could design a mold that could be lifted up and the top piece cut off. Through several iterations of CAD design we created the final design found below in Figure 32.

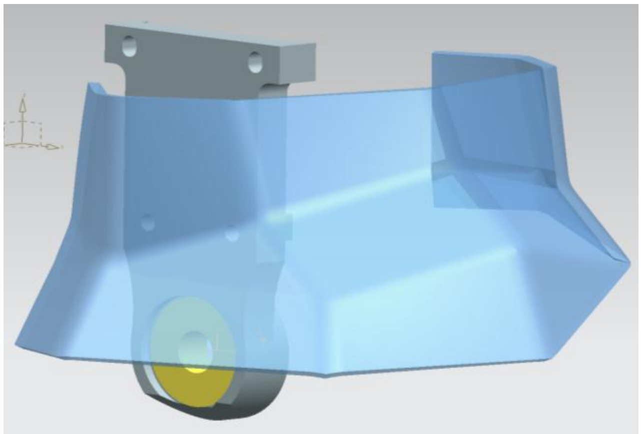


Figure 32. Final Upper hip design rendered as desired color and how it looks in production

Design Challenges

Some of the difficult challenges in creating this part were designing for the mold and the vacuum former. We had to design to allow the part to be machined on the CNC machine while at the same time designing for the correct draft angles and limitations of the Vacuum former. The vacuum former cannot create straight vertical surfaces or negative angles. An additional design challenge finding a location to mount on the robot that did not interfere with the robot.

Final Design

For the final design, the part was created in NX 7 around the previously constructed parts in the full assembly model of the robot. To do this we used sketches to provide important reference points around the model and then used 3D spline lines to connect these points and move to others. This allowed us to create more organic shapes in 3D. From this framework of splines, that was the basic shape of the cover, we then created sweeps using two or more guidelines that created a surface surrounding the assembly and defined our part shape. Since the sweeps were only 2D shapes without a thickness, we needed to give them body to allow us to create molded edges instead of sharp ones. For this we used the Thicken command and by selecting all of the sweeps at once and thickening the sweeps out away from the robot we were able to create a 3d shape that we could manipulate the edges to smooth them down. When this was completed the NX model looked as it would when the part was manufactured. After this step it was necessary to create a mold with the smooth surfaces of the curves as the lower bound. By extruding a solid block or blank up that covered the part and subtracting the thickened part away from the blank we are able to create a negative of our cover. From here we removed material in NX 7 to expose the upper surface of the mold by extruding away the remaining scrap material.

Manufacturing Process

For the purpose of manufacturing the needed molds we took the previously created mold files from NX and placed them in the CAMM portion of the program. The process uses standard speeds and feeds for the hard acrylic blocks that are used for the blanks of molds. The first step in the program first removed large amounts of the blank using a 4 inch square end mill, then traced the final shape of the interior of the cover with a 4 inch ball end mill. In our implementation we followed the guidance of our graduate advisors and used on only the sharpest mill bits. We also milled reliefs into the mold to allow the vacuumed formed material to form over the mold properly. After milling the mold we were able to produce as many covers as we need. In the production of the first cover we used the highest thickness vacuum formed material in order to protect the robot and its users.

The cover manufacture consisted of milling the mounts from one inch thick aluminum blank. The manufacture was simplified to two tool changes with drilling the holes for connecting to the robot first before milling. The milling consisted of a three eighths roughing end mill with no finishing passes. The team decided no finishing passes were necessary because the cover will cover up the finish effect of the mounts. The contour milling necessary to obtain the curvature of the covers on the mounts was accomplished with the roughing end mill. This was accomplished by reducing the step size of the contour milling and removing the angle on the outer curvature of the mounts. The angle of the curvature of the covers was introduced by sweep designs used in the initial design phase. The manufacture team decided to remove this angle to simplify the manufacture and deeming it unnecessary for effective fit and function. All of the CAM work was completed in NX using the CAD files provided by the design team.

