Design of a Snowboard Simulating Exercise Device

By

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ABSTRACT

Snowboarding, since its creation, has become one of the most widely practiced winter sports. Unfortunately, most snowboarding enthusiasts are unable to snowboard year round due to geographic and financial limitations. One possible solution to this dilemma is the development of a device that simulates snowboarding.

Using a Deterministic Design process developed in MIT's Precision Engineering Research Group, a Snowboarding Exercise Machine is created. This design features a carriage constrained to move back and forth along a curved track. Rotational sensations are created using an angular motion module mounted onto the carriage. The end result of this effort is a proof of concept prototype, which indicates that the output kinematics are desirable. Additional work and sponsorship is required to bring the proof of concept prototype to a commercially available product.

Thesis Supervisor: Alexander Slocum
Title: Professor of Mechanical Engineering

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1 Introduction

In the sport of snowboarding, a user starts at the top of a snowy slope with both feet rigidly attached to a composite board through bindings. The snowboarder then carves a path down the slope by gliding over the snowy surface until they reach the bottom. Like skiing, the sport of snowboarding started from humble beginnings of amateur inventors sliding down a hill standing on various types of boards. Since then, this "science experiment" has blossomed into a major sport, practiced by millions, and even officially recognized as an Olympic sport.

Despite this huge following of snowboarding enthusiasts, the availability of this sport depends entirely on the weather. Quite simply, if there is no snow, there is no snowboarding. This leaves most snowboarders with only a few options during the "off season". The first and most dreadful option is to go without, until the weather becomes cold enough for snow. The second option is to travel to where the snow is. Unfortunately this proves to be too expensive a proposition for all but the most hardcore snowboarders. The third and final option is to find some means of simulating snowboarding without the need for snow.

This third option is the principal motivator for this project. How does one go about creating a device that simulates snowboarding when an actual slope is not available? Furthermore, how can a snowboard simulating device be created that offers a reasonable facsimile of snowboarding, while also addressing and filling a market need, resulting in a profitable and highly marketable design? This thesis documents the entire design process and methodology used to develop one such snowboard simulating device from the initial conceptual stages, to a proof of concept prototype.

For this thesis, a Deterministic Design process developed in MIT's **P**recision **E**ngineering **R**esearch **G**roup (pergatory.mit.edu) is used. This design process utilizes various different organizational tools, in addition to an adaptive peer review process and reliance on fundamental engineering principles to create, evolve, and constructively evaluate designs.

The first step in this process is a complete background review and literature search. Numerous attempts have been made in the past to simulate snowboarding, and it is incredibly important to know what has already been done. This review looks carefully at all current snowboard simulating technologies, in addition to other technologies that could potentially result in new designs.

To better understand the problem at hand, it is also essential to consider the underlying physics of actual snowboarding. The motions of a snowboard can be broken down into individual simple motions. Understanding these individual motions provides insight into how best to replicate them in a simulator.

With the project background laid out, and the basic kinematics defined, the true design work can begin. The initial direction of this project considers balance board, exercise machine, and entertainment simulator strategies. Each of these strategies offers unique development and market opportunities, but ultimately an exercise machine for gym use is chosen as the most promising.

The remaining sections cover the evolution of this snowboard simulating exercise machine. The concept phase decides between exercise machine concepts. The module phase then breaks the chosen concept down into separate modules, and goes through the detailed design and manufacturing of each one. After complete detailed design and manufacturing of each individual module, the modules are then integrated into the finished proof of concept prototype. The proof of concept prototype verifies that the kinematics are acceptable, and provides insight into how the overall design can be improved in later versions of the exercise machine.

Reaching the proof of concept prototype level is a critical milestone in the development of the snowboard simulating exercise device. This, however, is only the first leg of the development cycle required to determine if an effort should be made to bring this product to the market.

2 The Deterministic Design Process

Before even attempting the design of a Snowboarding Simulator, it is critically important to lay down the groundwork for the project by selecting an appropriate design process. This process determines what project management tools are best suited to the design of the product, in addition to providing a system of checks and balances for the project during each phase of development. A solid design process critically evaluates the design, and streamlines the entire process, removing much of the ambiguity. In this specific design, the Deterministic Design process is highly effective at achieving these goals. The following summarizes the project management tools used in the process, and ties them all together in describing the full development cycle. [2-1] [2-2] [2-3]

2.1 FRDPARRC Tables

The FRDPARRC table is a project management tool for organizing a large amount of information in a small amount of space. The term FRDPARRC (pronounced fredpark) is an acronym. The letters of FRDPARRC stand for **F**unctional **R**equirements, **D**esign **P**arameters, **A**nalysis, **R**eferences, **R**isks, and **C**ountermeasures. These six topic headings address a minimum set of critical elements when considering and comparing designs. Instead of this information being scattered, or omitted entirely, it can instead all be found in one place. This organization reveals patterns in the design, and opportunities for improvement. The FRDPARRC Table is incredibly robust, and can be used and reused during each phase of the development process (specifically during the strategy, concept, module, and component phases).

The **F**unctional **R**equirements for a design refer to the goals for a design at the current stage of development. In simpler terms, this is a list of the functions that a design needs to accomplish. At the highest (coarse) level, these functional requirements are the overarching project goals. Through development, as the design evolves from coarse to fine detail, the functional requirements become far more specific. On the actual

FRDPARRC Table, the Functional Requirements are a list of words (in serial (1, 2, 3, 4…) or parallel (2A, 2B…)) describing what needs to be accomplished.

