Freedom Ski

For:
QL+
Dr. Bash

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Introduction

The current availability of water skis for people who are paraplegic or quadriplegic is very limited. The aim of our project is to design a system that improves upon the current models of specialized water skis. Our intent is to create a waterski system that is structurally stable and handles responsively, in order to ensure that anyone is capable of effectively using our system to waterski.

The main client of our project is Quality of Life Plus, an organization that aims to aid veterans of the armed forces who have physical disabilities to still enjoy a good quality of life. Their work is very broad, ranging from prostheses to active equipment. Our customer, Dr. Craig Bash, is a partial quadriplegic and veteran of the Air Force who leads a very active lifestyle and greatly enjoys waterskiing. However, his current waterski system does not effectively meet his needs, hence the creation of our team to design and build an improved waterski.

Our design will be based specifically around Dr. Bash’s requirements, as well as our own design recommendations from research and testing. Our specific aims are to create a waterski system that has great improvements in overall weight, responsiveness, drag, comfort, and ease of disassembly. By improving in these specific design areas, we will ensure that Dr. Bash will have a more rewarding waterskiing experience.

Background

Market Relevance and Device Audience

Approximately 250,000 Americans are currently living with a spinal cord injury. Of these 250,000, 52% are paraplegic and 47% are full or partial quadriplegics.
[1] For these people, participation in adaptive athletics is often their sole form of physical activity. At Team Freedom Ski, we intend to provide the necessary technology to improve the comfort, agility, and practicality of adaptive waterskiing for one of these athletes - Dr. Craig Bash. The technology that we develop can easily be used by many people with impairments similar to those of Dr. Bash.

QL+ Background

Quality of Life Plus is the facilitator of this project. QL+ is a nonprofit organization that aims to aid people (specifically service members and other public servants) who are injured in the line of duty. They were founded five years ago by Jon Monett after he came to the understanding and realization that many service members return from war or service duty with life-altering injuries like amputations and paralysis. The aim of QL+ is to develop technology to aid those with these types of injuries in having the maximum quality of life possible. The organization built a lab at Cal Poly in order to allow aspiring engineers a chance to work on projects that will help the people sponsored by QL+.

Similar Products in the Marketplace

Although there are products currently on the market for adaptive waterskiing, we feel that these products could be improved upon in order to provide a better experience for the user by optimizing carrying and mobility, agility, drag, comfort, safety, and the ski's ability to float.

The product Dr. Bash currently uses is the Ski Seat, an apparatus containing a seat

Figure 1. Ski-Seat Apparatus [product currently used] Water Sport Industries, Inc.

Figure 2. Sit-Ski Single Ski Apparatus (Liquid Access)

and frame attached to two skis, as shown in Figure 1. This design has several disadvantages, such as being too heavy to float adequately, containing sharp edges that can hurt the user, poor hydrodynamic capabilities resulting in drag, and lacking the appropriate cushion to absorb impacts, leading to spinal discomfort. Another product on the market is a seated single-ski, shown in Figure 2. Although this product has fewer safety and drag concerns when compared with the Ski Seat, it is significantly less agile and requires more strength

to use, something which is difficult for an adaptive skier-- especially a partial-quadriplegic such as Dr. Bash-- to adjust for.

In order to improve conditions for adaptive water skiers, Team Freedom Ski has researched current technology in the waterski industry and areas in which this technology may be applicable to an adaptive apparatus. With the Ski Seat specifically, weight is an important issue. Composite skis, especially those with honeycomb construction in the tip and tail, are much lighter and float more easily than the traditional wooden skis utilized in the Ski Seat product. Additional materials research suggests that metal alternatives to steel would significantly reduce the weight of the frame/structure or necessary similar parts.

We have researched other marine sporting equipment in order to get a better idea of current designs that may benefit our project as well. The seat on an Air Chair (Figure 3) contains more cushion and back support than the current Ski Seat design. Additionally, the seat belt on an air-chair limits the amount and magnitude of bouncing and resulting shock absorption for the user's spine. However, this feature could become unsafe if a disabled user falls and is unable to break away from the ski apparatus. Many other conventional seats, such as those used in go-carts, wheelchairs, and automobiles are too restrictive, and the seats of bicycles and unicycles do not provide enough support for our intended application. A new method of securing the skier to the apparatus will need to be explored.

Figure 3. Air Chair Seat Design (Air Chair Inc.)

Dr. Bash's Abilities and Issues with Current Device

Another issue to be addressed will be the grip strength of the user and how to develop a way to pull the adaptive athlete behind a boat. Only C7-8 quadriplegics can grasp anything without the use of electrically stimulating help. Dr. Bash has the ability to use his hands and grasp certain objects but ideally would like to have something to assist him, especially during the start when he is mostly submerged and drag is the greatest. He has strength in his upper arms and hands, but atrophied fore arms as a result of his injury. He also has issues with the seat size and cushion. Since there are not straps, belts, or bindings attaching Dr. Bash to the chair, he bounces around while riding, especially when crossing the boat wake. This bouncing causes compression and discomfort in his spine. Additionally, the steering system should be more responsive than that of the current design; currently, Dr. Bash must lean excessively for the ski to carve at a desired rate (Figure 4).

Figure 4. Dr. Bash using the current Ski-Seat apparatus

Design Considerations

To mitigate drag and safety concerns, several design and manufacturing standards were analyzed. The material used for the framework must be a metal or composite that is lightweight, strong, and resists corrosion. The old design is built around a steel frame, which is both heavy and corrodes very easily. It already has severe rust and pitting on the leading T joint mechanism as well as in the screws and the joint mechanisms. Over time, this type of rust will lead to frame weakness, which could possibly lead to critical system failure. New material choices are required to ensure that the new design will not have issues with corrosion or weight while maintaining strength.

Since the apparatus will need to be stored during transportation, it must be easy to take down and be of a reasonable weight for carrying. There are many manufacturing processes available and all will be considered. Each presents its own advantages and disadvantages. Welding would provide rigidity but not allow for takedown. Bolting members together would make for simpler take down but may make the apparatus more complicated and introduce sharp corners. A lot of the processes of manufacturing will depend on the material used in our final design.

Related Patents

Current patent searches show that there are similar products on the market. One of these products (Figure 5) is a foldable seat apparatus which can be attached to either a snow or water ski for adaptive use by paraplegic athletes. Another product, the Ski Seat structure (Figure 6) includes a front pole mount. Something similar to this could be utilized in our design to help with the athlete's reduced grip. Another possible solution for this could be the inclusion of handlebars in the design, comparable to the ski sledge (Figure 7). Another possibility is that an increase in the system's buoyancy will reduce the frontal area of the submerged apparatus, thus decreasing drag and making it easier for the rider to grip the handle.

Table 1. Patents researched and referenced during background research

Patent Reference	Patent Number	Patent Name	Reason Why Design is Interesting
Figure 5	US3778077 A	Ski with collapsible riding seat	Shows method of collapsing design for storage
Figure 6	US4921274 A	Ski Seat structure	Includes a front pole mount, which could provide inspiration for a reduced grip apparatus
Figure 7	US7762564 B2	Ski sledge	Includes front handlebars which could help with reduced grip

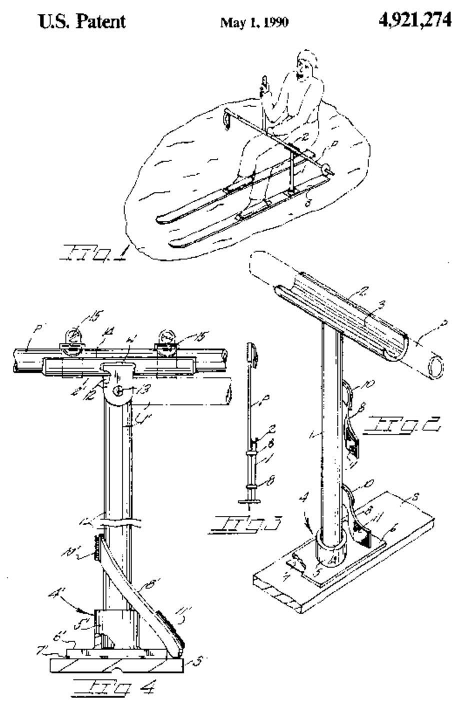
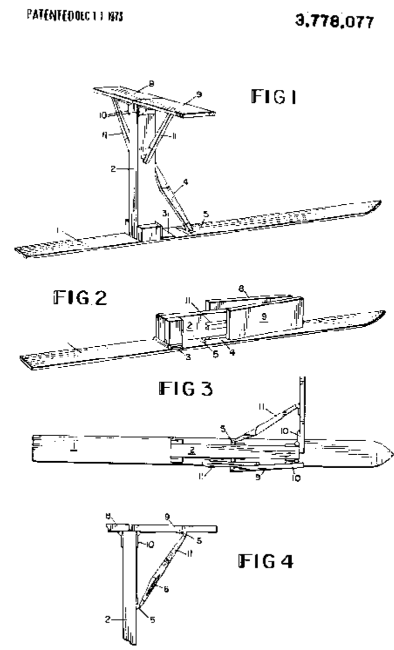


Figure 6. Ski Seat structure (US Patent No. 4921274A)



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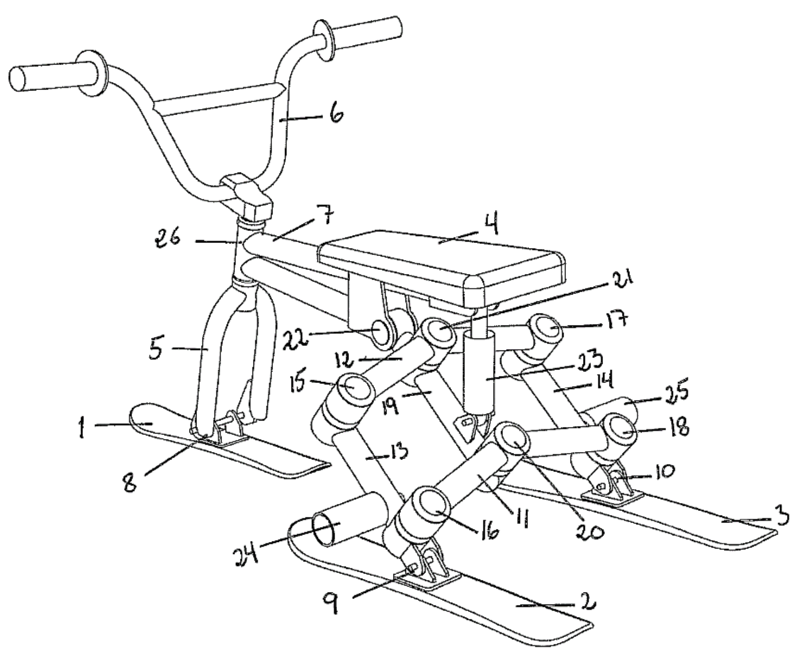


Figure 7. Ski sledge (US Patent No. 7762564B2)

Objectives

Problem Statement:

The recipient of our project, Dr. Craig Bash, is a partial quadriplegic veteran who enjoys waterskiing in his free time. He does not have use of his legs, and has partial use of his arms. Dr. Bash's grip strength is limited, so we will design a system that will mitigate drag so that there will be less resultant force on his hands. Currently, Dr. Bash uses a functional sitting-style water ski, though it is somewhat lacking in many ways: his current setup is rusting, heavy, aesthetically unappealing, and not as responsive to movement as Dr. Bash would like. Similarly, it creates excessive drag at the start of every run, which strains Dr. Bash unnecessarily. A new type of waterski system for Dr. Bash is needed to improve overall usability, specifically by decreasing the weight and drag. The system that will be designed with regards to Dr. Bash's physical capabilities and can also be used by people around the world who have similar physical conditions, people who are paralyzed below the waist, and anyone interested in using a sit-ski system on the water.

Quality Function Deployment:

The final recipient of our project, Dr. Bash, decided that he is not satisfied with his current sit-ski setup, and that he would like the new design to have the following traits, which are listed in our QFD House of Quality (Attachment 1) as the Customer Requirements:

- Lighter weight than current setup
- Comfort
- Interchangeability with different skis
- Must float nose-up with 30 – 40lbf on seat
- Must structurally support 250lb rider
- Collapsibility
- Stiffer steering base than current setup
- Does not corrode
- Aesthetically appealing
- Has no sharp corners
- Better carving ability than current setup

Since the Customer Requirements must be met, we came up with ways to measure the success of our design. The "Engineering Specifications" (listed at the top of the QFD

diagram) are specific measurable traits that we came up with in order to properly measure how well our design meets the Customer Requirements. Using Dr. Bash's input and application of engineering principles, our team came up with specific values for each of these specifications, labeled on the QFD diagram (near the bottom) as the "Targets." The Engineering Specifications and their corresponding Targets are listed in the table below.

Table 2 - Engineering Specifications Table

Spec. #	Parameter Description	Target	Tolerance	Risk	Compliance
1	Weight	25lb	Max.	H	A
2	Max. collapsed dimensions (WxHxL)	24"x30"x9"	Max.	M	A
3	Universal mounting system	Usable with current water skis on market	Go/No-Go	M	S
4	Buoyancy	Neutral Buoyancy	Min.	H	T
5	Fatigue life of center bar	200,000 cycles	Min.	M	A
6	Time to set up/collapse	10 minutes	Max.	M	T
7	Number of sharp corners	0	Go/No-Go	M	I
8	Yield stress of screws mounting shoes to skis	36,000 psi	Min.	L	A
9	Yield stress of pins at ankles	2,547 psi	Min.	L	A
10	Width of aluminum of shoes and feet at ankle joints	0.084 in	Min.	L	A
11	Presence of zinc sacrificial anode at junction between chrome moly main tube and aluminum section of frame	1 per connection	Go/No-Go	M	I

The risks associated with each parameter are noted in the table as Low ("L"), Medium ("M"), or High ("H"), based on how likely it is that our design could fail to meet that specific parameter. The last column of the Engineering Specification Table, the "Compliance" column, refers to the methods that will be utilized in order to determine if our design has met the target specifications. The different methods referenced in the table are: Analysis ("A") Testing ("T") Similarity to Existing Designs ("S") and Inspection ("I"). Specifications that must be analyzed are ones that should be calculated before the prototype is manufactured, in order to ensure compliance with the specifications. Testing will occur once the prototype is built, and these parameters will be tested using experiments and functional usage trials of the prototype. Parameters that must be similar to existing designs are ones that must be able to interface with existing products on the market, such as different brands of water skis. Inspection covers parameters that should be taken into consideration when designing and building the prototype, and will be inspected for compliance once the prototype is manufactured and ready to be tested.

Once the engineering specifications and their associated targets were determined, we used our engineering judgment to decide which direction indicates improvement for each engineering specification (the corresponding row lies just above the engineering specifications at the top of the QFD diagram). If a larger value is desired, the "▲" symbol is used, and "▼" is used to denote targets that should be as low as possible. If there is a specific quantitative or qualitative target, the "◊" is used.

Next, we decided which engineering specifications are interrelated using the pyramid at the top of the QFD Diagram. If there is a positive correlation, such as when one specification goes up, the other must rise as well, a "+" is used in the box where the two specifications' diagonal columns intersect. If there is a negative correlation, a "-" is used, and if there is no correlation, the box is left blank.

In the middle section of the QFD Diagram, we denoted how well the different engineering specifications correlate with each customer requirement, and how strong the correlation is. If an engineering specification heavily correlates with a certain customer specification (for example: "Weight" and "Lighter weight than current setup") there is a

"●" in the square where the customer requirement's row and the engineering specification's column intersect. If there is a mild or moderate correlation (for example: "Seat Size" and "Lighter [weight] than current setup"), there is a "○" in the appropriate box. If there is no correlation, "▽" is used.

The relative importance of each customer requirement was determined on a scale from 1 to 10, and is used in conjunction with the correlation symbols to determine the "Relative Weight" of each requirement, which is depicted on the left side of the QFD Diagram, directly next to their corresponding graphical representations (in bar chart form). Near the bottom, the "Technical Importance Rating" of each engineering specification is determined in a similar method, along with the "Relative Weight" and graphical representation of each specification's corresponding weight. For further information, refer to the QFD chart in Appendix D.

<u>QFD to Engineering Specifications</u>

After completing this section of the QFD House of Quality, we noticed that some of Dr. Bash's specifications correlate to multiple engineering specifications, which we can test and control. These are the specifications that we will have to consider the most while undergoing the design process.

The system's collapsibility correlated with the largest number of engineering specifications; it is affected by the system's maximum collapsed dimensions, universal mounting system, and time to set up/collapse. The Ski Seat that Dr. Bash currently uses does not easily collapse, and does not fold down to a subjectively manageable size. Since collapsibility is an important factor in a space-occupying device that will be transported to and from several locations and stored in finite spaces while not in use, we will have to pay special attention to our aforementioned engineering specifications.

After analyzing the different engineering specifications, we saw that buoyancy affected the second-largest number of Dr. Bash's requests. It relates to how well the system will float a 150lb rider, and how much lighter the system is, when compared to the current setup. The width of the aluminum shoes and feet at the pivoting ankle joints affected the

largest number of Dr. Bash's requests. This parameter affects how well the system will support a 250 lbf rider, the stiffness of the steering base, and thus, the carving ability of our system. In order to account for this, we over-designed our components with respect to this parameter. In addition to factors of safety regarding stress, it will also assist in avoiding unwanted deflection at the ankle joint, which could make the system difficult to control.

Similarly, the universal mounting system affects how well our apparatus may interchange with other sets of skis, and how collapsible the entire system is. Both of these factors are important for the sake of Dr. Bash's convenience, so we must make sure to incorporate a system that will allow our apparatus to easily interface with any ski set of Dr. Bash's choice.

In the "Current Product Assessment" section at the right side of the QFD Diagram, current products are compared to each other with respect to the customer requirements. We used the Ski Seat (which is the product that Dr. Bash has been using) as a datum, and compared it to Liquid Access's *Outrigger* and *Competition Sit-Ski*. Each product is evaluated for how well it meets each customer requirement on a scale from 1 to 5. This generates a chart on the right, where the line farthest to the right displays the most desirable traits. In our comparison, the Ski Seat best met the requirements. At the bottom of the QFD Diagram, the same products are evaluated on how well they meet the targets of the engineering specifications, and a similar chart is generated below, where the line closest to the top represents the most desirable product, which is the Ski Seat once again.

Management Plan

In order to better prepare for appropriate time management and project deadlines, we have developed a timeline with our projected completion dates for project deliverables, shown in Appendix E.

We planned to be complete with the above tasks by May 30, 2015, in time for the final design expo. In terms of task distribution, the ideation process took place as a group, and Ashley lead the report finalization and presentation requirements for all further reporting. Design analysis was led by Justin, and CAD modeling was led by Mark for the

duration of the project. Toby was responsible for ordering parts and Mark was responsible for initiating the building phase. Justin, Toby, and Mark were responsible for the overall manufacturing. The testing phase that followed was led by Justin and Ashley, and the final report was led by Ashley. This schedule has took into account holiday periods, including Thanksgiving, winter and spring breaks, when catch-up work was completed, but no other considerable progress was expected from the group. Though each individual is in charge of certain portions, everyone was responsible to help each other when able to and when it is needed. For a more specific breakdown of team member duties, please refer to Table 3.

Table 3. Project Responsibilities by Team Member

Team Member	Responsibilities
Ashley	• Report Writing • Presentations • Administration
Justin	• Analysis • Manufacturing
Toby	• Communications • Administration • Manufacturing
Mark	• Design • Manufacturing

Design Development

In order to determine the best solution for all of our engineering specifications, we identified the following functions for our waterski device:

- Enable skiing
    - Reduce drag
    - Improve grip
    - Increase control/carving
- Improve safety.

    - Absorb shock
    - Avoid incidental injury
- Increase buoyancy
- Decrease storage size
- Aid user
    - Improve grip
- Support rider

We thought of various ideas, both individually and as a group, through our brainstorming and brainwriting activities for each of the following functions: increase control/carving, absorb shock, decrease storage size, and support rider. Once we had drawn out some of these ideas and discussed as a group, we began testing the operation of these ideas with rough prototypes. We used Legos, foam, Popsicle sticks, straws, and Play-Doh to design small scale, functional models of our ideas. In doing so, we were able to determine which ideas would work and which did not work as well, reducing the number of ideas we had for each function accordingly. Next, we used Pugh matrices to determine the best solutions for each of the individual functions. These diagrams, which can be found in Appendix A, were used to find solutions for seat comfort, steering, universal mounting systems, and collapsibility. After sharing our matrices and reviewing the practical feasibility (i.e. ability to provide sensation of skiing, customer comfort level and expectations, and safety concerns in extreme situations) of the top three solutions for each function, we looked to incorporate the ideas for each function together using a morphological attribute matrix (Appendix B). In doing so, we were able to determine that some of the individual function solutions should be combined, such as the caged and molded seat ideas. Once we had condensed these ideas, we listed out all of the feasible combinations and began discussing as a group which ideas we thought would work. From this discussion, we determined four top ideas, which we have further analyzed here.

Proposed Designs

Option 1: Compressed Ski Seat Steering; Molded Seat; Side-to-Side Collapsibility; Pins for Universal Mounting

This system incorporates our ideas of pins for universal mounting, a molded seat, side-to-side collapsibility, and the compressed Sit-Ski steering mechanism.

The universal mounting system works by having pins that connect a base, which is rigidly attached to the skis, to a square extrusion. There is a set of holes in the base and the square extrusion that are aligned horizontally for use with a pin. The pin will

be easily inserted, and can be easily removed if direct force is applied. The need for direct force in removal of the pins will keep this system stable and intact while in use, but will allow for disassembly and storage with minimal effort. Identical pins will be used in each pin connection in order to decrease assembly time. Square extrusions are used in order to prevent unwanted rotation of the members of the steering system, thus reducing undesired wear of the pins and holes.

The compressed Ski Seat steering system will be controlled by tilting of the seat, in order to most accurately mimic the motion of a waterski that is operated by a standing rider. The steering mechanism will include small raised struts that will be used to tilt the inner ski slightly more than the outer ski, because the inner ski will follow a smaller radius of curvature when going around turns. It will be connected to the skis and rotate about pin joints in a manner similar to that of the Ski Seat, but will reduce the risk of injury to the rider. The "compressed Ski Seat" steering system will involve bars that only go under the legs of the rider, so there is a minimized possibility of the rider getting hit by the waterski system when falling forward or backward. The rigid mounts of the universal mounting system will allow for the rider's weight to be distributed properly, even when the steering system does not extend in front of the rider's knees.

The seat will be molded with a ridge in the middle and raised sides for increased control and a decreased chance of the rider slipping off the side of the seat. For increased comfort, the seat will be made of a soft material that will dampen vibrations and absorb shock from jumps, so that the rider's spine undergoes less stress than it would with the current Ski Seat system.

When the system is not in use, it can be easily disassembled by removing the pins from the mounting system and folding the legs of the steering mechanism upwards toward the center. The legs will inwards from the sides, towards the center of the mechanism. This way, when they are rigidly attached to the mounting system, they will not be able to tilt forward or backward. This design is shown in Figure 8.

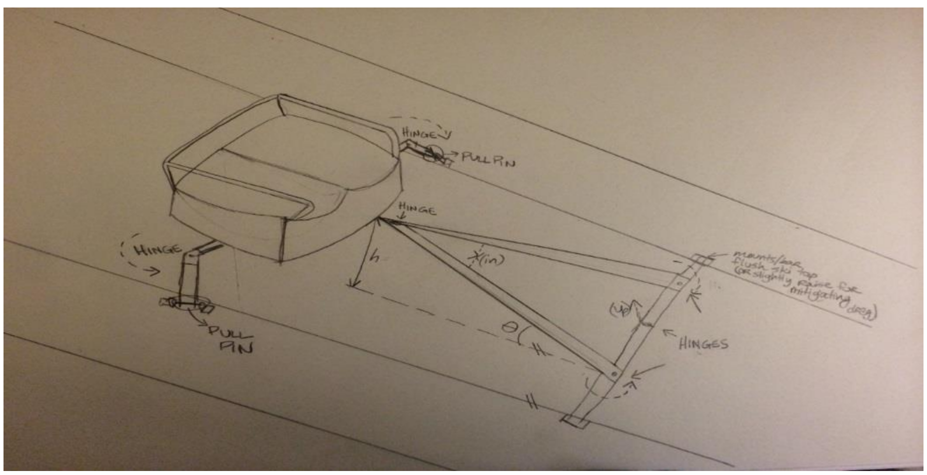


Figure 8. System Design Option 1: Compressed Ski Seat Steering; Molded Seat; Side-to-Side Collapsibility; Pins for Universal Mounting

Option 2: Raised Steering, Molded Seat, Side to Side Collapsibility, Pin Mounting

This design starts with a seat that is molded and contoured to keep the rider on the seat while turning. The frame is attached to the skis via a mounting system that utilizes pins. There will be a top mount (called a foot) that stays attached to the frame and has a through hole in it, and a bottom part (called a shoe) that will stay attached to the skis via adhesive or screws that also has a through hole in it. When the foot is inserted into the shoe,

the through holes will align and a pin can be inserted to stop the foot from coming out of the shoe. The frame will be attached to each ski behind and in front of the rider. The frame is collapsible in 4 different places. Each leg, once removed the feet are removed from the shoes, will be collapsible via hinges. The hinges will cause the legs of the frame to swing in, like dead bug legs. In order to turn the skis while riding, two raised steering bars will be attached to the skis. The bars will contact the shoulders of the riders. In order to turn, the rider will simply lean to the side that they wish to turn towards. The rider’s shoulder will contact the steering bar and rotate the skis. The steering bars will also be attached via the universal mounting system with modified feet and shoes. This design is shown in Figure 9.

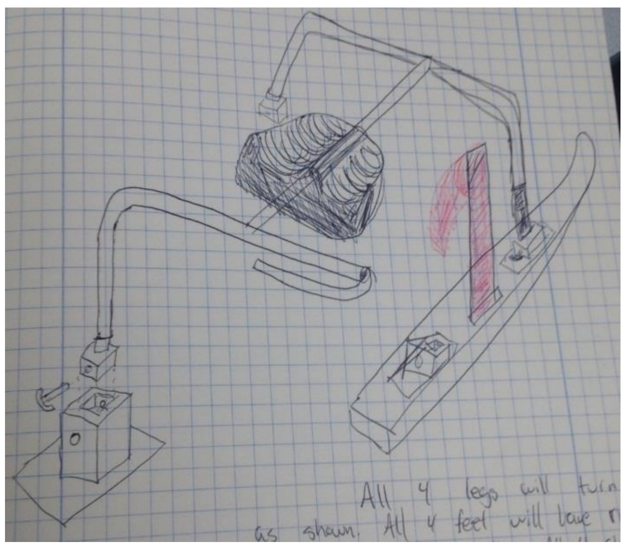


Figure 9. System Design Option 2: Raised Steering; Molded Seat; Side-to-Side Collapsibility; Pins for Universal Mounting

<u>Option 3: Raised Steering, Molded Seat, Front-to-Back Collapsibility, Pin Mounting</u>

This design incorporates a new steering system when compared to the original design as the major visible improvement. The new steering mechanism consists of two structures mounted on the skis which bend in and up, ending around the height of the rider's shoulders. They also extend backward approximately one foot. Their purpose is to enable

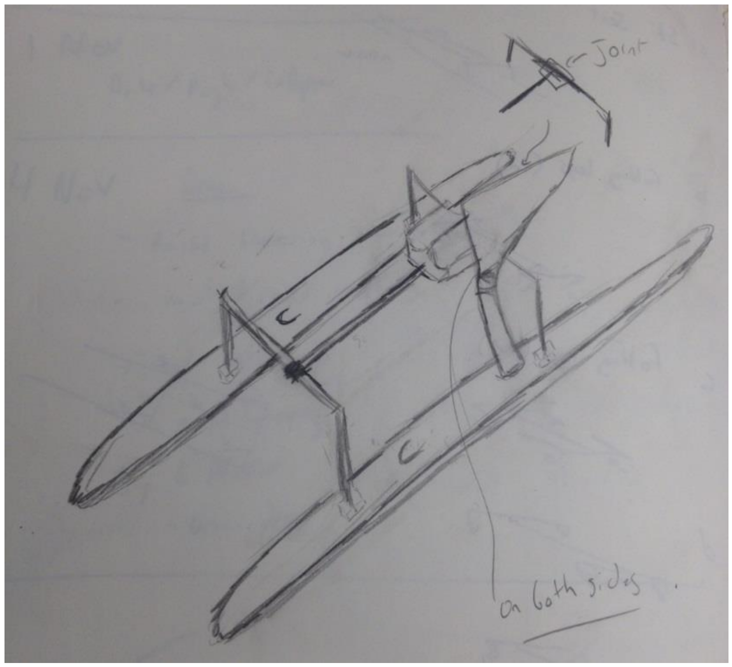


Figure 10. Sketch of Final Design Option 3

the rider to turn the device via body lean, as opposed to lean on the seat itself. The seat itself is improved as well- it is molded to fit well under the rider's legs as well as cage in their lower torso. This allows much better grip to the seat so the rider stays centered much more easily. The final improvement in this design is the improved collapsibility, derived from the pin-based mounting system. The skis are attached with a pin-based mounting system, which allows for integration of any type of skis to the overall system. By having easily detachable skis from the frame, this allows the frame to have fully collapsibility. This is realized via a push-button system on the legs which allows them to fold up towards the center of the system. This design allows for interchangeable parts, quick setup and takedown, and agile movement. This design is shown in Figure 10.

Option 4: Compressed Ski-Seat; Molded Seat; Front-to-Back Collapsibility; Pins for Universal Mounting

This system is similar to the currently used design with several improvements for easier use. One such improvement is the compressed frame design, meaning the bars located in front of the seat will be redesigned so that they are at a lower level comparable

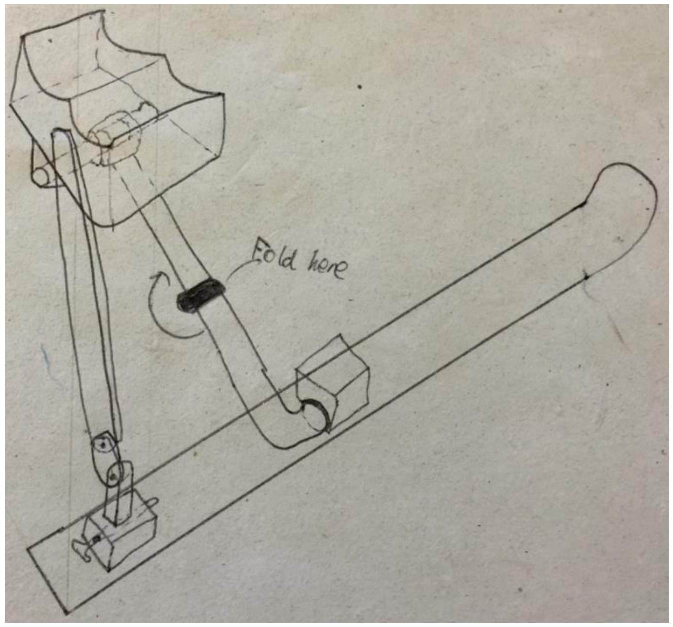


Figure 11. Sketch of Final Design Option 4

to the rider's location in order to prevent contact injuries during a fall. This new design would also involve moving the drivetrain underneath the seat, so that the ski is more responsive to the movement of the rider. This change in drivetrain location, along with the addition of a caged seat will give the rider control of the steering system by allowing him to lean further in each direction, while still retaining control and contact of the seat--something the previous design lacks. The front-to-back collapsibility would make the system smaller for storage. The system would be collapsed by folding each ski in towards the middle of the frame. The system would also include a universal mounting system, in which the frame would be connected to each set of skis by a set of pull pins, so it could easily be removed and then remounted on a different set of skis (Figure 11).

Design Assessment

In order to assess the final four designs, we utilized a decision matrix (Table 4). To determine the importance of each criterion, we used a method of pairwise comparison.

Further details regarding the use of pairwise comparison, as well as the explanation of design ratings for individual criteria may be found in Appendix C.

Table 3. Final Design Matrix for Top 4 Options

	Option 1: Compressed Ski Seat with Side to Side Collapsibility	Option 2: Raised Shoulder Steering with Front-to-Back Collapsibility	Option 3: Raised Shoulder Steering with Side-to-Side Collapsibility	Option 4: Compressed Ski Seat with Front to Back Collapsibility		Option 1	Option 2	Option 3	Option 4
					Weight				
cost	0	-1	-1	1	5	0	-5	-5	5
weight	0	-1	-1	0	16	0	-16	-16	0
durability	0	-1	-1	1	9	0	-9	-9	9
size	0	-1	-1	0	5	0	-5	-5	0
agility/control	0	1	1	0	20	0	20	20	0
manufacturability	-1	-1	0	1	2	-2	-2	0	2
versatility	1	0	0	1	18	18	0	0	18
buoyancy	0	1	1	0	9	0	9	9	0
shock absorption	0	1	1	0	7	0	7	7	0
aesthetics	0	-1	-1	0	9	0	-9	-9	0
Total:						**16**	**-10**	**-8**	**34**

Once we completed the design matrix, we did a practicality check on our results and agreed that Option 4 best meets the customer's needs.

Preliminary Assessment of Chosen Design

Our chosen design works similar to the current Ski Seat design, with a few improvements. These improvements allow for enhanced safety and function of the device. One of the first improvements is the restructuring of the current Ski Seat frame. The current design could pose a threat to rider safety, causing him to hit his legs on the front bars if he accelerates forward during a fall. To prevent this, we have changed the design to include a lowered, Y-shaped front bar structure. The new design will also feature a molded and caged seat for improved rider stability and greater control during carving. In order to aid with

collapsibility and adaptability, a universal mounting system has been implemented in our new design.

The universal mounting system has a “shoe” piece that attaches to the pre-threaded holes in the skis, so that the skis will not be damaged by our system, and so that the system can be adapted to several different pairs of skis that are currently on the market. Each “foot” of the universal mounting system is connected to a “shoe” while the system is in use, and can be easily removed for rapid collapsibility. The shoe also connects to the support bars and the steering strut, which will adequately connect the whole system, while allowing proper rotational motion.

In addition to the universal mounting system, locking hinges and pin joints will be used to aid in the collapsibility of the system. They are implemented in a way that allows the support bars and steering strut to fold front-to-back or back-to-front, towards the center of the steering system, once the universal mounting pins are removed. This will allow for decreased storage size and easier transportation.

The use of a Y-shaped front support bar will slightly decrease the weight of the assembly, and it will reduce the risk of shin injury while the device is in use, without negatively affecting the responsiveness of the steering system.

In order to maximize the responsiveness of the steering system, which is a four-bar linkage, the section of the foot that attaches to the steering strut will be lengthened. This will allow for “tighter” turns of a smaller radius to be made with less rotation of the seat than the current Ski Seat requires.

While our design (Figure 12) improves performance of the system, it will also improve comfort through the use of a molded seat. The seat will be thicker and have more surface area than the seat on the Ski Seat, and will be molded to the contours of the Gluteus Maximus muscle. This design will allow the seat to absorb shock and high frequency vibrations transferred through the steering system, and will allow the rider to grip the seat more easily while water skiing.