Future Recommendations

Our team learned important lessons about milling and vacuum forming from this project. The first lesson learned is to carefully choose a milling method that has the least redundancy. Our first cutting operations wasted time and energy cutting air. The second lesson we learned is that the machine can easily cut at higher feed rates with a greater proportion of the bit. We also uncovered a peril of our particular mill, if the chuck is not completely tightened the mill head will pull out of the chuck and gouge the material. This was due to the extra long bits being used for the manufacture, to reach the bottom of the part the long bit was placed at its absolute furthest position, which created enough force to pull the bit out of the chuck. We recommend designs that use a thinner cross section to reduce this effect. The final lesson we learned about milling nylon was to use very large part stock to prevent the square end mill from cutting into the final face of the mold and creating unwanted marks in the final mold. We also learned several lessons about the vacuum forming process. The first lesson was that in addition to cleaning off the debris from the mold we must also remove milling waste from the operators before vacuum forming. In our first trial a nylon shaving fell onto the mold and created a blemish on our initial cover. We also learned that when using thicker material it is important to allow the heating element to warm the material longer in order to allow the material to form around the mold easily.

Conclusion, Covers

The covers sub team has created a solid foundation for the covers protecting the robot. We have accomplished our mission of developing covers that protect the main joints of the robot and prevent users from hurting themselves. The covers are formed of a vacuum formed polycarbonate. The covers are mounted to the robot using milled aluminum brackets screwed into the frame of the robot. Our initial cover designs protect the hip and knee joints. As new components are designed for the SAFFiR platform the team will construct new covers to protect them. The role of the senior design team will be the manufacture of these covers. In order to operate effectively the senior design covers sub team will utilize the lessons learned in the construction of the first set of covers and with this knowledge will apply these lessons to future revisions of the project.

For the purpose of the near future the cover team has effectively finished its project and will move on to other projects at the end of the semester. The future work that may be involved for the covers will be the graduate students taking over the remainder of the project for future iterations, and the covers sub team members would be involved in the manufacture of the molds and the production of the covers on the vacuum former. This is due to the fact that the team members are now the most experienced in these tasks and their involvement would be in a purely manufacturing and advising role.

In the long term, in its role as a fire fighting robot, the covers will undergo a huge transformation as the vacuumed formed plastics will not hold up to the heat and stress subjected to them in a real world environment. The designs and mold structure will still be able to be used but will likely change material and process of manufacture. These processes will likely be part of the final needs of the robot and will not occur for many years.

Plan for Spring Semester

Because the gantry and covers projects will be coming to a close at the end of the semester, the graduate students have requested that we complete two new projects. There is a need to double the output of the linear actuators by mounting a second motor to the system as well as redesign the foot to be more adept at crossing the uneven terrain of a naval vessel. Our senior design team is prepared to assume responsibility for these projects and complete them by graduation in May 2012.

Linear Actuator Redesign Project

One of the projects that was proposed by the graduate students was a redesign of the compliant linear actuators. It has been determined that the current power output of the system will not be sufficient for SAFFiR to perform all of the desired tasks and motions and needs to be increased. RoMeLa currently uses some of the most sophisticated motor technology and efficient ball screws, so in order to double the power output it is necessary to devise a system that allows two motors to be mounted on one actuator. This will require mounting two motors as well as keeping the tension in the belts that drive them. It has also been requested to strongly consider manufacturing, as each one of these systems is highly time consuming to create and requires many specialty tools. Since these mounts are used on all of the actuators on the robot, any time saved during this process can be multiplied across all of them. Major constraints of the system will be keeping the system lightweight, simplifying manufacture, creating a compact design, and minimizing friction. The schedule for accomplishing a redesign of the system can be seen below in Figure 33.

Task Name	Duration	Start
Linear Actuator Timeline	**125 days?**	**Mon 11/14/11**
Project Planning	**38 days**	**Wed 11/16/11**
Mission Statement	18 days	Wed 11/16/11
Time Line	20 days	Sat 11/19/11
Identify Customer N	22 days	Wed 11/16/11
Develop Product Sp	22 days	Wed 11/16/11
Concept Generation	**36 days?**	**Mon 12/5/11**
External Searching	10 days?	Mon 12/5/11
Internal Searching	10 days?	Thu 12/8/11
Systematic Exploration	10 days?	Wed 12/14/11
Reflect on the Conc	10 days	Fri 1/20/12
Concept Selection	**8 days?**	**Thu 1/26/12**
Concept Screening	4 days?	Thu 1/26/12
Concept Scoring	2 days	Sat 1/28/12
Detailed Design	**36 days**	**Tue 1/31/12**
Manufacturing	**48 days?**	**Tue 2/21/12**
Testing	**20 days**	**Mon 3/26/12**
Design Refinement	**66 days**	**Fri 4/6/12**