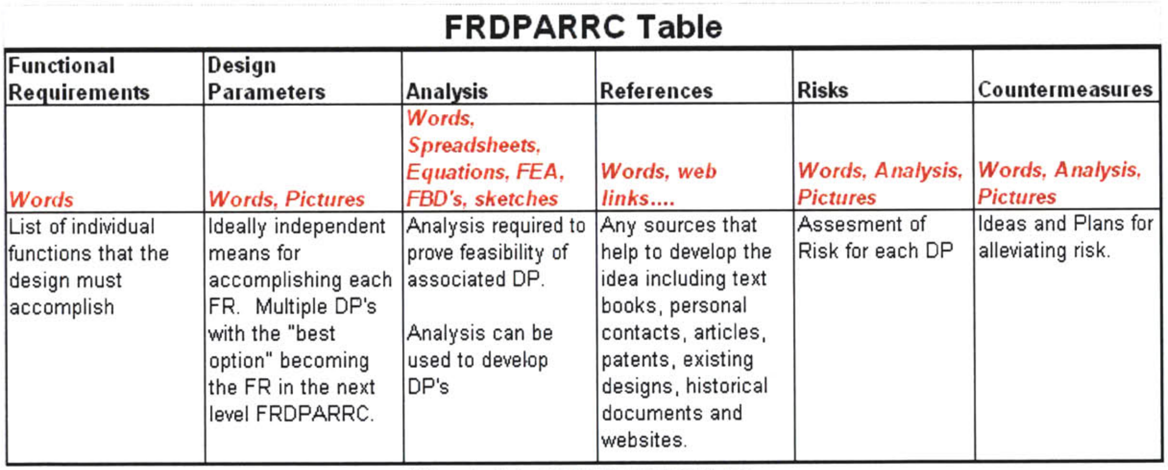
If the Functional Requirements answer the question "what", then the Design Parameters answer the question "how". The **D**esign **P**arameters are a set of ideally independent means to accomplish the previously established functional requirements. Any design challenge will have numerous potential solutions. In the same way, every functional requirement has numerous potential design parameters. The DP column of the FRDPARRC contains both word explanations and pictures to illustrate possible solutions. The FRDPARRC Table organizes all the possible solutions, such that a concept selection matrix can be used to choose the "best" means of achieving the functional requirements. Furthermore, the chosen DP's become the FR's for the next level of detail.

Analysis is required to prove the feasibility of the associated design parameters. When laying out design parameters, calculations must be done to differentiate one idea from another. These include economic analysis, mechanical analysis, manufacturing analysis etc… On the FRDPARRC this can be included as a description of the analysis required (in words), as results based on bench level experiments and more involved analysis, or as spreadsheets, equations, and FEA. Including this in the table allows the reviewer a chance to see the analysis and results for each design parameter side by side, which allows for a more informed decision when selecting design parameters. The analysis also can be used in reverse to create design parameters.

References refer to any outside sources that help to develop the idea. References include (but are not limited to) text books, personal contacts, articles, patents, existing designs, historical documents, and websites. References establish how much previous work has already been done on an idea, and indicate available resources for the project.

Risk assessment is among the most important steps in comparing design parameters. For each design parameter a serious consideration of development risk is necessary. When considering risk, however, people often incorrectly identify it. Certain "risk" factors are simply design problems, which can easily be fixed by doing slight modification to the design. Risk on a FRDPARRC Table refers to more serious concerns, where simple design modifications will not fix the problem. Included in this are fundamental safety issues, not meeting time completion requirements, and other more detrimental problems. Risks can be presented on the table through words, pictures, or analysis to illustrate the risk.

Countermeasures are the ideas and plans for alleviating or mitigating the risks of the associated design parameter. For each risk there are ways to reduce the problems, or eliminate them entirely. Countermeasures can consist of simple off-the-shelf solutions, or more unique out-of –the box solutions. By including these for each DP, a reviewer can see all of the inherent risk, and assess the feasibility of alleviating the risk.



FRDPARRC Table

Functional Requirements	Design Parameters	Analysis	References	Risks	Countermeasures
Words	*Words, Pictures*	*Words, Spreadsheets, Equations, FEA, FBD's, sketches*	*Words, web links....*	*Words, Analysis, Pictures*	*Words, Analysis, Pictures*
List of individual functions that the design must accomplish	Ideally independent means for accomplishing each FR. Multiple DP's with the "best option" becoming the FR in the next level FRDPARRC.	Analysis required to prove feasibility of associated DP. Analysis can be used to develop DP's	Any sources that help to develop the idea including text books, personal contacts, articles, patents, existing designs, historical documents and websites.	Assesment of Risk for each DP	Ideas and Plans for alleviating risk.

Figure 2-1: FRDPARRC Table

Each of these subjects addresses the critical concerns when selecting a design. In the end FRDPARRC Tables greatly streamline the process, resulting in a much better final design.

2.2 Weighted Concept Selection Chart

In the Deterministic Design Process, weighted concept selection charts are used to select between different design parameters and designs. When selecting between concepts, there is an enormous amount of ambiguity when selecting between designs unless there is a well established, unbiased means to differentiate between them. The weighted concept selection chart minimizes the opportunity for bias in the selection process, and can continue to be used after design selection as a design tool.