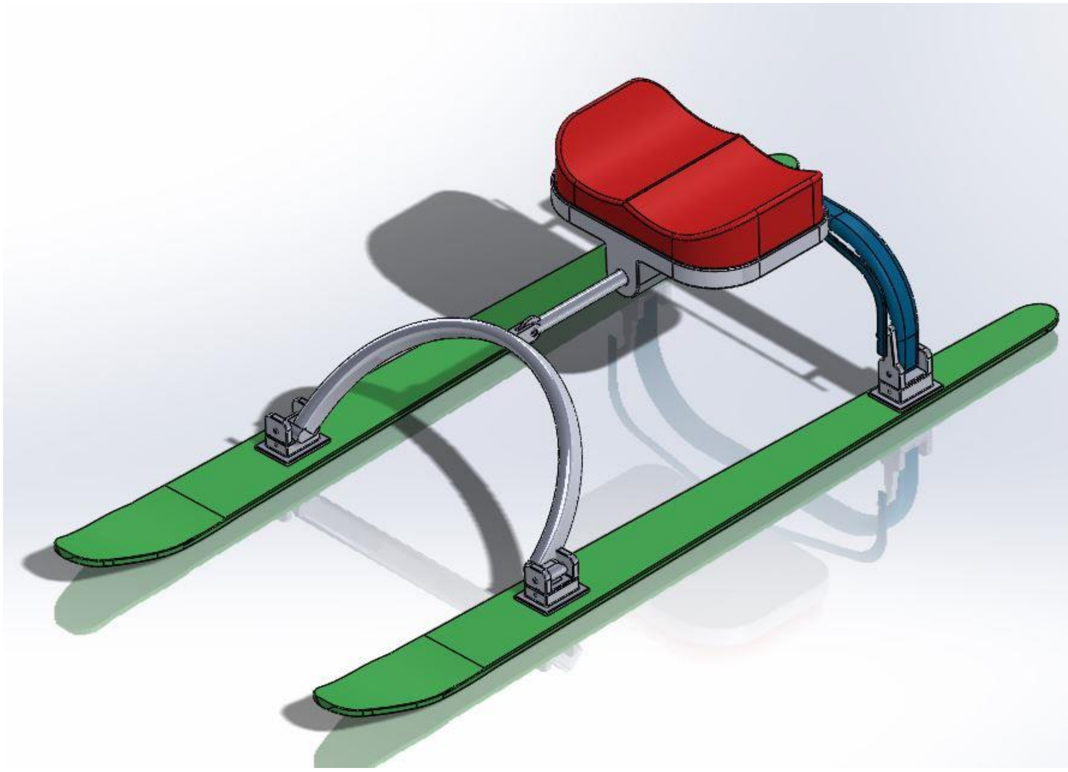


Figure 12. Isometric of Final Design Concept

Final Design

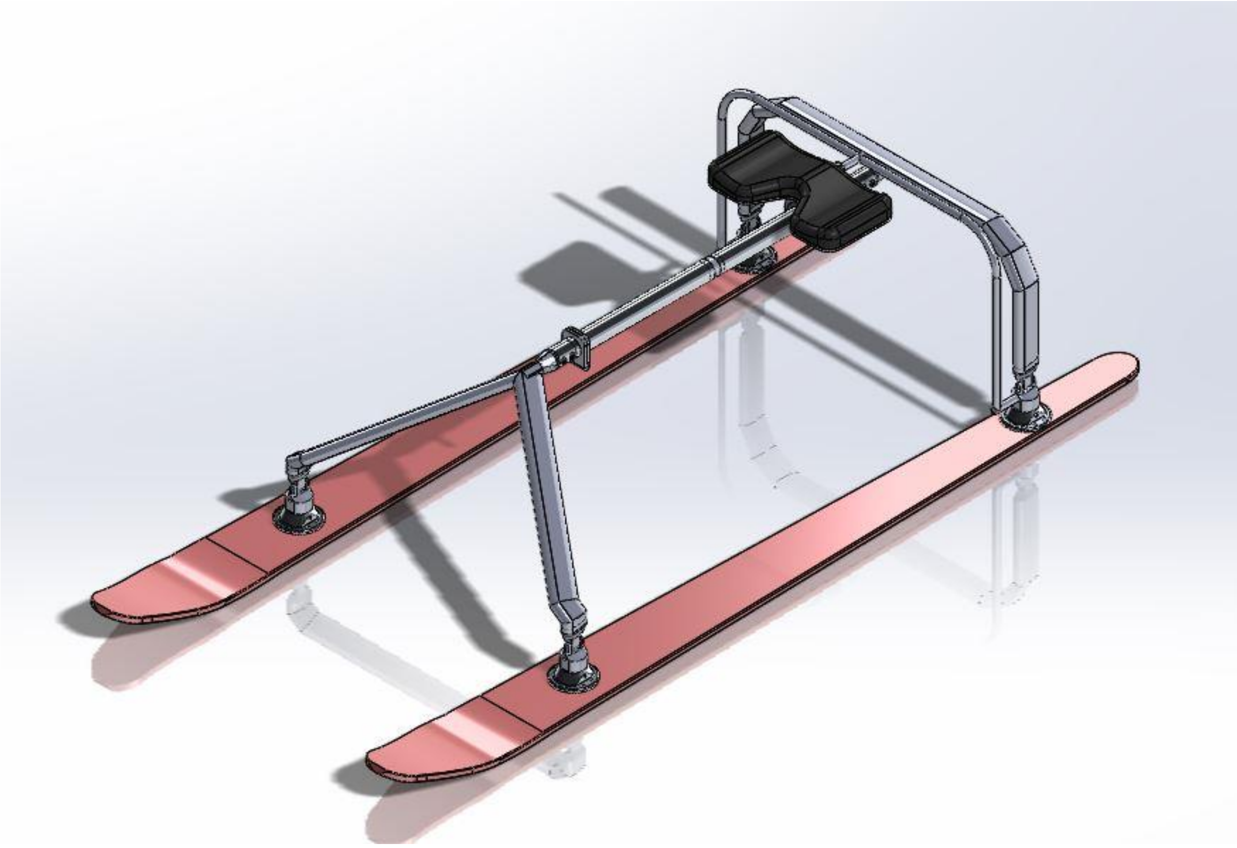


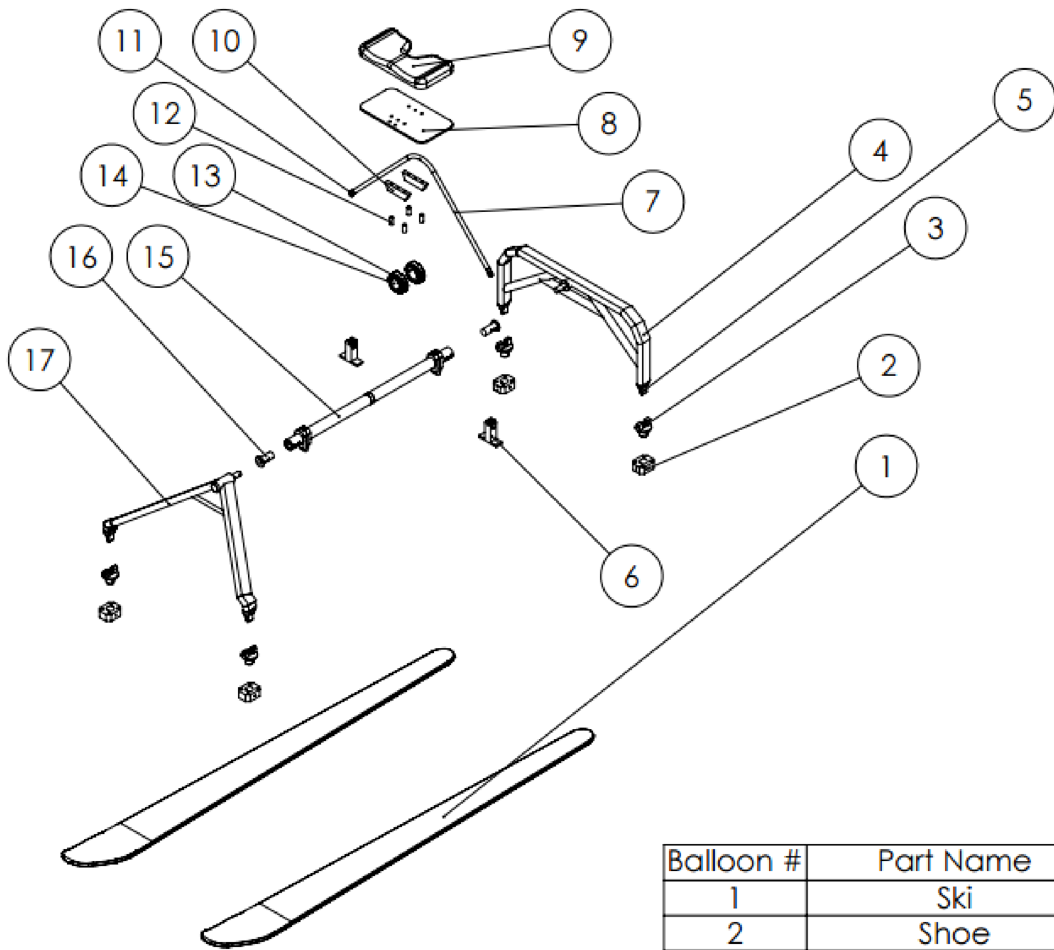
Figure 13. Final Design Original Look and Layout

The final design, shown in the figure above has many improvements upon the old design. The biggest and most noticeable change is in the tubing. Instead of circular steel tubing we chose to use airfoil-shaped aluminum tubing in order to reduce the drag and improve the overall aesthetics. The tubing that the seat rotates around, however, will still be circular tubing due to the hinges we are using, as detailed later. Another main change was the addition of hinges. As seen along the central frame, the hinges allow for the frame to be folded twice, minimizing the storage and transportation space needed. The final big change was in the connection of the tubing. We opted to have the frame pieces welded together to make the three large components. This cuts down on the fasteners needed and makes the fasteners we need to use much more low profile, and out of the direct flow of the water.

As discussed further in the Manufacturing section, the final design was modified slightly to improve machinability. After these changes, the final design looked similar to

Figure 14 below. These changes allow for similar form to the original while maintaining function, but with simpler manufacturing processes, making the final design cheaper to manufacture and easier for the team to build in a timely manner.

Figure 14. Modified Version of Final Design



Balloon #	Part Name	Quantity
1	Ski	2
2	Shoe	4
3	Foot	4
4	Back Tubing	1
5	Ankle	4
6	Steering Bracket	2
7	Steer Bar	1
8	Seat Plate	1
9	Seat Cushion	1
10	Height Spacer A	2
11	Rod End	2
12	Height Spacer B	4
13	Shaft Collar	2
14	Seat Bushing	2
15	Central Frame	1
16	Connection Bushing	2
17	Front Tubing	1

Figure 15. Final Design Exploded View

The exploded drawing above shows how the entire system goes together. Balloon 2 corresponds to the shoe, part number 202. These are attached to the skis, balloon 1, part number 400, with the use of potting inserts, part 505, in the skis. The potting inserts are

epoxied into custom drilled holes in the skis. The frame attaches to the shoes via the feet, balloon 3, part 201. Once the foot is in the shoe, a stainless steel pin, part 504, will be inserted to secure the foot into place. All four feet and shoe combinations will need the pins to be held together.

The front tubing, balloon 12, part 100, is made up of 9 separate pieces that are welded together. The back tubing, balloon 4, part 101, is made up of 10 separate pieces that are welded together. These two parts are attached to the center frame, balloon 11, part 102, via 2 screws, part 501, each that have lock nuts, part 507, and flat washers, part 506, on them to hold them in place. Between the front tubing and central frame is a central bushing, part 300, made of a hard plastic. The central bushing is to prevent any galvanic corrosion that would be caused by the steel tubing of the central frame and the aluminum tubing of the front and back tube sections. The back tubing, balloon, 6, part 101, is attached likewise. The central frame, as mentioned above, is made of steel tubing. The reason for this is that the central frame also has hinges that were donated from Brompton Bicycles, a folding bicycle company. These hinges came with steel tubing already attached via an internal and external braising process. The central frame was made by cutting these tubes to length and welding them to a central I joint. The central bushings were inserted into the ends of the tubes and bolted through to attach the front and back tubing, as previously mentioned. The seat cushion, balloon 7, part 401, was a purchased part that is designed to absorb shock and is contoured to hold the rider centralized. This is attached to the seat plate, balloon 8, part 203, via a two-part epoxy. Welded onto the seat plate are two shaft collars, balloon 10, part 402. These surround the seat bushings, balloon 9, part 301, which will rotate around the central frame. These are made out of a wear resistant, self-lubricating plastic. Attached to the back of the seat plate is the steer bar, balloon 6, part 103 which is made out of straight tubing. The steer bar attaches to the seat and the steering mounting brackets with pull pins, part 500.

In order to set up the entire system, the user will have to close the hinges, and tighten the screws in the hinges to lock them. Then they will have to insert the four feet into the requisite shoes that will already be attached to the skis. Once the pins are attached, the user

will have to insert the three pins through the steer bar into the seat (1) and each steering bracket (2). Once these steps are complete, the system is ready to ride. In total there will be seven pins and the tightening of two bolts between the user and waterskiing.

Table 4. Assembly Supplemental Bill of Materials

Part No.	Description	Quantity Needed
100	Front Tubing	1
101	Back Tubing	1
102	Central Frame	1
103	Steer Bar	1
200	Ankle	4
201	Foot	4
202	Shoe	4
203	Seat Plate	1
300	Central Bushing	2
301	Seat Bushing	4
400	Ski	2
401	Seat Cushion	1
402	Shaft Collar	2
500	1/4-20 Should Screws with 5/16" shoulder dia, 2" length	3
501	1/4-20 Partially threaded socket head cap screws	4
503	6-32x1/4" low profile socket head cap screws	16
504	Stainless steel pins	4
505	Potting Inserts	16
506	1/4" Flat Washers	11
507	1/4-20 Lock Nuts	4
508	#6 Washers	16

Materials Selection

In order to decrease weight, drag and corrosion of the frame, the new frame is be made with 6061-T6 aluminum airfoil piping. Additionally, the commercially purchased skis are made of a foam core, carbon fiber and fiberglass composite layup—increasing performance and buoyancy compared to the current solid wood ski design. The front and

back connecting joints will also be turned on a lathe from of 6061-T6 aluminum, the central I joint was turned on a lathe from steel. The hinges, which allow the frame to fold, are made from steel and provided by Brompton Bicycles. A 1/4 inch piece of aluminum sheet metal was shaped to form the seat plate, which is bolted to aluminum shaft collars around the central bar.

To prevent the occurrence of galvanic corrosion, a plastic sleeve was be placed in either side of the center bar which the aluminum portions of the legs may then fit inside. This three piece assembly was then be fasted with zinc-coated stainless steel screws. The plastic sleeve provides a barrier between the chromoly and the aluminum and the zinc coating on the screws provides a sacrificial anode, preventing corrosion from occurring on the frame.

Motion Analysis

Solidworks was used to create a motion analysis in order to determine the height at which the steering mechanism should be attached. An extended steering bar attachment point was created with sixteen different options at which the steering response to seat angle could be examined and quantified. Figure 16, below, shows the steering response when attached to the bottom pin, and Figure 17 shows the steering response when attached to the top pin. Because the seat angle changes the horizontal displacement of the steering mechanism, the further down the steering mechanism is attached to the skis the greater the resultant angle of the skis will be. Using this analysis, we determine that the best possible design for Dr. Bash would be an attachment point as near to the ski as possible to create the most responsive steering as possible.

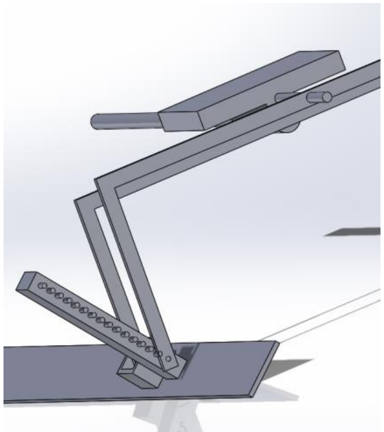


Figure 16. Bottom Pin Attachment

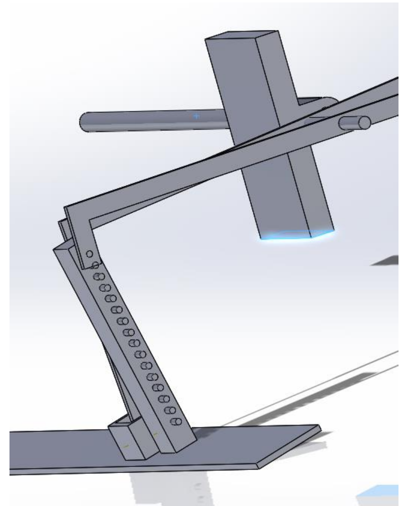


Figure 17. Top Pin Attachment

(Note: The long bar shown in the above images is for motion analysis only and will not be included in the final prototype or recommended design.)

Stress Analysis

In order to ensure that our design will not fail, we have completed MATLAB code for the stress analysis of the seat plate and the frame. The cross-section of the airfoil tubing is approximated as an ellipse. In order to ensure the design will hold up under worst-case conditions, we chose a factor of safety of 2.5. We also designed for a 250 pound force—roughly 100 pounds more than the weight of our customer. Using data for 6061-T6 aluminum, we determined that our frame has a design factor of 2.65.

Several points of interest were analyzed in order to ensure factors of safety within the system we designed. First, the stresses in the airfoil tubes that comprise the frame were analyzed. The load applied to the tubes was 250lbf, but our customer only weighs 150lbf. This acted as an implied safety factor, just in case somebody else uses the system in the future, or if the user jumps the wake. The cross-section of the actual tubes is a hollow airfoil shape, but a hollow elliptical cross-section with similar dimensions was analyzed in order to allow for simple analysis. The maximum bending stress in each airfoil-shaped tube was calculated, and resulted in a design factor of 2.65 using the 250lbf load, and a design factor of 4.15 was calculated using our customer's weight. With these design factors, our system should remain stable without failure.

Subsequently, the stress in the chrome-moly center bar was calculated. Since this bar will be subjected to repeated loads, the repeated load was calculated to be 15,868psi. This stress was used to find the fatigue life of the bar, which was 3.03*10^16 cycles. This is far greater than the 200,000 cycles maximum that we strove to achieve, so this center bar will suffice.

Next, seat plate stress was analyzed. The aluminum seat plate conforms to the perimeter of the Air Chair seat cushion, whose thinnest point is at the middle, with about a 3.5in width. The force caused by half of the rider's weight on each side of the seat's pivot was used to calculate the bending moment at the center of the plate of 1/4in thickness. Using a 250lbf rider (and a 125lbf load on each side of the pivot), a design factor of 3.03, was achieved, and using our customer's weight resulted in a design factor of 4.74.

Stress was then calculated for the screws that will hold our system's shoes to the platform of the ski. The minimum diameter of these screws (0.13in) was determined by measuring the inner diameter of the existing threaded holes in the skis. This diameter was used to calculate the screws' minimum area, and shear force was calculated. A shearing force of 492lbf would be needed to shear one screw, but our system is using four screws per shoe, so 1968lbf are needed to truly cause the system to fail. The rider will have to support this shear force with his hands because of the direction that the skis are oriented in the water. With his diminished forearm strength, our customer will not be able to sustain the force necessary to shear these screws, so these screws (#10-32 machine screws) will be used.

Lastly, the components of the ankle connection were analyzed with a 250lbf load. Our analysis involved calculations of shear stress in the pin and bearing stress in the foot and shoe. Shear stress in the pin was calculated using the double-shear loading case, and proved that the steel pin must have a diameter greater than 0.0665in. In order to create less bearing stress, avoid unwanted deflection, and use standard pin sizes, our calculations continued with the use of a 0.25in steel pin. The minimum width (to avoid bearing stress failure) of the Aluminum foot and shoe were calculated, and it was proven that the width of the shoe and foot must each be greater than 0.0833in for a design factor of 6. This high

design factor was chosen because static loads can be greatly amplified when impact is considered, but due to the nature of energy absorption from the water, seat cushion, and rider, a confident impact loading calculation could not be undergone. Additionally, the high design factor inherently makes the system stiffer in the lateral direction, which is ideal because our customer complained that his current system deflects too much, which makes his current system less responsive than he would ideally prefer.

Our calculations and factors of safety have allowed us to safely over-design our system for static loading, and thus compensate for moderate impact loading. As can be seen from our analysis, our system will not fail under standard conditions of use.

For further detail on the calculations involved, please refer to our MatLab code in Appendix K.

Comfort Analysis

In order to meet the needs of our customer in terms of spinal compression, we have chosen an off-the-shelf Air Chair seat cushion, which has been designed for lower compression. It is made of 1 ¼" thick closed cell foam, with contouring in the middle of the seat, as requested by Dr. Bash. He has used Air Chair seats before and requested we use a similar, if not exact, type of seat for our design.

Figure 18. Chosen Contoured, Cushion Seat from AirChair

Long-Term Design Improvements

In addition to operation improvements between this design and its predecessor, the new product is designed with long-term durability in mind. (For the purpose of this discussion, the "current design" will refer to the Ski Seat, the apparatus given to us by Dr. Bash at the start of the project.) The current design has the most severe visible corrosion on parts conjoined by bolts. In order to limit corrosion build up on similar areas in the new design, the majority of the joints along the legs of the frame are welded. Additionally, the current frame is made of steel, while most of the new frame is made of 6061-T6 Aluminum alloy. This will yield a frame that is much lighter and more corrosion-resistant. Untreated 6000-series aluminum is far more corrosion-resistant than 4130 steel in aquatic applications. To add an extra layer of protection, the frame will be primed, spray painted, and clear-coated after assembly—allowing for even longer preservation of the structure before visible corrosion occurs. However, the joining of chrome-moly steel and aluminum—as will be the case with the central tube—exposes the apparatus to the risk of galvanic corrosion. In order to prevent this, we have chosen to fit a plastic sleeve between the two materials, which will then be joined by mechanical fasteners. We have chosen zinc-plated steel bolts for these fasteners, since they have a higher strength than aluminum fasteners, and their threads are less likely to be damaged over time. Additionally, the zinc coating will act as a sacrificial anode, which will greatly prolong the initiation of the effects of galvanic corrosion at the few points of aluminum-steel contact. With this design, the bolts can easily be replaced by the operator if corrosion appears.

The current design has additional flaws, which caused a quicker degradation of performance, so we sought to remedy these in the new design. In the current design, the screw, which attaches the steering bar to the seat, is screwed into a 1-inch piece of threaded aluminum. As a result, the steel screw has stripped the threads on the aluminum attachment, which allows for the bolt to disengage during use. To correct this in the new system, a mounting bracket has been welded to the bottom of the seat plate, and a pin with a spring-

loaded detent connects the steering bar to the mounting bracket without inhibiting rotation or compromising structural stability.

Safety Discussion

Our system is designed to present a minimum number of safety hazards to the rider. To ensure that the system itself does not harm the rider due to critical failure from stress (in the mechanical fasteners) and fatigue (in the center bar), we completed a number of calculations to determine the factor of safety our material selection would provide. Our attachment junctions are also designed to provide a high factor of safety, as junctions such as the Y and T joint could be major areas of failure without appropriate sizing and bracing. The front section of the frame was designed by using Dr. Bash's lower leg length. We used his shin length to determine what angle could be used in the Y junction at the bow of the design to make sure that the frame would not interfere with his legs. Our seat pad was selected to maximize impact absorption, as detailed in the comfort analysis. Furthermore, using a contoured seat pad can help prevent rectal prolapse by helping keep the rider centered and attached to the seat.

Manufacturing

To ensure that the project remained on schedule during manufacturing, we had a specific timeline and Gantt chart for this portion of our project (Appendix F).

Once the final design and parts list was determined, the materials, hardware, and special tooling were ordered. Most of the hardware and tooling was purchased through McMaster-Carr, as previously mentioned in the Bill of Materials.

Estimated Part Manufacturing Times

Table 5. Estimated Manufacturing Time for Each System Component

Part Name	Manufacturing Time		
	Time Per Part (Hours)	Number of Parts	Total Time (Hours)
Airfoil Tube Cutting (front and back frame)	2	15	30
Ankles	6	4	24
I-Joint	12	1	12
T-Joint	12	1	12
Welding Jigs	5	4	20
Center Bar	20	1	20
Welding (total)	20	1	20
Feet	3	4	12
Shoes	4	4	16
Seat Plate	10	1	10
Seat Components	5	1	5
Steering Bar	10	1	10
Steering Brackets	4	2	8
Potting	2	1	2
Final Assembly	8	1	8
Painting	12	1	12
Total			**222**

Overall Prototype

Figure 19. Final Prototype

Airfoil Frame

The first step in the manufacturing process involved cutting pieces of the airfoil tubing to length for the frame.

The tubes were first cut to rough sizing using the horizontal band saw. The vise was adjusted to the appropriate angles to ensure that segments which make up the corners and connect to the Y- and T- joints would align correctly in the final assembly.

Initially, the idea was to mill the tubing down to its final size to ensure accuracy. However, fixturing was very difficult and time consuming, causing long delays in manufacturing. Additionally, the fixturing was not secure, causing the tubing to rip out of the vise at times. Due to this, the procedure was deemed unsafe and new manufacturing methods were explored. Upon shop tech recommendation, we decided to modify the process, and proceeded to grind the tubes to size.

To ensure this process was completed accurately, each segment of tubing was measured using dial calipers, and the desired amount of material to be removed was indicated on the part. Then, the tubing was held with vise grips and carefully ground while being measured frequently, until the desired size was achieved.

Figure 20. Measurement of Tubing for Precise Length

Ankles

As initially stated, the plan was to CNC the ankles, since cutting the airfoil profile is difficult. However, further exploration of the CNC process turned out to be much more expensive than initially estimated since the actual tubing profile is proprietary and the

shape must be known in order to easily generate the G code, which runs the CNC. As a result, the ankles were instead cut on the mill by hand and being smoothed on the grinder and polishing wheels.

Since this process began with stock material, rough dimensions were cut on the vertical bandsaw. This reduced the amount of material to remove using the mill and saved machining time. The correct longitudinal dimension was then completed with the mill. Then, the top surface of each piece of ankle stock was sanded and colored with Dye-Chem. The inside of the airfoil profile was drawn onto each ankle by tracing a piece of tubing onto the top surface with a scratch awl. Once this process had been completed, the ankle was re-fixtured in an angle vise and the profile was milled by hand. The process was done entirely by human interpolation, with small cuts being made until all material had been removed up to the traced profile. This created an insert to go into the airfoil tubing, and a shoulder for it the tubing to butt up against. Then, the same process was repeated for the outer profile of the tubing, with the part still fixtured in the angle vise of the mill. Once this was complete, the tab at the bottom was ground on a disk sander so that it matched the airfoil profile, and the bottom corners were rounded out. The part was then taken to a Scotch-Brite wheel to remove sharp edges and smooth all external surfaces. The buffing wheel was then used to remove blemishes and polish the outside of the ankles.

Figure 21. Fully-Machined Ankles

Y-Joint

The Y-joint was redesigned multiple times, with the final design being made from round aluminum bar stock. It was faced to length and then turned down to the appropriate diameter. The visible portion of the Y-joint had a larger diameter of 1.375", while the segment responsible for connecting the Y-joint to the center bar was turned down to a much smaller diameter of 0.625". The end of the visible portion was then chamfered to provide a smoother transition and nicer appearance without sharp edges. To reduce the weight, the chamfered end of the Y-joint was cut away from the Y-joint and the center of the joint was bored out, removing unnecessary material from the part. The two pieces of the Y-joint were then welded back together to create a hollow part.

With this new design, connection between the airfoil tubing and the Y-joint required tube notching on the airfoil tubing. Two holes were drilled through the portion connecting to the center bar, allowing the tubes to be joined by bolts upon final assembly.

T-Joint

The T-joint was also redesigned for manufacturability—making it possible to be machined by hand rather than being cut on the CNC. The new T-joint also began as round aluminum bar stock before being faced and turned to the appropriate length and diameter on the lathe. Manufacturing of this part was very similar to the Y-joint, with the only differences being length of the visible portion of the part and style of the chamfer. This part has a deeper chamfer, giving the visible portion a conical look. Since it connects to the center of a piece of airfoil tubing, the T-joint itself was notched on a mill to fit around the tubing, rather than the other way around.

<u>Welding of Frame</u>

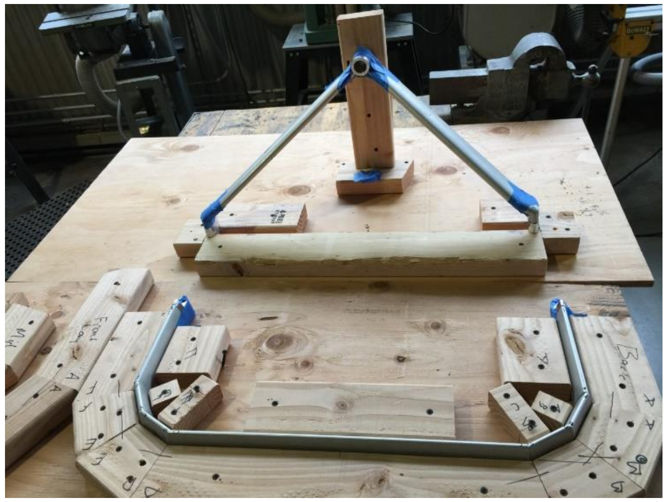


Figure 22. Welding Jigs Built to Keep Tubing in Place

Special jigs were created for the front and back legs of the frame so that the tube segments, Y-joint, and ankles could be connected, as specified by the frame design.

Figure 23. Side View of Welding Jig for Front Legs

<u>Feet</u>

The feet were cut from round aluminum bar stock. This stock was cut to rough size on the horizontal band saw. In order to allow for adequate grip on the part while in the chuck, the bar was initially cut into two 5-inch lengths. Each length was then faced to length and turned to the appropriate diameters. Once this was complete, the feet were separated from the stock with a parting tool.

Figure 24. Feet after Turning is Completed

The tops of the feet were then milled down to serve as the outer section of the hinges between the ankles and feet.

Figure 25. Feet and Shoes Together: The top feet are complete while the two bottom feet need hinges.

The edges and corners were then filed, leaving no sharp corners on the parts.

<u>Shoes</u>

The shoes were cut to rough length from rectangular stock using the vertical bandsaw. The width of each was then milled to appropriate size. Next, the part was placed horizontally in the vise on parallel bars, and the location of one edge was found using an edge finder and the DRO. Next, the hole-pattern was drilled using a center drill, using the central hole's axis as the zero to decrease machining time. Then, the small holes were drilled through using a #11 drill bit. The countersunk holes were then created with the mill above the four screw holes. The one-inch center hole was then drilled in the drill

press by stepping up the drill bits in size from #11 to one inch, and was chamfered using a chamfer tool. Once the hole patterns were drilled, the four corners of the shoe were chamfered on the mill using a chamfer bit and an angle vise.

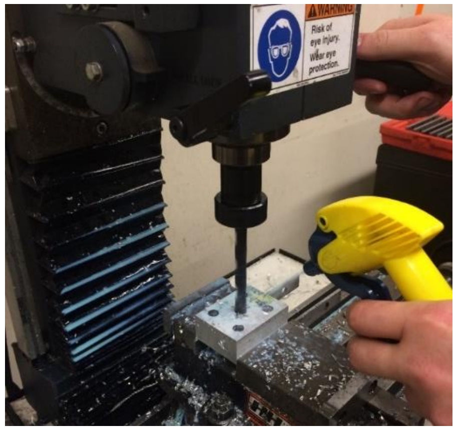


Figure 26. Hole Pattern on the Shoes Being Milled

Figure 27. Shoe with Final Hole Pattern and Chamfering

Pin Connection for Feet and Shoes

To allow for easy setup and take down, the shoes and feet are connected by pins with a spring-loaded detent ball. Once both the shoes and feet had been completed, they were placed together in a vise, with the feet hinges level, and a quarter-inch hole was drilled through both pieces of material. The shoe (with the foot inside it) was placed on

parallels to ensure that the hole could be drilled all the way through without causing damage to the vise or drill press table.

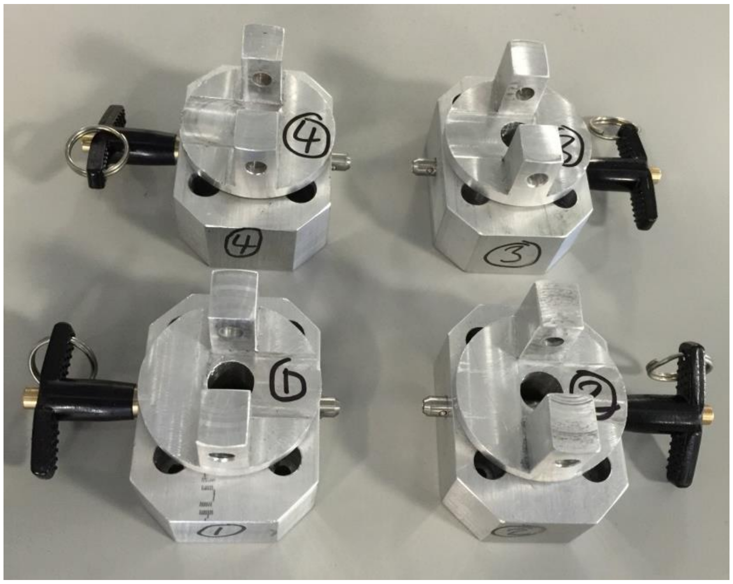


Figure 28. Shoes and Feet Connected by Ball-Detent Pins

Seat Plate

The seat plate was machined out of a quarter-inch-thick plate of aluminum. In order to reduce the weight, slots were milled into one side of the plate. The corners were then rounded using the vertical bandsaw and the grinding wheel. The slots and edges were then smoothed with the Scotch-Brite wheel to ensure that no sharp edges could injure the rider. Next, the steering bar mounting bracket was milled from one-inch bar stock and aligned with the seat's central axis. This was eventually welded on.

Figure 29. Grooves and Holes Milled in Seat Plate to Reduce Weight

Figure 30. Finished Seat Plate

Center Bar

The hinges that came from Brompton were already brazed onto tubing with bike fixtures on the ends. These were first cut off at the appropriate lengths with the chop saw. The paint was removed using the wire wheel and the I-joint was made from round thick-walled chromoly tubing on the lathe. The I-joint was welded between the two tubes that had hinges attached. On the other side of the hinges, material was bored out of the center to allow for the Y- and T-joints to be inserted, and thick walled chromoly tubing was cut and welded to the outside to keep a consistent diameter on the outside. Once everything was welded, holes were drilled in the ends of the tubes to allow for connection to the

front and back tubing sections with bolts. Then, a pin was press-fit into each set of hinges using a combination of a press and a bench vise.

Steering System

The mounting brackets were milled from one-inch solid square 6061 Aluminum rods. A 3/8" slot was milled in the top to allow for the ¼-28 rod ends to fit snugly. Then, the bases were cut to length on the vertical bandsaw and the mounting hole patterns were drilled with the mill. These were later welded in the appropriate configuration.

Figure 31. Steering Bracket Slots Being Milled

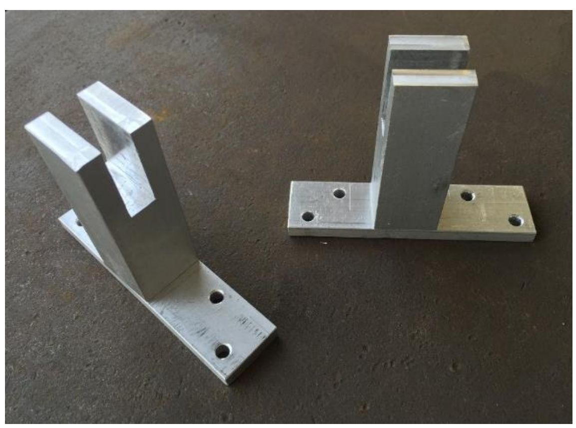


Figure 32. Finished Steering Brackets

Each side of the steering bar was cut from a hollow aluminum rod. The length of these rods was the same for both sides, and was determined based on the layout and position of the point of steering bar connection with the seat plate and frame, and the point of connection with each of the steering brackets. The steering bar pieces were placed into a

jig so that the middle and end connection points could be welded on, allowing for pinned connections in the final assembly.

Potting in Skis

Since the location and hole patterns necessary for the frame's connection to skis is different from the bindings used in a traditional waterski setup, new inserts needed to be added to the water skis for frame mounting. This was the last step of manufacturing—completed after the frame had been assembled to ensure that any small differences in frame alignment would not be magnified by frame mounting.

Once the frame and steering bar had been assembled, the assembly (shoes included) was placed on top of the two skis and positioned appropriately, relative to the length of the skis. The outlines of the shoes and steering brackets were then drawn onto masking tape on the skis, with the symmetry of the shoes and steering brackets being used to determine the location of the hole pattern on the skis.

Once hole placement was determined, the holes were ready to be drilled. A piece of masking tape was wrapped around the drill bit, starting a quarter inch above the end of the bit. This way, drill depth could be monitored to ensure that the drill bit would not penetrate through the thickness of the skis.

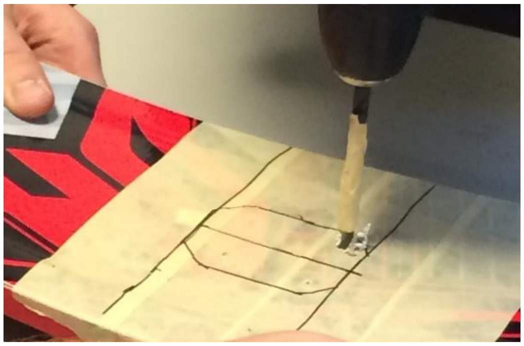


Figure 33. The First Step to Potting: Drilling the Holes for Insert Placement

Once the skis were drilled into, the foam core was cleared out from around the inside of the holes to ensure there was space for the epoxy to sit around each of the potted inserts. Next, Loctite marine epoxy was applied in each of the holes and the threaded inserts were placed on top of the holes. Since the inserts are press-fit, they were hammered into the epoxy-lined holes until the top of each insert was flush with the surface of the skis.

Excess epoxy was then removed with a paper towel. Any holes that were not used were then filled with epoxy to ensure that no water would enter the core of the ski.

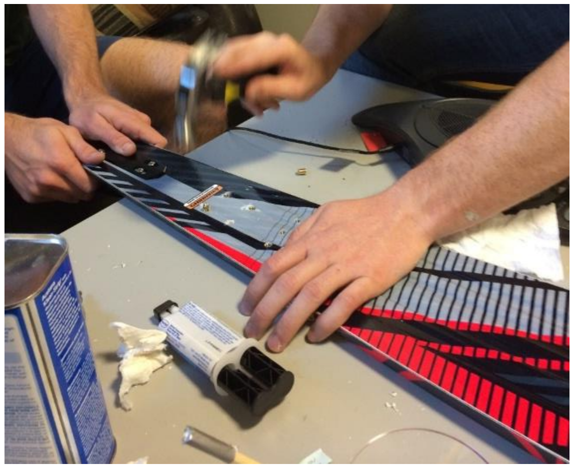


Figure 34. Steps Two and Three of Potting: Place Marine Epoxy into Hole and Hammer in Press Inserts

Figure 35. Potting Finished Product

Frame and Overall Assembly

Once the individual parts were finished, assembly began. This involved using the appropriate hardware to connect the frame together, as shown in Figure 36.

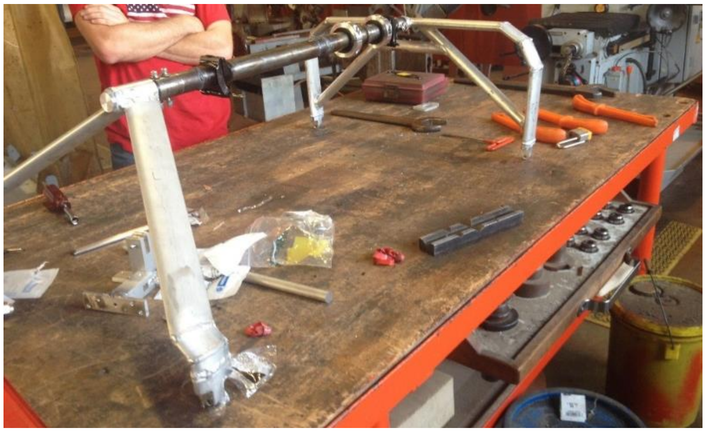


Figure 36. Frame Assembly

Notable features of this assembly include the hinges ability to fold (demonstrated in Figure 37). After the frame was put together, the feet were connected and placed into the shoes, which were already attached to the skis. Once the fit of the overall assembly was confirmed, painting of the individual components could begin.