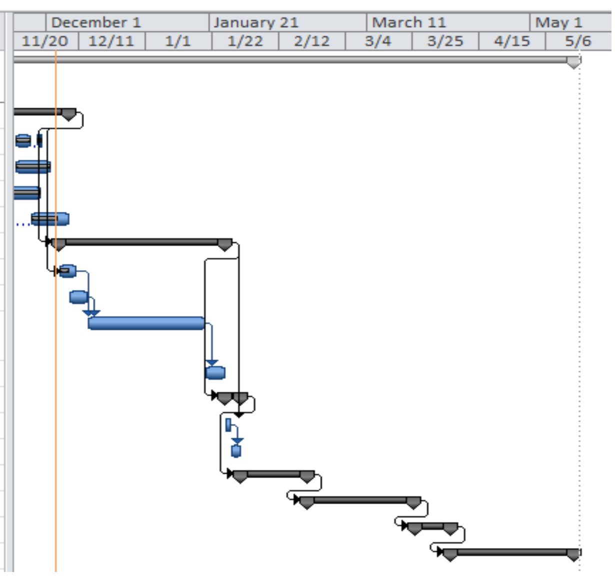


Figure 33. Gantt chart for Spring semester linear actuator project. This will be completed by April 1 to allow for a month of design refinement.

As seen above, this project will begin in the final weeks of the fall semester and continue until May. Concept generation will be completed after winter break, and concept selection will occur when we return. This will necessitate quick and efficient decision making in order to pursue detail design and manufacturing early and to learn from our past mistakes of underestimating the time necessary to complete these tasks. Upon completion of this project, SAFFiR will be better outfitted to support the load that will be associated with all of the firefighting equipment it will have to carry.

Foot Redesign Project

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 foot 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 May 3, 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.

In order to accomplish the goal of having a fully functional foot implemented on the robot by May 3, 2012, the team has set into place the following plan as shown in the Gantt Chart in Figure 34.

Task Name	Duration	Start
Foot_Gantt_Chart_111	**121 days**	**Thu 11/17/11**
Concept Generation	44 days	Thu 11/17/11
Customer Needs	7 days	Wed 11/23/11
Target Specifications	3 days	Tue 11/29/11
Concept Selection	6 days	Tue 1/17/12
Detail Design	21 days	Tue 1/24/12
CAD	16 days	Tue 1/24/12
CAM	16 days	Tue 1/24/12
Manufacturing	28 days	Tue 2/7/12
Preliminary Testing	22 days	Thu 3/15/12
Redesign (CAD&CAM)	9 days	Thu 3/29/12
Manufacturing	22 days	Tue 4/10/12
Final Testing	8 days	Tue 4/24/12
Winter Break	22 days	Fri 12/16/11
Spring Break	7 days	Sat 3/3/12
Deliver Prototype	0 days?	Fri 3/2/12
Deliver Final Product	0 days?	Mon 4/2/12

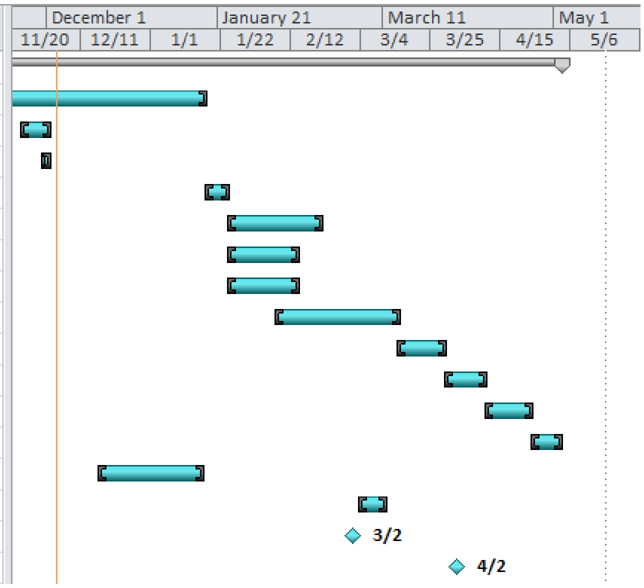


Figure 34. Gantt chart for Spring semester foot redesign project. This will be completed by April 2nd to allow for a month of design refinement.