The first step in creating a weighted concept selection chart is to refer to the FRDPARRC Table. The designs being compared are the design parameters, while the design metrics they are being judged on are the functional requirements. These should be placed on opposite "axes" of the weighted CSC.

The next step is to assign weightings to the design metrics. During this step it is imperative to ignore the design parameters. It is incredibly easy to falsify the selection process by fixing the weightings so that one design triumphs over another. Instead the functional requirements should be ranked in order of importance (and agreed upon by all involved in the process). Then the rank order should be reversed, to assign points for a given metric. In Figure 2-2, assume that functional requirements 1-3 have already been ranked in terms of importance. Since functional requirement 1 is the most important, it receives the most points (in this case 3). Assigning weightings in this way makes it much more difficult to fix the process.

The development of a ratings scale can be handled in several ways. Typically concept selection matrices and Pugh charts use large rating scales (commonly 1-10, or a (--/-/0/+/++) system). The problem with using such a large ratings scale is that often reviewers are unwilling to use the entire range of the scale. Instead of rating from 1-10, the reviewer may rank everything from 6-10. In the end, everyone uses the scale differently, and the results have to be normalized. The other concern with this method is that at this stage there are many unknowns with every design. What is the difference between a 6 and a 7, or a + and a ++? A more coarse ratings scale is required.

Using a simple (-1/0/1) system removes the ambiguity of a large scale. There is little to no question as to the difference between a –1 and a 0, or a 0 and a 1, and any point difference in the totals between designs is significant. The only drawback in this approach is that there is the potential for more ties. In the case of ties, however, both designs have the same potential, and more information is needed to choose between them.

The actual evaluation of designs also has options. Often an existing design is added in with a 0 score as the baseline, and other designs are compared based on that design. For this project, a straight comparison is made between the designs, without a baseline. The ratings are assigned for each design parameter, multiplied by the weight, and totaled for the final score. Once the selection has been made, the weighted CSC remains useful.

Weighted Concept Selection Chart

		Design Parameters		
Selection Criteria	**Weighting**	**Baseline Design**	**Design Parameter 2**	**Design Parameter 3**
Functional Requirement 1	3	0	1	0
Functional Requirement 2	2	0	1	1
Functional Requirement 3	1	0	-1	-1
Total Score:		**0**	**4**	**1**

Figure 2-2: Weighted CSC

Barring a perfect design (all 1's), a selected design has room for improvement. In any columns where the selected design falls short, it is possible to "borrow" elements from other designs to improve the selected design. In this respect the weighted concept selection chart becomes phenomenally useful as a design tool as a well as a selection tool.

2.3 Peer Review Evaluation Process (PREP)

The final project tool of the Deterministic Design process is the Peer Review Evaluation Process (PREP). PREP is a way of reviewing designs, such that every person working on the design has input to the process. During PREP meetings, each team member brings copies of individually developed pictures, analysis, FRDPARRC Tables, and other related items for every member of the team. Each team member then reviews others' work individually at first, and writes comments, initialing every comment they make. The goal of leaving comments is to praise good ideas, offer constructive criticism with suggestions for improvement, and to propose new suggestions for the design. The initialing of ideas gives every person in the process a say, even if they are unwilling to speak up in group meetings. [2-3]

After individual review, the team reconvenes, returning the PREP'd documents to their owners. At this point every member of the team has had a chance to individually reflect on all of the designs, and a dialogue can begin, where the design is able to evolve to the next level of development.

For this project, the majority of the work is done individually. This does not mean that PREP is not needed. In this case PREP is of critical importance as a sanity check. After each design iteration the design needs to be reviewed by the project advisor, coworkers, shop personnel, and peers. This will catch errors in the design, and tap into the extensive experience of the reviewers. Similarly PREP can be used on others' suggestions to improve the design even further. Using this approach provides everyone involved with a sense of ownership in the design, which results in more willingness and consideration in making the design better.

2.4 *The Deterministic Design Process*

The deterministic design process uses the above design tools in a thorough, yet streamlined approach to design. [2-1] At the heart of this process is a coarse to fine approach, where the initial concept is wide open to numerous different design options, but through the design evolution, is funneled down to a well thought out design. Through the use of FRDPARRC Tables, weighted Concept Selection Charts, and the PREP Process, in conjunction with fundamental design principles, wonderful designs can be produced extremely fast.

The first step in the deterministic design process for the snowboarding simulator is to run a thorough literature and background search of all existing, pertinent technologies and to take stock of available project resources. The background search is incredibly important for three major reasons. The first is that it shows what has already been designed, so that no work is repeated, and there is no chance of designing an already patented device. The second is that studying the related technology provides fantastic insight into the state of the industry, and what has and has not worked. The third reason is that it fuels the design process by identifying market gaps, and serving as a basis for improving existing designs, or borrowing existing design elements for an entirely new design.

Taking stock of available project resources is also extremely important. First, the time requirements, and necessary resources must be considered. This design effort involves a great deal of design and manufacturing. A support network of coworkers and peers are required to serve as a PREP group during the design. Even though this is a primarily individual project, reviewers are essential to offering feedback, suggestions, and help during the entire design process. Next, design tools are required for the design. For this project Pro/Engineer™, Solidworks™, MATLAB®, Excel™, OMAX™ Waterjet Software, and other programs are necessary for the design of the machine. These resources must be procured early on. Finally, shop access is required for the machining of the proof of concept prototype. By making arrangements early on, much of the hassle of finding shop space is eliminated. Outside of these areas, all additional resources can be found on an as needed basis.