Figure 37. Folded Frame Assembly

Figure 38. Painted Frame Assembly

Painting

Once the final assembly had been constructed, it was painted to improve aesthetics and corrosion resistance. The chrome-moly center bar was first primed—both inside and

Figure 39. Painted Parts Laying Out to Dry

out—and then painted to improve corrosion resistance. The aluminum parts were then spray painted using a Rustoleum Paint & Primer combination, with pieces being alternated red and black to create a dynamic contrast. The parts were either laid down, or hung using wire, and sprayed with 6 coats of color and then 2 coats of matte clear.

Manufacturing Issues

Airfoil Tube Fixturing

The initial plan for fixturing was to use a V-block to secure the airfoil tubing into the vise for milling. Unfortunately, this did not provide a tight enough hold on the tubing and a special jig was needed. To accommodate this, we built a wooden jig which squared off the airfoil tubing for placement in the vise. However, this jig broke after a couple of uses. Another wooden jig was then built so that the remaining tube segments could be cut to size. However, we also had issues with the tubing ripping out of the vise with this jig. As a result, we decided to change our process—as explained above—to grinding the tubes to size instead.

CNC Issues

CNC manufacturing was too expensive for our budget since the complexity of our parts required hours of labor to generate the G-code for a 5-axis machine. Although we did redesigns to make our parts simpler, the use of airfoil tubing still complicated efforts to implement CNC manufacturing. After exploring several CNC options, the team decided it was best to move forward with hand manufacturing as a result of these complications.

Original Shoe Design Unmanufacturable

Originally, the shoes were intended to be created from circular aluminum bar stock, with their shape remaining circular. However, it was discovered that the bar stock needed to obtain the necessary shoe diameter was too large to be faced on the lathe due to the inability to effectively fit the piece in the chuck. Although these should have been easy to manufacture in theory, the lathe could not handle the size of the stock and still maintain a stable rotation. Therefore, the parts were redesigned, as described above.

Cost Analysis

The overall cost of our prototype was broken down into the major components of the design. Table 6 details the main costs of each system of the design, with Attachment 4 including the full table with the breakdown by labor, overhead, and with sources

listed. Table 7 discusses production of our design on a small-scale run of ten pieces, and Table 8 details doing a large production run.

The majority of our costs for the prototype will be from the tubing and the aluminum for the machined parts. All of our welding will be handled by professionals on campus, which will greatly reduce our overall cost when compared to using a full machine shop. Additionally, our hinges and skis have been donated, further lowering our overall cost. The goal on the outset of our project was to keep the total cost under $1500. Our total cost to build the prototype, as shown in Table 7, was just over $1000—keeping the team well under budget for this project.

The small-scale production is aimed at producing ten models. Because of this scale of production, most of the machining would be outsourced to a machine shop. This outsourcing raises the overall cost of production by a large amount. In addition, none of the parts would be able to be bulk ordered, as with the large-scale production. As shown in Table 8, the major cost comes from the production cost and machining. This combination of factors leads to the highest individual product cost.

The large-scale production looks at mass-producing our design to 100,000 units and is detailed in Table 9. Our production here includes overhead costs based on purchasing welding setups, mills, and a full 5-axis CNC machine. However, the ability to order parts in bulk and the much diminished machining costs lead to an overall product cost that is a third of the small scale production costs.

Table 6. Prototype Cost

Prototype		
Operation	**Detail**	**Total**
Tubing		
Airfoil Tube	$14.10/ft*12ft=$169.20	$197.06
Cut Tubing		subsidized
Weld Tubing		subsidized
Paint Tube		$50
Steering Tubing	6 feet, $31.31	$31.30
Interstitial Shaft Collar Tubing	1 foot, $21.21	$21.21
Total		**$299.57**
Aluminum Stock		

Ankles	$40.56 1"x2.25"x24"	$40.56
Y/T Joint	Rod, 6061, OD 1 3/8"x12"	$22.79
I Joint	$4.45 1.5"x3" Round	$4.45
Feet	$26.83 2"x24" bar stock	$26.83
Shoe	$36.04 3.25"x6" bar stock	$36.04
Chromoly sleeve (internal in center bar)	0.120" wall, 1.375"ODx1ft	$20.83
Paint		n/a (included above)
Total		**$151.50**
Seat Plate		
Material	6"x12" $19.13	$19.13
Bend to shape		subsidized
Paint		n/a
Steel Plate to Weld To		$7.67
Total		**$26.80**
Drivetrain		
Material	1/2" tube, 6' $18.47	$18.47
Bend to shape		subsidized
Paint		n/a
Total		**$18.47**
Delrin Bushings		
material (shaft collars)	12" $17.28	$17.28
Machine to shape		subsidized
material (Y and T joint)	12" $9.98	$9.98
Machine to shape		subsidized
Total		**$27.26**
Shaft Collar	$28.66 each	**$57.32**
Pins	$15/each	**$60**
Seat	$32 each	**$72.00**
Bolts		
Seat to Drivetrain bolt	$5.49	$5.49
Drivetrain screws	1/4-20 shoulder screws with 5/16" shoulder dia and 2" length, for 6	$8.58
Y/T connection screws	Socket head cap screws 1/4-20 partially threaded for Y and T joint connections, bag of 25	$11.19
Shoe to ski screws	4 per ski, low profile Allen	$8.25
Total		**$33.51**
Potting	package of 25 inserts	**$11.49**
Tooling		
RH lathe tool	turning	$21.19
LH Lathe tool	facing	$21.19
Total		**$42.38**

Engineering Design		**$0.00**
Shipping and Taxes		**$280**
Total		**$1,080.30**

Table 7. Small Scale Production Cost

Small Scale		
Operation	**Material**	**Total**
Tubing		
Airfoil Tube	$14.10/ft*12ft=$169.20	$1,970.56
Cut Tubing		$180
Weld Tubing		$500
Powdercoat Tube		$300
Steering Tubing	$31.31	$613.00
Interstitial Shaft Collar Tubing	$21.21	$210.21
Total		**$3,773.77**
Aluminum Stock		
Ankles	$40.56 1x2.25x24	$405.60
Y/T Joint	Rod, 6061, OD 1 3/8" 12"	$22.79
I joint	$4.45 1.5x3" Round	$44.50
Feet	$26.83 2"x24" bar stock	$268.30
Shoe	$36.04 3.25"x6" bar stock	$360.40
Machining of Joints	$80/hr*200hrs	$16,000.00
Chromoly sleeve (internal in center bar)	0.120" wall, 1.375"ODx1ft	$208.30
Powdercoat		n/a
Total		**$17,310**
Seat Plate		
Material	38.21	191.3
Machine to shape	$80/hr*2hrs	$160
Powdercoat		n/a
Steel Plate to Weld To		$76.70
Total		**$351.30**
Drivetrain		
Material	$18.47	$184.70
Bend to shape	$80/hr*5hrs	$160
Powdercoat		n/a
Total		**$344.70**
Delrin Bushings		
material (shaft collars)	$17.28	$172.80
Machine to shape	$80/hr*5hrs	$160
material (Y and T joint)		$99.80
Machine to shape	$80/hr*5hrs	$160
Total		**$592.60**
Shaft Collar	28.66 each	**$573.20**
Pins	$15/each	**$600**
Seat	$32 each	**$320.00**

Bolts		
Seat to Drivetrain bolt	$5.49	$54.90
Drivetrain screws	1/4-20 shoulder screws with 5/16" shoulder dia and 2" length, for 6	$85.80
Y/T connection screws	Socket head cap screws 1/4-20 partially threaded for Y and T joint connections, bag of 25	$22.38
Shoe to ski screws	.132" shoes to ski x 4	$82.50
Total		**$163.08**
Potting	package of 25 inserts	**$110.49**
Engineering Design		**$22,500**
Skis	$700	**$7,000.00**
Hinges (price for pair)	$300	**$3,000.00**
Total		**$57,231.63**
	Total Per:	**$5,723.16**

Table 8. Large Scale Production Cost

Large Scale		
Operation	**Material**	**Total**
Tubing		
Airfoil Tube	$3/foot*8 feet each, $24 per	$2,400,000.00
Cut Tubing		$150,000
Weld Tubing		$150,000
Powdercoat Tube		$200,000
Steering Tubing	$26.21 per foot	$1,310,500.00
Interstitial Shaft Collar Tubing	bulk	$221,000.00
Total		**$4,431,500.00**
Aluminum Stock		
Ankles	$40.56	$3,042,000.00
Y/T Joint	Rod, 6061, OD 1 3/8" 12", bulk	$279,000.00
I joint	$4.45	$333,750.00
Feet	$26.83	$2,012,250.00
Shoe	$36.04	$2,703,000.00
Mill to shape		$50,125
Powdercoat		n/a
Chromoly sleeve (internal in center bar)	0.120" wall, 1.375"ODx1ft	$20.83
Total		**$8,420,125.00**
Seat Plate		
Material	Bulk	8210000
Bend to shape		$30,000
Powdercoat		n/a
Steel Plate to Weld To		$300,000.00
Total		**$8,240,000.00**
Drivetrain		
Material	Bulk	$147,000.00
Bend to shape		$30,000
Powdercoat		n/a
Total		**$177,000.00**
Delrin Bushings		
material (shaft collars)	$17.28	$17.28
Machine to shape		subsidized
material (Y and T joint)		$9.98
Machine to shape		subsidized
Total		**$27.26**
Shaft Collar	28.66 each, bulk order reduction	**$866,000.00**
Pins	$5/each	**$2,000,000**

Seat	$32 each	**$3,200,000.00**
Bolts		
Seat to Drivetrain bolt	bulk price	$250,000.00
Drivetrain screws	1/4-20 shoulder screws with 5/16" shoulder dia and 2" length, for 6	$58,000.00
Y/T connection screws	Socket head cap screws 1/4-20 partially threaded for Y and T joint connections, bag of 25	$119,000.00
Total		**$427,000.00**
Potting	package of 25 inserts	**$101,000.00**
Tooling		
Total	Haas 5 axis CNC	**$125,000.00**
Engineering Design		**$22,500**
Skis	$700	**$70,000,000.00**
Hinges (price for pair)	$300	**$30,000,000.00**
Engineering Design		**$22,500**
Total		**$128,032,679.52**
	Cost Per:	**$1,280.33**

Testing

In order to ensure that the apparatus is safe and effective for its appointed use, we have developed a testing plan to be implemented following construction of our design. This testing plan ensures that the apparatus both abides by the engineering specifications that have been set forth, and ensures the safety of the rider during use. In an effort to thoroughly cover all necessary aspects of testing, FMEA and DVP&R processes were used to document all possible types of failure, as well as testing procedures for the most crucial aspects. These can be found in Appendix I.

Steering Angle Test

The steering angle test was measured with three protractors—one for measurement of the seat angle and two for measurement of the angle of each ski. Once these protractors had been safely anchored, two team members held the system in the air so that the skis may rotate freely. A third team member then proceeded to turn the seat an incremental number of degrees while the fourth recorded the corresponding turn amount of each ski. The results from the test with the initial steering bar showed that the steering system itself was in fact designed to respond with a 1:1 ratio. However, the center bar

provided for some interference on one side of the steering bar, limiting the 1:1 turn ratio to small angles only (prior to the point at which interference begins).

Table 9. Results of Steering Angle Test

Seat Angle Turned	Left Ski Angle	Right Ski Angle
-15.0º	-14.5º	-15.5º
-30.0º	-31.0º	-29.0º
-45.0º	-44.5º	-45.5º
15.0º	15.0º	15.0º
30.0º	29.0º	31.0º
45.0º	31.0º	34.0º

To rectify this, the steering bar was modified, cutting the straight tubes about an inch and a half from the top steering pin and re-welding the longer bar lengths to the top piece at an angle, providing more clearance for the steering bar to turn around the center bar.

Floatation Test

The system was placed in a pool to determine whether or not it would float prior to rider testing. Unfortunately, the system did not float. However, it sank slowly, suggesting that it could still be placed in the lake without being lost.

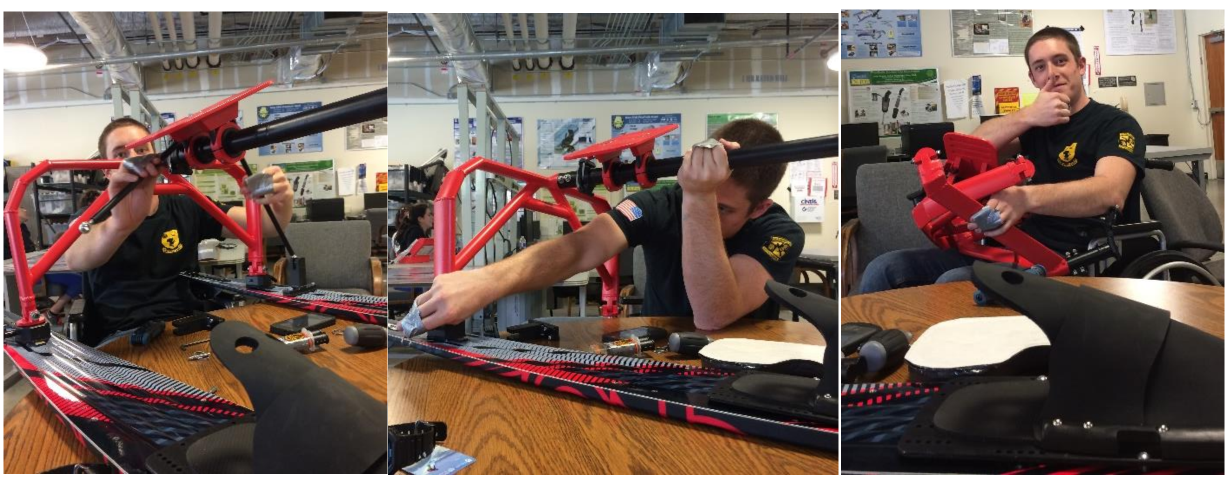
Figure 40. System during Floatation Test

To remedy this, piping insulation was added to the center bar and bracing to improve floatation upon further use. Once the piping insulation had been added, the system was able to successfully float when place in water.

Figure 41. System with Piping Insulation Added to Improve Floatation

Handicapped Setup/Breakdown Test

It is important that the system is easy for our customer to setup and take down with his reduced grip strength. To test this, one of our members sat in a wheelchair and duct-taped his fingers together, leaving only his thumbs and pinkies available for use. He proceeded to take the system apart quite easily—doing so in four minutes and twelve seconds.



Figures 42-44. Toby Performs the Handicapped Breakdown Test

The same process was repeated to determine the amount of time needed for setup. Setup is slightly more difficult, since frame and steering alignment play a role. However, the setup time was still under the 10-minute limit, coming out at seven minutes and fifteen seconds.

Rider Test

Ashley, an experienced water skier, and Mark, another team member, attempted to ride the system, assessing its performance compared to that of the Ski Seat. Unfortunately, the first round of this test resulted in a failure that is believed to have been caused by a faulty weld on the steering bar. When the steering bar failed the steering angle test, we revised it, cutting the straight tubes about an inch and a half from the top steering pin and re-welding the longer bar lengths to the top piece at an angle, providing more clearance for the steering bar to turn around the center bar. During testing, failure occurred at one of these welds, suggesting the weld was too weak to handle the dynamic load placed on it as the rider rises out of the water. To rectify this, the next revision of the steering bar was made from chromoly steel for improved strength. The new steel bar is bent slightly near the top steering pin to prevent interference with the center bar, while maintaining structural integrity and safety.

Figure 45. Mark Attempts Rider Test

Figure 46. Mark Riding the Freedom Ski Prototype

The test with the new steer bar was much more successful, as shown in the photos below.

Figure47-48. Second Rider Test

Dr. Bash will conduct the same test and assess our project's performance.

Testing Summary

The following table gives a summary of the testing results discussed above.

Table 10. Summary of Testing Results

Test	Desired Result	Actual Result
Steering Angle	1:1 Ratio (Seat Angle: Outer Ski Angle)	1:1 for Left Turn; Less for Right Turn
Steering Angle with Revised Steering Bar	1:1 Ratio (Seat Angle: Outer Ski Angle)	1:1 Ratio for Both Turns

Floatation	Zero Buoyancy	Sinks Slowly
Floatation with Piping Insulation	Zero Buoyancy	Floats
Handicapped Setup	<10 minutes	07:15
Handicapped Breakdown	<10 minutes	04:12
Rider Test	Fun, Easy and Responsive (Go/No-Go)	No-Go: Broken Weld
Rider Test with 2nd Revised Steering Bar	Fun, Easy and Responsive (Go/No-Go)	Go

Lessons Learned

Our biggest challenges came during the manufacturing segment of this process. We quickly discovered at the beginning of manufacturing that many of our parts were not as easy to CNC or manufacture by hand as we thought they would be. This led to several re-designs in order to make things easier to manufacture, while still maintaining a sleek look. As young engineers, this was definitely the greatest challenge, as well as the one that school could prepare us for the least. This experience has shown the importance of reaching out to those experienced in industry who have a greater familiarity with what is possible in terms of manufacturing and product design.

Additionally, communication was a huge issue at times. The most crucial case of this involves our communication with Brompton Bicycles, who donated materials and hinges for the center bar. They had told us they would send four sets of hinges with long tubing on either side of each so that they could be cut to size for our purposes. This agreement was made in January, with hopes of receiving the tubing an estimated six weeks later. After repeated attempts to gain further information from Brompton, we finally received the materials in April—with several unexpected features. One side of each of the hinge sets had a short tube that was significantly smaller in diameter. To rectify this, the team had to prepare and weld a tube on top of the smaller tube, bringing the diameter up to size. This added unplanned for time to our manufacturing plan and weight to our final product. Additionally, Brompton did not include the hardware that went with the hinges. We were able to purchase the correct pins, but had to quickly find the correct hardware to use to close the hinges. Fortunately, a company called Brompfication, who makes aftermarket parts for Brompton Bicycle owners, was willing to donate a set of titanium

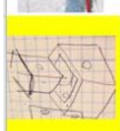
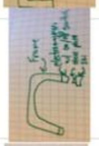
hinge clamps to our project. In the future, these issues could be avoided by providing Brompton with a timeline upfront and explaining to them the importance of us receiving these materials on time. This way, if the materials received were not as expected, there would be more time to rectify the situation with an appropriate solution.

Conclusion

Our final design incorporates a universal mounting system to allow for adaptability and easy setup, a molded seat to aid with comfort and control, a collapsibility scheme that reduces size for transport and maintain rigidity while in use, and a steering system similar to that of the Ski Seat, which will allow for intuitive and responsive steering capabilities. Our team was able to successfully build and implement this design—with a few changes—in order to deliver a quality product which meets and surpasses standards to our project sponsor, Dr. Craig Bash. Lessons learned from this project highlight the importance of designing for manufacturability and incorporating lag time into timelines in case of unforeseen delays.

Appendices

Appendix A: Pugh Matrices for Individual Functions

											
Concept/ Criteria	SkiSeat	Slide onto ski	**Pins with base attached to ski via bolts or adhesives**	Buckle (ski boot) system	Ratchet (snowboard) system	Side Clips	Single bar with vise mounts on apparatus	Screw base plate to ski with standard pattern	Magnets	Velcro	**Adhesive base plate to ski**
Universability	0	1	1	1	1	-1	1	1	1	1	1
Manufacturability	0	-1	1	-1	-1	-1	-1	1	1	1	1
Set up time	0	0	1	1	1	1	0	0	1	1	1
Collapsability	0	1	1	1	1	1	-1	1	1	1	1
Ease of use	0	0	1	-1	1	-1	0	0	0	1	1
Buoyancy	0	0	0	0	0	0	0	0	0	0	0
Weight	0	0	-1	-1	0	-1	-1	-1	-1	1	-1
Safety	0	-1	1	1	1	0	-1	1	-1	-1	1
Cost	0	-1	0	-1	-1	-1	-1	1	-1	1	1
Drag	0	-1	0	-1	-1	-1	-1	0	0	-1	0
Σ	0	-2	5	-1	2	-4	-5	4	1	5	6

1 better than current design
0 same as current design
-1 worse than current design

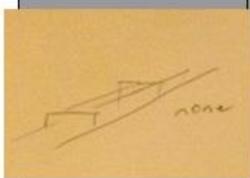
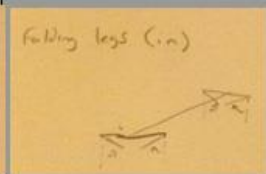
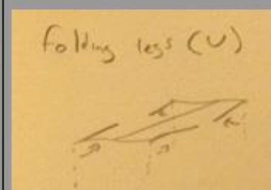
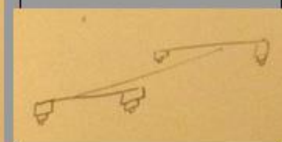
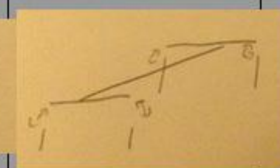
Pugh Matrix - Steering Systems

1 better than current design

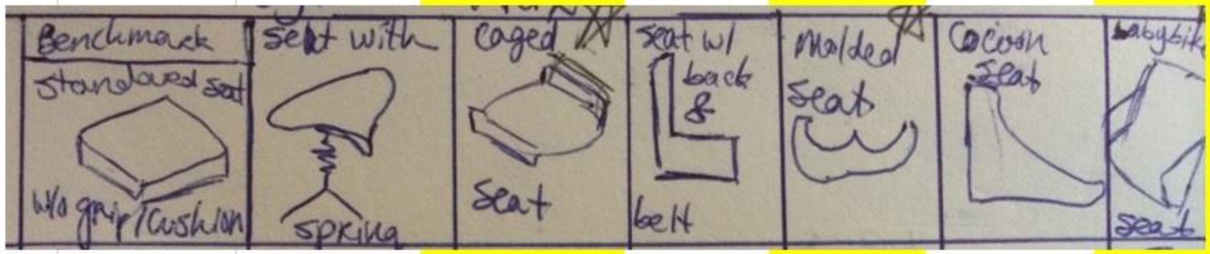
0 same as current design

-1 worse than current design

Concept/ Criteria	*SkiSeat*	Spring-On-Ski	Raised Steering	"Shift" Knobs	Handlebars	Trunk Twist	Rudder	Outrigger-style	Joystick	Gears	Bungees tilt skis	Compressed SkiSeat
Skiing Sensation	0	0	0	-1	-1	-1	0	0	-1	0	-1	0
Manufacturability	*0*	-1	-1	0	0	-1	0	-1	0	-1	0	0
Responsiveness	*0*	-1	1	1	1	-1	1	-1	1	1	1	0
Collapsibility	*0*	0	0	0	0	0	0	-1	0	-1	1	1
Ease of use	*0*	0	1	-1	0	-1	0	0	0	1	1	0
Buoyancy	*0*	0	1	0	0	0	1	1	0	-1	0	1
Weight	*0*	-1	-1	0	0	0	-1	-1	0	-1	0	1
Safety	*0*	0	0	-1	0	0	-1	1	-1	1	-1	1
Cost	*0*	-1	0	0	0	-1	0	-1	0	-1	0	0
Σ(+1)	*0*	0	3	1	1	0	2	2	1	3	3	4
Σ(-1)	*0*	4	2	3	1	5	2	5	2	5	2	0
Σ	**0**	**-4**	**1**	**-2**	**0**	**-5**	**0**	**-3**	**-1**	**-2**	**1**	**4**

	SkiSeat	folding legs (toward center frame)	folding U legs (towards mid)	telescopic legs	removable legs	collapsing X frame	sprung folding to skis
							
Weight	0	0	0	-1	0	-1	0
size	0	1	1	1	1	0	1
buoyancy	0	0	0	-1	0	0	0
ease of use	0	1	1	0	1	1	1
cost	0	-1	-1	-1	0	-1	-1
manufacturability	0	1	1	-1	-1	-1	-1
safety	0	0	0	-1	0	0	-1
Setup time	0	1	1	0	-1	1	1
Sum	0	3	3	-4	0	-1	0

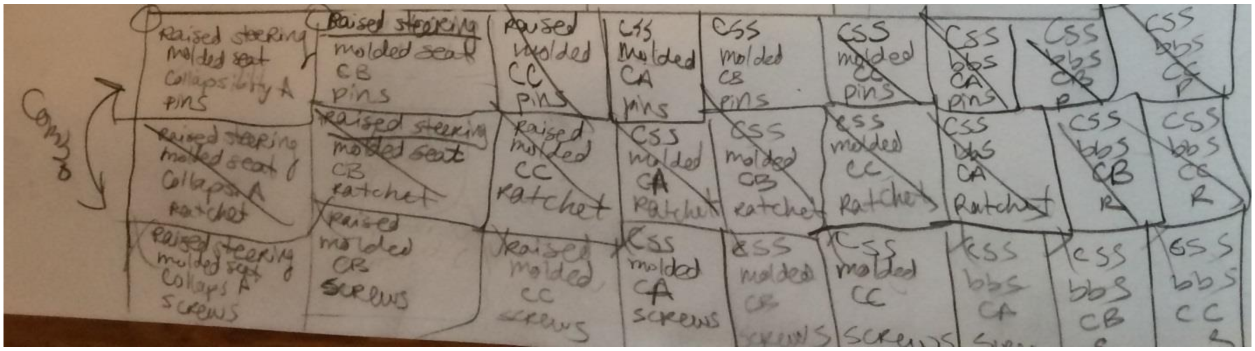
Key:
1 better than current
0 equal to current
-1 worse than current

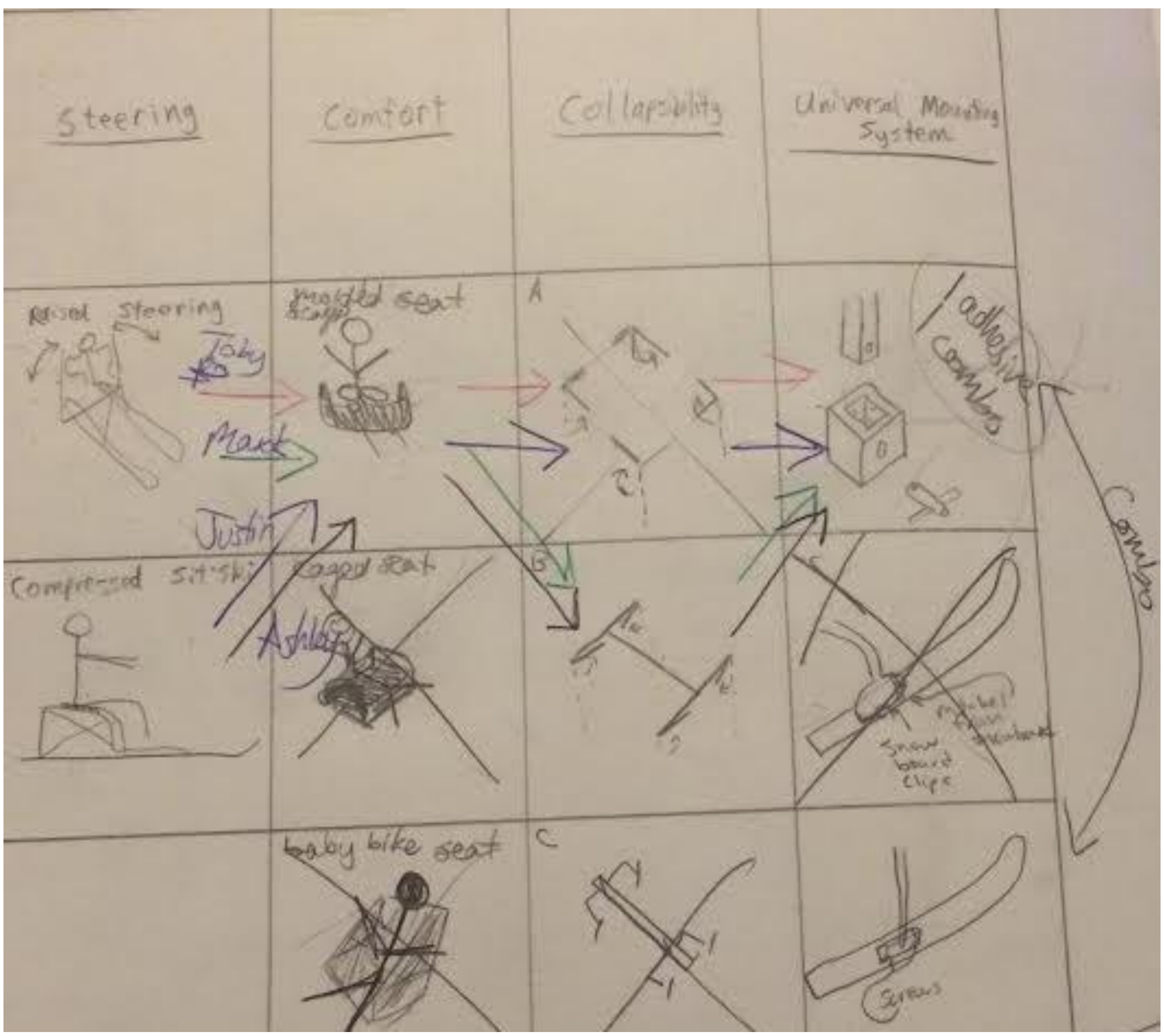


	Ski Seat cushion	Seat with Spring	Caged Seat	Seat with back and belt	Molded Seat	Cocoon Seat	Baby Bike Seat
low cost	0	-1	-1	-1	-1	-1	0
easy to use	0	-1	1	1	1	1	1
buoyant	0	-1	0	1	0	-1	1
absorbs shock	0	1	0	1	0	1	0
small size	0	0	0	-1	0	-1	-1
collapsible	0	1	0	-1	0	-1	-1
comfortable	0	1	1	1	1	1	1
holds skier in place	0	-1	1	1	1	1	1
does not inhibit skier agility	0	-1	1	-1	1	-1	1
weight	0	0	0	-1	0	-1	-1
safety	0	-1	1	-1	0	-1	1
durability	0	-1	0	0	0	0	0
Total	**0**	**-4**	**4**	**-1**	**3**	**-3**	**3**

Appendix B: Morphological Attribute Matrix

Different ideas for each subsystem of the assembly were chosen, and each one was paired with each of the others. Unfeasible ideas were crossed off, as shown below, and then four different possible final designs were chosen based on the “top ideas,” as shown by the color-coded arrows in the bottom figure.





Appendix C: Further Explanation of Decision Matrix and Design Assessment

Use of Pairwise Comparison:
In order to obtain our weights for the Decision Matrix, a pairwise comparison was done to ensure the categories were scaled appropriately.

CRITERIA	*cost*	*weight*	*durability*	*size*	*agility and control*	*manufacturability*	*versatility*	*buoyancy*	*shock absorption*	*aesthetics*	points	**Score**
cost		0	0	0	0	1	0	0	1	0	2	**5**
weight	1		1	1	0	1	0	1	1	1	7	**16**
durability	1	0		1	0	1	0	0	1	0	4	**9**
size	1	0	0		0	1	0	0	0	0	2	**5**
agility and control	1	1	1	1		1	1	1	1	1	9	**20**
manufacturability	0	0	0	0	0		0	0	0	1	1	**2**
versatility	1	1	1	1	0	1		1	1	1	8	**18**
buoyancy	1	0	1	1	0	1	0		0	0	4	**9**
shock absorption	0	0	0	1	0	1	0	0		1	3	**7**
aesthetics	1	0	1	1	0	0	0	1	0		4	**9**

Explanation of Individual Criterion

Cost:

The decisions for the overall waterski cost include the materials used, complexity of the machining required to create the parts, and how expensive outsourced parts would have to be. The following scale was used:

-1: The design was estimated to be more expensive than was necessary to fulfil Dr. Bash's requirements based on complexity of materials or machining

0: The design was estimated to be a reasonable cost when considering Dr. Bash's requirements based on complexity of materials or machining

1: The design was estimated to be well within the budget considering Dr. Bash's requirements based on complexity of materials or machining

As a result of these criteria, each of the final four designs was awarded the following scores:

Design	Score
Compressed Ski Seat, Collapsible Side-to-Side	0
Raised Shoulder Steering, Collapsible Front-to-Back	-1
Raise Shoulder Steering, Collapsible Side-to-Side	-1
Compressed Ski Seat, Collapsible Front-to-Back	1

Compressed Ski Seat, Collapsible Side-to-Side:
This design is similar in complexity to the fourth design, and also uses a more inexpensive steering mechanism when compared to the second and third. However, the collapsibility mechanism uses more joints than necessary to achieve the goal, increasing overall price.

Raised Shoulder Steering, Collapsible Front-to-Back:
The combination of raised shoulder steering (which would most likely require expensive carbon fiber wing attachments) and extra joints raised the cost of this design well past what was considered necessary.

Raised Shoulder Steering, Collapsible Side-to-Side:
This design again has the expensive carbon fiber wing attachments to facilitate steering. However, this model uses half as many joints as the previous, lowering the overall cost. Despite this, the carbon fiber wings would be prohibitively expensive, giving it a low overall score.

Compressed Ski Seat, Collapsible Front-to-Back:
This design is the most inexpensive of the four while still achieving all of Dr. Bash's requirements. The basic steering system keeps the cost low while allowing for good overall control. In addition, the usage of only two joints for collapsing the design allows us to minimize cost while getting the same result.

Weight:

The decision for weight came from differences in estimated material needed to create each design. This included anything that was different between designs. For example, skis were not taken into account because they are equal across all designs. However, collapsing front-to-back only needs two hinges as opposed to collapsing side-

to-side, which needs four. For all of the designs, oval hollow aluminum tubing will be used.

-1: The design was estimated to be heavier than the other design options and heavier than the current Ski Seat.

0: The design was estimated to be lighter than some of the design options and

1: The design was estimated to be lighter than the other design options and significantly lighter than the Ski Seat.

Design	Score
Compressed Ski Seat, Collapsible Side-to-Side	0
Raised Shoulder Steering, Collapsible Front-to-Back	-1
Raised Shoulder Steering, Collapsible Side-to-Side	-1
Compressed Ski Seat, Collapsible Front-to-Back	0

Compressed Ski Seat, Collapsible Side-to-Side:
The compressed Ski Seat would be lighter than the current design due to a smaller frame. The hinges will be about the same weight as the current connections, so that will not affect the weight. The universal mounting system will be heavier but will not overcome the weight of the material change.

Raised Shoulder Steering, Collapsible Front-to-Back:
The raised shoulder steering would be significantly heavier than the current design. Shoulder steering members will add a large amount of material and a third pair of universal mounts.

Raised Shoulder Steering, Collapsible Side-to-Side:
This was the heaviest of the designs because of the shoulder steering members, the third pair of universal mounts, and the need for four hinges to make it collapsible.

Compressed Ski Seat, Collapsible Front-to-Back:
This design was the second lightest. The compressed Ski Seat will again have less material in the frame and be made of aluminum. Both of these will decrease the weight. However, having four hinges will be heavier than having two so it was determined to be heavier than the front-to-back collapsible design.

Durability:

Considerations for ski durability include the materials used and their corrosion resistance, the possibility of complications with the joints, springs, or other moving parts used in the system, and the overall robustness of the ski during use (either properly or not). The scale is then used as follows:

-1: The design contains two of the following weaknesses: the material is more susceptible to corrosion than the current Ski Seat design, there are more joints/moving parts involved which could break, or the system itself seems more vulnerable to breakage as a whole.

0: The design contains zero or one of the following weaknesses (when compared with the Ski Seat) and does not contain more than one strength in these categories: the material is more susceptible to corrosion, there are more joints/moving parts involved which could break, or the system itself seems more vulnerable to breakage as a whole.

1: The design contains two of the following strengths (when compared with the Ski Seat): the material is more resistant to corrosion, there are fewer joints/moving parts involved that could break, or the system seems less vulnerable to breakage as a whole.

As a result of these criteria, each of the final four designs was awarded the following scores:

Design	Score
Compressed Ski Seat, Collapsible Side-to-Side	0
Raised Shoulder Steering, Collapsible Front-to-Back	-1
Raise Shoulder Steering, Collapsible Side-to-Side	-1
Compressed Ski Seat, Collapsible Front-to-Back	1

Compressed Ski Seat, Collapsible Side-to-Side:
Although this design is more resistant to corrosion than the Ski Seat, there are more joints that could break on the apparatus and the overall system has about the same level of robustness as the current design.

Raised Shoulder Steering, Collapsible Front-to-Back:

This design is less susceptible to corrosion than the Ski Seat, but it has more joints and moving parts that could break and the overall system is more likely to break given the added complications that could arise with the raise steering components.

Raised Shoulder Steering, Collapsible Side-to-Side:
Again, this design is less susceptible to corrosion than the Ski Seat. However, it also has more joints and moving parts that could break and the overall system is less robust due to the added steering components (much like its' front-to-back collapsible counterpart).

Compressed Ski Seat, Collapsible Front-to-Back:
This design is the most durable of the four. Just like the other three, it is also more resistant to corrosion. There are a couple more joints included in this design when compared with the Ski Seat for collapsibility. However, moving the drive train under the rider's seat will reduce the number of necessary components there, so the overall susceptibility to breakage is less for the moving parts and less as a whole-- making this system more robust.

Size:

Dr. Bash would like to easily transport his new waterski system, so the size of the collapsed system is very important. When fully assembled and in use, the size is far less crucial, as long as it is still compact enough to maneuver in the water. Based on these criteria, the following ratings were given to each design in our Decision Matrix:

-1: The design is larger than the disassembled Ski Seat when collapsed.

0: The design is approximately the same size as the Ski Seat when collapsed.

1: The design is smaller than the disassembled Ski Seat when collapsed.

As a result of these criteria, each of the final four designs was awarded the following scores:

Design	Score
Compressed Ski Seat, Collapsible Side-to-Side	0
Raised Shoulder Steering, Collapsible Front-to-Back	-1
Raise Shoulder Steering, Collapsible Side-to-Side	-1
Compressed Ski Seat, Collapsible Front-to-Back	0

Compressed Ski Seat, Collapsible Side-to-Side:

The supports in this design will be able to fold inwards, making the design flatter than the original Ski Seat, but the thicker seat will add some thickness, making it about the same size as the completely disassembled Ski Seat.