The strategic plan is to have a manufactured foot before spring break so that any design flaws can be worked out. This way the team can deliver the highest quality product to RoMeLa and have the greatest positive influence on the SAFFiR project. After the last two projects, the team determined that time was greatly underestimated so the schedule to be followed is much faster paced to allow for more time at the end. Also, two full weeks is allotted for CAD and CAM which is short window but is necessary to accomplish the task at hand within the deadline set to have a fully functional foot that will be valuable to SAFFiR as well as to allow for the most time for manufacturing which proved to take far longer than expected this semester. This allows for 31 days of redesign and manufacturing to produce a better product at the end of the semester. Overall, this fast-paced front loaded timeline should give the team the best setup for a solid contribution to the SAFFiR team.

Conclusion and Future Work

The nine members of the SAFFiR senior design team have put in a great effort this semester. As documented in the above report both the covers and gantry teams have done well in meeting their proposed design goals. Each project had an accelerated schedule that put our team ahead of the typical senior design track. This was because of our primary objective for the year which is to support the graduate students in the development of the SAFFiR Project.

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 semester, 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.

Both the gantry and covers teams followed the design process from project planning, to testing and refinement. There are only a few remaining tasks to complete before these projects can be closed and the team as a whole can shift their entire attention to the new design challenges.

These new design challenges are the foot redesign project and the linear actuator redesign projects. This opportunity to reiterate the design process is a chance for the team to develop components that most other senior design teams will not have the chance to do. Throughout this semester ever team member has not only learned how to operate the tools and machines available to us in RoMeLa but also how to work effectively as a team and use the design process to their advantage. Having already gone through every stage of the design process the team was able to identify problems and potential speed bumps in each step. Solutions to these problems have been identified and next semester's projects should more smoothly as we implement those changes.

The project planning phase of the design process has been completed for each of these new projects and the teams are beginning to move into the concept generation phase. Progress will slow down over winter break but will pick right up again with concept selection during the first week of spring semester. Sticking to the schedule next semester is incredibly important if the team is to deliver a prototype by spring break and a completed final design by April 1st. This demanding schedule has been set to ensure that after the components are assembled the teams have enough time to test, document, and revise their designs.

By the onset of winter break the SAFFiR senior design team will have completed their current design tasks and have delivered both a Gantry and set of covers to the graduate students so that they can begin testing the assembled SAFFiR. By the spring design showcase the SAFFiR team will be able to present two additional components that are ready for implementation into the overall SAFFiR Project. The redesigned foot and linear actuators will be components that push the boundaries of their respected fields and their failure or success has the potential to directly affect the failure or success of the SAFFiR Project as a whole. The experience learned by iterating this design process and working as a team will be one of the most important experiences we take away from our time here at Virginia Tech. Details about progress made next semester will be available in May as part of the final spring report .

References

[1] Ulrich, K. T., and Eppinger, S. D., 2007, “Product Design and Development, Fourth Edition,” Mc-Graw Hill, New York City

Iron Man. Dir. Favreau Jon. Pref. Robert Downey Junior. Paramount Pictures, 2008.

I, Robot. Dir. Alex Proyas. Pref. Will Smith. 20th Century Fox, 2004.

Appendices

Appendix A: Customer Needs and Importance
Appendix B: Matlab Code for Spring Design

Appendix A: Customer Needs and Importance

Table A35. Customer needs statement and interpreted needs for the SAFFiR gantry. This information was obtained from an interview by the design team. Interpreted needs marked with a "!" were identified as latent needs.