The second step in the process is to thoroughly define and understand the problem at hand before diving into the solution. In the case of a snowboarding simulator, this requires a thorough understanding of the physics of snowboarding. In this study, the goal is to determine the underlying rules, limitations, and constraints on how a snowboard moves. This problem must be explored from numerous different angles. Watching the motions of snowboarders on video and in person is an important first step. Professional snowboarders on television are able to push the limits of what is capable on a snowboard. On the opposite end of the spectrum, amateurs snowboarding at a ski resort focus on routine, basic motions. Both extremes should be considered when designing a snowboarding device with universal appeal. Next, force and motion analysis, and the development of free body diagrams are required to understand how these motions are possible, so that they can be replicated. Finally, a great deal is learned by actually going snowboarding, and experiencing the motions first hand. In this way, the designer can directly relate the feel of the prototype machine to the sensations of actual snowboarding.

After pooling resources and doing the appropriate background research, the task of actually designing a snowboard simulating device can begin. This process starts at the **strategy** level. Strategies refer to different approaches to solving the problem. At this stage all that is known is the most general functional requirements for the project. The resulting strategies are similarly general, focusing only on an approach, rather than a specific design. Designers consider the desired output kinematics, and through simple analysis and bench level experimentation, generate viable strategies in both words and pictures. Strategy generation yields numerous potential strategies, which are organized on a **strategy** level FRDPARRC. The **FR**'s at this level of detail are the overall **project goals**. The **DP**'s are the various different **strategies**. After organizing these strategies into a FRDPARRC Table, the "best strategy" is selected using a weighted concept selection chart (CSC) and is moved on to a higher level of detail.

The next level of detail is the **concept** phase. This phase is identical to the **strategy** phase, except at one higher level of detail. The goal of this phase is to generate **concepts** which implement the chosen **strategy**. Again, analysis and bench level experimentation are used to address feasibility, and generate possible designs in words and pictures. It is also appropriate to begin sketches of possible machines, which address basic form, and functionality, without diving into specifics. The **concept** level FRDPARRC uses the chosen **strategy** as a **FR**, while the generated **concepts** are the **DP**'s. The weighted CSC again determines which of the concepts best meet the functional requirements of the machine.

Now that a basic machine design is chosen, the design must be split into **modules**. Of these, one module must be chosen as the most critical module (MCM). The MCM is the one module that is most integral to the overall function of the machine, and is thus the primary focus of the design effort. Development of the **modules** is again at one level higher than the **concept** phase. At this level, more involved design is required. Now words, analysis, pictures, and solid models are necessary. The **module** level FRDPARRC is slightly more complicated than in previous phases. On the **module** level FRDPARRC, the selected **concept** should provide the **FR**'s, but, in reality, these **FR**'s must be subdivided for each **module**. The difference is that one FRDPARRC is required for each **module**, and the **concept** **FR**'s are not necessarily appropriate for each **module**. The **FR**'s then are specific for each **module**, and the **DPs** are the **module ideas**. The weighted CSC's sort through the numerous module designs to generate a chosen module idea.

At the **component** level, the specific implementation of the **module ideas** is selected. This phase also requires a higher level of detail than the previous phases. Unfortunately, in the design of a snowboarding simulator, the component selection can be quite different depending on if the design is a proof of concept prototype, or a finished commercial model. For this project, **component** level FRDPARRC's are not used. Instead, the detailed design of each **module** considers implementation of the chosen modules for both a prototype and a finished design. **Component** level design requires explanation in words, detailed analysis, sketches and solid models. For each of these design variants, the **component** level design is presented.

The next step of the design process is detailed engineering and manufacturing review. Detailed engineering requires selection and sizing of the individual **elements** used, solid models showing the exact mechanical assembly, and analysis to verify that everything works as it should. The second part of this is looking at the full manufacturing process, and making sure that the design can be made in the simplest way possible (or that is can be made at all).

Once the design has been checked out, the only remaining step is to lay out the detailed drawings for the design, so that it can be manufactured quickly and properly. With completed drawings the design can be built, tested, and modified as necessary. After completing the prototype, the only remaining step is to officially document the process.

The specific goal of this project is to develop the proof of concept prototype for a snowboarding simulator. As such, the design process is to be followed through to the final documentation step for the proof of concept prototype. However, this is only a small portion of the full product development cycle. Modification of the proof of concept prototype is undoubtedly required for a commercial design. If the design is to progress to a commercially available product, it will need to go back to the component phase, where the design will be modified to further simplify manufacturing and improve performance, ultimately resulting in added development work.