Raised Shoulder Steering (both systems):
The raised shoulder steering system introduces a rigid strut that will extend approximately three feet in the vertical direction, which will inevitably increase the collapsed size of the entire system.

Compressed Ski Seat, Collapsible Front-to-Back:
Similar to the first design, the supports will be able to fold inwards, making the design flatter than the original Ski Seat, but the thicker seat will add some thickness, making it about the same size as the completely disassembled Ski Seat. However, since this collapses side-to-side, it will prevent unwanted forward-to-back motion while in use, making this system's collapsibility scheme better than the others.

Agility/Control:

Considerations for agility/control include the design's responsiveness to the skier and the design's ability to do so in a controlled manner. The scale is used as follows:

-1: The apparatus is more difficult to steer and turns less quickly than the Ski Seat apparatus.

0: The apparatus has roughly the same abilities for steering and turning when compared with the Ski Seat.

1: The apparatus is easier to steer and turns more quickly than the Ski Seat apparatus.

Design	Score
Compressed Ski Seat, Collapsible Side-to-Side	0
Raised Shoulder Steering, Collapsible Front-to-Back	1
Raised Shoulder Steering, Collapsible Side-to-Side	1
Compressed Ski Seat, Collapsible Front-to-Back	0

Compressed Ski Seat, Collapsible Side-to-Side:
The compressed Ski Seat has roughly the same steering capabilities as the current Ski Seat design, since both apparatuses have the same steering setup.

Raised Shoulder Steering, Collapsible Front-to-Back:

The raised shoulder steering design will be more agile for the user since the vertical panels are connected directly to the ski, allowing for more responsive turning.

Raised Shoulder Steering, Collapsible Side-to-Side:
The raised shoulder steering design will be more agile for the user since the vertical panels are connected directly to the ski, allowing for more responsive turning.

Compressed Ski Seat, Collapsible Front-to-Back:
The compressed Ski Seat has roughly the same steering capabilities as the current Ski Seat design, since both apparatuses have the same steering setup.

Manufacturability:

-1: The design has more than two locations where collapsibility will occur. Additional large parts will be necessary for steering. Lots of welding will be required. Multiple frame members will have to be bent an excessive amount of times.

0: Additional large parts are needed for steering but less hinges are needed to collapse frame. Welding will be required but minimally. Frame members will need to be bent.

1: The frame only needs to be hinged in two places and the steering mechanism does not require a lot of machine time to make. Welding will be required but minimally. Parts can be made using a CNC. Frame members will need to be bent a minimal number of times.

Design	Score
Compressed Ski Seat, Collapsible Side-to-Side	1
Raised Shoulder Steering, Collapsible Front-to-Back	0
Raised Shoulder Steering, Collapsible Side-to-Side	-1
Compressed Ski Seat, Collapsible Front-to-Back	-1

Compressed Ski Seat, Collapsible Side-to-Side:
This design only needs two hinges where the center support meets the front and back supports. The steering mechanism will be part of the universal mounting system and therefor add very little time to the manufacturing stages.

Raised Shoulder Steering, Collapsible Front-to-Back:

The raised shoulder steering introduces a pair of large parts that will need to be machined. This also introduces a need for a third pair of universal mounting systems, which will take extra time to make. Only needing two hinges kept this design at a 0 rating.

Raised Shoulder Steering, Collapsible Side-to-Side:
This design will also need the large extra parts for steering along with the universal mounting systems for those. However, this design was rated at -1 because it also would need four hinges to collapse fully.

Compressed Ski Seat, Collapsible Front-to-Back:
This design was rated at -1 because of the four hinges that would be needed to collapse the frame. The hinges will be welded on and we have determined that welding will take the longest because we will need to outsource the job to someone with better skills.

Versatility:

The system's "versatility" relates to its ability to be easily adapted to any pair of water skis that Dr. Bash would like to use. The system received ratings based on this criterion, as described below:

-1: The system would be more difficult to interface with other existing sets of water skis than the Ski Seat is.

0: The system would be just as difficult to adapt to different skis as the Ski Seat system is.

1: The system would adapt to different sets of skis more easily than the Ski Seat.

Design	Score
Compressed Ski Seat, Collapsible Side-to-Side	1
Raised Shoulder Steering, Collapsible Front-to-Back	0
Raised Shoulder Steering, Collapsible Side-to-Side	0
Compressed Ski Seat, Collapsible Front-to-Back	1

Compressed Ski Seat Systems:
The systems with the Compressed Ski Seat steering mechanisms are both easier to interface with other skis than the Ski Seat because of the addition of the Universal

Mounting System. Since there are no additional parts that must be added to the skis, the systems utilizing the Compressed Ski Seat steering systems are more versatile than the original Ski Seat.

Raised Shoulder Steering Systems:
The systems with Raised Shoulder steering will still incorporate the Universal Mounting System, but they also have a strut that must be directly interfaced with the ski in order to steer effectively, which will make it difficult to remove from the ski without causing undesired damage. Due to this factor, the systems with Raised Shoulder steering are just as versatile as the Ski Seat.

Buoyancy:

Considerations for buoyancy include both the overall buoyancy of the system and the location of the buoyant segments of the design relative to their impact on the skier's resting location in the water during start. The ideal apparatus would have slightly more buoyancy in the front of the ski, so that the ski tips would remain out of the water during the skier's start.

-1: The apparatus is heavier and therefore less buoyant than the current design.

0: The apparatus has approximately the same amount of buoyancy as the current design.

1: The apparatus is lighter and therefore more buoyant than the current design.

Design	Score
Compressed Ski Seat, Collapsible Side-to-Side	0
Raised Shoulder Steering, Collapsible Front-to-Back	1
Raised Shoulder Steering, Collapsible Side-to-Side	1
Compressed Ski Seat, Collapsible Front-to-Back	0

Compressed Ski Seat, Collapsible Side-to-Side:
The compressed Ski Seat would have approximately the same amount of buoyancy as the current design.

Raised Shoulder Steering, Collapsible Front-to-Back:
The raised shoulder steering design will be more buoyant, since the raised steering mounts on each side will be made from buoyant materials, i.e. Styrofoam.

Raised Shoulder Steering, Collapsible Side-to-Side:
The raised shoulder steering design will be more buoyant, since the raised steering mounts on each side will be made from buoyant materials, i.e. Styrofoam.

Compressed Ski Seat, Collapsible Front-to-Back:
The compressed Ski Seat would have approximately the same amount of buoyancy as the current design.

Shock Absorption:

The system's ability to absorb shock and vibrations from the skis affects the comfort of the rider because the skis' vibrations are transferred to the rider if they are not dissipated by the system. In addition, the design of the seat in the system (specifically the dampening ability of the seat's padding) will affect the user's comfort. Each system is rated according to the following scale:

-1: Less of the high-frequency vibrations would be absorbed by the evaluated design than by the Ski Seat and would be less comfortable to use.

0: The system would absorb vibrations just as effectively as the Ski Seat, and be of a similar comfort level.

1: The system would dissipate more vibrations than the Ski Seat and be more comfortable to the user.

Design	Score
Compressed Ski Seat, Collapsible Side-to-Side	0
Raised Shoulder Steering, Collapsible Front-to-Back	1
Raised Shoulder Steering, Collapsible Side-to-Side	1
Compressed Ski Seat, Collapsible Front-to-Back	0

Compressed Ski Seat Systems:
The systems with the Compressed Ski Seat steering mechanisms have structures similar to the current Ski Seat, so the vibration dissipation quality of the new designs will be comparable to that of the Ski Seat. The seat will also be designed to provide more comfort and absorb some of the shock transferred through the steering system.

Raised Shoulder Steering Systems:
The systems with Raised Shoulder steering will have a strut that attaches to the skis, which will absorb and dissipate many vibrations from the skis. As long as the natural frequency of the strut is not maintained while in use, these vibrations will not be excessively transferred to the rider. As a result, the Raised Shoulder steering system will dissipate more vibrational energy than the Ski Seat.

Aesthetics:

Considerations for aesthetics are based around how sleek the design looks when in use over the water

-1: The apparatus is bulky looking, oddly shaped, or looks weird.

0: The apparatus has a similar aesthetic appearance to the current model

1: The design looks like a fighter jet over water.

Design	Score
Compressed Ski Seat, Collapsible Side-to-Side	0
Raised Shoulder Steering, Collapsible Front-to-Back	-1
Raised Shoulder Steering, Collapsible Side-to-Side	-1
Compressed Ski Seat, Collapsible Front-to-Back	0

Compressed Ski Seat, Collapsible Side-to-Side:
Looks much like the current design, though with a much improved color scheme and better skis. The side-to-side collapsibility mechanism will force us to use a more square-shaped frame which is not as aesthetically pleasing as a more streamlined frame.

Raised Shoulder Steering, Collapsible Front-to-Back:
The shoulder panels, though effective, look rather goofy. Although the front-to-back collapsibility allows for a more streamlined shape, the wings will distract from the overall look of the design.

Raised Shoulder Steering, Collapsible Side-to-Side:

The shoulder panels, though effective, look rather goofy. Additionally, the side-to-side collapsibility will take away from the desired streamlined look.

Compressed Ski Seat, Collapsible Front-to-Back: Looks much like the current design, though with a much improved color scheme and better skis. In addition, the front-to-back collapsibility will allow this design to have a very streamlined look.

Appendix D: House of Quality

This appendix contains the House of Quality—used to convert customer requirements to engineering specifications and determine level of importance.

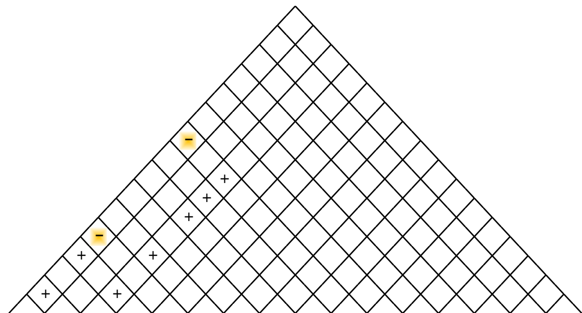
QFD: House of Quality

Project: Freedom Ski
Revision: 2
Date: 10/26/14

Correlations	
Positive	+
Negative	−
No Correlation	

Relationships	
Strong	●
Moderate	○
Weak	▽

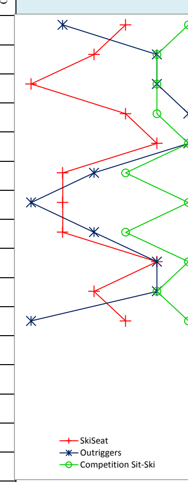
Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼



WHO: Customers

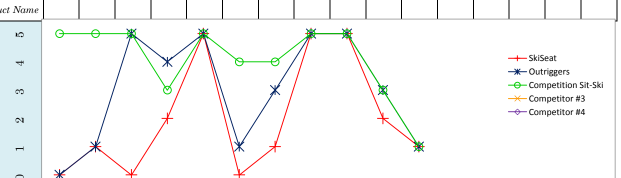
NOW: Current Product Assesment - Customer Requirements

				Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16						
				Direction of Improvement	▼	◇	◇	▲	▲	▼	▼	▲	▲	▲	◇											
Row #	Relative Weight	Customer 1: Importance to Dr. Bash (1 - 10)	Maximum Relationship	HOW: Engineering Specifications / WHAT: Customer Requirements (explicit & implicit)	Weight	Max. collapsed dimensions (WxHxL)	Universal mounting system	Buoyancy	Fatigue life of center bar	Time to set up/collapse	Number of sharp corners	Yield stress of screws mounting shoes to skis	Yield stress of pins at ankles	Width of aluminum of shoes and feet at ankle joints	Presence of zinc sacrificial anode at junction between chrome moly main tube and aluminum section of frame						SkiSeat	Competitor #1: *Liquid Access Outriggers*	Competitor #2: *Liquid Access Competition Sit-Ski*	Competitor #3: *Product Name*	Competitor #4: *Product Name*	Row #
1	10%	8	9	Lighter [weight] than current setup	●	○	▽	●	○	▽	▽	▽	▽	○	▽						3	1	5			1
2	8%	6	3	Comfort	○	○	▽	▽	▽	▽	▽	▽	▽	▽	▽						2	4	4			2
3	5%	4	9	Interchangeability with different skis	▽	▽	●	▽	▽	○	▽	○	○	○	▽						0	4	4			3
4	9%	7	9	Must float nose-up with 30 - 40lbf on seat	○	▽	▽	●	▽	▽	▽	▽	▽	○	▽						3	5	4			4
5	10%	8	9	Must structurally support 200 ± 40lb rider	○	▽	▽	○	●	▽	▽	●	●	●	▽						4	5	5			5
6	5%	4	9	Collapsibility	▽	●	●	▽	▽	●	▽	○	○	○	▽						1	2	3			6
7	11%	9	9	Stiffer steering base than current setup	▽	▽	▽	▽	○	▽	▽	○	○	●	▽						1	0	5			7
8	5%	4	9	Does not corrode	○	▽	▽	▽	▽	▽	▽	▽	▽	▽	●						1	2	3			8
9	13%	10	1	Aesthetically appealing	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽	▽						4	4	5			9
10	13%	10	9	No sharp corners	▽	▽	▽	▽	▽	▽	●	○	○	○	▽						2	4	4			10
11	11%	9	9	Better carving ability than current setup	▽	▽	○	○	▽	▽	▽	▽	▽	●	▽						3	0	5			11
12	0%																									12
13	0%																									13
14	0%																									14
15	0%																									15
16	0%																									16



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
HOW MUCH: Target	Weight < 22lb	Max. collapsed dimensions < (24"x30"x9")	Universal mounting system	Buoyancy > 0 lb when fully submerged	> 200,000 cycles	Setup time < 10min	0	>36,000 psi	>2,547 psi	>0.084 in	1 per connection					
Max Relationship	9	9	9	9	9	9	9	9	9	9	9					
Technical Importance Rating	244.3	175.9	203.8	294.9	224.1	150.6	201.3	249.4	249.4	446.8	140.5					
Relative Weight	9%	7%	8%	11%	9%	6%	8%	10%	10%	17%	5%					
Weight Chart																
SkiSeat	0	1	0	2	5	0	1	5	5	2	1					
Competitor #1: Liquid Access Outrigger	0	1	5	4	5	1	3	5	5	3	1					
etitor #2: Liquid Access Competition Sit-Ski	5	5	5	3	5	4	4	5	5	3	1					
Competitor #3: *Product Name*																
Competitor #4: *Product Name*																

Current Product Assesment - Engineering Specifications



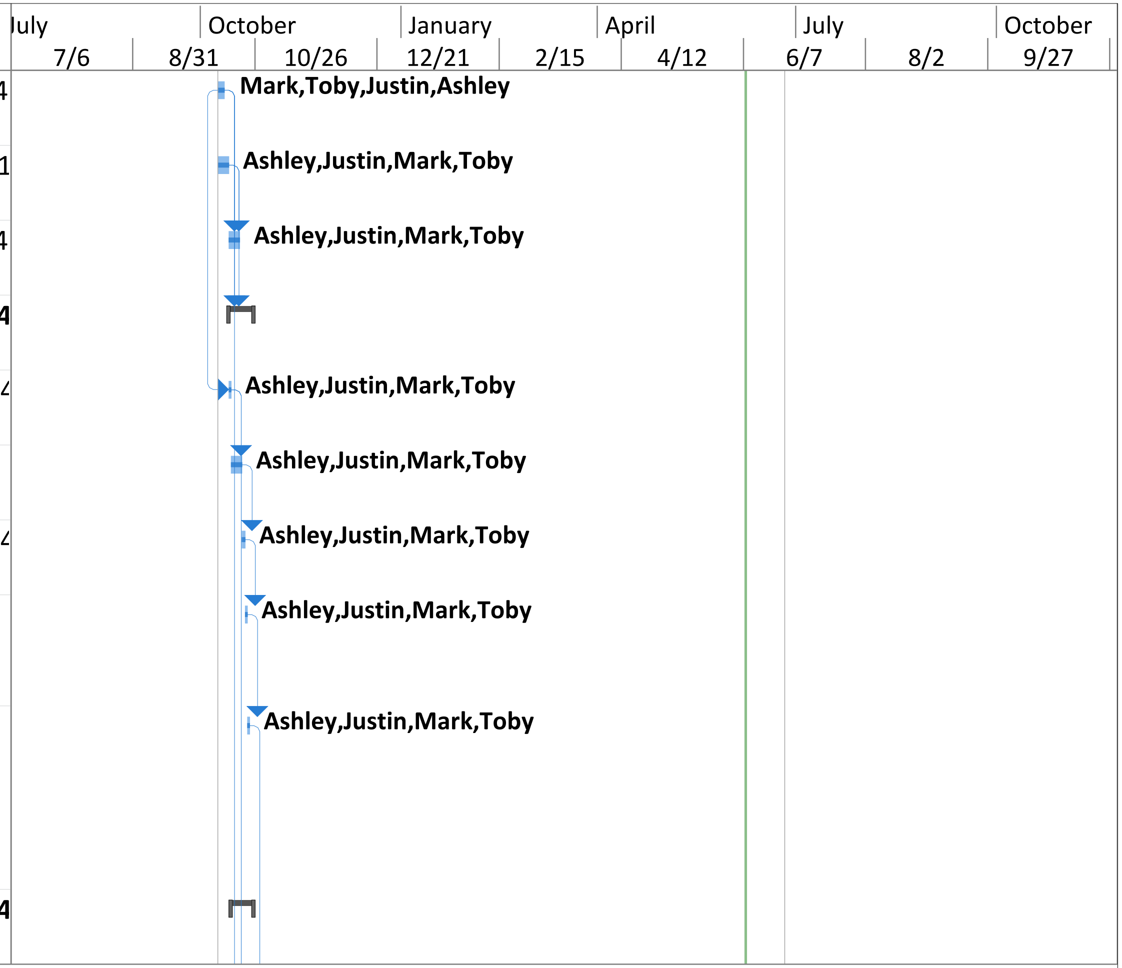
Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

Template Revision: 0.9 Date: 4/23/2010
Christopher Battles

Appendix E: Project Gantt Chart

This appendix details project tasks, durations and completion dates for the entire project duration. This plan includes tasks for the initial research and requirements phases, design and analysis phase and manufacturing and testing phases of the project.

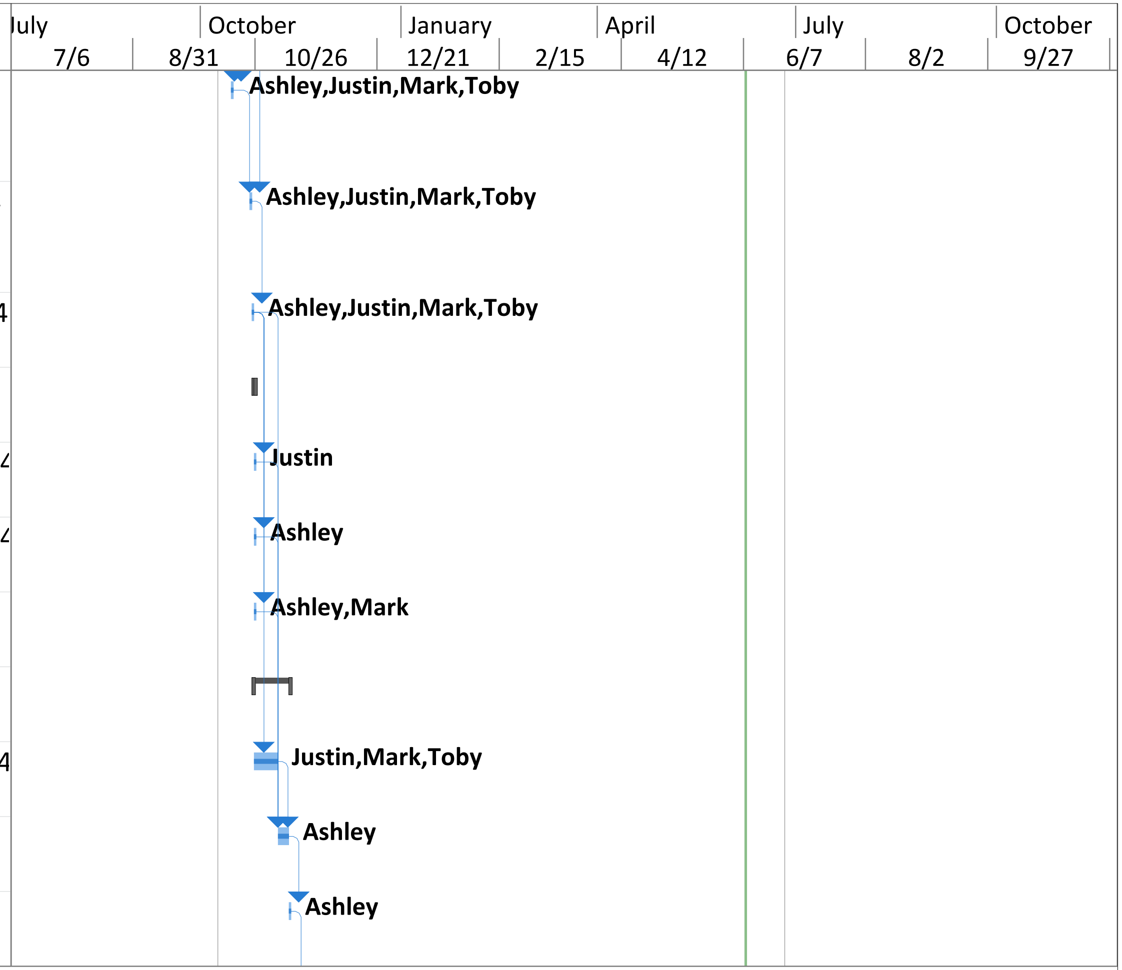
ID	Task Name	Duration	Start	Finish
1	Define Requirements	3 days	Thu 10/9/14	Sat 10/11/14
2	Background Research	5 days	Thu 10/9/14	Mon 10/13/1
3	Project Proposal	5 days	Tue 10/14/14	Sat 10/18/14
4	**Design Ideation**	**11.5 days**	**Tue 10/14/14**	**Sat 10/25/14**
5	Identify functions.	1 day	Tue 10/14/14	Tue 10/14/14
6	Brainwriting activities.	5 days	Wed 10/15/14	Sun 10/19/14
7	Build rough models	1.5 days	Mon 10/20/1	Tue 10/21/14
8	Evaluate function ideas with Pugh matrices.	1 day	Tue 10/21/14	Wed 10/22/14
9	Use Morphological Attribute Matrix for combining subsystems into design.	1 day	Wed 10/22/14	Thu 10/23/14
10	**Decision matrix**	**10.5 days**	**Wed 10/15/1**	**Sat 10/25/14**



Project: Waterski Senior Project G
Date: Mon 6/8/15

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

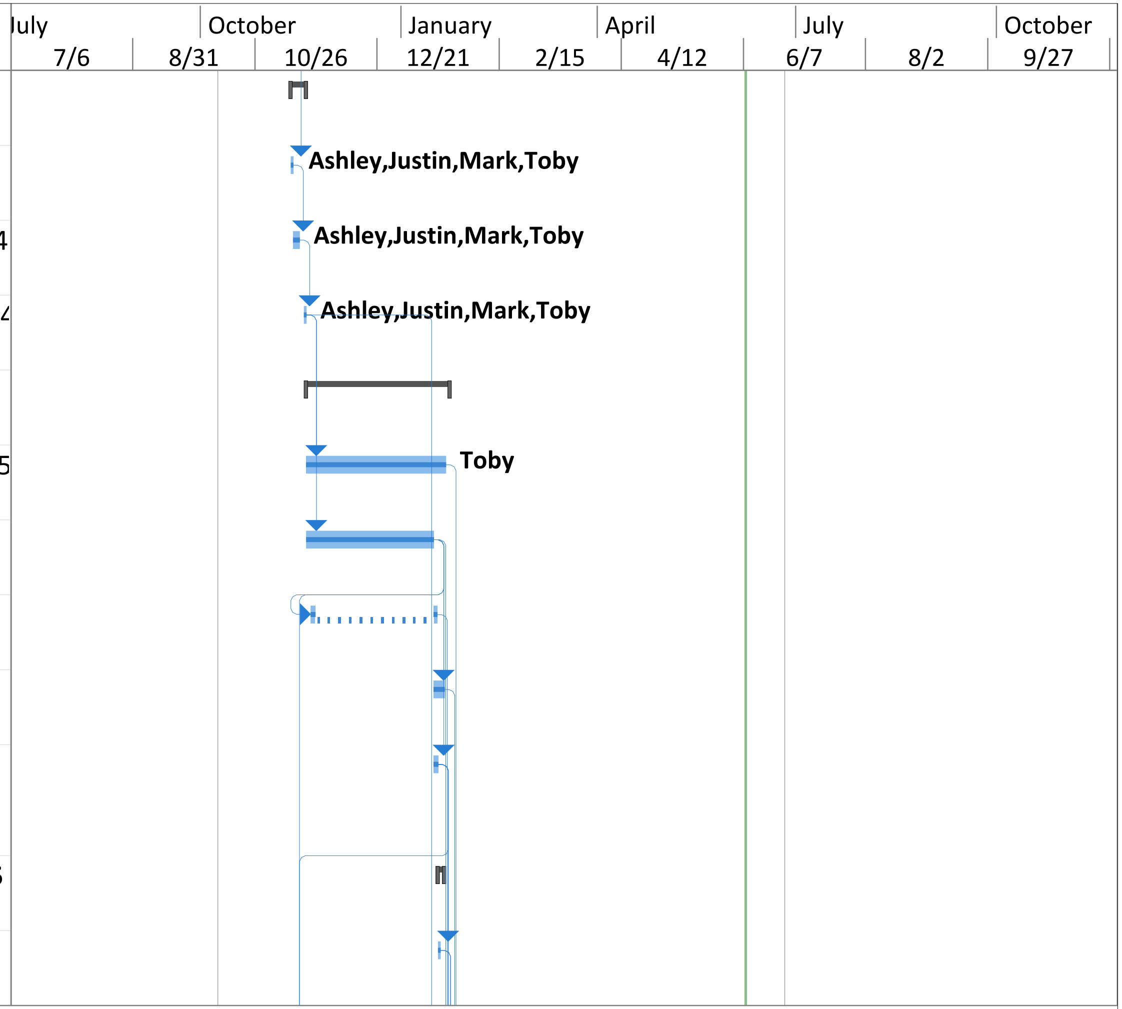
ID	Task Name	Duration	Start	Finish
11	Use pairwise comparison for criteria.	1 day	Wed 10/15/14	Wed 10/15/14
12	Evaluate criteria for each of four designs.	1 day	Thu 10/23/14	Fri 10/24/14
13	Choose design	1 day	Fri 10/24/14	Sat 10/25/14
14	**Preliminary Analysis of Chosen Idea**	**1 day**	**Sat 10/25/14**	**Sun 10/26/14**
15	Vibration Analysis	1 day	Sat 10/25/14	Sun 10/26/14
16	Stress Analysis	1 day	Sat 10/25/14	Sun 10/26/14
17	Manufacturing Analysis and	1 day	Sat 10/25/14	Sun 10/26/14
18	**Preliminary Design Report**	**17 days**	**Sat 10/25/14**	**Tue 11/11/14**
19	CAD Modeling	11 days	Sat 10/25/14	Wed 11/5/14
20	Finalize Report Writing	5 days	Wed 11/5/14	Mon 11/10/14
21	Finalize Report Presentation	1 day	Mon 11/10/14	Tue 11/11/14



Project: Waterski Senior Project G
Date: Mon 6/8/15

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

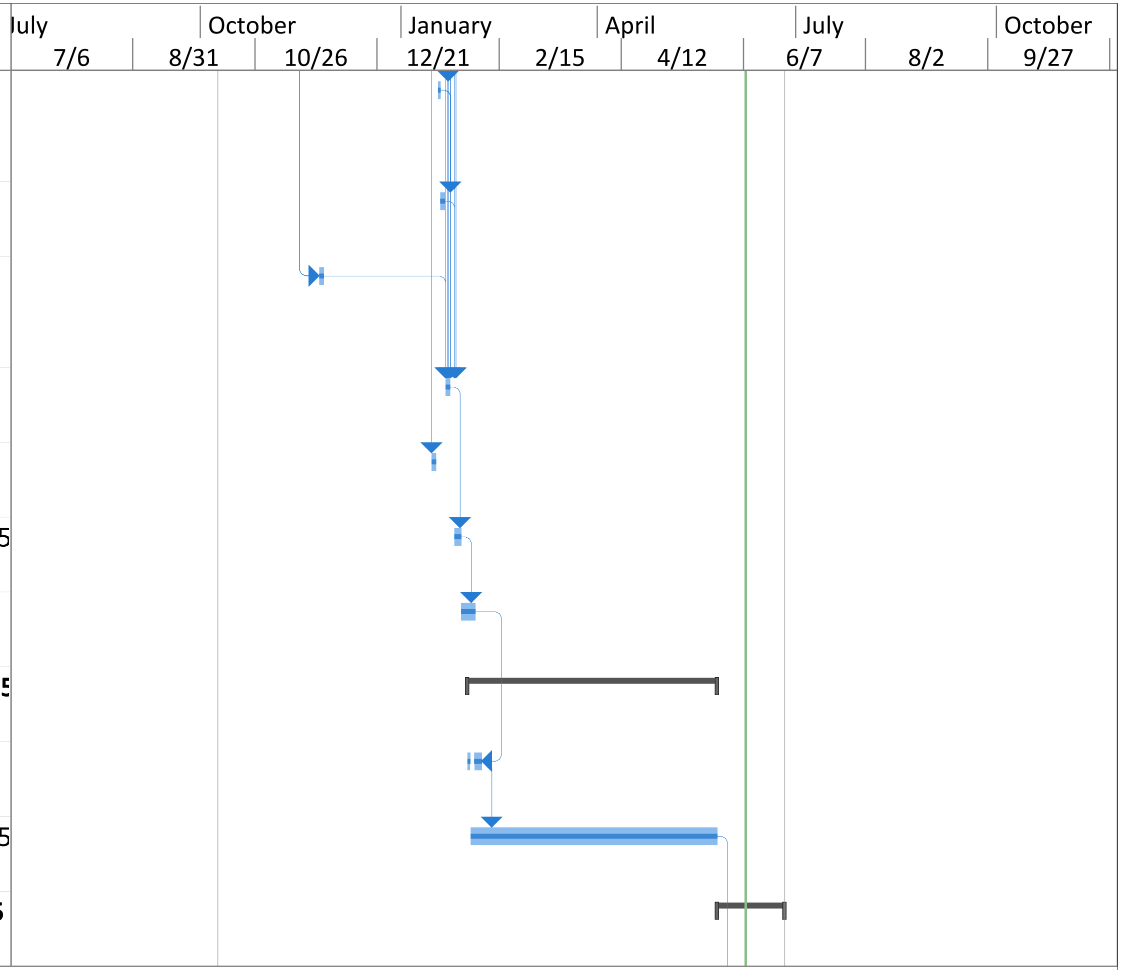
ID	Task Name	Duration	Start	Finish
22	**Preliminary Design Review**	**7 days**	**Tue 11/11/14**	**Tue 11/18/14**
23	Present to class and receive	1 day	Tue 11/11/14	Wed 11/12/14
24	Amend presentatio	3 days	Wed 11/12/1	Sat 11/15/14
25	Present to Sponsor	1 day	Mon 11/17/1	Tue 11/18/14
26	**Design Analysis**	**66 days**	**Tue 11/18/1**	**Fri 1/23/15**
27	Motion Analysis	64 days	Tue 11/18/14	Wed 1/21/15
28	Material Selection	58.5 days	Tue 11/18/14	Thu 1/15/15
29	Specific Stress Analysis	4 days	Thu 11/20/14	Sat 1/17/15
30	Comfort Analysis	5 days	Fri 1/16/15	Tue 1/20/15
31	Final Sizing and Tolerancing of CAD model	2 days	Fri 1/16/15	Sat 1/17/15
32	**CAD drawings**	**3 days**	**Sun 1/18/15**	**Tue 1/20/15**
33	CAD part drawing	1 day	Sun 1/18/15	Sun 1/18/15



Project: Waterski Senior Project G
Date: Mon 6/8/15

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

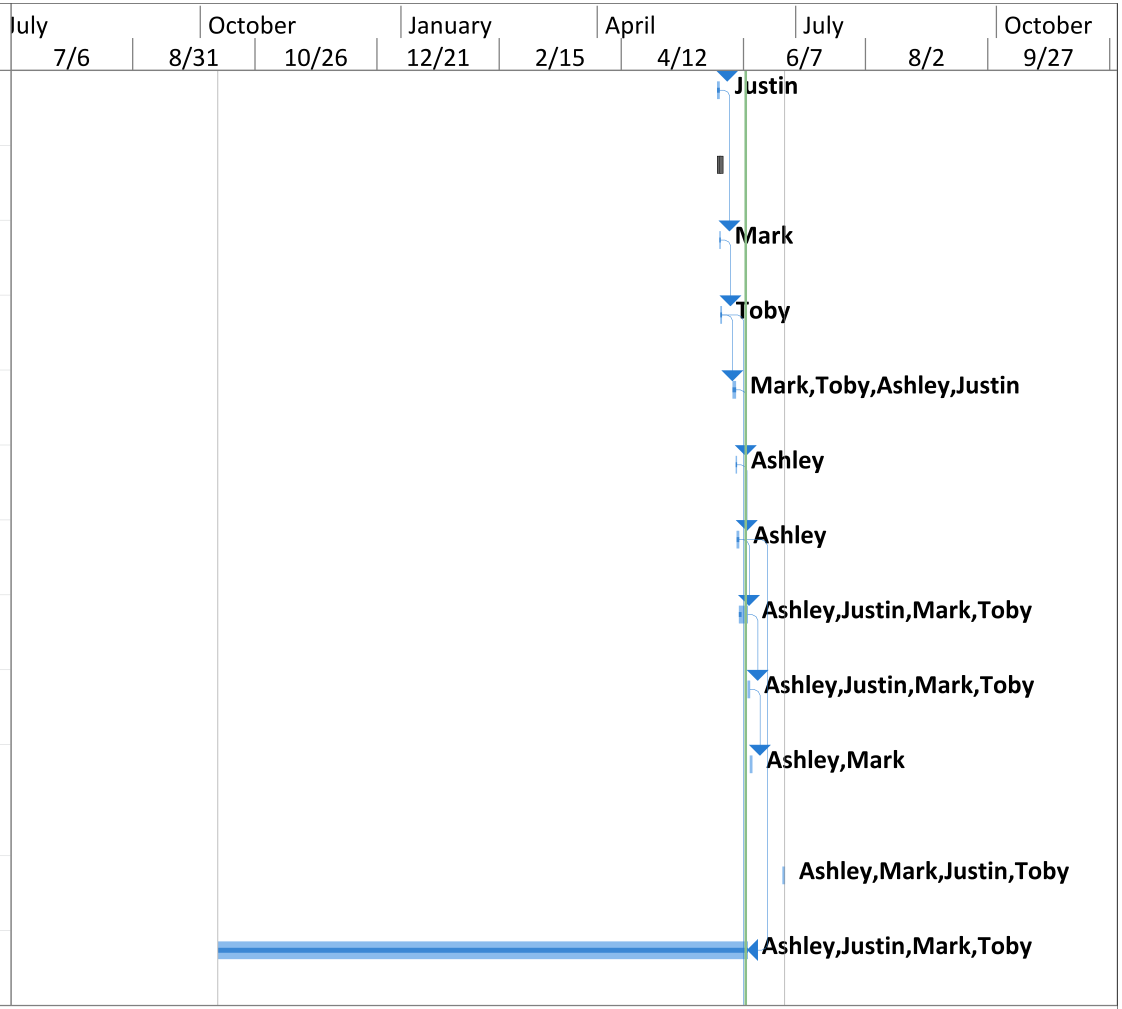
ID	Task Name	Duration	Start	Finish
34	CAD Assembly Drawings and B.O.M.	1 day	Sun 1/18/15	Sun 1/18/15
35	Manufacturing Drawings	2 days	Mon 1/19/15	Tue 1/20/15
36	Reevaluation of Manufacturing Analysis	2 days	Mon 11/24/14	Wed 11/26/14
37	Cost Analysis	2 days	Wed 1/21/15	Fri 1/23/15
38	Testing Plan	2 days	Thu 1/15/15	Fri 1/16/15
39	Concept Design Revie	3 days	Sun 1/25/15	Wed 1/28/15
40	Concept Design Repor	6.5 days	Wed 1/28/15	Tue 2/3/15
41	**Build Design**	**114.5 days**	**Sat 1/31/15**	**Mon 5/25/15**
42	Order parts	4.5 days	Sat 1/31/15	Fri 2/6/15
43	Build*	113 days	Mon 2/2/15	Mon 5/25/15
44	**Test**	**24 days**	**Tue 5/26/15**	**Thu 6/25/15**



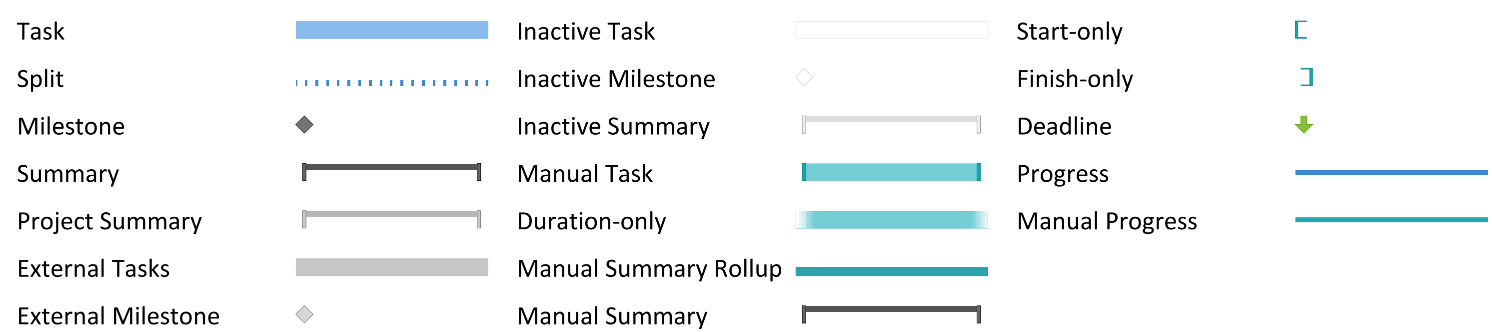
Project: Waterski Senior Project G
Date: Mon 6/8/15

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

ID	Task Name	Duration	Start	Finish
45	Floatation Test	1 day	Tue 5/26/15	Tue 5/26/15
46	**Motion Analysis Testing**	**1 day**	**Wed 5/27/15**	**Wed 5/27/15**
47	Range of Motion Test	0.5 days	Wed 5/27/15	Wed 5/27/15
48	Relative Angle Change Test	0.5 days	Wed 5/27/15	Wed 5/27/15
49	First Round Changes	1.5 days	Tue 6/2/15	Wed 6/3/15
50	Safety Inspection	0.5 days	Wed 6/3/15	Wed 6/3/15
51	Rider test-- Ashley	1 day	Thu 6/4/15	Thu 6/4/15
52	Second Round Changes	2 days	Fri 6/5/15	Mon 6/8/15
53	Retest	1 day	Tue 6/9/15	Tue 6/9/15
54	Second Round Safety Inspection	1 day	Wed 6/10/15	Wed 6/10/15
55	Rider test-- Dr. Bash	1 day	Thu 6/25/15	Thu 6/25/15
56	Final Project Report	240 days	Thu 10/9/14	Mon 6/8/15



Project: Waterski Senior Project G
Date: Mon 6/8/15

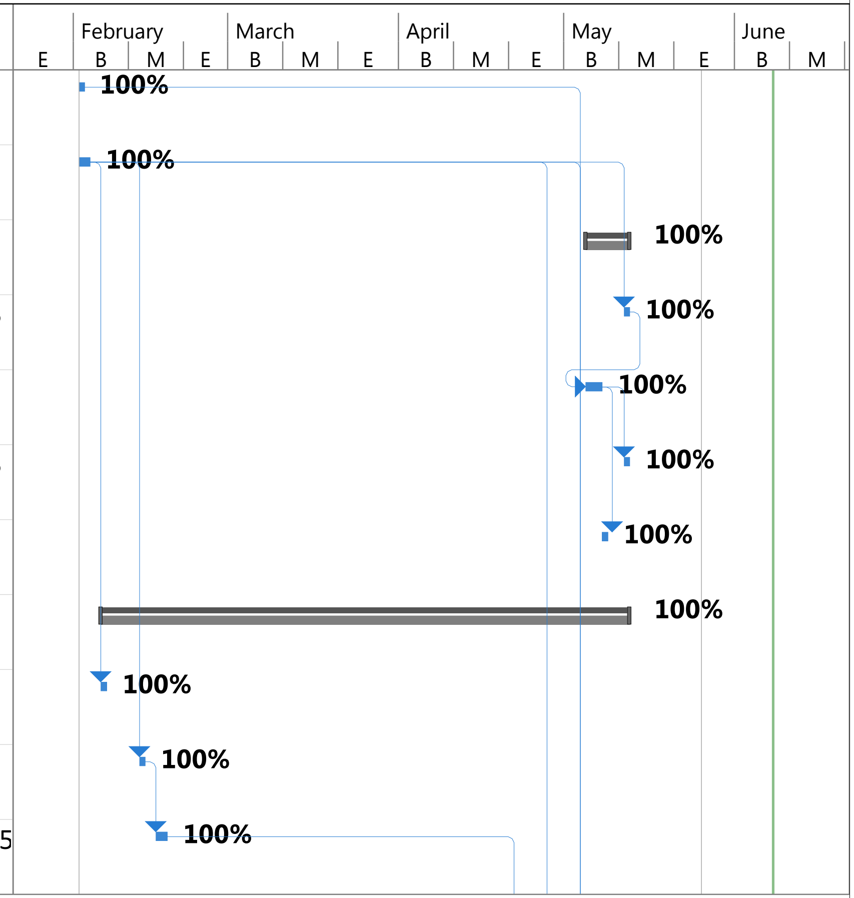


Appendix F: Manufacturing Gantt Chart

This appendix details the project's manufacturing process, including specific parts to be manufactured and the starting and ending times and durations of corresponding processes for each part.