Customer:	Derek Lahr	
Interviewers:	SAFFiR Senior Design Team	
Date:	8/25/2011	
Question/ Prompt	**Customer Statement**	**Interpreted Need**
Prototype Safety	The prototype must not fall freely.	The gantry restricts the fall of the robot.
	Shock can damage sensitive electronic components.	The gantry absorbs shock from falling.
	Impact from falling can break actuator mechanisms.	The gantry prevents impact from falling.
	There needs to plenty of open space surrounding the robot.	The gantry leaves space around the robot.
	Full falling weight needs to be supported.	The gantry supports SAFFiR's dynamic falling weight.
Structure/ Operation	Our prototype needs be easily visible.	The gantry does not obstruct line of sight with the robot.
	The robot's natural gait must not be obstructed.	The gantry does not obstruct the robot's natural gait.
	It would be nice if the gantry's height is modifiable.	The gantry's height is modifiable.
	The robot will probably travel to demonstrations.	The gantry can travel easily. (!)
	Setup can be done quickly with two people.	The gantry can be setup by two people quickly.
	Our shipping cases are only 3ft long.	Any part of the gantry is less than 3 ft long. (!)
	It's difficult to travel with more than 30 lbs.	The gantry is less than 30 lbs total. (!)
	The gantry needs to move with the robot.	The gantry moves along with the robot.
	It would be convenient if it could hoist the robot.	The gantry is capable of hoisting and supporting the robot.
	Should fit through tight doorways.	The gantry fits through tight doorways.

Appearance	RoMeLa projects share a common black and white theme. Identifiable as SAFFiR gantry. We've used carbon fiber before for appearance. Larger structures look more stable.	The gantry looks similar to other RoMeLa projects. (!) The gantry compliments SAFFiR's appearance. The gantry looks sleek and modern. The gantry appears secure, safe, and strong.
Manufacturability	We have a three degree of freedom CNC. The delivery deadline is October 15th tentatively. You (all) need to machine your designed parts.	Each part of the gantry is manufacturable on the CNC. (!) Gantry manufacturing is doable in 14 days. (!) Each part of the gantry is machinable by its designer.

Customer:	Derek Lahr
Interviewers:	SAFFiR Senior Design Team
Date:	8/25/2011

Question/ Prompt	**Customer Statement**	**Interpreted Need**
Operator Safety	The covers must provide protection from pinch points. The hip joint provides multiple pinch points. The linear actuators provide up to 300 lbs of force. When the robot falls an operator can safely catch it.	The covers prevent hands from entering pinch points. The covers cover multiple pinch points at a time. The covers protect linear actuators and force members. The covers prevent harm to operator while catching robot.
Structure/ Operation	Covers must be clear for initial Navy inspection. Must provide some support and protection in case of fall. Mount can be mounted to the skeleton of the robot. Covers cannot impede the motion of the robot.	The covers allow viewers to see internal parts. The covers protect internal components. The covers will be mounted by stiff aluminum mounts. The covers allow full range of motion of all parts.
Appearance	RoMeLa projects share a common black and white theme. The covers will set the theme of the robot. Covers are the main focal point for any audience. Some exposed mechanics is okay (linear actuators). Some blue can be introduced to set SAFFIR theme. Need to make the robot leg look similar to a human leg. Needs a lot of sleek blended edges.	The covers stay true to the RoMeLa precedent. The covers show off the theme of the robot. The covers catch the eye of anyone who sees the robot. The covers show some of the more advanced mechanics. The covers implement some new color schemes. The covers allow the robot to seem more humanlike. The covers have smooth edges and a sleek design.
Manufacturability	Covers must be easily machined with one day turnaround. The delivery deadline is October 15th tentatively. Follow some of the CHARLI manufacture techniques You (all) need to machine your designed parts.	The covers must be manufactured swiftly in case a cover breaks. The first set of leg covers will cover the robot by Oct. 15. The covers follow the machining techniques of CHARLI. The design team will manufacture each part.

Table A36. Customer needs statement and interpreted needs for the SAFFiR covers. This information was obtained through interview.

Need No.	**The gantry ensures safe testing of SAFFiR prototypes.**	Importance
1	The gantry restricts the fall of the robot.	5
2	The gantry absorbs shock from falling.	5
3	The gantry prevents impact from falling.	5
4	The gantry supports SAFFiR's dynamic falling weight.	5
	The gantry travels and assembles easily.	
5	The gantry can be setup by two people quickly.	4
6	Any part of the gantry is less than 3 ft.	2!
7	The gantry is less than 30 lbs total.	3!
	The gantry is easily used/ manipulated when testing SAFFiR.	
8	The gantry promotes clear line of sight with the robot.	3
9	The gantry promotes the robot's natural gait.	5
10	The gantry's height is modifiable.	2
11	The gantry leaves space around the robot.	3
12	The gantry moves along with the robot.	4
13	The gantry is capable of hoisting and supporting the robot.	3
14	The gantry fits through tight doorways.	3
	The gantry is aesthetically attractive.	
15	The gantry looks similar to other RoMeLa projects.	2!
16	The gantry compliments SAFFiR's appearance.	3
17	The gantry looks sleek and modern.	2
18	The gantry appears secure, safe, and strong.	4
	The gantry can be manufactured in 14 days.	
19	Each team member can machine their own designs.	3
20	Each part of the gantry is manufacturable on the CNC.	2!