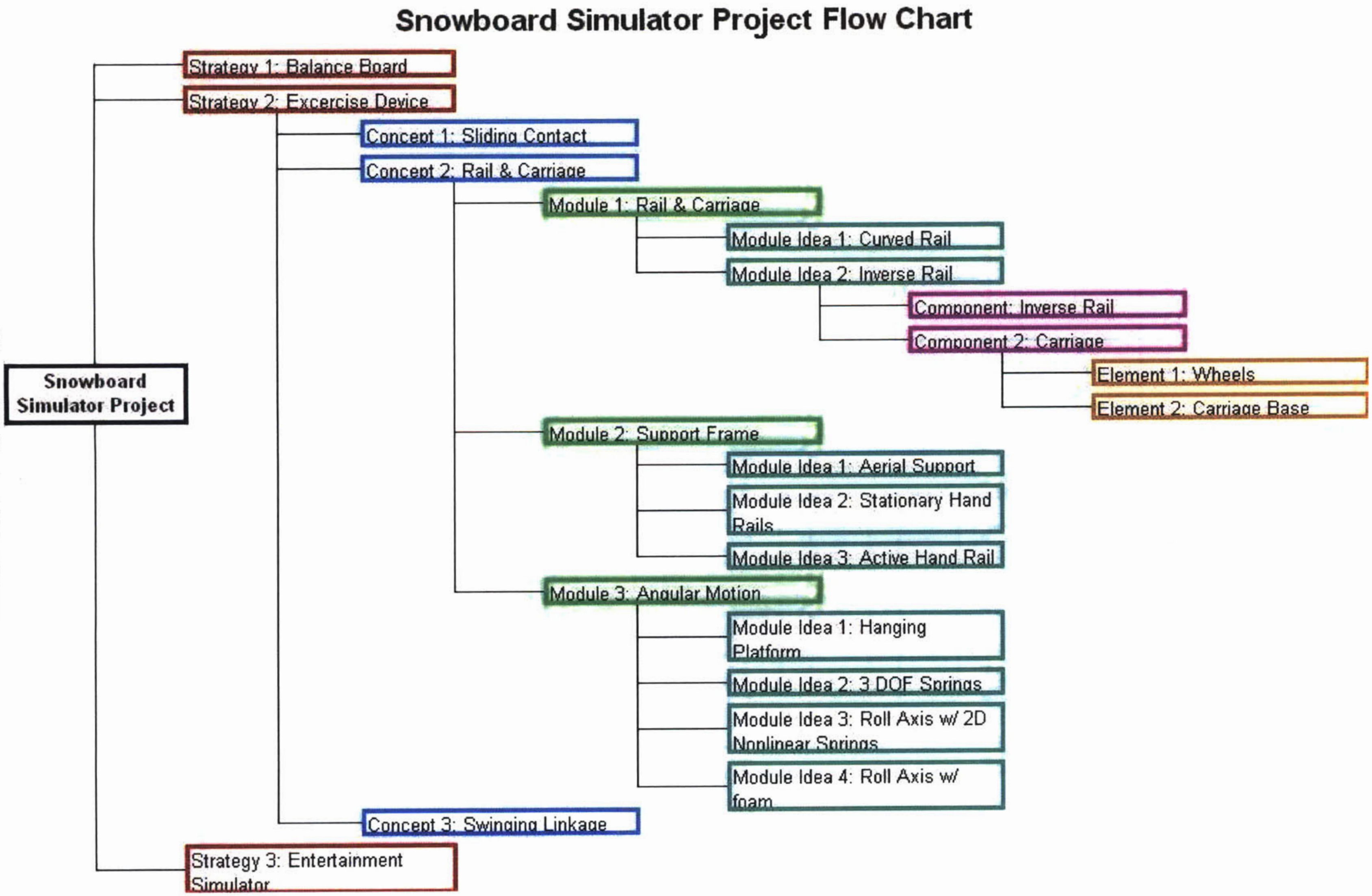


Figure 2-3: Project Flow Chart

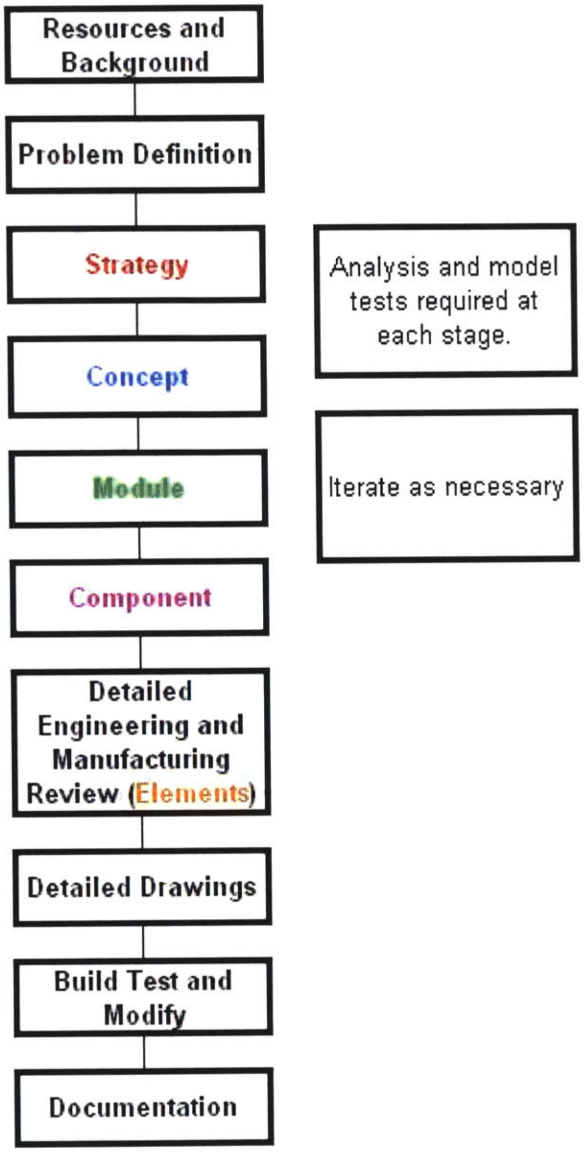


Figure 2-4: Deterministic Design Process Flowchart

3 Project Background

3.1 Snowboarding and Snowboard Simulators

Snowboarding is the result of a natural combination of skiing, surfing, and skateboarding into a single, new sports medium. The origins of snowboarding date back to the mid twentieth century where people developed crude, home-made designs. The first official snowboard to be introduced to the market, however, was Sherman Poppet's "Snurfer" in 1965, which consisted of two skis bound together with a guiding rope. Since then, snowboarding has fought to gain equal footing with its alpine skiing counterpart, to the point of being recognized as a medal worthy sport in the 1998 Winter Olympics in Nagano, Japan. [3-1] Now, snowboarding has become one of the fastest growing sports in the world [3-3], with 2002 US participation at around 5.6 million people, and 2002 US equipment sales totaling almost 250 million dollars. [3-4] Within five years, snowboarding is expected to make up almost half of the winter sports market. [3-2]

Figure 3-1: Then and Now: Sherman Poppet's Snurfer and 2002 US Olympic Snowboarder Chris Klug

This huge growth potential has resulted in numerous attempts to artificially simulate the sport, ranging from simple wooden balancing devices, to complex arcade and exercise machines.

One of the first attempts at designing such a device was a snowboard simulator by Jean-Albert Eggenberger in 1989 [US Patent 4,966,364]. The goal of the design is to create a balancing/exercise device to teach users about proper snowboard balance and use. The design of the simulator consists of a board mounted over springs, with roller bearings, permitting tipping in the roll and pitch directions, and 360° rotation in the yaw direction. This design is only capable of three degrees of freedom, and does not provide any kind of electronic interface to a control system. [3-5]