Manufacturing Gantt Chart

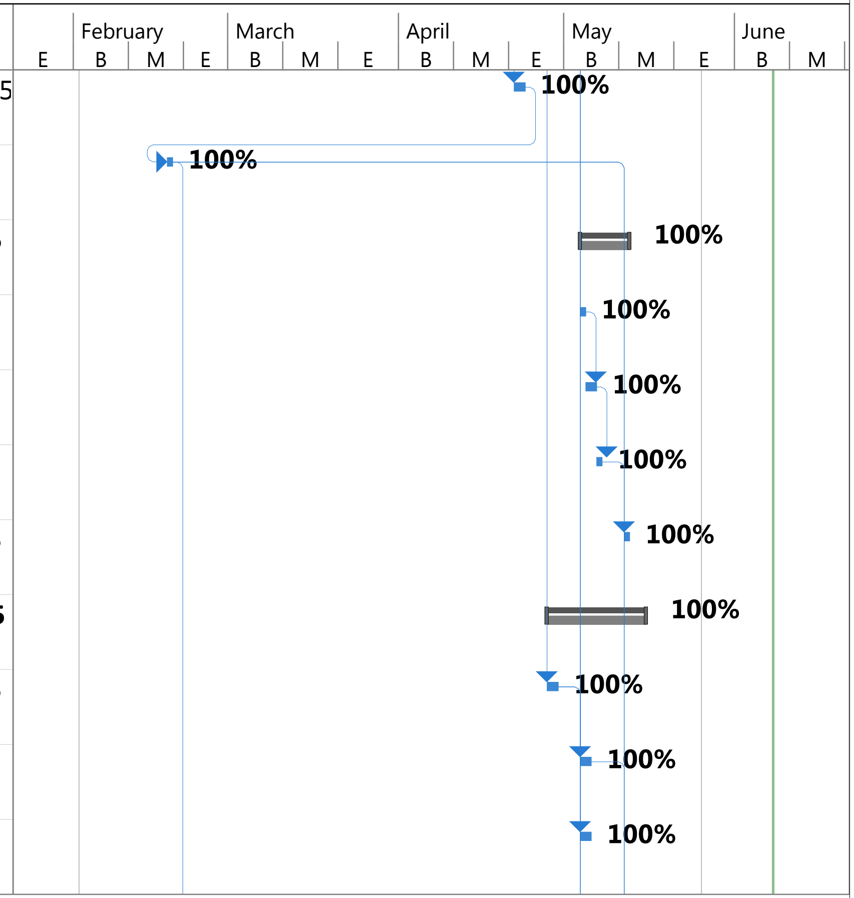
ID	Task Name	Duration	Start
1	Order Parts	1 day	Mon 2/2/15
2	Order Materials	2 days	Mon 2/2/15
3	**Feet**	**6 days**	**Tue 5/5/15**
4	Cut Material for feet	1 day	Tue 5/12/15
5	Lathe Material to correct diameters	3 days	Tue 5/5/15
6	Mill slot for ankle	1 day	Tue 5/12/15
7	Drill holes for shoe attachment and pins	1 day	Fri 5/8/15
8	**Frame**	**68 days**	**Fri 2/6/15**
9	Cut material for joints, feet and ankles	1 day	Fri 2/6/15
10	Cut frame tubing	1 day	Fri 2/13/15
11	Sand frame tubing down to size	2 days	Mon 2/16/15

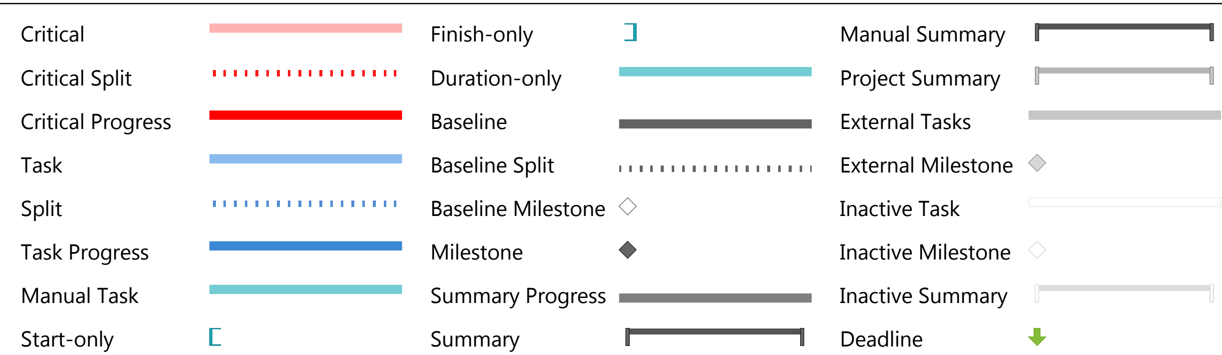


Critical		Finish-only		Manual Summary	
Critical Split		Duration-only		Project Summary	
Critical Progress		Baseline		External Tasks	
Task		Baseline Split		External Milestone	
Split		Baseline Milestone		Inactive Task	
Task Progress		Milestone		Inactive Milestone	
Manual Task		Summary Progress		Inactive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

Manufacturing Gantt Chart

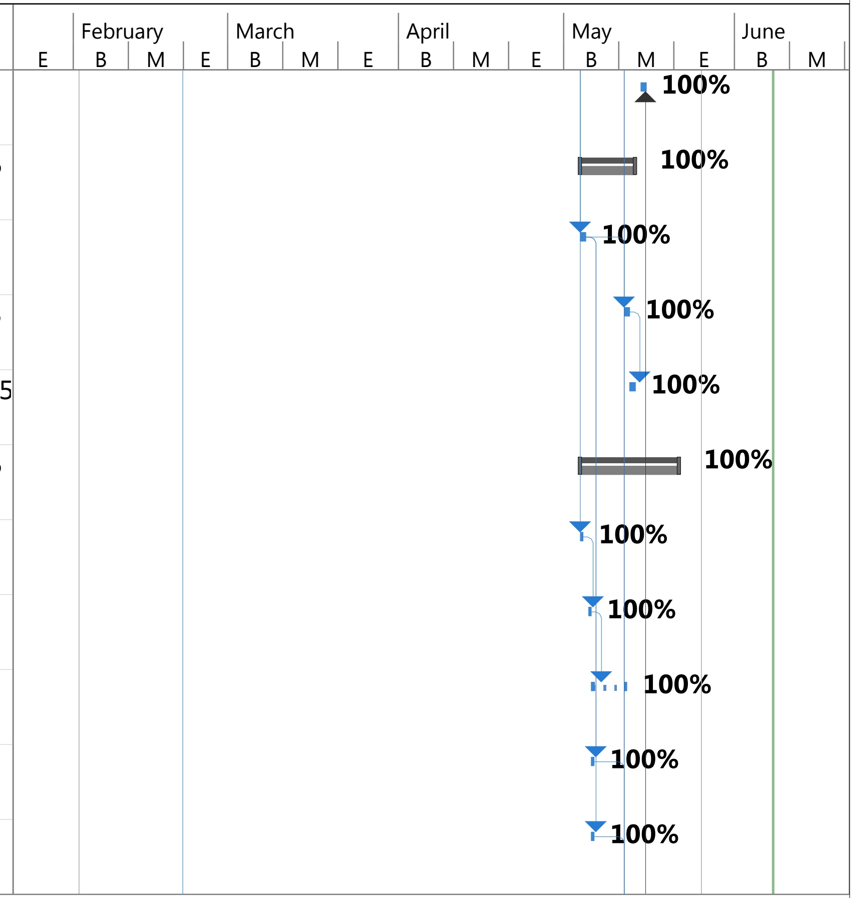
ID	Task Name	Duration	Start
12	Build welding jig	2 days	Wed 4/22/15
13	Tack weld the frame pieces together at joints and ankles	1 day	Wed 2/18/15
14	**Center Bar Assembly**	**7 days**	**Mon 5/4/15**
15	Find hardware for hinges	1 day	Mon 5/4/15
16	Assemble all pieces into bar	2 days	Tue 5/5/15
17	Prepare ends for assembly with Y and T joints	1 day	Thu 5/7/15
18	Build welding jig	1 day	Tue 5/12/15
19	**Shoes**	**14 days**	**Tue 4/28/15**
20	Cut Material to rough length	2 days	Tue 4/28/15
21	Drill hole pattern for screws and feet	2 days	Mon 5/4/15
22	Use mill to create through hole for pin	2 days	Mon 5/4/15

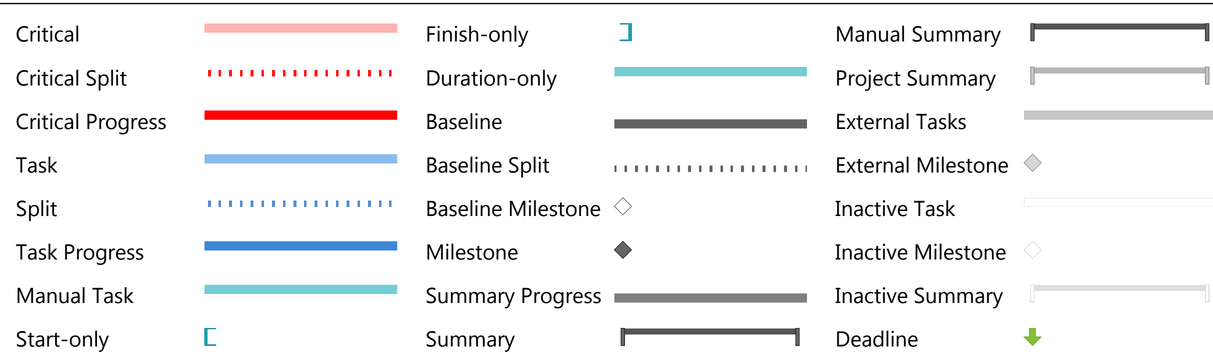




Manufacturing Gantt Chart

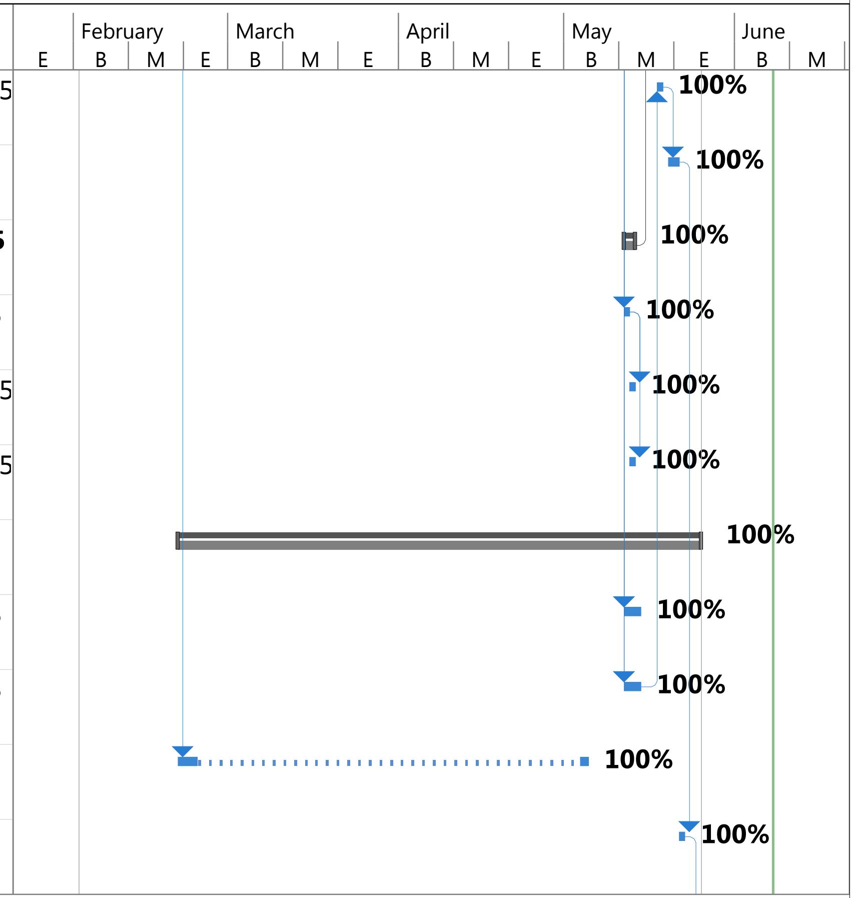
ID	Task Name	Duration	Start
23	Assemble shoes on skis	1 day	Fri 5/15/15
24	**Drivetrain**	**8 days**	**Mon 5/4/15**
25	Cut bar stock for drive train	1 day	Mon 5/4/15
26	Drill holes in drive train for seat and ankle attachments	1 day	Tue 5/12/15
27	Attach to frame with quick release at seat	1 day	Wed 5/13/15
28	**Seat**	**14 days**	**Mon 5/4/15**
29	Trace Seat Pattern	0.5 days	Mon 5/4/15
30	Machine seat plates	0.5 days	Tue 5/5/15
31	Bend/Machine Seat Plate Ribs	1 day	Wed 5/6/15
32	Machine piece that connects seat plate to drivetrain	0.5 days	Wed 5/6/15
33	Machine piece that connects seat plate to steering bar	0.5 days	Wed 5/6/15

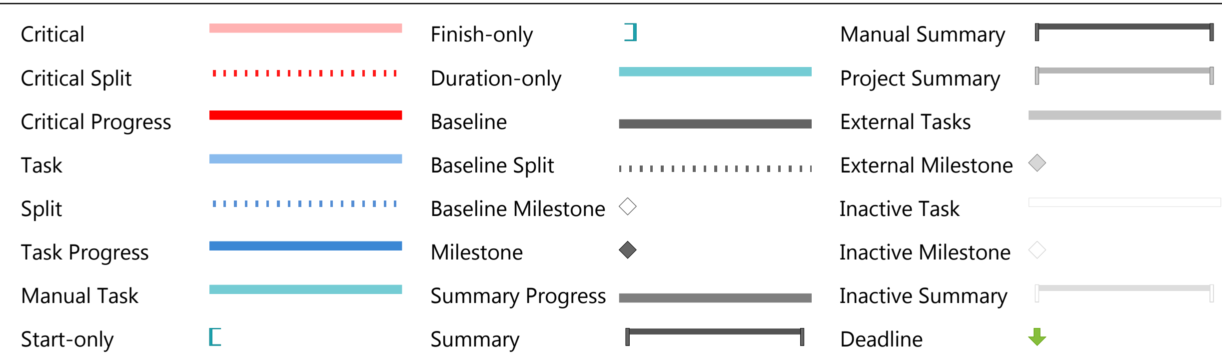




Manufacturing Gantt Chart

ID	Task Name	Duration	Start
34	Attach seat to central member of frame	1 day	Mon 5/18/15
35	Attach quick release from drivetrain to seat	2 days	Wed 5/20/15
36	**Ski Preparation**	**2 days**	**Tue 5/12/15**
37	Drill Holes for Inserts	1 day	Tue 5/12/15
38	Insert Inserts	1 day	Wed 5/13/15
39	Epoxy empty holes in skis	1 day	Wed 5/13/15
40	**Weld and Heat Treat Parts**	**67 days**	**Fri 2/20/15**
41	Weld piece that connects seat plate to drivetrain to the seat plate	3 days	Tue 5/12/15
42	Weld piece that connects seat plate to steering bar onto seat plate	3 days	Tue 5/12/15
43	Have IME department structurally weld frame	3 days	Fri 2/20/15
44	Assemble	1 day	Fri 5/22/15





Manufacturing Gantt Chart

ID	Task Name	Duration	Start	February: E B M · March: E B M · April: E B M · May: E B M · June: E B M
45	Spray paint frame	1 day	Mon 5/25/15	100%

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

Appendix G: Production, Small Scale and Large Scale Costs

This appendix details associated costs with prototype production, as well as projected costs for small scale and large scale production of the system.

Prototype

Operation	Detail	Labor	Overhead	Total	Notes	Source
Tubing						
Airfoil Tube	$14.10/ft*12ft=$169.20			$197.06	12ft min, they can cut it, price incl shipping/tax est	http://aircraftproducts.wicksaircraft.com/item/aircraft-aluminum-metals/6061-t6-aluminum-streamline-tubing/sl20-85-4-t6?
Cut Tubing		subsidized	subsidized	subsidized	self cut or cut at manufacturer	
Weld Tubing		subsidized	subsidized	subsidized	Kevin Williams	
Powdercoat Tube		$50		$50	Possible subsidization from Chris Szarec	http://fullspectrumpowdercoating.com/index.php 805-234-7755 Chris Szarec possible subsidization
Steering Tubing	6 feet, $31.31	subsidized		$31.30	9056K66	
Interstitial Shaft Collar Tubing	1 foot, $21.21			$21.21	7767T66	
Total				**$299.57**		
Aluminum Stock						http://www.mcmaster.com/#=vk3q0q
Ankles	$40.56 1"x2.25"x24"			$40.56	8975K39	
Y/T Joint	Rod, 6061, OD 1 3/8"x12"			$22.79	8974K17	
I joint	$4.45 1.5"x3" Round			$4.45	7392T12	
Feet	$26.83 2"x24" bar stock			$26.83	8974K18	
Shoe	$36.04 3.25"x6" bar stock			$36.04	8974K86	
Machining of Joints	$16/hr*20hrs			$320.00	via calpoly machine shop, estimate	
ChoMoly sleeve (internal in center bar)	0.120" wall, 1.375"ODx1ft	machined by us		$20.83	89955K169	
Powdercoat				n/a	will be powdercoated with tubing	http://fullspectrumpowdercoating.com/index.php
Total				**$472**		
Seat Plate						
Material	6"x12" $19.13			$19.13	4459T145	http://www.mcmaster.com/#=vk3q0q
Bend to shape		subsidized	subsidized	subsidized		

Powdercoat				n/a	will be powdercoated with tubing	http://fullspectrumpowdercoating.com/index.php
Steel Plate to Weld To				$7.67	8910K571	
Total				**$26.80**		
Drivetrain						
Material	1/2" tube, 6' $18.47			$18.47	9056K66	http://www.mcmaster.com/#=vk3q0q
Bend to shape		subsidized	subsidized	subsidized	in the shop	
Powdercoat				n/a	will be powdercoated with tubing	http://fullspectrumpowdercoating.com/index.php
Total				**$18.47**		
Delrin Bushings						
material (shaft collars)	12" $17.28			$17.28	8576K29	http://www.mcmaster.com/#=vk3q0q
Machine to shape		subsidized	subsidized	subsidized		
material (Y and T joint)	12" $9.98			$9.98	8576K24	
Machine to shape		subsidized	subsidized	subsidized		
Total				**$27.26**		
Shaft Collar	$28.66 each			**$57.32**	6100T24	http://www.mcmaster.com/#=vk3q0q
Pins	$15/each			**$60**	LG-4CT2000	http://www.southco.com/en-us/lg-lm/lg-4ct2000
Seat	$32 each			**$72.00**	price plus shipping, purchasing a spare	http://www.airchair.com/#!seats-and-seat-accessories/cq1e
Bolts						
Seat to Drivetrain bolt	$5.49			$5.49	91251A859	http://www.mcmaster.com/#=vk3q0q
Drivetrain screws	1/4-20 shoulder screws with 5/16" shoulder dia and 2" length, for 6			$8.58	91259A591	
Y/T connection screws	Socket head cap screws 1/4-20 partially threaded for Y and T joint connections, bag of 25			$11.19	93705A544	
Shoe to ski screws	4 per ski, low profile Allen			$8.25	92220A141	
Total				**$33.51**		

Potting	package of 25 inserts			**$11.49**	94648A330	
Tooling						
RH lathe tool	turning			$21.19	3240A101	http://www.mcmaster.com/#one-piece-lathe-tool-bits/=voil55
LH Lathe tool	facing			$21.19	3240A102	
Total				**$42.38**		
Engineering Design		300hrs per quarter		**$0.00**		
Total				**$1,147.56**		

Small Scale

Operation	Material	Labor	Overhead	Total	Notes	Source
Tubing						
Airfoil Tube	$14.10/ft*12ft=$169.20			$1,970.56	12ft min, they can cut it, price incl shipping/tax est	http://aircraftproducts.wicksaircraft.com/item/aircraft-aluminum-metals/6061-t6-aluminum-streamline-tubing/sl20-85-4-t6?
Cut Tubing		$60/hr*3hrs total		$180	using machine shop estimates	price via Viktor Steinberger, professional welder/machinist
Weld Tubing		$80/hr*5hrs	$100	$500	using machine shop estimates	price via Viktor Steinberger, professional welder/machinist
Powdercoat Tube		$50/hr*6hrs		$300		http://fullspectrumpowdercoating.com/index.php, http://www.powdercoatme.com/pricing.html
Steering Tubing	$31.31	$50/hr*6hrs		$613.00	9056K66	
Interstitial Shaft Collar Tubing	$21.21			$210.21	7767T66	
Total				**$3,773.77**		
Aluminum Stock						http://www.mcmaster.com/#=vk3q0q
Ankles	$40.56 1x2.25x24			$405.60		8975K39
Y/T Joint	Rod, 6061, OD 1 3/8" 12"			$22.79		8974K17
I joint	$4.45 1.5x3" Round			$44.50		7392T12
Feet	$26.83 2"x24" bar stock			$268.30		8974K18
Shoe	$36.04 3.25"x6" bar stock			$360.40		8974K86
Machining of Joints	$80/hr*200hrs			$16,000.00		
ChoMoly sleeve (internal in center bar)	0.120" wall, 1.375"ODx1ft			$208.30		89955K169
Powdercoat				n/a	will be powdercoated with tubing	http://fullspectrumpowdercoating.com/index.php
Total				**$17,310**		
Seat Plate						
Material	38.21			191.3	4459T145	http://www.mcmaster.com/#=vk3q0q
Bend to shape	$80/hr*5hrs			$160		

Powdercoat				n/a	will be powdercoated with tubing	http://fullspectrumpowdercoating.com/index.php
Steel Plate to Weld To				$76.70	8910K571	
Total				**$351.30**		
Drivetrain						
Material	18.47			$184.70	9056K66	http://www.mcmaster.com/#=vk3q0q
Bend to shape	$80/hr*5hrs			$160		
Powdercoat				n/a	will be powdercoated with tubing	http://fullspectrumpowdercoating.com/index.php
Total				**$344.70**		
Delrin Bushings						
material (shaft collars)	$17.28			$172.80	8576K29	http://www.mcmaster.com/#=vk3q0q
Machine to shape	$80/hr*5hrs			$160		
material (Y and T joint)				$99.80	8576K24	
Machine to shape	$80/hr*5hrs			$160		
Total				**$592.60**		
Shaft Collar	28.66 each			**$573.20**	6100T24	http://www.mcmaster.com/#=vk3q0q
Pins	$15/each			**$600**	LG-4CT2000	http://www.southco.com/en-us/lg-lm/lg-4ct2000
Seat	$32 each			**$320.00**	price plus shipping, no spare	http://www.airchair.com/#!seats-and-seat-accessories/cq1e
Bolts						
Seat to Drivetrain bolt	$5.49			$54.90	91251A859	http://www.mcmaster.com/#=vk3q0q
Drivetrain screws	1/4-20 shoulder screws with 5/16" shoulder dia and 2" length, for 6			$85.80	91259A591	
Y/T connection screws	Socket head cap screws 1/4-20 partially threaded for Y and T joint connections, bag of 25			$22.38	93705A544	this is for a total of 50, as we only need 4 per build
Shoe to ski screws	.132" shoes to ski x 4			$82.50	92220A141	
Total				**$163.08**		

Potting	package of 25 inserts			$110.49	94648A330	
Engineering Design		300hrs, $75/hr		$22,500	standard design fee	
Skis	$700			$7,000.00		
Hinges (price for pair)	$300			$3,000.00		
Total				$57,231.63		
			Total Per:	$5,723.16		

Large Scale						
Operation	**Material**	**Labor**	**Overhead**	**Total**	**Notes**	**Source**
Tubing						
Airfoil Tube	$3/foot*8 feet each, $24 per			$2,400,000.00	reduced for large scale, bulk	http://aircraftproducts.wicksaircraft.com/item/aircraft-aluminum-metals/6061-t6-aluminum-streamline-tubing/sl20-85-4-t6?
Cut Tubing		$10/hr*1hrs each	$50,000	$150,000		
Weld Tubing		$10/hr*1hrs each	$50,000	$150,000		
Powdercoat Tube		$16/hr*1hr each	$40,000	$200,000		http://fullspectrumpowdercoating.com/index.php
Steering Tubing	$26.21 per foot			$1,310,500.00	9056K92	
Interstitial Shaft Collar Tubing	bulk			$221,000.00	7767T66	
Total				**$4,431,500.00**		
Aluminum Stock						http://www.mcmaster.com/#=vk3q0q
Ankles	$40.56			$3,042,000.00	8975K39	
Y/T Joint	Rod, 6061, OD 1 3/8" 12", bulk			$279,000.00		8974K17
I joint	$4.45			$333,750.00	7392T12	
Feet	$26.83			$2,012,250.00	8974K18	
Shoe	$36.04			$2,703,000.00	8974K86	
Mill to shape		$25/hr*5hrs	see below, 5axis CNC	$50,125		http://www.haascnc.com/vmc_mt.asp?webID=5AXIS_VMC#gsc.tab=0
Powdercoat		$20/hr*1hr, included with frame powdercoat	$40000 (already paid for)	n/a	will be powdercoated with tubing	http://fullspectrumpowdercoating.com/index.php
ChoMoly sleeve (internal in center bar)	0.120" wall, 1.375"ODx1ft			$20.83		89955K169

Total				**$8,420,125.00**		
Seat Plate						
Material	Bulk			8210000	89015K31	http://www.mcmaster.com/#=vk3q0q
Bend to shape		$10/hr, 30 per hour		$30,000		
Powdercoat		$20/hr*1hr, included with frame powdercoat	$40000 (already paid for)	n/a	will be powdercoated with tubing	http://fullspectrumpowdercoating.com/index.php
Steel Plate to Weld To				$300,000.00	8910K571	
Total				**$8,240,000.00**		
Drivetrain						
Material	Bulk			$147,000.00	9056K66	http://www.mcmaster.com/#=vk3q0q
Bend to shape		$10/hr, 30 per hour		$30,000	in the shop	
Powdercoat				n/a	will be powdercoated with tubing	http://fullspectrumpowdercoating.com/index.php
Total				**$177,000.00**		
Delrin Bushings						
material (shaft collars)	$17.28			$17.28	8576K29	http://www.mcmaster.com/#=vk3q0q
Machine to shape		subsidized	subsidized	subsidized		
material (Y and T joint)				$9.98	8576K24	
Machine to shape		subsidized	subsidized	subsidized		
Total				**$27.26**		
Shaft Collar	28.66 each, bulk order reduction			**$866,000.00**	6100T24	http://www.mcmaster.com/#=vk3q0q

Pins	$5/each			**$2,000,000**	LG-4CT2000	http://www.southco.com/en-us/lg-lm/lg-4ct2000
Seat	$32 each			**$3,200,000.00**	price plus shipping, purchasing a spare	http://www.airchair.com/#!seats-and-seat-accessories/cq1e
Bolts						
Seat to Drivetrain bolt	bulk price			$250,000.00	91251A859	http://www.mcmaster.com/#=vk3q0q
Drivetrain screws	1/4-20 shoulder screws with 5/16" shoulder dia and 2" length, for 6			$58,000.00	91259A591	
Y/T connection screws	Socket head cap screws 1/4-20 partially threaded for Y and T joint connections, bag of 25			$119,000.00	93705A544	
Total				**$427,000.00**		
Potting	package of 25 inserts			**$101,000.00**	95185A127	
Tooling						
Total	Haas 5 axis CNC			**$125,000.00**		
Engineering Design		300hrs per quarter		**$22,500**		
Skis	$700			**$70,000,000.00**		
Hinges (price for pair)	$300			**$30,000,000.00**	would require hinge redesign due to copyright	
Engineering Design		300hrs, $75/hr		**$22,500**	standard design fee	
Total				**$128,032,679.52**		
			Total Per:	**$1,280.33**		

Appendix H: Bill of Materials

This appendix contains the Bill of Materials for the final design.

Part No.	Description	Quantity Needed
100	Front Tubing	1
101	Back Tubing	1
102	Central Frame	1
103	Steer Bar	1
200	Ankle	4
201	Foot	4
202	Shoe	4
203	Seat Plate	1
300	Central Bushing	2
301	Seat Bushing	4
400	Ski	2
401	Seat Cushion	1
402	Shaft Collar	2
500	1/4-20 Should Screws with 5/16" shoulder dia, 2" length	3
501	1/4-20 Partially threaded socket head cap screws	4
503	6-32x1/4" low profile socket head cap screws	16
504	Stainless steel pins	4
505	Potting Inserts	16
506	1/4" Flat Washers	11
507	1/4-20 Lock Nuts	4
508	#6 Washers	16

Appendix I: FMEA and DVP&R

This appendix contains the FMEA and DVP&R, for use in making design and testing decisions in order to address safety concerns.