Figure A1. Hierarchical list of primary and secondary customer needs for the SAFFiR gantry. Importance of the secondary needs are ranked from 1-5, where 5 denotes critically important needs. Latent needs are denoted with an additional !.

Need No.	**The covers provide safety to the robot and operator**	Importance
1	The covers prevent hands from entering pinch points	5
2	The covers cover multiple pinch points at a time	4
3	The covers protect linear actuators and force members	2
4	The covers prevent harm to operator while catching robot	5
	The covers protect robot and do not constrain motion	
5	The covers allow viewers to see internal parts	4
6	The covers protect internal components	3
7	The covers will be mounted by stiff aluminum mounts	1
8	The covers allow full range of motion of all parts	5
	The covers provide a futuristic look	
9	The covers stay true to the RoMeLa precedent.	4
10	The covers show off the theme of the robot.	3
11	The covers catch the eye of anyone who sees the robot.	5
12	The covers show some of the more advanced mechanics.	2
13	The covers implement some new color schemes..	1
14	The covers allow the robot to seem more humanlike.	2
15	The covers have smooth edges and a sleek design.	4
	The covers can be manufactured easily and swiftly	
16	The covers must be manufactured swiftly in case a cover breaks.	3
17	The first set of leg covers will cover the robot by Oct. 15.	4
18	The design and manufacture of covers follow the path of CHARLI.	1
19	The design team will manufacture each part.	4

Figure A1. Hierarchical list of primary and secondary customer needs for the SAFFiR covers. Importance of the secondary needs are ranked from 1-5, where 5 denotes critically important needs.

Appendix B: Matlab Code for Spring Design

This appendix contains the Matlab code that was used to both evaluate the multi spring system and display the graph portrayed in Figure 22.

```
%Elastomeric Die Spring Design Analysis
%% Description:
%This Code will calculate and output the spring design chart for the case of
%two elastomeric Die Springs placed in series.  The reason for this is to
%optimize the spring absorption for a typical loading situation but create
%a high load absorption zone for the worst case loading scenario

clc
clear all
%Light Spring Specs
defl_max_light = 1.7*2.54; %cm
F_max_light = 300*4.448; %Newtons
Kl=F_max_light/defl_max_light; %N/cm

%Heavy Spring Specs
defl_max_heavy = 0.99*2.54; %cm
F_max_heavy = 1600*4.448; %Newtons
Kh=F_max_heavy/defl_max_heavy; %N/cm

%% Calculation of spring load curve
% Region 1: the light zone where both springs are acting in series
K1 = (1/Kl+1/Kh)^-1; %calculate regions spring constant
F1 = F_max_light; %calculate regions max load
defl_region1 = F_max_light/K1; %calculate regions max deflection

% Region 2: the heavy zone where the light spring has bottomed out
K2 = Kh; %calculate regions spring constant
F2 = F_max_heavy; %calculate regions max load
defl_tot = defl_max_light+defl_max_heavy;
defl_region2 = defl_tot-defl_max_light; %calculate regions max deflection

%% Plot Graph Displaying Results
%Define Spring Curve Lines
X = [0 defl_region1 defl_tot];
Y = [0 F1 F2];
%define Region 1 lines
R1X = [0 defl_region1 defl_region1];
R1Y = [F1 F1 0];
%Define Region 2 lines
R2X = [0 defl_tot defl_tot];
R2Y = [F2 F2 0];
plot(X,Y,'r-',R1X,R1Y,'b--',R2X,R2Y,'m--','linewidth',2.5)
axis([0 defl_tot*1.05 0 F2*1.05])
xlabel('Deflection (cm)','fontsize',11)
ylabel('Force (N)','fontsize',11)
grid on
legend('Spring Curve','Series Springs','Medium Load
Spring','Location','west')
```