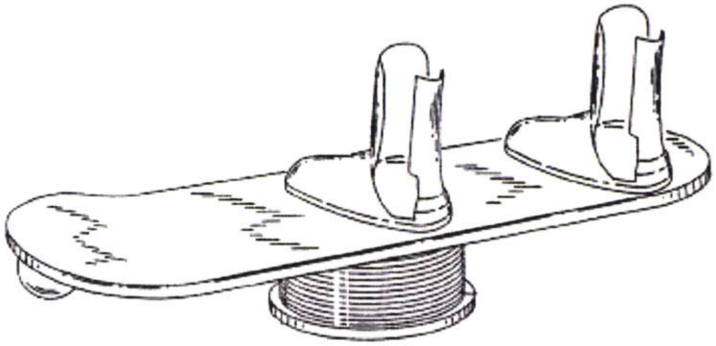


Figure 3-2: Eggenberger's Snowboard Simulator [US Patent 4,966,364]

In 1991, 1995, and 2000 three similar wooden balancing devices were developed for dry land training. The first was a device by Bruce "Brew" Moscarello [US Patent 5,152,691], now popularly referred to as a Vew-Do™ Balance Board. This design features a board with adjustable length tapered runners and a longitudinal guide rail underneath, which fits into grooves on a roller (with tapered sections) mounted perpendicularly to the board. The user stands on top of the board, and is capable of maintaining balance, while being able to turn the snowboard. [3-6] Similar to this, Andrew Corcoran designed a snowboard device [US Patent 5,545,115] with runners perpendicular to the board axis, which fits into grooves on a longitudinally mounted roller. [3-7] The third board, by Daniel William Martin, [US Patent 6,666,797] uses contoured ridges underneath the board, such that it can sit on a hard solid surface and pivot in 3 dof. [3-8] A fourth board, commercially available as the BoarDRock™, developed by FitterFirst™, utilizes two rounded plastic pivots, again allowing the user to get various tipping sensations. [3-17] All four of these designs are able to replicate certain board motions well, though they lack the complexity to truly replicate all snowboard motions. In addition, these designs all contain rollers or contours which move relative to the ground. This lack of constraint would make it difficult to mount actuators for any degree of force feedback. In reality, boards of this type have evolved into their own unique sport, where users are able to incorporate skateboarding skills into performing tricks on the balance boards.

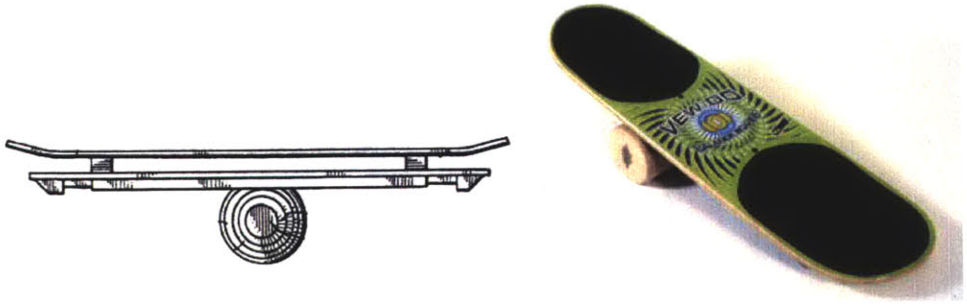


Figure 3-3: Moscarello's Vew-Do Balancing Board [US Patent 5,152,691]