Freedom Ski DVP&R

Report Date: 3 February 2015			Sponsor: QL+				Component/Assembly: Freedom Ski			REPORTING ENGINEER: Justin Satnick					
TEST PLAN										**TEST REPORT**					
Item No	Specification or Clause Reference	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES TESTED		TIMING		TEST RESULTS			NOTES		
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail			
1	Weight	System hung from scale	<25 lbs	Mark	DV	1	B	3/16/2015	3/17/2015	29 lbs	0	1	System heavier than expected due to unforeseen modifications		
2	Buoyancy	Place in pool	Floats	Ashley	PV	2	C	3/17/2015	3/18/2015	Floats	1	1	Passed with piping insulation added for floatation		
3	Setup Time	Student sits in wheelchair and assembles/collapses system with only pinkies and thumbs	<10minutes	All	PV	1	C	3/16/2015	3/16/2015	7:15	1	0			
4	Breakdown Time	Student sits in wheelchair and assembles/collapses system with only pinkies and thumbs	<10minutes	All	PV	1	C	3/16/2015	3/16/2015	4:12	1	0			
5	Load Test	250lb load placed on seat	No failures or visible deformations	Toby	DV	4	B	4/30/2015	5/8/2015	Frame Legs Splay	2	2	Bracing added to front and back legs for added support--> test passed		
6	Relative Angle Verification	Verify that the skis/steering turns at a 1:1 ratio with the seat.	1:1 ratio	Mark	PV	2	C	5/26/2015	5/27/2015	1:1 ratio	2nd Steering Bar	1st Steering Bar			
7	Steering Safety Check	Verify that the seat stays connected to the mount and within the range of motion.	Go/No-Go	Justin	DV	1	B	6/2/2015	6/2/2015	Go	1	0			
8	Rider Test- Ashley	Verify that the ski works to the specifications of the customer and "is fun" and safe for the user.	Go/No-Go	Ashley	PV	1	V	6/3/2015	6/4/2015	No-Go	0	1	Will retest with modification week of 6/8		
9	Rider Test- Dr. Bash	Verify that the ski operates to customer satisfaction.	Go/No-Go	Ashley	PV	1	V	6/20/2015	6/25/2015	TBD	0	0	Lake access with wheelchair access required		

Failure Mode and Effect Analysis
(Design FMEA)

FMEA Number:

Design Responsibility:

Pg 1 of 1

Key Date:

Prepared by: Ashley Scharff, Justin Satnick, Mark Rutner

FMEA Date (Orig.) 11-20-2014 (Rev.) 12-1-2014

Item/Function	Potential Failure Mode	Potential Effects of Failure	Sev	Potential Cause(s)/Mechanism(s) of Failure	Occur	Crit	Recommended Actions	Responsibility & Target Completion Date	Actions Taken	Sev	Occur	Crit
Seat												
Allows user to sit	The seat cover rips	The seat absorbs water and becomes heavier	5	Insufficient material strength	2	10	Research seat cover material	Toby (December 12th)	none required			
				Insufficient material flexibility	2	10			none required			
Connects user operation to steering	The connection between the seat and the drivetrain breaks	The rider cannot control the waterski system	8	Fatigue	5	40	Use appropriate material for cyclical fatigue loading		system accounts for fatigue and wear			
				Corrosion	5	40						
	The drivetrain connection becomes loose	The rider has difficulty maintaining control of the skis	8	Clearance	3	24						
				Wear	7	56						
				Corrosion	5	40						
Improves comfort for the user	Padding breaks down	The user experiences increased spinal compression over time	9	Fatigue	5	45	Research seat padding material		none required			
		Seat is uncomfortable	5	Seat material is not shock absorbant	1	5			seat can be replaced by user			
Holds user onto the device	The rider slides off of the edge of the seat	User falls off the device unexpectedly	8	Seat side connections fail	2	16	Use appropriate material for cyclical fatigue loading		none required			
				Seat material rips	5	40	Research seat cover and padding material for ultimate yield strength		none required			
Drivetrain												
Converts user's motion to movement of skis	Seat bearing cracks	Rattling noises	4	Fatigue	5	20	Find rotational bearings for use in water rich environments		Recommended Actions Complete			
		Sharp corners exposed	7	Corrosion	5	35	Find bearing that is to be used over a long period of time					
	Seat bearing binds	Rider loses control	8	Particulate infultrates bearing	2	16	Use sealed bearing					
	Steering bar deforms	Loss of ability to steer	8	Insufficient material strength	2	16	Use material that is appropraitely strong for given function					
				Wear	3	24	Test material for fatigue over a series of cycles		Not required			
		Sharp corners exposed	7	Insufficient material strength	2	14	Design specific fail points to avoid sharp edges		Recommended Actions Complete			

Translates pressure on skis which turns/rotates the ski for carving	Connection points on skis and seat are not calibrated relative to each other	Skis do not turn accurately	8	Insufficient material strength	2	16	incorporate an ability to calibrate ski rotations	Mark (December 12th)	Created steering brackets with the ability to move height on bracket			
		Skis has difficulty going straight	6	Insufficient material strength	3	18						
	Drivetrain breaks or becomes dislodged from skis	Skis become detached from drivetrain	9	Wear	4	36	Connect skis to drivetrain with material that can take the cyclical stress		Not required, cyclical stress not an issue			
				Corrosion	5	45	Use material that will not corrode in water		Recommended Actions Complete			
				Insufficient bond	5	45	Test different bonding techniques		Not required, bonding technique is adequate			
		Loss of ability to steer	8	Insufficient material strength	4	32	Use material that is appropraitely strong for given function		Recommended Actions Complete			
				Fatigue	5	40	Use appropriate material for cyclical fatigue loading					
Frame												
Connects all other portions of the apparatus together, including the seat, skis and drivetrain	A hinge on the frame fails	The ski system may not collapse properly and become difficult to control	6	Fatigue	5	30	Research hinges for strengths	Ashley (December 12th)	Recommended Actions Complete			
				Material bending causes miss alignment	2	12						
		System feet no longer fit into all 4 shoes	8	Interference	6	48						
	A tube on the frame fails	The ski system may become difficult to control and injure rider	10	Insufficient material thickness	2	20	Research tubing for shape and wall thickness		Recommended Actions Complete			
		Frame is no longer safe to ride	9	Fracture has sharp edges	2	18						
		Frame won't fit onto skis	9	Interference	2	18						
	A connection point between the frame and other components fails	The ski system may become difficult to control and injure rider	9	Inefficient turning	5	45	Use material that is appropraitely strong for given function		Recommended Actions Complete			
		System feet no longer fit into all 4 shoes	9	Interference	3	27	Allow for enough clearance in case of slight misalignment		Recommended Actions Complete			
		Feet bind and no longer rotate	10	Interference	3	30						
				Corrosion	5	50						
Acts as pivot points of the four-bar linkage for drivetrain operation	A frame failure affects operation of the drivetrain	Skis will not turn properly	7	Insufficient material thickness	2	14	Use material that is appropraitely strong for given functions		Recommended Actions Complete			
Disconnects from skis and folds up to allow for easy storage	The frame folds during use	The rider could get pinched, crushed, or bucked off of apparatus	10	Insufficent locking ability	3	30	Research strong locking system for the hinged joints		Recommended Actions Complete: Brompton Hinges			
		Frame breaks other system components	9	Interference	1	9	Use appropriately strong material for the frame		Recommnneded Actions Complete			
	The frame is locked in place, either folded up or fully expanded	The apparatus will be difficult to transport	5	Not able to fold to smallest dimensions	2	10	Make sure hinges and the locks will not be the part of the system that will fail		Recommended Actions Complete: Brompton Hinges			
				Frame remains in bulky set up	2	10						
		The apparatus will be difficult to set up and take down	6	Frame won't collapse or expand fully	2	12						
Bindings												
Holds users feet to the skis	Ripped material	The riders feet disengage from the skis, loss of support	8	Insufficient material flexibility	1	8	Use material that is significantly stronger than needed so as to protect feet	Justin (December 12th)	Used specific potting methods to ensure safety			
				Insufficient material strength	1	8						
		The rider loses foot attachment and feet drag in the water	8	Insufficient material flexibility	1	8						
			8	Insufficient material strength	1	8						
Prevents feet from dragging in the water	Failure of attachment to skis	The rider loses foot attachment and feet drag in the water	9	Insufficient bonding to skis	1	9	Research adhesive methods					
	Poorly sized binding fail to contain foot	The rider loses foot attachment and feet drag in the water	7	Poorly measured feet size	2	14	Take accurate foot measurement of consumer		None required; bindings provided by the user			

Appendix J: Safety Checklist

Potential Hazard	Design has…
Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and shear points?	X
Can any part of the design undergo high accelerations?	
Will the system have any large moving masses or large forces?	
Will the system produce a projectile?	
Could the system fall under gravity creating injury?	
Will a user be exposed to overhanging weights in the design?	
Will the system have any sharp edges?	
Will any part of the electrical systems not be grounded?	
Will there be any large batteries or electrical voltage in the system above 40 V either AC or DC?	
Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?	
Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?	
Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?	X
Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?	
Can the system generate high levels of noise?	
Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc.?	X
Is it possible for the system to be used in an unsafe manner?	X
Will there be any other potential hazards not listed above?	X

Safety Checklist Actions List

Description of Hazard	Corrective Actions to be Taken	Planned Completion Date	Actual Completion Date
The system has pinch points located within the four bar linkage of the drivetrain.	Move the drivetrain underneath the seat and enclose areas where pinching may occur.	12/1/2014	1/10/2015
The user of the design will be required to lean heavily, shifting his bodyweight in order to operate the system steering.	This is the case with the current system as well, and we have reason to believe the user we are designing for is capable of handling operation.	N/A	N/A
The device will be continually exposed to water, sunlight and extreme temperatures through both its use and storage.	The materials and manufacturing processes selected will account for these environmental conditions, allowing for durability.	12/10/2014	1/10/2015
The system could be used in an unsafe manner, since it includes a universal mounting system which could be attached to any type of ski.	The possible risks associated with misuse will be discussed with the user.	2/20/2014	5/20/2015

Appendix K: MatLab Codes and Calculations

This appendix details engineering analysis performed, including MatLab codes and hand calculations.

Stress Calculations

```
%Freedom Ski Frame Analysis Code

n=2.5; % desired factor of safety

%Material Properties
E= 10000000; %[psi] modulus of elasticity
nu= 0.33; %poisson's ratio
G= E/(2*(1+nu)); %modulus of rigidity
sigma_yield= 40000; %[psi] tensile yield strength

%Frame Dimensions
L_c= 10; %[in] length of center bar of frame
L_f= 5; %[in] length of front bars of frame
L_b= 5; %[in] length of back bars of frame

%Pipe Cross-Section Dimensions
t=0.049; %[in] wall thickness
d_1= 2.023; %[in] major axis
d_2= 0.857; %[in] minor axis

I_x= pi/4*(((d_2/2)*(d_1/2)^3)-((d_2/2-t)*(d_1/2-t)^3)); %x-bending moment of inertia, approximated as an ellipse
I_y= pi/4*(((d_2/2)^3*(d_1/2))-((d_2/2-t)^3*(d_1/2-t))); %y-bending moment of inertia, approximated as an ellipse

%Forces
W= 250; %[lbs] weight of skier

%Impact
h= 48; %[in] assumed maximum height skier falls from air to impact water
J= W*h; %impact energy
```

```
%Bending
M_x= W*L_c; %[lb-in] maximum x-bending moment in the frame
M_yf= W*L_f; %[lb-in] maximum y-bending moment in front legs
M_yb= W*L_b; %[lb-in] maximum y-bending moment in back legs

%Bending Stress
x=d_2/2; %[in] distance of maximum bending, from neutral axis
y=d_1/2; %[in] distance of maximum bending, from neutral axis
sigma_xf= M_yf*x/I_x %front bending stress in minor axis direction
sigma_xb= M_yb*x/I_x %back bending stress in minor axis direction

n_d1= sigma_yield/sigma_xf
n_d2= sigma_yield/sigma_xb
```

OUTPUTS:

```
sigma_xf = 6.4909e+003

sigma_xb = 6.4909e+003

n_d1 = 6.1625

n_d2 = 6.1625
```

```
%Calculates the stress in one side of the seat plate, assuming it is made out of a flat plate of Aluminum.
%Modeling as a cantilever beam that is fixed in the middle of
%the plate, in order to induce an inherent factor of safety

hwall = 0;%.75; %Height of the side walls, in
t = 5/16; %Thickness of seat plate, in
w = 3.5; %Width of seat plate (front to back), in
hc = (hwall*t*hwall/2 + t*w*t/2)/(hwall*t+t*w); %Location of the neutral axis
I = (1/12)*(w/2)*t^3+w*t*(hc-t/2)^2 + (1/12)*t*hwall^3+t*hwall*(hc-hwall/2)^2; %Sum of I at weakest cross-section, 1/12bh^3+Ad^2
d = 3; %Distance from center of seat to buttock, in
F = 160/2; %Force of one cheek on the seat plate, lbf
M = F*d; %Moment that each cheek exerts on the plate, in-lbf
c = t/2;%-hc; %Distance from point of stress that we're worried about to neutral axis
Stress = M*c/I %Stress on top of flat part of plate, psi
YS = 40000; %Yield Stress of seat plate material, psi
FoS = YS/Stress %Factor of safety, must be greater than 2.5
```

OUTPUTS:

```
Stress = 8.4261e+003

FoS = 4.7472
```

Fatigue strength of center bar (Chrome Moly) f

$\sigma_f' = S_{ut} + 345\,MPa = 1000 + 345\,MPa$

$\sigma_f' = 1345\,MPa$

$S_e' = 480\,MPa$

$N_e = 200{,}000$ cycles? (100 turns/day)(100 days/yr)(20 yr)

$b = \frac{\log(\sigma_f'/S_e')}{\log(2N_e)} = \frac{\log\left(\frac{1345}{480}\right)}{\log(400{,}000)} = -0.0799$

$f = \frac{\sigma_f'}{S_{ut}}(2\cdot 10^3)^b = \frac{1345}{1000}(2\cdot 10^3)^{-0.0799} = 0.733$

$S_f' = 0.733(480\,MPa) = 352\,MPa = S_f'$?

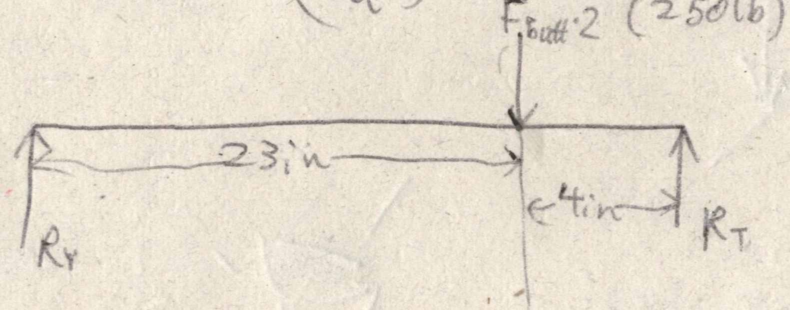
$a = \frac{(f S_{ut})^2}{S_e} = \frac{(0.733\cdot 100\,MPa)^2}{480\,MPa} = 119.04\,MPa = a$ (turn)

$$b = -\frac{1}{3}\log\left(\frac{f\,S_{ut}}{S_e}\right)$$

$$= -\frac{1}{3}\log\left(\frac{0.733 \cdot 1000\,MPa}{480\,MPa}\right)$$

$$b = -0.061$$

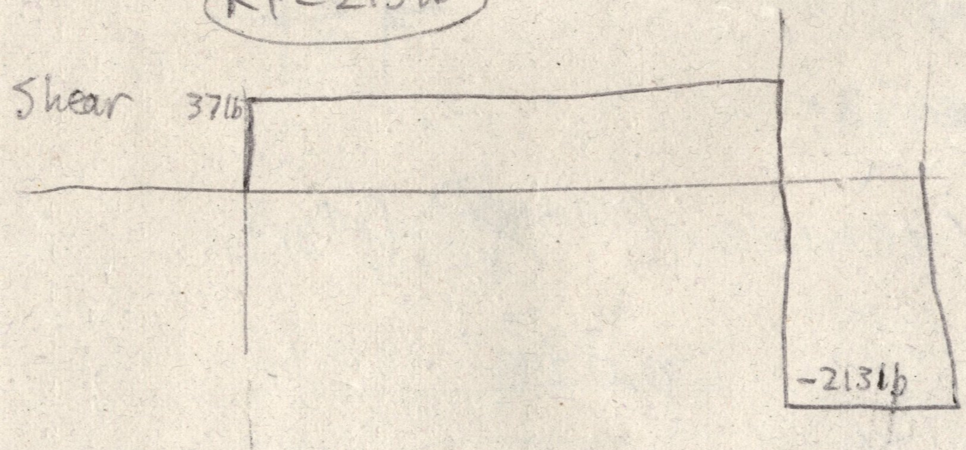
$$N = \left(\frac{\sigma_{rev}}{a}\right)^{1/b}$$

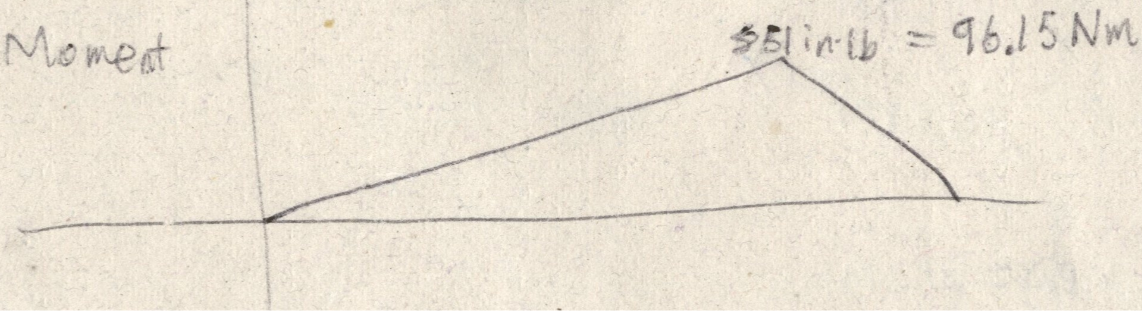


$$\Sigma M_T = 0 = (4in)(250lb) - (27in)(R_y)$$

$R_y = 37lb$

$R_T = 213lb$





$$\sigma_{rev} = \frac{Mc}{I}$$

$M = 96.15\ Nm$

$c = \frac{1 \frac{3}{8}}{2}\ in.$

$C = 0.6875in.$

$d_i = 1\frac{3}{8}in - 2mm = 1.375in - 2mm\left(\frac{0.0394in}{mm}\right)$

$d_i = 1.296in$

$$I = \frac{\pi}{64}\left(d_o^4 - d_i^4\right)$$

$$= \frac{\pi}{64}\left((1.375in)^4 - (1.296in)^4\right)$$

$I = 0.036869in^4$

85 in·lb

$$\sigma_{rev} = \frac{Mc}{I} = \frac{(96.15\ N\cdot m)\left(\frac{0.2248\ lbf}{N}\right)(\ \ )\left(\frac{39.37in}{1m}\right)(0.6875in)}{0.036869in^4}$$

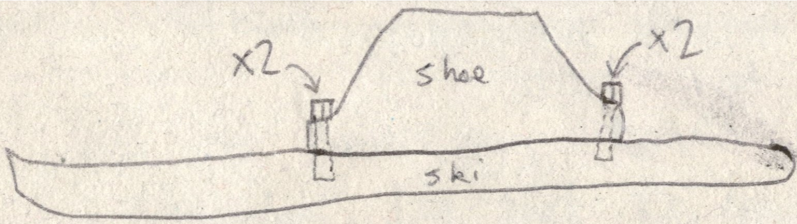
$\sigma_{rev} = 15,868psi$

$$N = \left(\frac{\sigma_{rev}}{a}\right)^{1/b} = \left(\frac{15868psi\ (6894.76\ Pa/psi)}{1,119,040,000\ Pa}\right)^{1/-0.061}$$

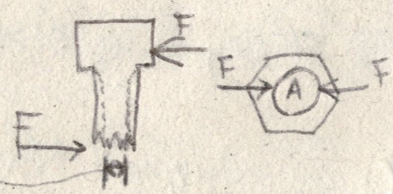
$N \simeq 3.03 \cdot 10^{16}$ cycles before failure

↑

The Chrome Moly tube (center bar) WILL survive in fatigue loading situations



← Not drawn to scale.



$d_{hole\,in\,ski} = 0.132in = 3.43mm$

$\sigma_y = 36{,}000\,psi$ minimum

In reality, $\tau = \left(\frac{1}{4}\right)\left(\frac{F}{A}\right)$, but for FoS of 4, $\tau \approx \frac{F}{A}$.

$\tau_{allow} = \sigma_{yield}$

$F = A \cdot \tau_{allow} = A \cdot \sigma_{yield}$

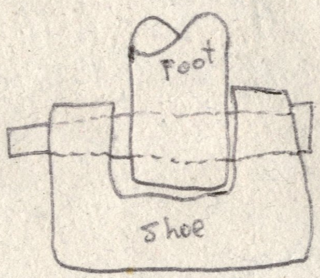
↑ From bolt size, measured from skis...

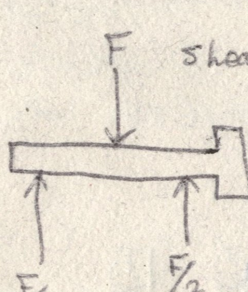
$F_{max} = \frac{\pi}{4}(0.132in)^2\left(36{,}000\frac{lbf}{in^2}\right)$

Use as few mounting screws as possible b/c Fmax is so high!

$\boxed{F_{max} = 492\,lbf}$ if force is concentrated on 1 screw, so unless Dr. Bash can hold onto 493 lbf, 1 screw can bear load, Alone.

1-31-2015





shear case since tight fit.

In worst case $F = W_{rider} = 250\,lbf$

$$\tau = \left(\frac{F}{A}\right) = \frac{F/2}{\frac{\pi}{4}(d_{bolt})^2} = \sigma_y \Rightarrow \left(36000\frac{lbf}{in^2}\right) = \frac{125\,lbf}{\left(\frac{\pi}{4}\right)(d_{bolt})^2} \div d_{bolt} \geq \sqrt{\frac{(125\,lbf)}{\left(\frac{\pi}{4}\right)\left(36000\frac{lbf}{in^2}\right)}}$$

$\boxed{d_{bolt} \geq 0.0665in.}$

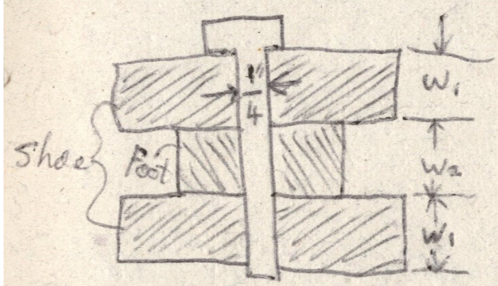
1-31-15, cont'd.

n_d for $\frac{1}{4}$-20 low-strength steel zinc-plated bolt

$$\frac{\sigma_y}{\tau} = n_d = \frac{36000\,psi}{\left(\frac{125\,lbf}{\left(\frac{\pi}{4}\right)(0.25in)^2}\right)} = \frac{36000\,psi}{2546.48\,psi} = \boxed{14 \approx n_d}$$

for $\frac{1}{4}$-20 bolts at ankles! Yippee!

For bearing stress w/ quarter-inch bolts...



$$\sigma = \frac{F}{A} = \frac{F/2}{(0.25in)(w_{min})} \leq \sigma_{yield}$$

$$w_{min} \geq \frac{125\,lbf}{(0.25in)\left(36000\frac{lbf}{in^2}\right)}$$

$w_{min_1} \geq 0.014$ in in static loading with static loading and $n_d = 1$

$w_{min_2} = 2w_{min_1} \geq 0.028in$

$$\text{Bearing FoS} = 6 = \frac{\sigma_y}{\left(\frac{F}{(0.25in)(w_{min})}\right)}$$

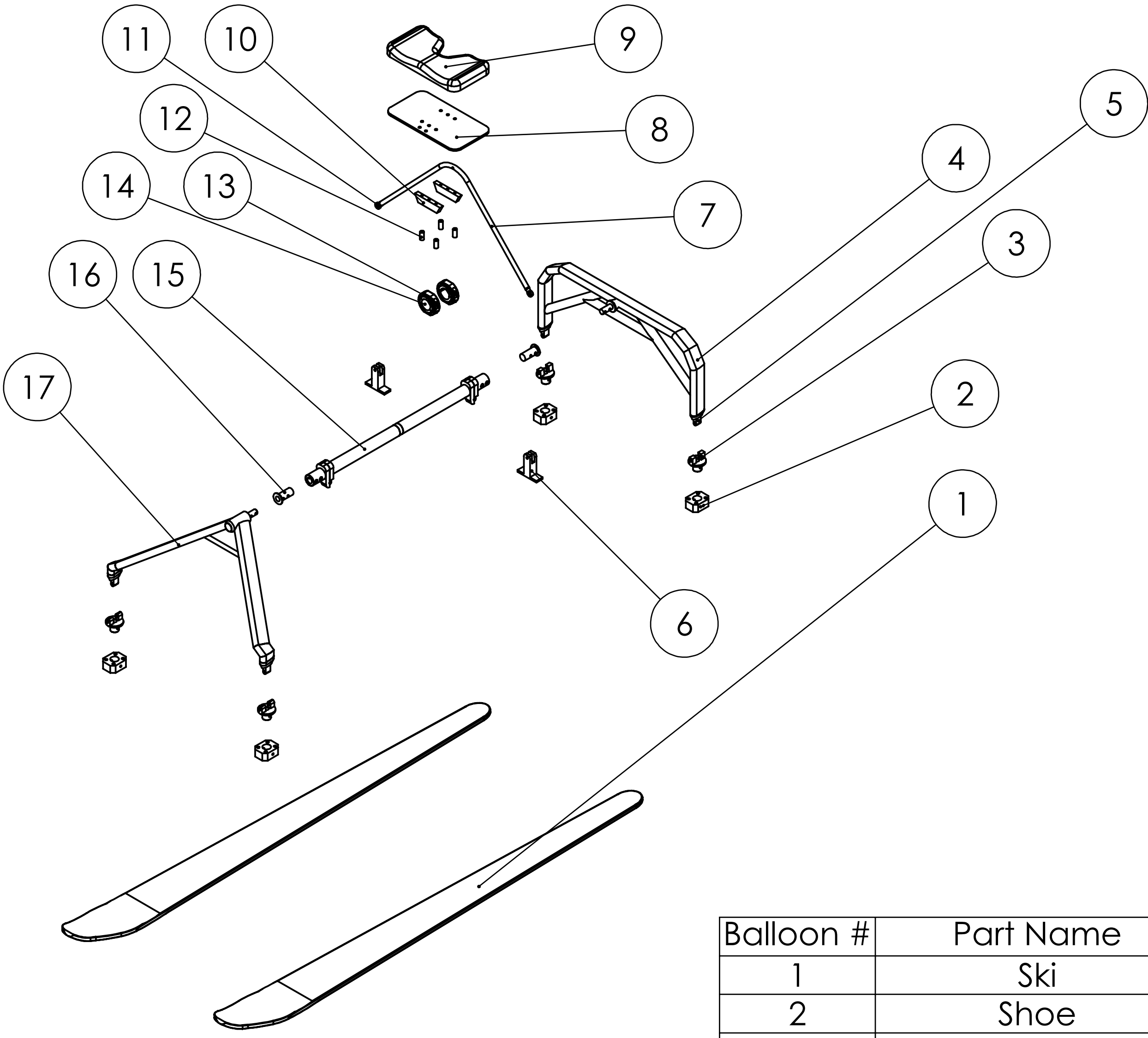
$$6 = \frac{(36000\,psi)(0.25in)(w_{min})}{125\,lbf}$$

$w_{min_1} \geq 0.0833$ in. For bearing stress w/ $n_d = 6$

$w_{min_2} \geq 0.1666$ in. for bearing stress w/ $n_d = 6$

Appendix L: Part and Assembly Drawings

This appendix contains engineering drawings for individual parts and overall assemblies. These drawings are to be used to show overall form and fit of portions of the apparatus, as well as design details for manufacturing and analysis purposes.



Balloon #	Part Name	Quantity
1	Ski	2
2	Shoe	4
3	Foot	4
4	Back Tubing	1
5	Ankle	4
6	Steering Bracket	2
7	Steer Bar	1
8	Seat Plate	1
9	Seat Cushion	1
10	Height Spacer A	2
11	Rod End	2
12	Height Spacer B	4
13	Shaft Collar	2
14	Seat Bushing	2
15	Central Frame	1
16	Connection Bushing	2
17	Front Tubing	1

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES: ±0.010
LINEAR: ±0.010
ANGULAR: ±1°

FINISH: Spray Paint

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Freedom Ski Exploded View

MATERIAL:

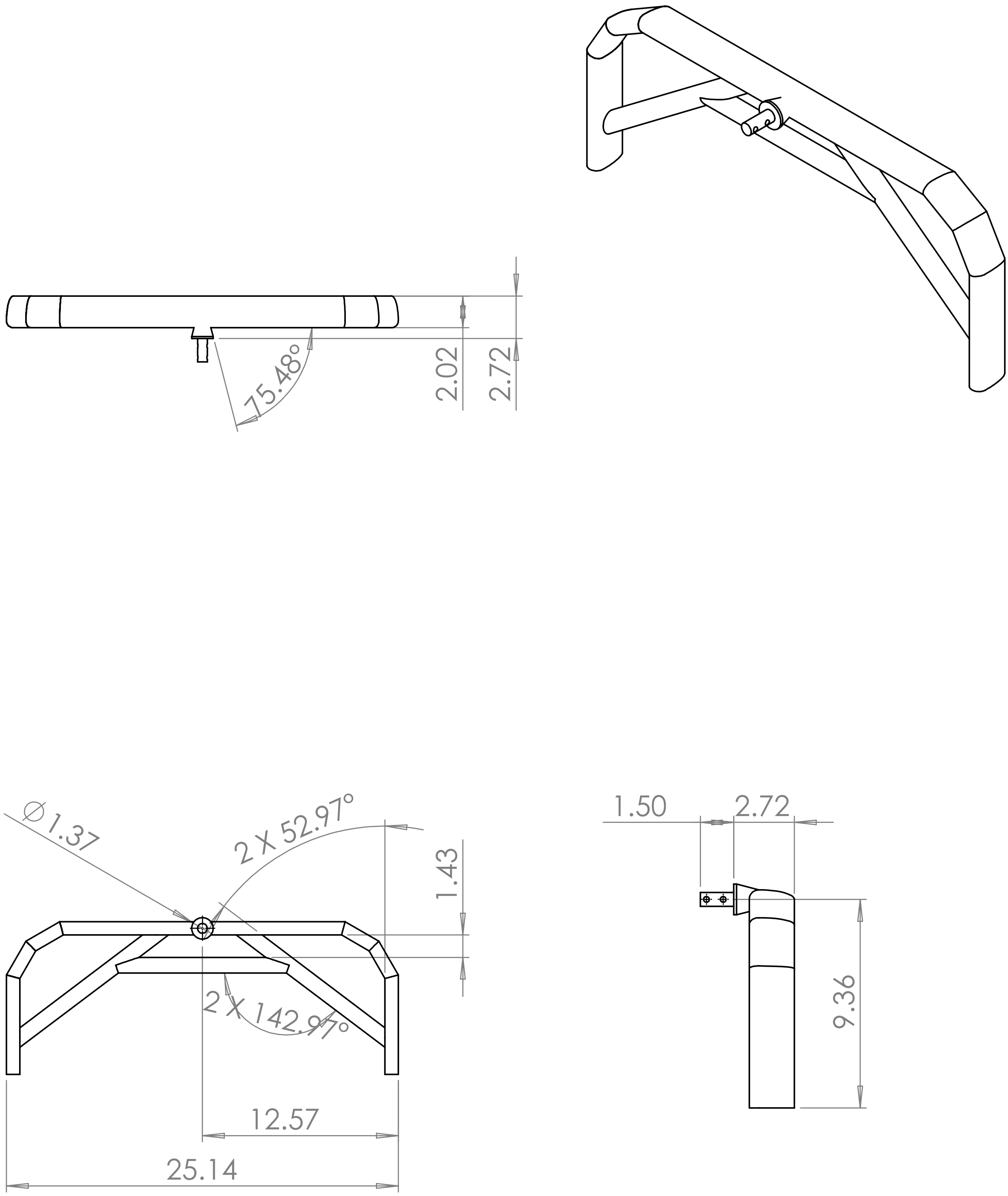
WEIGHT:

PART NO.

A4

SCALE:1:50

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES:
LINEAR: X.XX = ±0.050
X.XXX= ±0.025
X.XXXX= ±0.010
ANGULAR: X.XX = ±2°

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Back Tubing Assembly

MATERIAL:
6061-T6 Al, painted

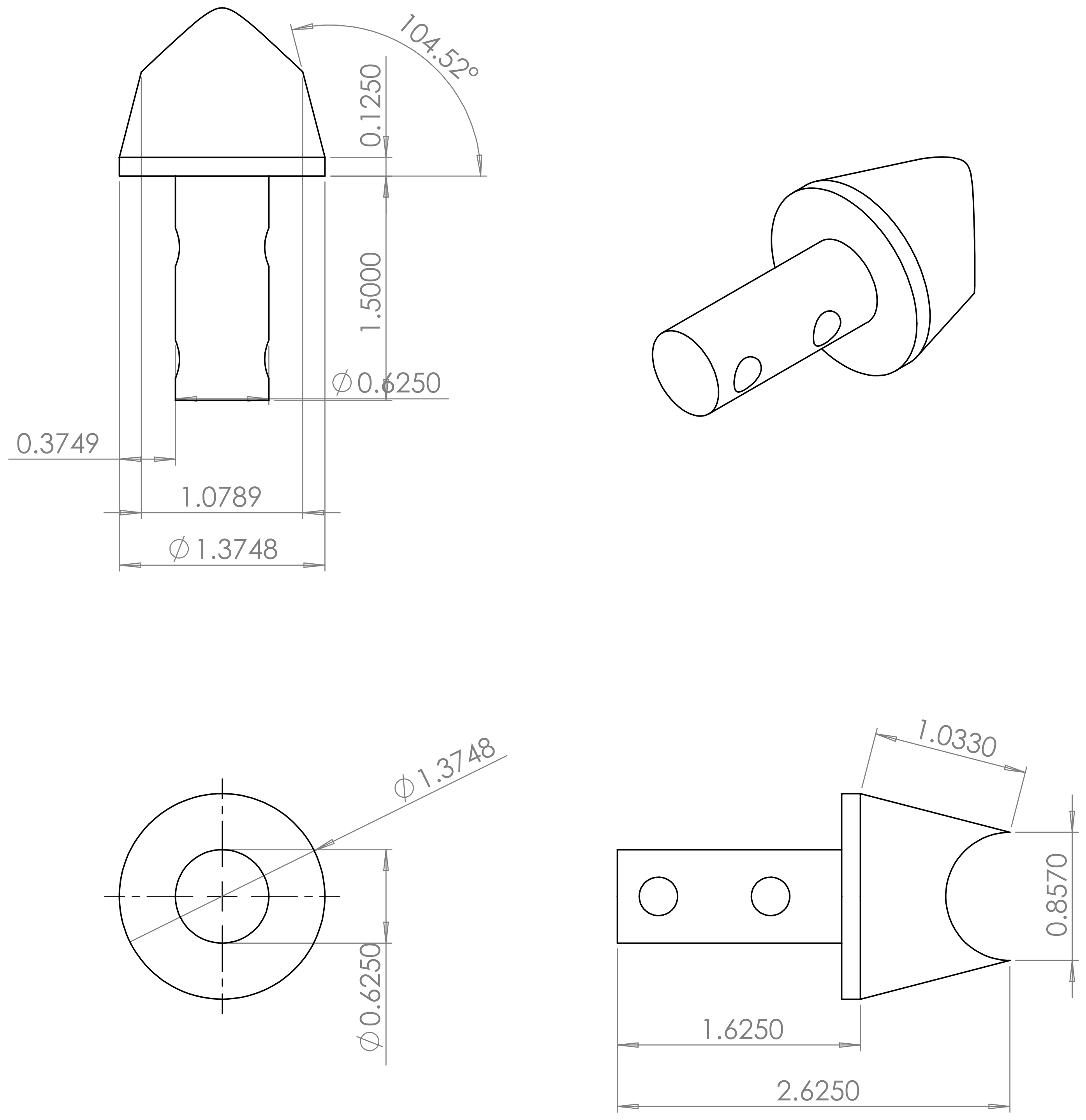
WEIGHT:

DWG NO. 101

A4

SCALE:1:10

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES:
LINEAR: X.XXX ±0.010
X.XXXX ±0.005
X.XXXXX ±0.001
ANGULAR: X.XXX ±.5°

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

T-Joint

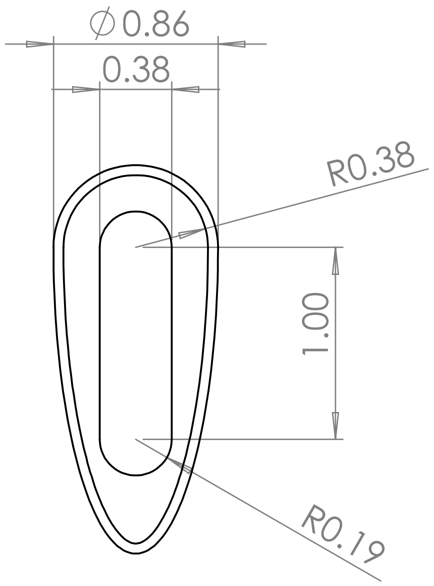
DWG NO. 320

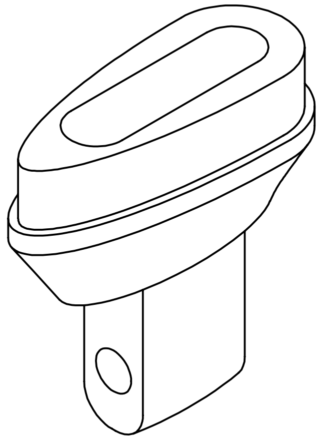
A4

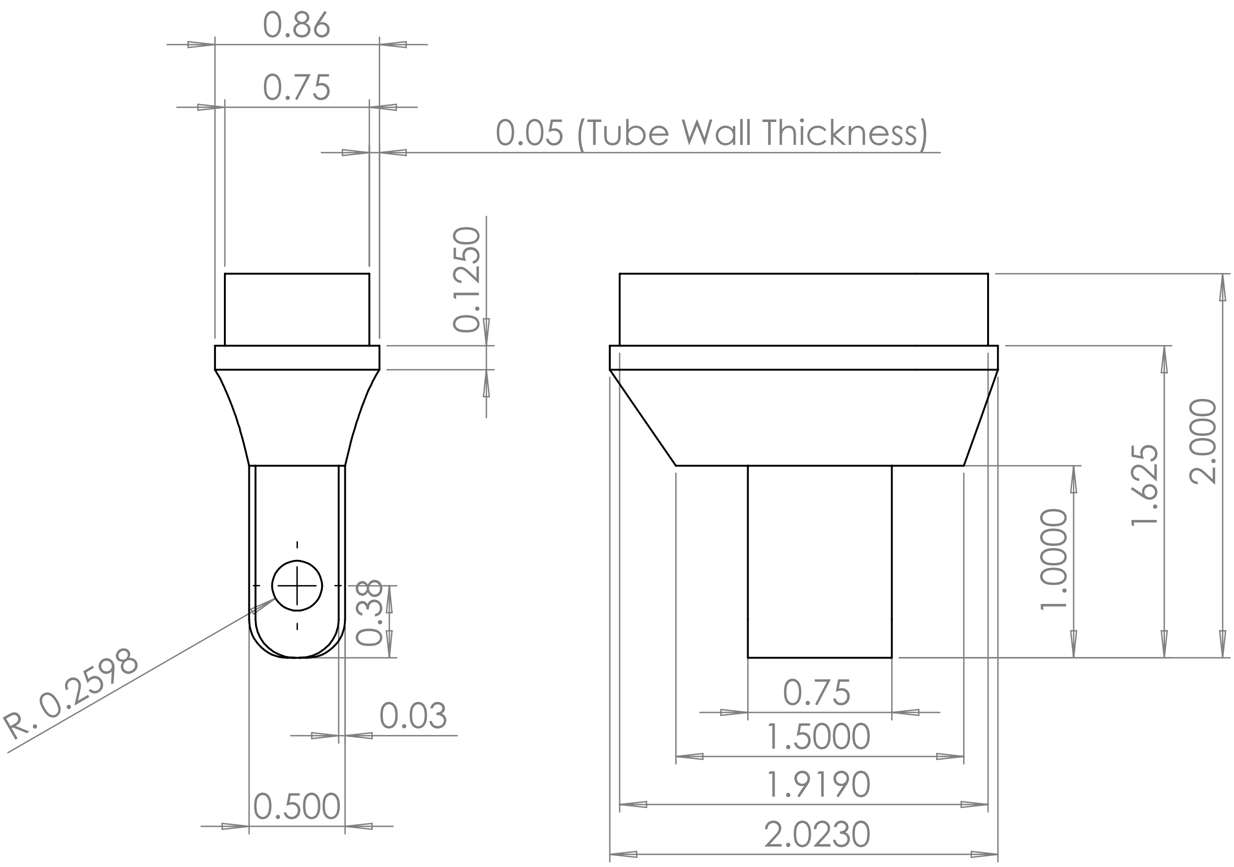
SCALE:1:1

SHEET 1 OF 1

- Cut raw material to length (go long)
- Make Tab (thicker than in drawing)
- Grind to outer airfoil profile
- Grind to inner airfoil profile
- Mill slot in center to make it weldable
- Loft down to approximate desired size







UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES:
LINEAR: X.XX = ±0.10
X.XXX= ±0.05
X.XXXX= ±0.01
ANGULAR: X.XX = ±5°

FINISH:

DEBUR AND BREAK SHARP EDGES

	NAME	SIGNATURE	DATE
DRAWN	Ashley Scharff		2/2/2015
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL: 6061 T6 Aluminum

WEIGHT:

TITLE:

Ankle

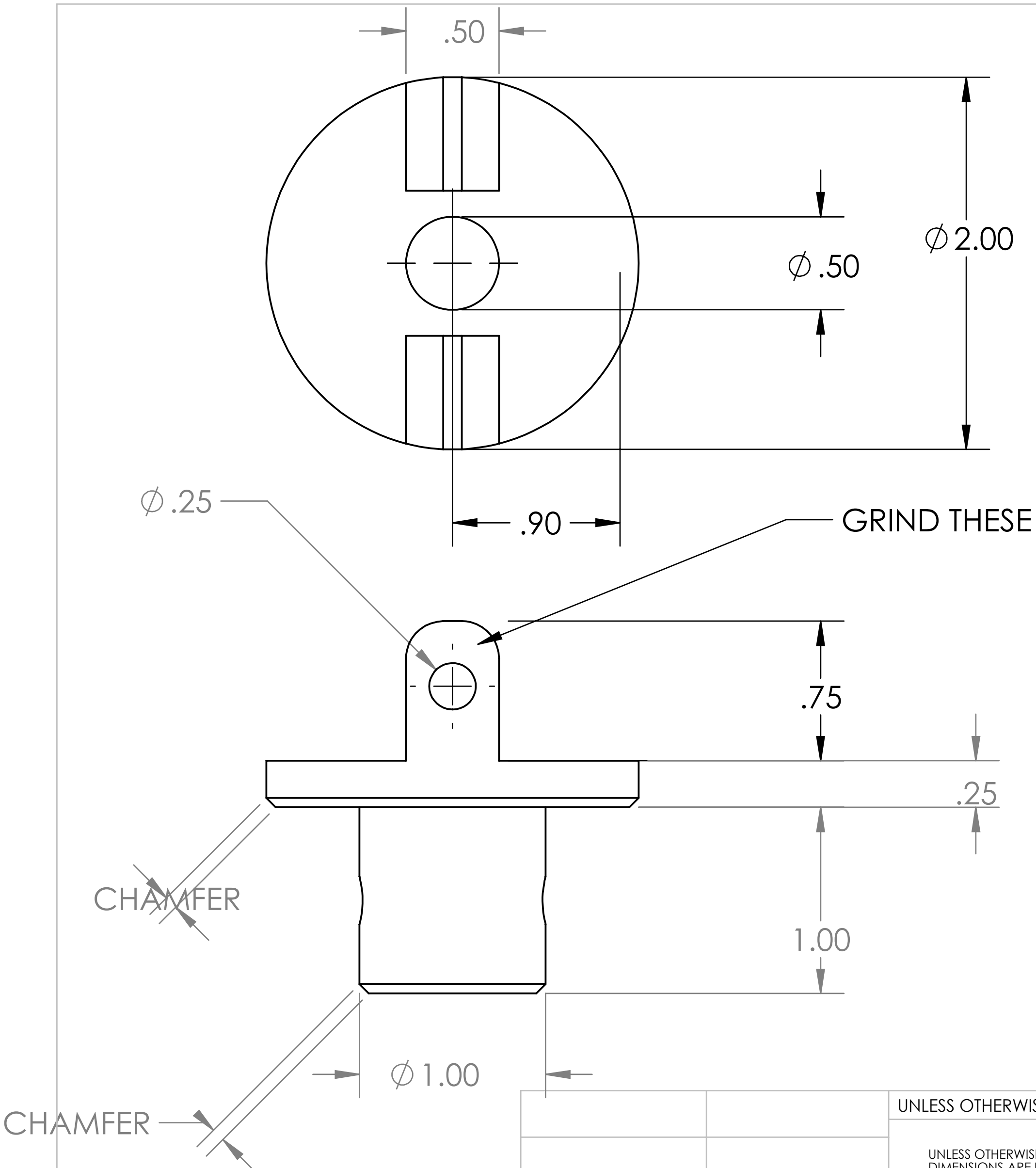
DWG NO. 123

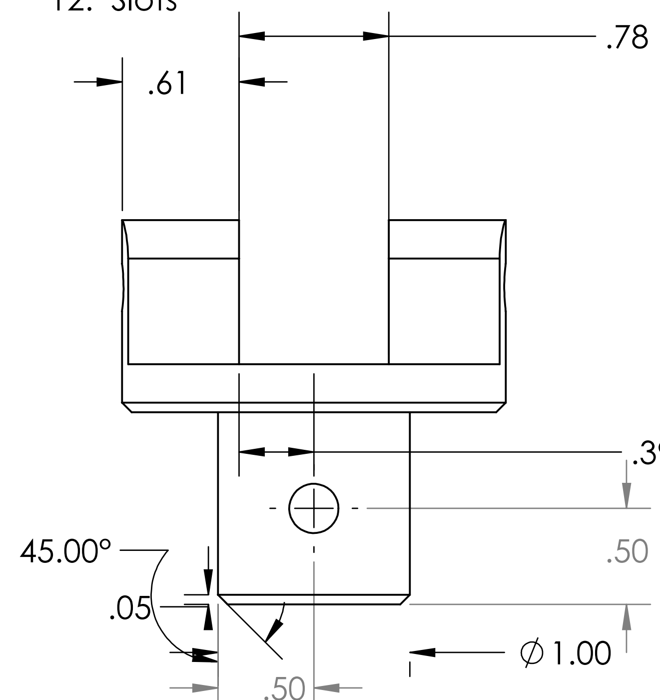
A4

SCALE:1:1

SHEET 1 OF 1

1: Band Saw to length
2. Face to length (do each side)
3. Turn to width (.005", fat end)
4. Center drill
5. Drill up to 1/2" (.125, .25. 375, .5)
6. Turn down small diam
7. Chamfer
8. Repeat.
9. Mill (use V block to setup)
10. Lower hole
11. Upper hole (use level to get perpendicular)
12. Slots





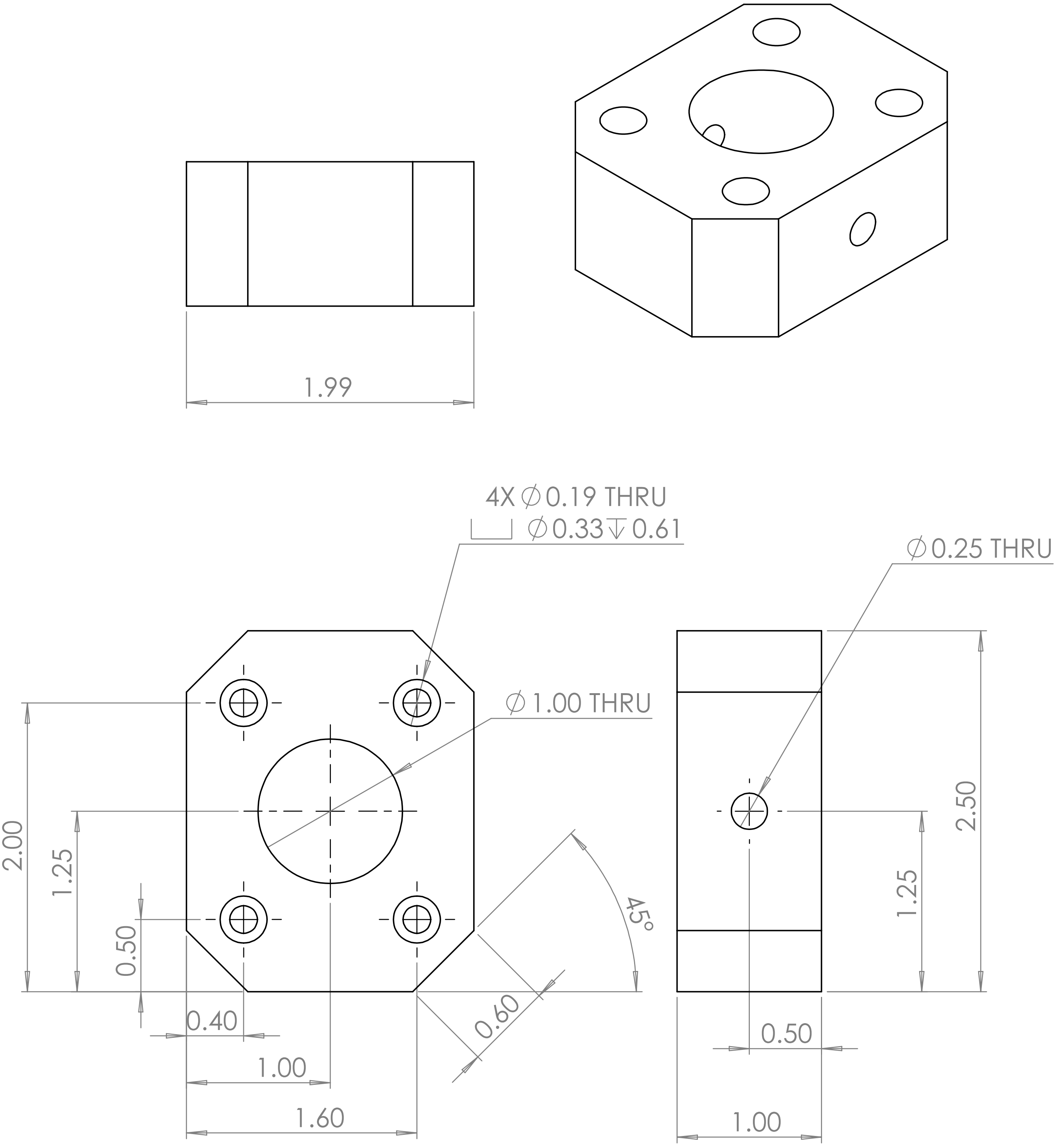
		UNLESS OTHERWISE SPECIFIED:		NAME	DATE
		UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES SURFACE FINISH: TOLERANCES: LINEAR: X.XX = ±0.10 X.XXX= ±0.05 X.XXXX= ±0.01 ANGULAR: X.XX = ±5°	DRAWN		
			CHECKED		
			ENG APPR.		
			MFG APPR.		
		INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
		MATERIAL	COMMENTS:		
NEXT ASSY	USED ON	FINISH			
APPLICATION		DO NOT SCALE DRAWING			

TITLE:

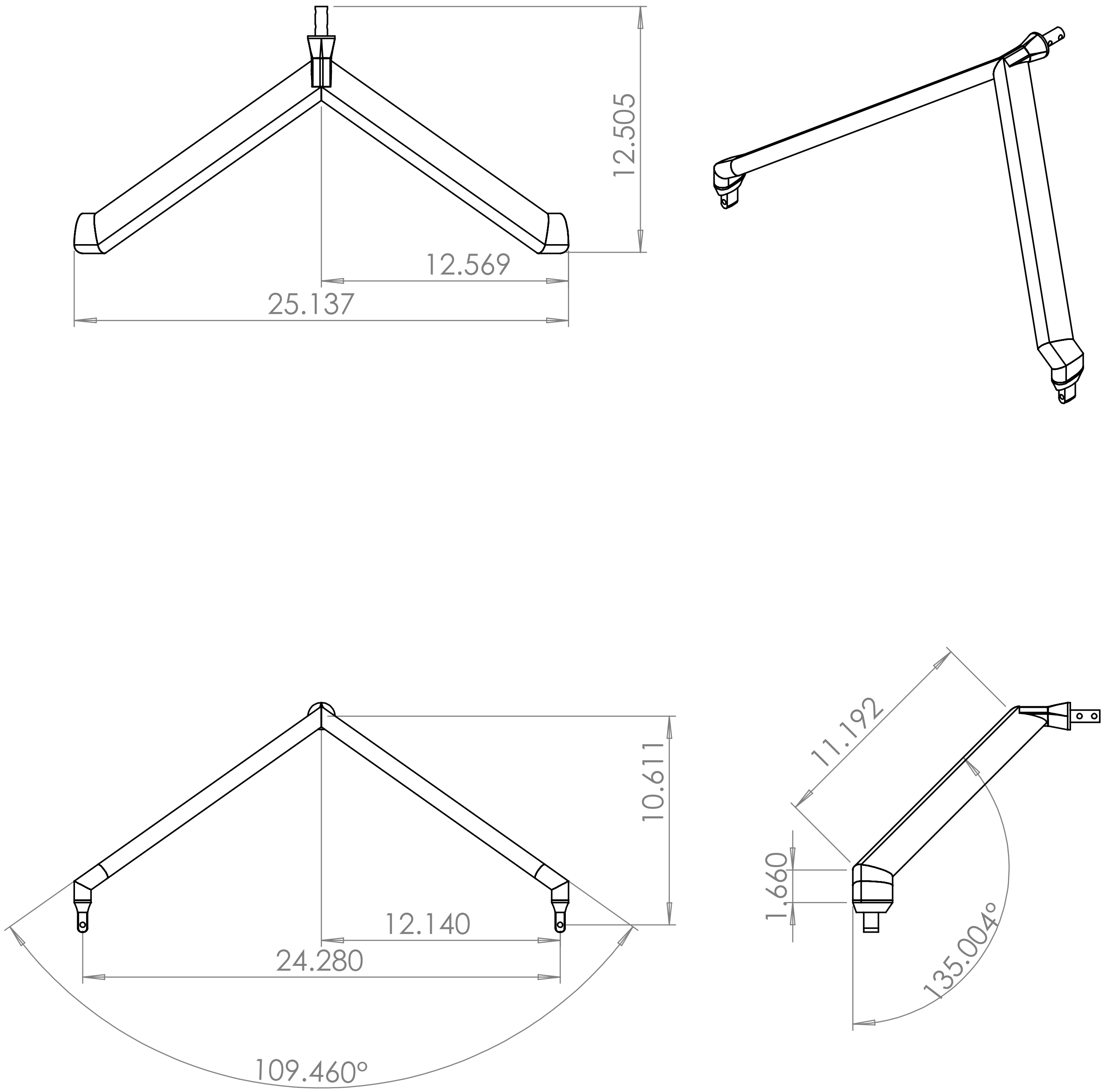
Feet

SIZE	DWG. NO.	REV
A	201	
SCALE: 1:1	WEIGHT:	SHEET 1 OF 1

5 4 3 2 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES SURFACE FINISH: TOLERANCES: ±0.010 LINEAR: ±0.010 ANGULAR: ±1°	FINISH:			DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION	
	NAME	SIGNATURE	DATE		TITLE: Shoe		
DRAWN							
CHK'D							
APPV'D							
MFG							
Q.A				MATERIAL: 6061-T6 Aluminum	PART NO. 202		A4
				WEIGHT:	SCALE:1:1	SHEET 1 OF 1	



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES:
LINEAR: X.XX = ±0.10
X.XXX= ±0.05
X.XXXX= ±0.01
ANGULAR: X.XX = ±5°

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Front Tubing Sub Assembly

MATERIAL:
Al Air Foil Tubing

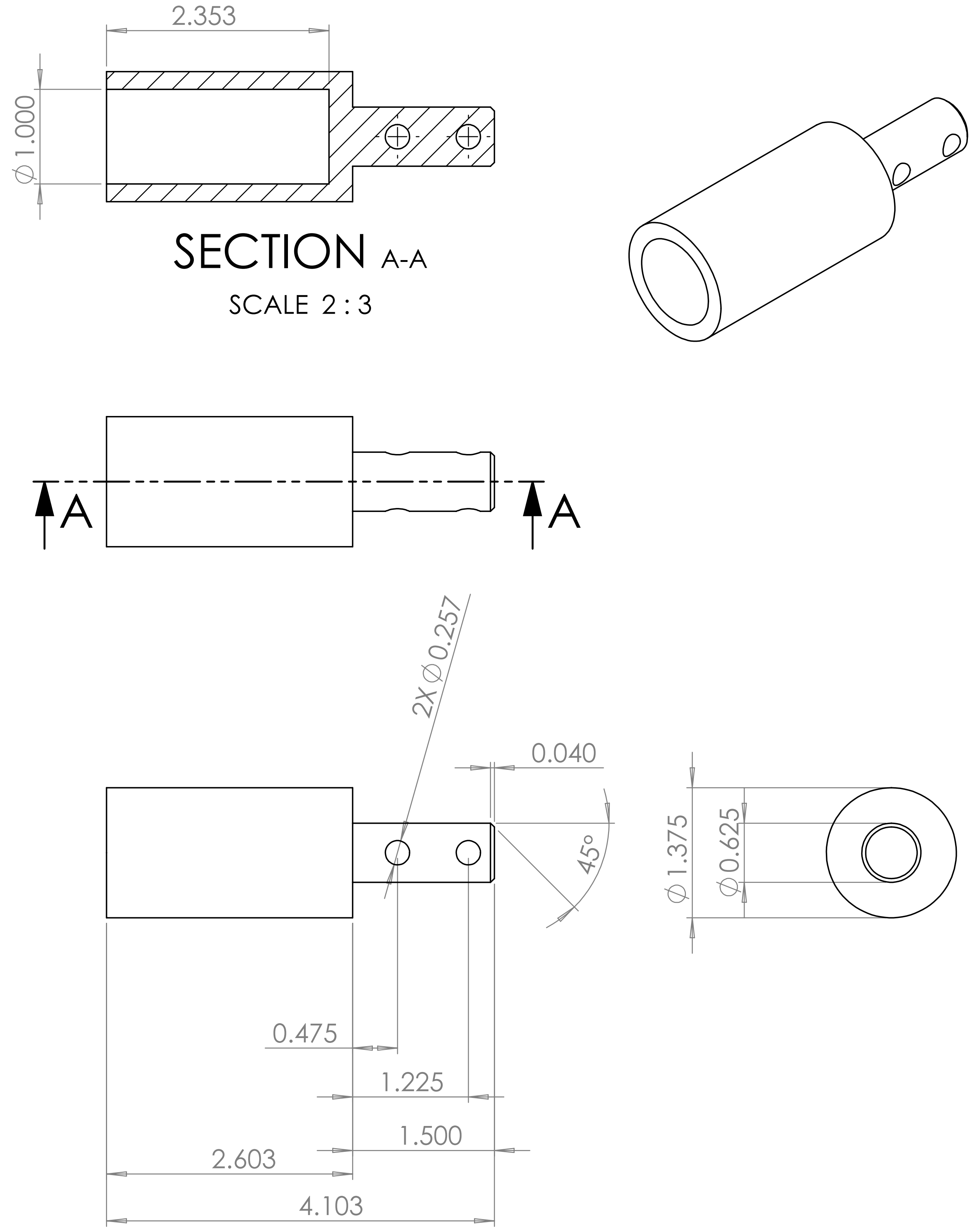
PART NO.
100

A4

WEIGHT:

SCALE:1:10

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES:
LINEAR: X.XX = ±0.10
X.XXX= ±0.05
X.XXXX= ±0.01
ANGULAR: X.XX = ±5°

FINISH: NONE
MATERIAL 6061 AL

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

MATERIAL:

WEIGHT:

TITLE:

Y Joint

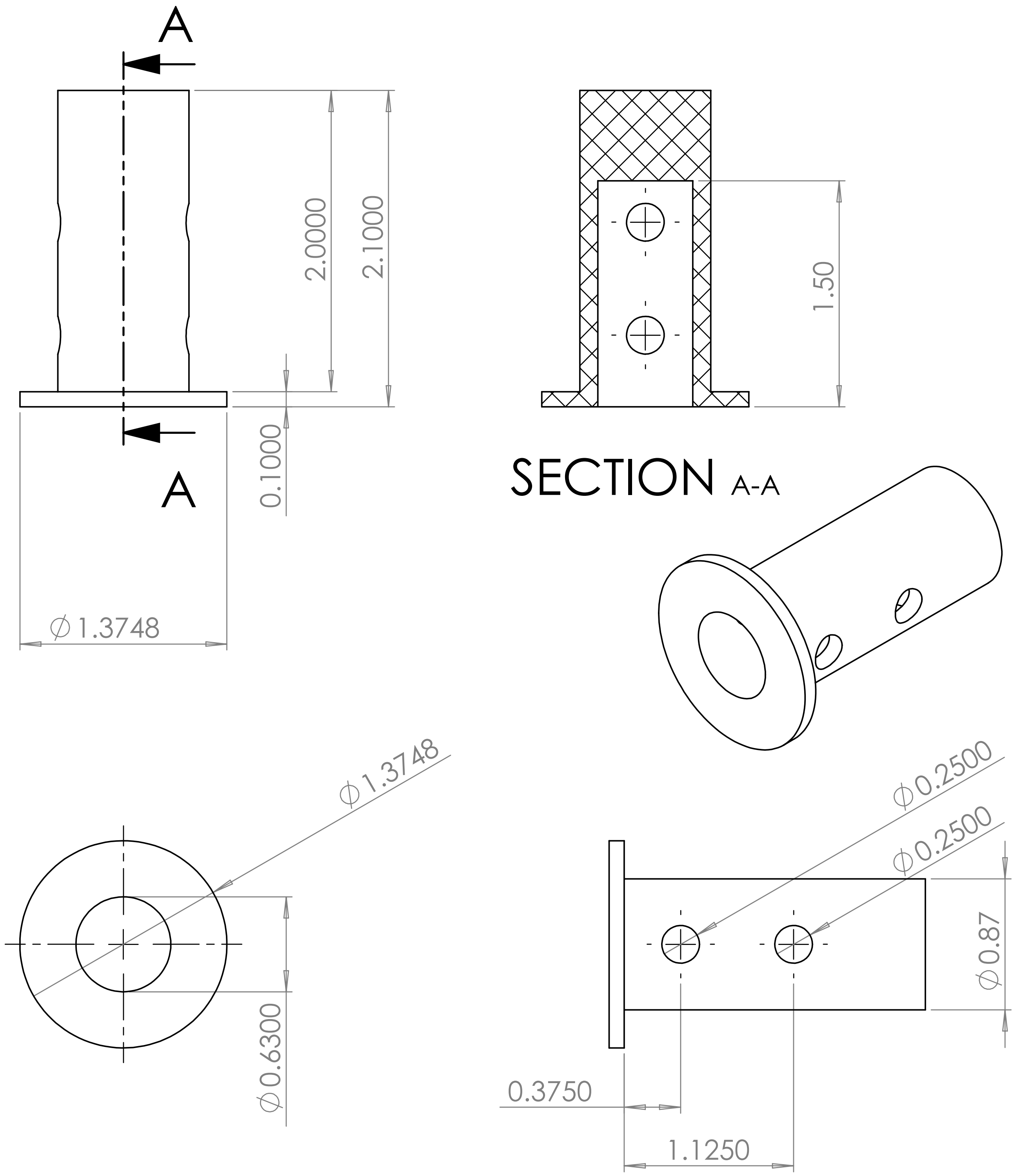
DWG NO.

310

A4

SCALE:1:2

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES SURFACE FINISH: TOLERANCES: ±0.010 LINEAR: ANGULAR:	FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Connection Bushing

MATERIAL: Delrin

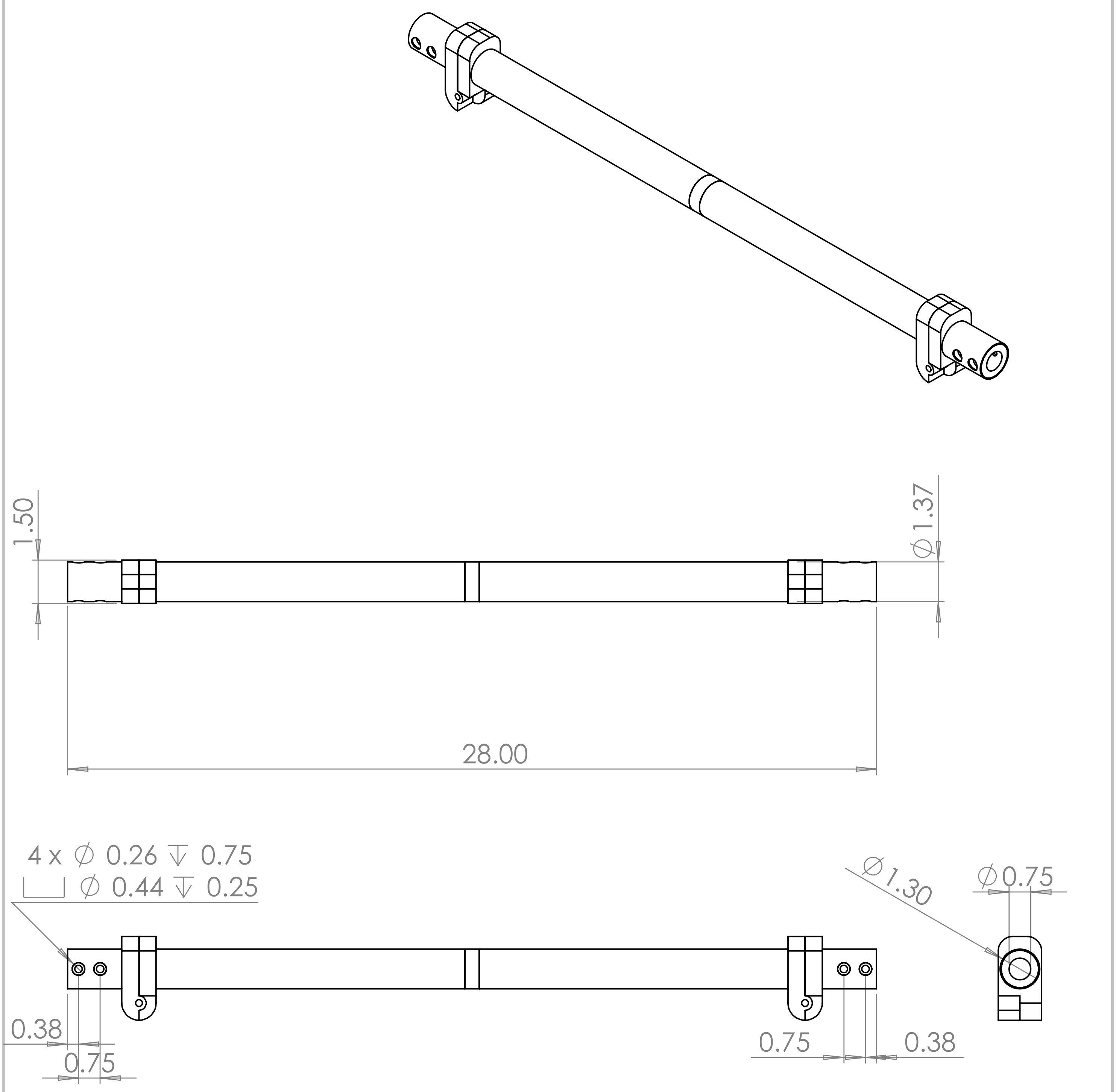
PART NO. 300

A4

WEIGHT:

SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES:
LINEAR: X.XX = ±0.10
X.XXX= ±0.05
X.XXXX= ±0.01
ANGULAR: X.XX = ±5°

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Central Frame Sub Assembly

MATERIAL:
Chromoly Tubing
O.D.34.92mm x I.D.32.92mm

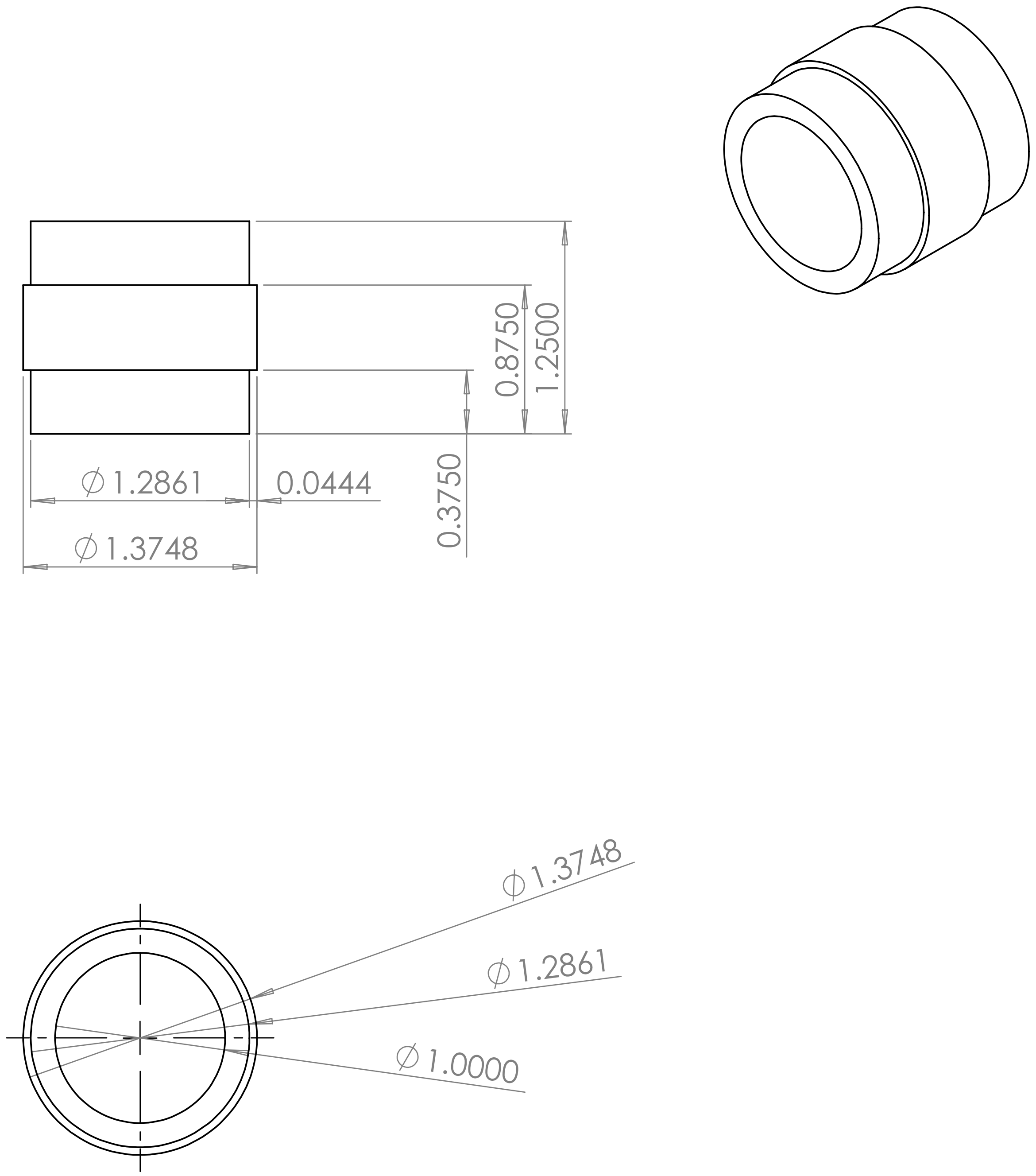
PART NO. 102

A4

WEIGHT:

SCALE:1:10

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES SURFACE FINISH: TOLERANCES: LINEAR: X.XX = ±0.10 X.XXX= ±0.05 X.XXXX= ±0.01 ANGULAR: X.XX = ±5°	FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING / REVISION

	NAME	SIGNATURE	DATE		
DRAWN					
CHK'D					
APPV'D					
MFG					
Q.A					

MATERIAL:

WEIGHT:

TITLE:

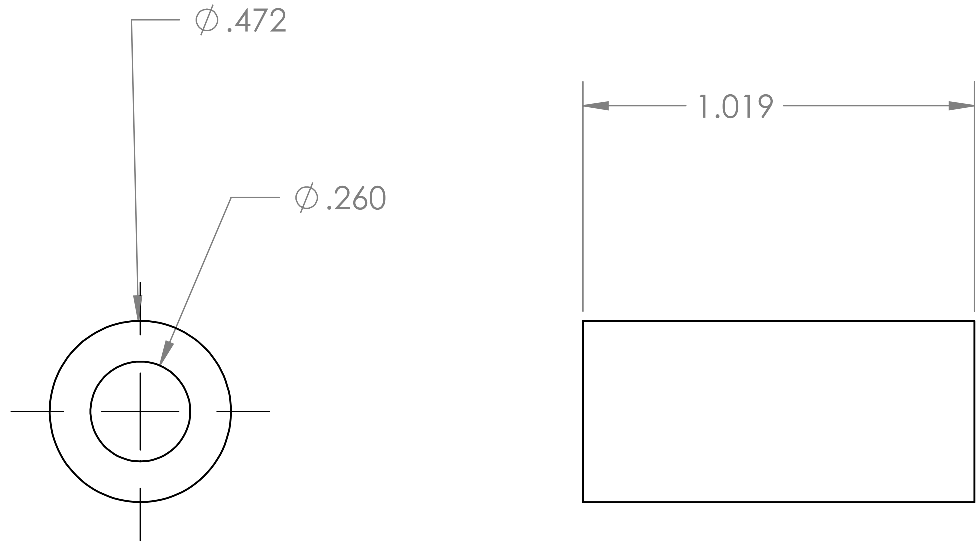
Central Joint

DWG NO. 110

A4

SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

NEXT ASSY	USED ON
APPLICATION	

PROPRIETARY AND CONFIDENTIAL

THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.