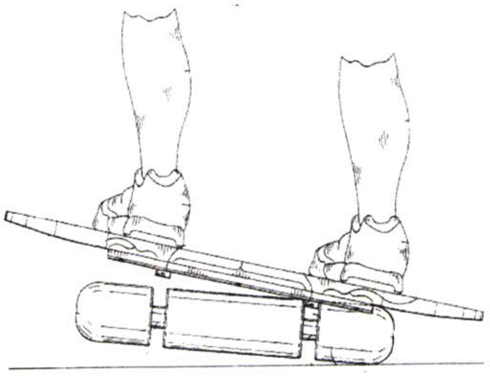


Figure 3-4: Corcoran's Balancing Board [US Patent 5,545,115]

Figure 3-5: FitterFirst's BoarDRock

Another variety of balancing device involves the use of semi flexible, or inflatable elements to recreate board motion. The first is an exercise device by Ron Richard Romero in 1998 used for rehabilitation. [US Patent 5,897,474] This invention uses a semi-flexible ball constrained by a central opening in the board allowing +/- 25° of motion in the pitch direction, and +/- 50° of motion in the roll direction. [3-9] A similar concept was adapted for entertainment use in 1997 when Matthew McGuiness developed a surfing simulator utilizing inflatable bladders. [US Patent 6,168,551] Here an existing surfboard or snowboard is strapped onto two inflatable bladders at the front and rear ends of the board. When the user stands on the board, their weight distribution determines board position. By using these bladders, it is possible to obtain motion in all angular directions, and to recreate the unstable feel of a surfboard on water. FitterFirst™ has also developed an extensive line of different balance boards incorporating numerous board configurations. The problem with all of these boards comes in trying to offer force feedback, or any degree of linear board motion. Balance boards are limited to tipping in the pitch, yaw, and roll directions, and do not have a stationary reference with which to provide input to, or output from the board.[3-10] [3-17]

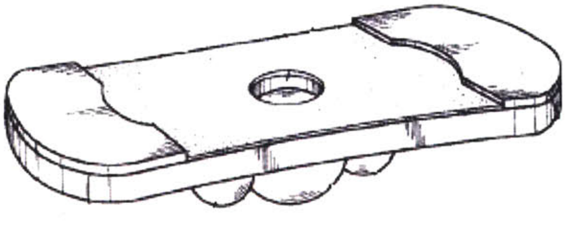


Figure 3-6: Romero's Rehabilitation Board [US Patent 5,897,474]

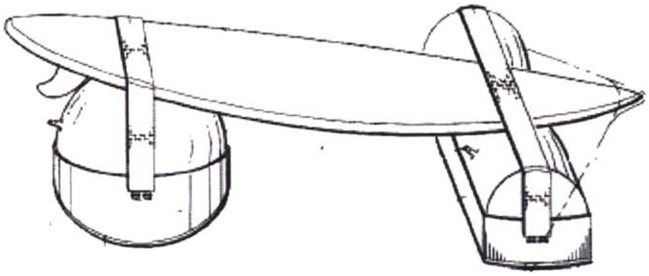


Figure 3-7: McGuiness' Surfing Simulator [US Patent 6,168,551]

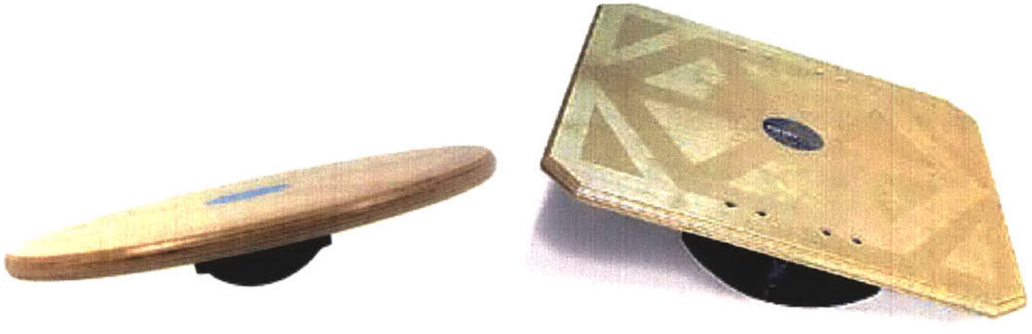


Figure 3-8: FitterFirst Balance Boards

One of the first patented attempts to create a snowboard simulator with an electronic interface came in 1997, with a Riding Board Game Controller [US Patent 5,860,861] by John Lipps. This board is a small portable device that connects to a home console gaming system. The board mounts to the support structure through springs, allowing for tipping in the pitch and roll directions. The rider input to the console is achieved through strategically mounted dual state switches. This design offers a limited range of motions, in addition to not offering any variety of force feedback. [3-11]

SEGA® improved upon this in 1998 with a snowboarding input device to be used in arcade machines. [US Patent 6,368,217] In this design the board is mounted to an oscillating arm, permitting approximately +/- 45° of motion in the yaw direction. In between the arm and the board, are a series of superimposed 1 dof rotational joints which allow tipping in the pitch and roll directions. All of the user inputs are collected through photointerruptors, and sent to a processing device. SEGA® has used this mechanism in numerous arcade games, ranging from skateboarding half-pipes, to riding ocean waves on a surf board. The device only offers 3 dof, and does not offer force feedback. [3-12]