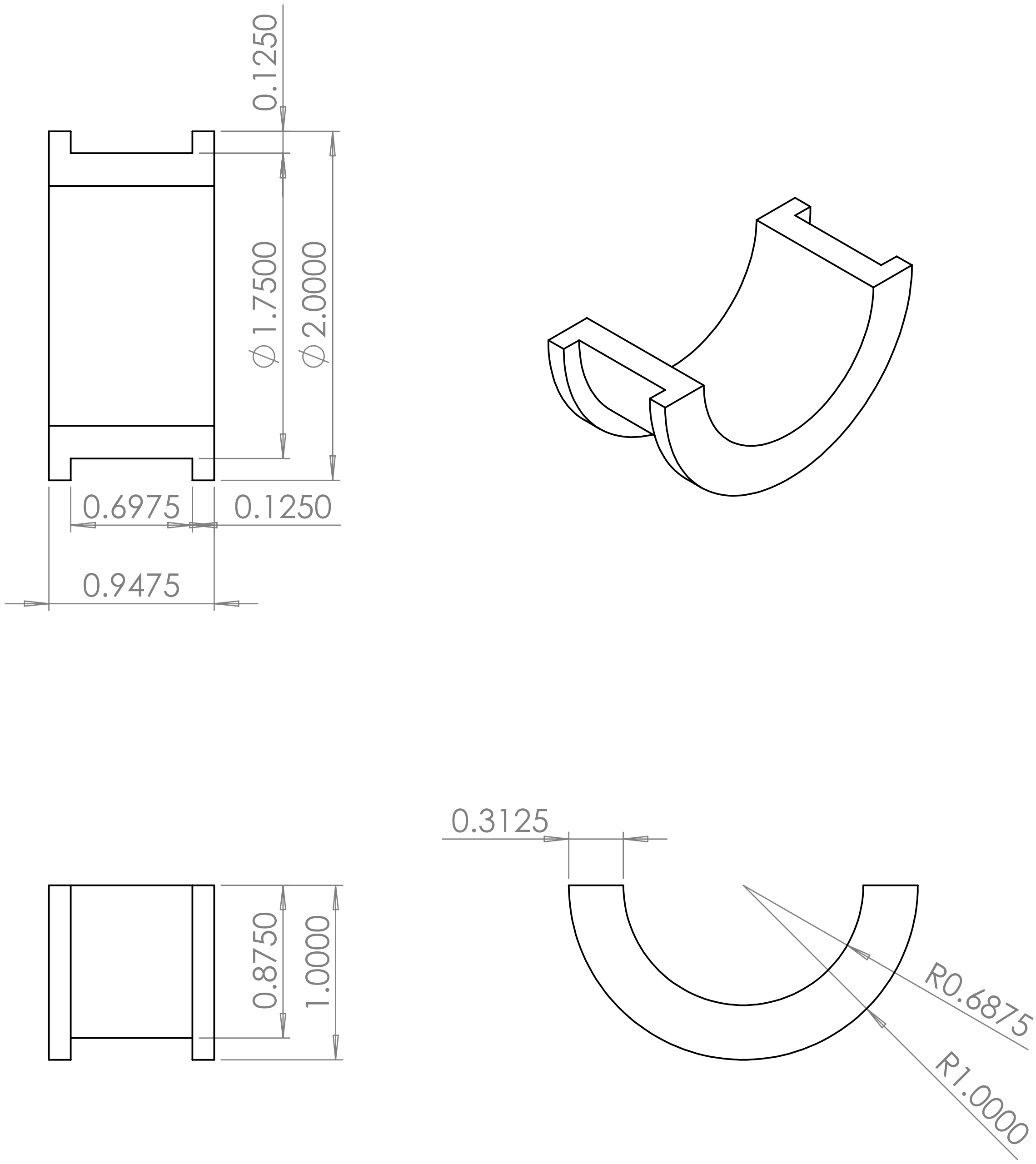
TITLE:

Seat to shaft collar spacer

SIZE A | DWG. NO. 212 | REV

SCALE: 2:1 | WEIGHT: | SHEET 1 OF 1

5 4 3 2 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES: ±0.010
LINEAR:
ANGULAR:

FINISH:

DEBUR AND BREAK SHARP EDGES

	NAME	SIGNATURE	DATE			
DRAWN						
CHK'D						
APPV'D						
MFG						
Q.A						

TITLE:

Seat Bushing

MATERIAL:
Delrin

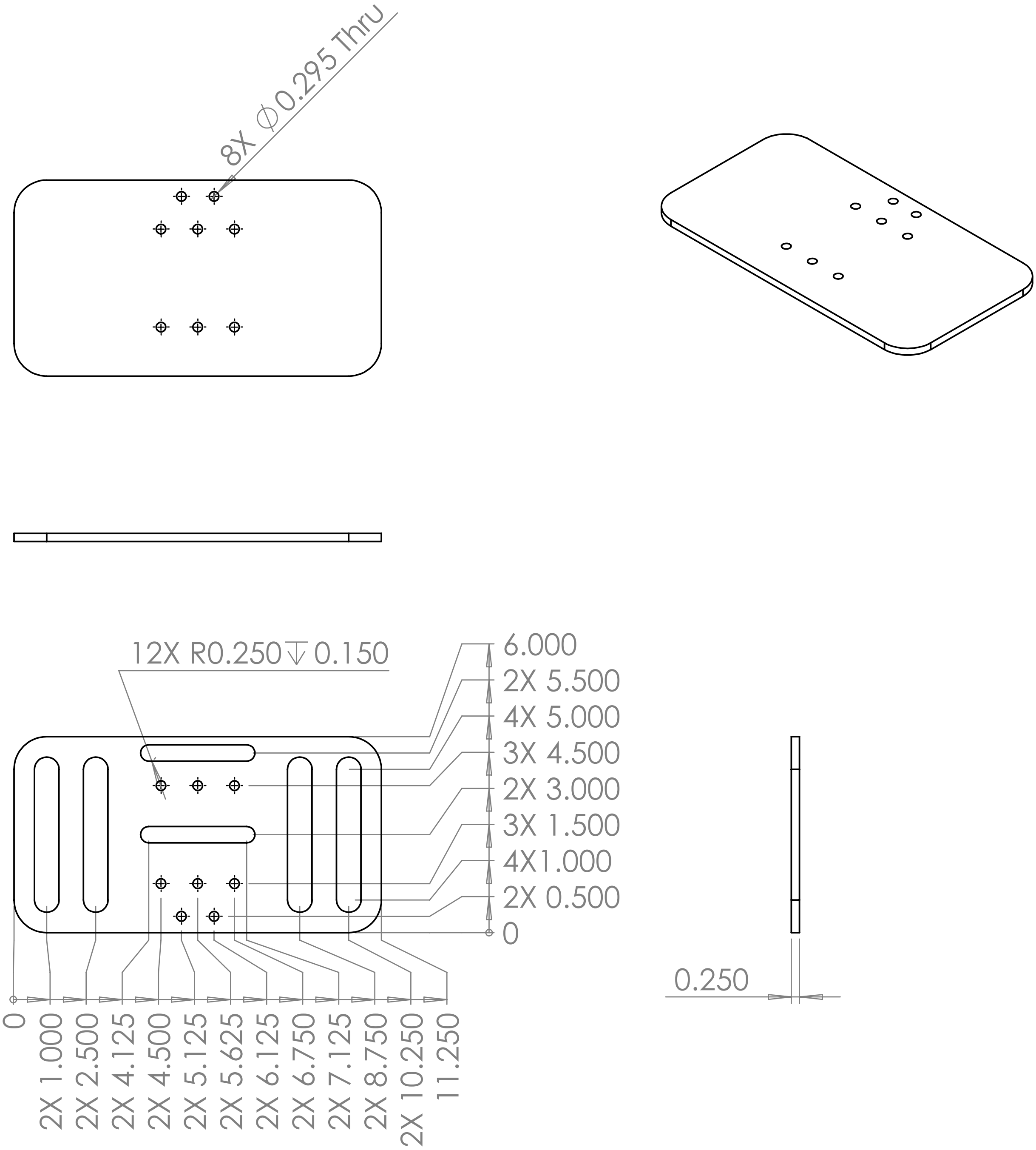
WEIGHT:

PART NO. 301

A4

SCALE:1:1

SHEET 1 OF 1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES: ±0.010
LINEAR: ±0.010
ANGULAR: ±1°

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Seat Plate

MATERIAL:
6061-T6 Aluminum

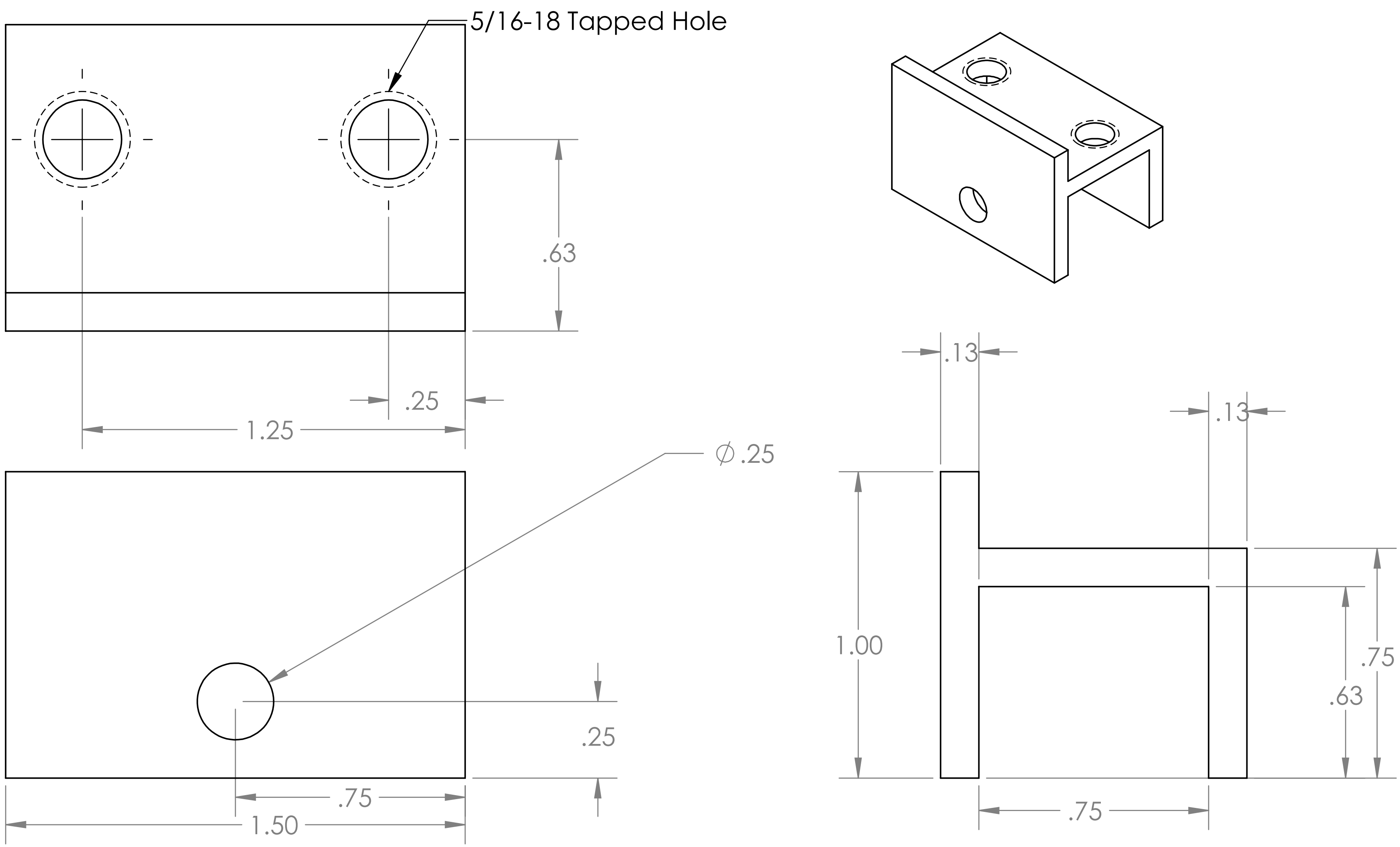
PART NO. 203

A4

WEIGHT:

SCALE:1:5

SHEET 1 OF 1



PROPRIETARY AND CONFIDENTIAL

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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES:
LINEAR: X.XX = ±0.10
X.XXX= ±0.05
X.XXXX= ±0.01
ANGULAR: X.XX = ±5°

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN		
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

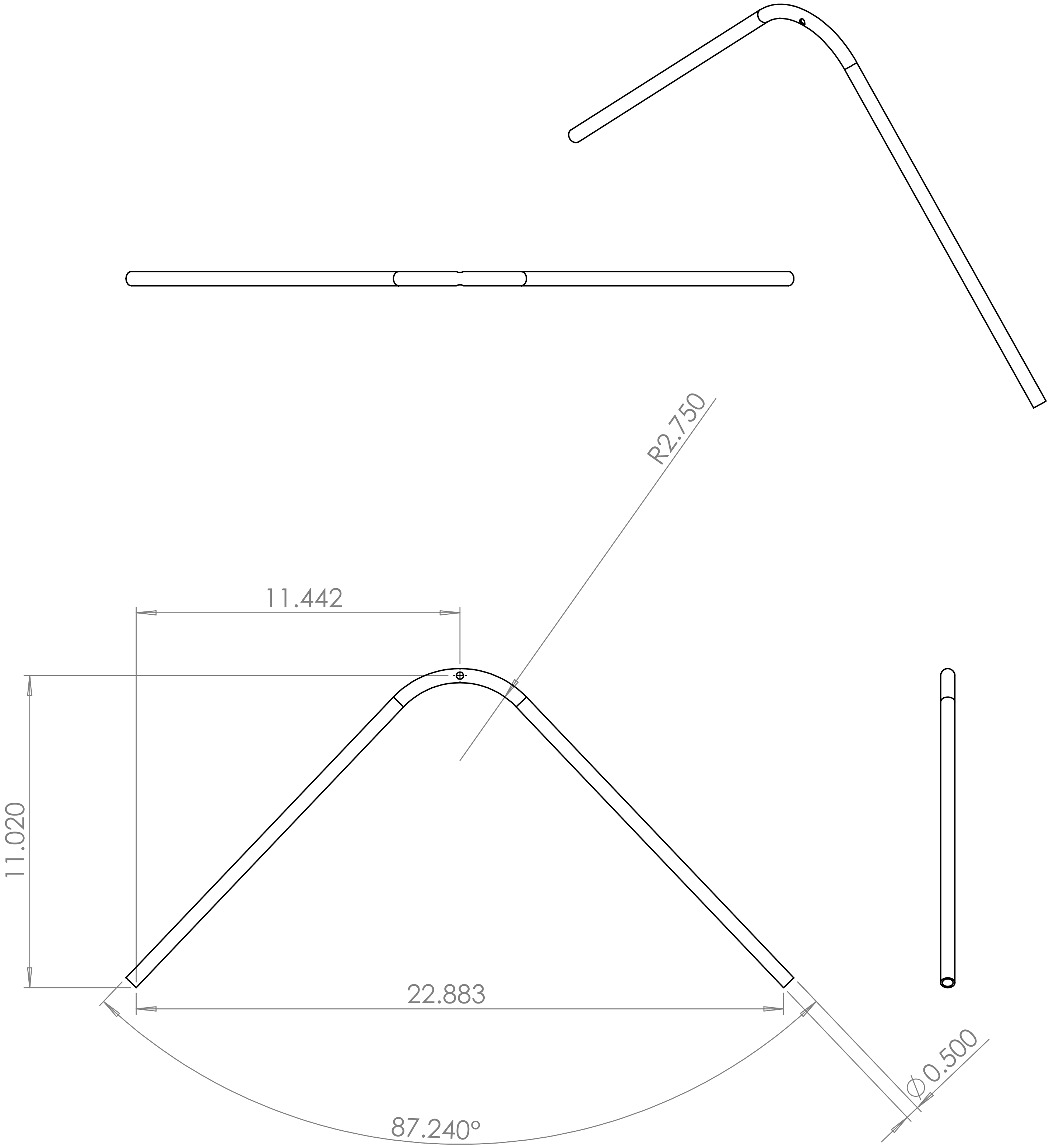
TITLE:

Seat Connection

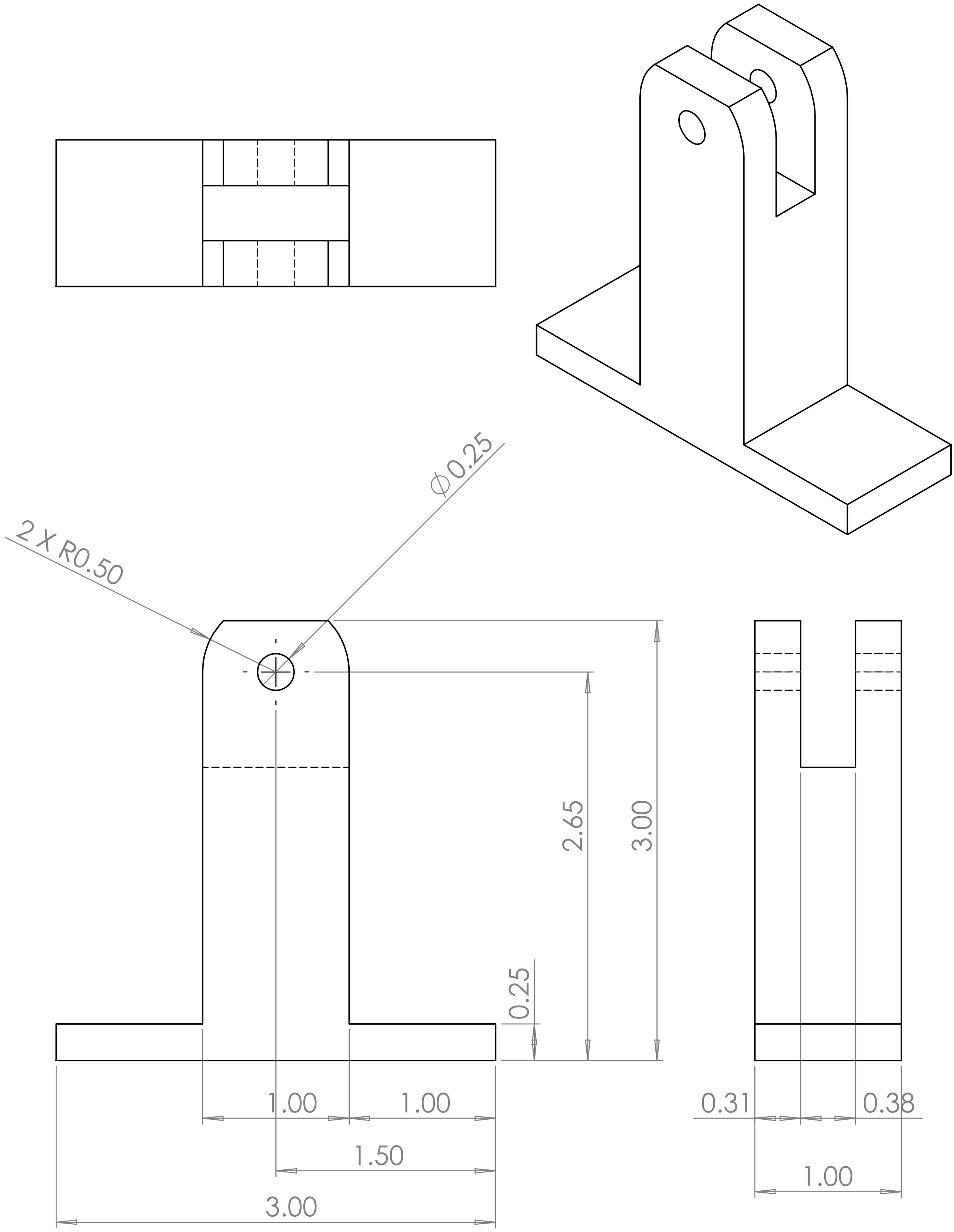
SIZE	DWG. NO.	REV
A	207	

SCALE: 2:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES SURFACE FINISH: TOLERANCES: ±0.010 LINEAR: ±0.010 ANGULAR: ±1°	FINISH:	DEBUR AND BREAK SHARP EDGES	DO NOT SCALE DRAWING	REVISION		
	NAME	SIGNATURE	DATE	TITLE:		
DRAWN				Steer Bar		
CHK'D						
APPV'D						
MFG						
Q.A			MATERIAL: 0.500" x 0.058" Chromoly Steel Tube	PART NO. 103		A4
			WEIGHT:	SCALE:1:10	SHEET 1 OF 1	



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
SURFACE FINISH:
TOLERANCES:
LINEAR: X.XX= ±0.10
ANGULAR: X.XX= ±5°

FINISH:

DEBUR AND BREAK SHARP EDGES

DO NOT SCALE DRAWING

REVISION

	NAME	SIGNATURE	DATE
DRAWN			
CHK'D			
APPV'D			
MFG			
Q.A			

TITLE:

Steering Bracket

MATERIAL:

WEIGHT:

DWG NO.

A4

SCALE:1:1

SHEET 1 OF 1

Appendix M: Off the Shelf Product Spec Sheets

This appendix contains specification sheets provided by the supplier of off the shelf parts.

southco®

ASSEMBLY, LOCKWELL PIN, "T" HANDLE SINGLE ACTING

DATE	DRAWN	CHKD	SCALE	DRAWING NUMBER
23JAN2009	MJS	JF	1.25:1	J-LG-CT

INCHES

ALL DIMENSIONS WITHOUT TOLERANCES ARE FOR REFERENCE ONLY.

THIRD ANGLE PROJECTION — B PAPER SIZE

CAGE CODE SV287

REV	DATE	DRAWN/CHKD	DESCRIPTION
A	23JAN2009	MJS/JF	INITIAL RELEASE

NOTES :

A. MATERIAL AND FINISH:

SHANK AND SPINDLE- TYPE 17-4 PH STAINLESS STEEL PER AMS 5643 OR EQUIVALENT, PASSIVATED PER ASTM A967
HANDLE- CAST ALUMINUM ALLOY PER ASTM B85 OR 6061-T6 EXTRUDED ALUMINUM PER AMS-QQ-A-A200/8, BLACK ANODIZE PER AMS-A-8625.
BUTTON- TYPE 303 STAINLESS STEEL PER ASTM A581/582, PASSIVATED PER ASTM A967 OR 2024 ALUMINUM ALLOY PER AMS QQ-A-225/6, BLACK ANODIZE PER AMS-A-8625.
BALLS- 440C STAINLESS STEEL PER AMS-QQ-S-763, PASSIVATED PER ASTM A967.
WASHER- TYPE 300 SERIES STAINLESS STEEL PER ASTM A240, PASSIVATED PER ASTM A967.
SPRING- TYPE 302 STAINLESS STEEL PER ASTM A313, PASSIVATED PER ASTM A967.
ATTACHING RING- 302 STAINLESS STEEL PER ASTM A313 PASSIVATED PER ASTM A967 OR HARD DRAWN CARBON STEEL WIRE PER ASTM A227.
LANYARD- STAINLESS STEEL CABLE PER MIL-DTL-83420, TYPE 1, COMP. B WITH VINYL COATING PER MIL-I-631, TYPE F, GRADE A, CAT. 1, COLOR GREEN.

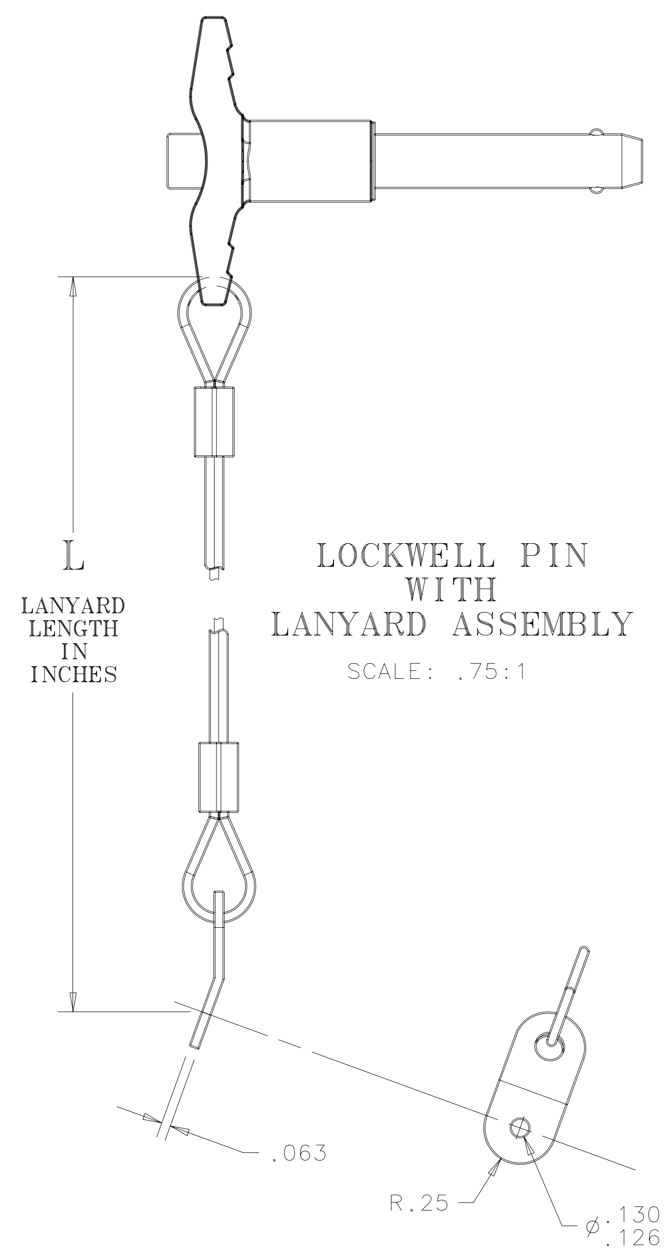
B. SOUTHCO IS A QSLM CERTIFIED MANUFACTURER OF QUICK RELEASE PINS. THE LOCKWELL QUICK RELEASE PINS ON THIS DRAWING CAN BE MANUFACTURED TO THE SPECIFICATIONS OF MS17985 AND NAS1333 THRU NAS1346. PARTS ORDERED TO MS AND NAS SPECIFICATIONS ARE CERTIFIED TO NAS1332 AND NASM23460.

C. WHEN MANUFACTURED TO MS OR NAS SPECIFICATIONS, MS OR NAS IS PUNCHED IN THIS LOCATION.

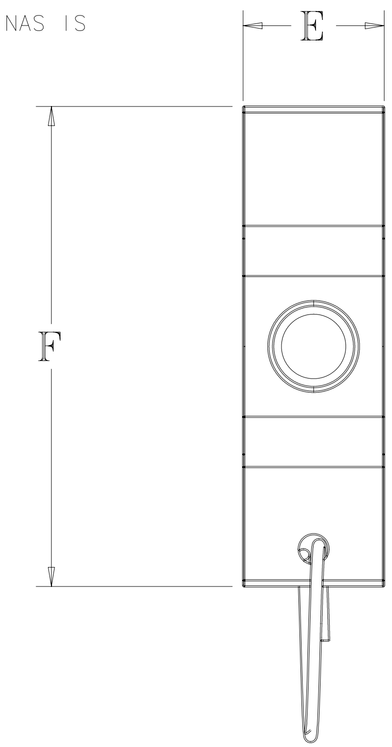
PART NUMBER:

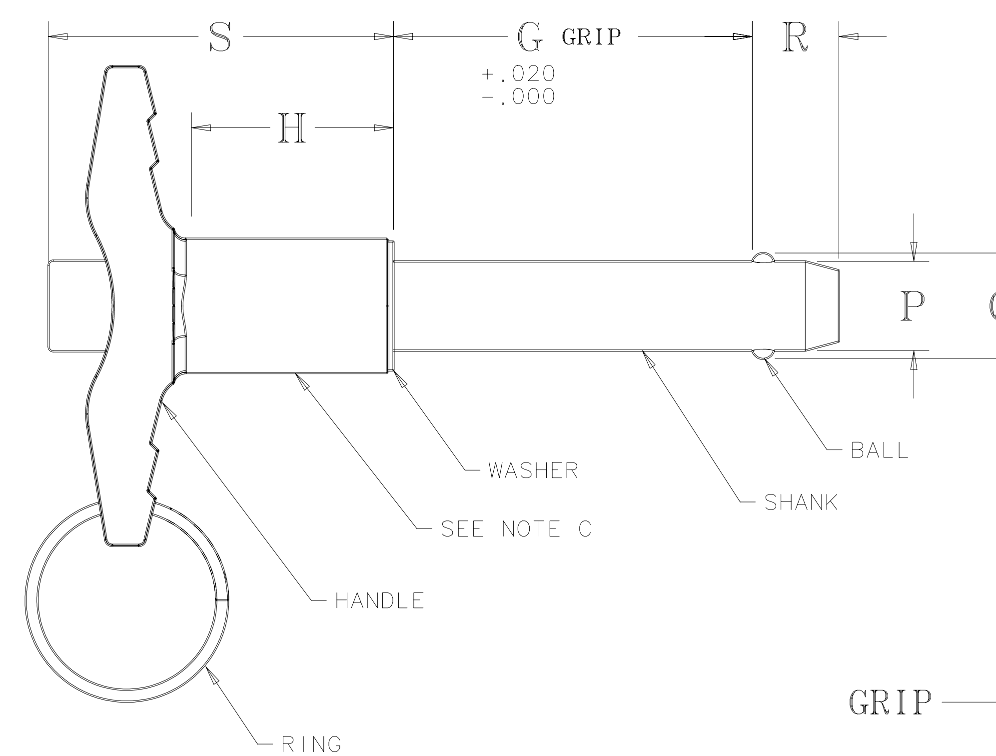
LG-D C T G F 750 L12

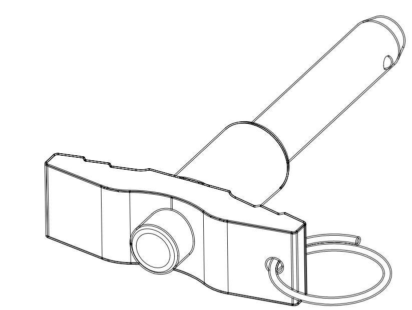
- D — SHANK DIA (SEE TABLE)
- G — GRIP IN THOUSANDTH INCH INCREMENTS
  EX: LG-4CT1000L6 = 0.25 in. DIAMETER, 1 in. GRIP LENGTH, 2-BALL, 6 in. LANYARD
- F — "F" = 4 BALL (OMIT FOR STANDARD LENGTH 2 BALL)
- 750 — LONGER NON-STD "R" DIM IN THOUSANDTH INCH INCREMENTS. (OMIT FOR STD. "R" DIM)
- L12 — LANYARD LENGTH IN INCHES (OMIT IF NO LANYARD REQUIRED)

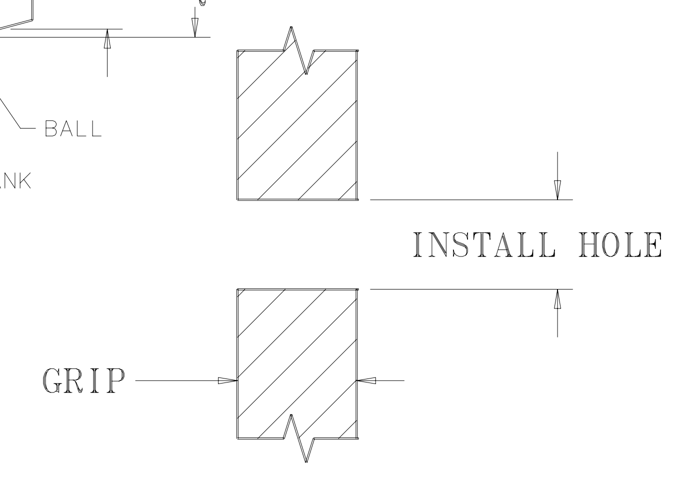


LOCKWELL PIN WITH LANYARD ASSEMBLY
SCALE: .75:1







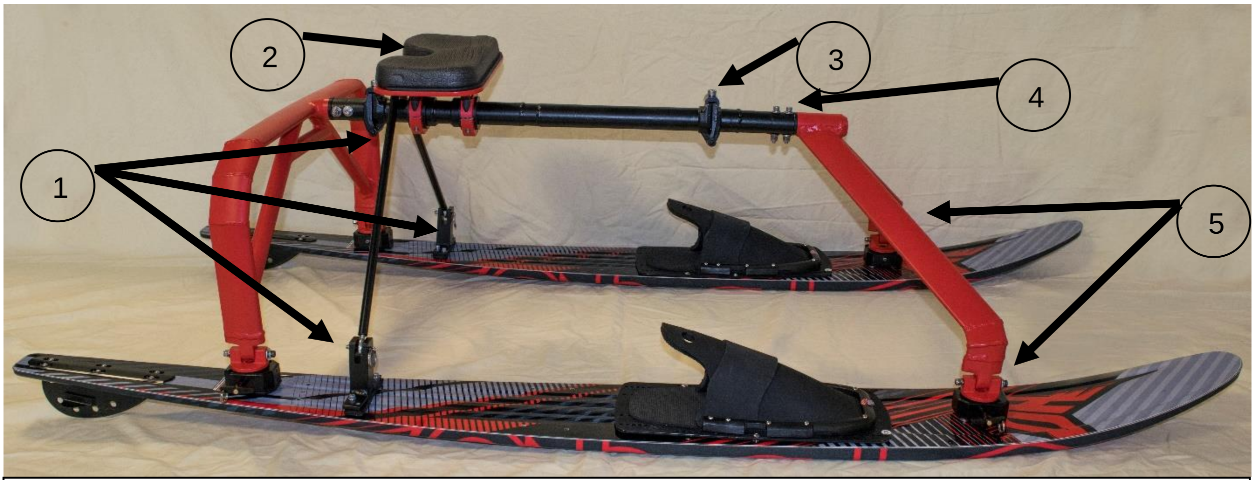


INSTALL HOLE

PIN SIZE	D	ØP +.0000 -.0015	Q ±.005	R +.000 -.030	E	F	S MAX.	H MIN.	MIN. TENSION LOAD CAPABILITIES 2-BALL	MIN. TENSION LOAD CAPABILITIES 4-BALL	CALCULATED DOUBLE SHEAR STRENGTH	INSTALL HOLE Ø MIN.	INSTALL HOLE Ø MAX.
3/16	3	.1885	.220	.260	.500/.380	1.815/1.750	1.270	.800	200 lbf	260 lbf	5150 lbf	.190	.194
1/4	4	.2485	.289	.290	.500/.380	1.815/1.750	1.270	.800	230 lbf	290 lbf	9200 lbf	.250	.254
5/16	5	.3110	.375	.330	.500/.380	1.815/1.750	1.270	.800	510 lbf	630 lbf	14400 lbf	.3125	.3165
3/8	6	.3735	.440	.365	.625/.510	2.000/1.935	1.450	.850	575 lbf	740 lbf	20600 lbf	.375	.379
7/16	7	.4360	.509	.380	.625/.510	2.065/2.000	1.470	.850	710 lbf	920 lbf	28000 lbf	.4375	.4425
1/2	8	.4985	.594	.460	.800/.630	2.345/2.250	1.600	.885	1160 lbf	1500 lbf	36800 lbf	.500	.505
9/16	9	.5610	.666	.510	.800/.630	2.345/2.250	1.600	.885	1420 lbf	1840 lbf	46000 lbf	.5625	.5675
5/8	10	.6235	.750	.580	.975/.810	3.000/2.250	1.700	.980	2070 lbf	2690 lbf	57500 lbf	.625	.630
3/4	12	.7485	.887	.670	1.000/.810	3.000/2.250	1.720	1.030	2950 lbf	3835 lbf	82500 lbf	.750	.757
7/8	14	.8735	1.046	.760	1.320/1.120	3.000/2.750	2.140	1.310	3900 lbf	5070 lbf	112500 lbf	.875	.882
1	16	.9985	1.219	.890	1.320/1.180	3.000/2.750	2.140	1.310	5480 lbf	7120 lbf	147000 lbf	1.000	1.010

Appendix N: Operator's Manual

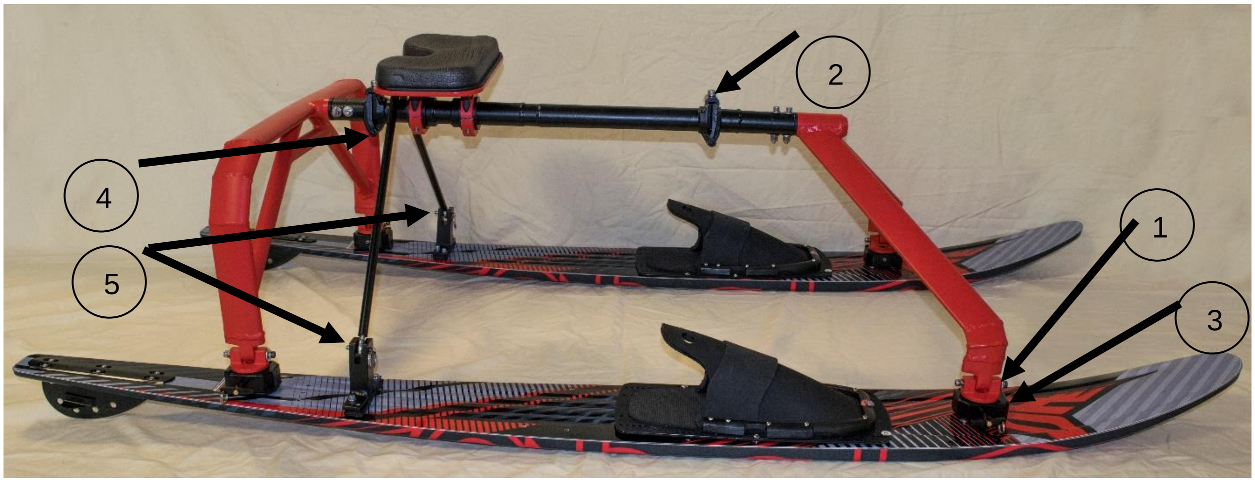
System Specifications and Features



Key Features:

1. Steering Bar Pins
2. Seat Cushion
3. Frame Hinges
4. Center Bar Connecting Bolts
5. Ski Connection Pins

Setup and Takedown



In order to assemble the system, perform the following steps:

1. Unfold and carefully stand up the frame with the feet flat on the ground.
2. Using the Allen wrench, fully tighten the hinge screws on the center bar.
3. Place the frame onto the skis by fitting each foot into a shoe. Secure each foot-shoe connection with a pin.
4. Place the steering bar into its position under the seat and secure it onto the frame by placing a pin through the hole.

5. Finish securing the steering bar by aligning it with the steering brackets on each ski. Complete attachment by placing pins in these holes.
6. System is ready for operation!

In order to collapse the system, perform the following steps:

1. Pull the three pins connecting the steering bar to the frame and skis.
2. Remove the steering bar.
3. Pull the pin in each of the foot-shoe connections.
4. Remove the frame from the skis and use the Allen wrench to unscrew the hinge clamps on the center bar.
5. Fold the frame up for storage and be sure to place the pins in a safe place for future reassembly.

Device Operation

Use of this device requires manipulation of balance and weight from the rider. To begin, the rider will wear a lifejacket, a helmet, and other applicable safety equipment. Then, the rider will place himself in the water with feet in the bindings, suspending the ski below him. The rider will then hold onto the ski rope which is connected to the boat and alert the driver when he is ready to begin. Once the rider has signaled to the driver, the driver will accelerate, allowing the boat to pull the rider out of the water. During this process, it is the rider’s responsibility to grasp the handle, maintain contact with the seat, and remain facing the boat while the skis gain stability. Once the rider has been pulled out of the water and the skis plane the surface, the rider is free to maneuver. To turn the skis, the rider should lean in the desired direction of turn using his upper body. When the rider is finished skiing, he will let go of the rope and remain seated as the skis begin to sink. The rider should not reach under the seat at any point during use; this precaution will prevent fingers from getting caught in the steering system.

Maintenance

Regular maintenance is necessary in order to maintain quality and product longevity. After each use, the entire apparatus should be sprayed with a hose in order to prevent corrosion, and should then be stored in a cool, dry place, such as a garage. It is recommended that the owner apply a coat of paint and a clear coat each year to prevent weathering and corrosion from affecting appearance and performance of the system. Additionally, the center bar connection bolts and seat cushion should be replaced every five years, or sooner if wear and tear becomes visible.

Repairs

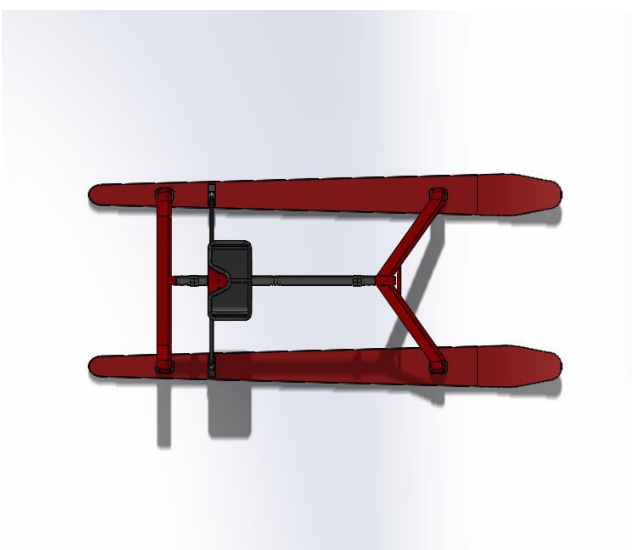
Unfortunately, due to the custom nature of this system, few replacement parts are available in the event that a repair must be performed. However, pins which have been purchased off-the-shelf can be replaced.

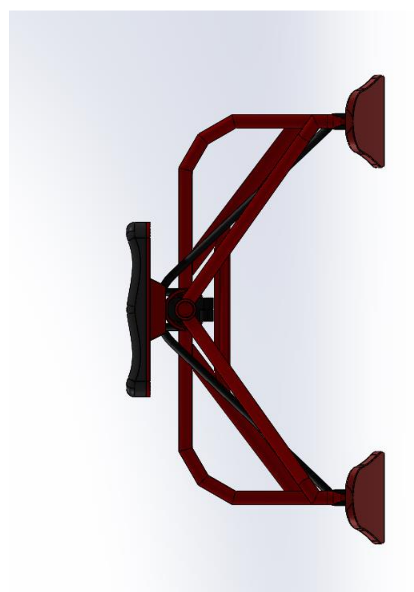
Pins for the foot-shoe connection can be replaced by purchasing part number 90293A137 from McMaster Carr. If these are unavailable, a ball-detent pin with a 1/4 inch diameter and 1-1/4 inch length will work was well.

Pins for the steering bar connection can be replaced by purchasing part number 91585A178 from McMaster Carr. If these are unavailable, a dowel pin with a 55 mm length, or English equivalent, and an M6 diameter, or English equivalent, can be used instead.

If there are further questions or concerns, please contact Team Freedom Ski for further assistance.

Appendix O: Isometric Views of Final Design





[1] “Spinal Cord Injury Facts & Statistics.” *National Spinal Cord Injury Association.* Web. 11 October 2014.