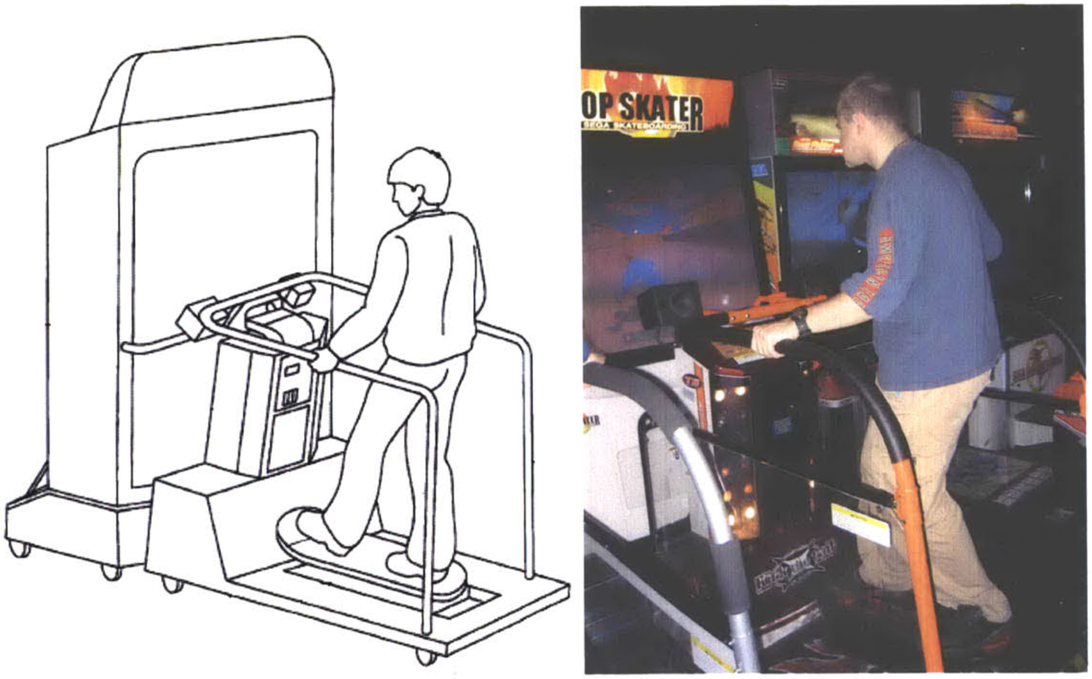


Figure 3-9: SEGA Boarding Arcade [US Patent 6,368,217]

In 1999, Slingshot Game Technologies produced a similar device for use with home PC's. [US Patent 6,543,769] This snowboard simulator (called the Catapult) is placed on the ground, and consists of a hemispherical pivot, mounted underneath the board, allowing for tipping in the pitch and roll directions. 360° rotation in the yaw direction is obtained through rollers mounted at one end of the board. The user input to the PC is gathered through optical encoders, and allows interaction with numerous programmed slopes. [3-13]

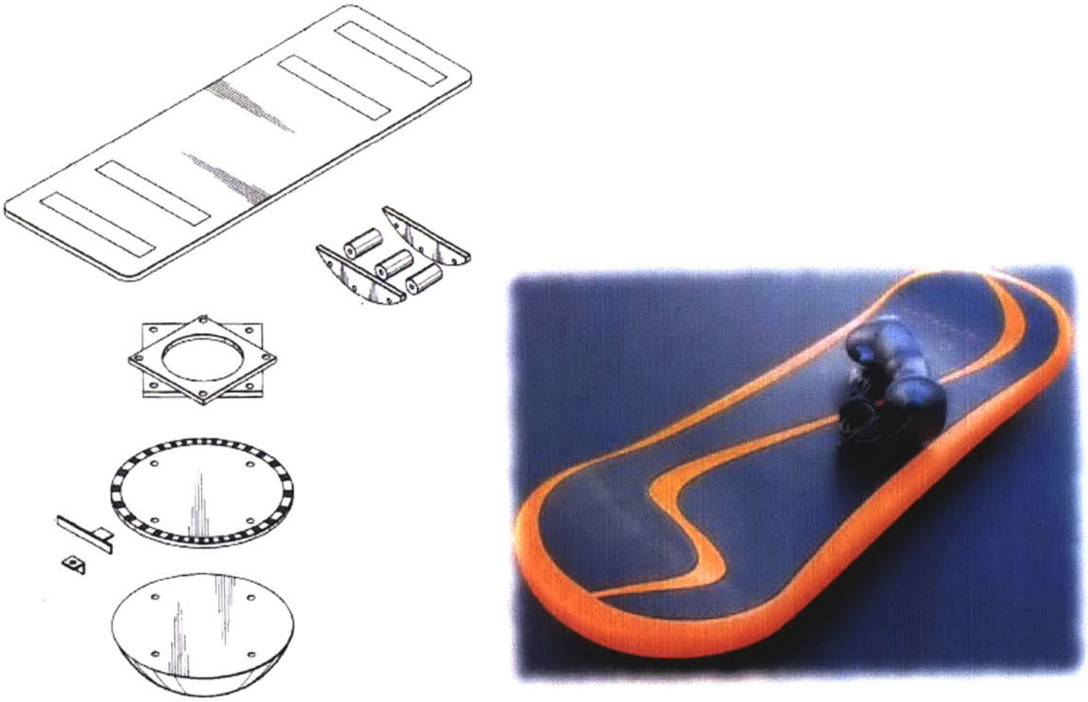


Figure 3-10: Catapult Game Controller [US Patent 6,543,769]

The final category of snowboard simulators are exercise machines. The first "snow exercise machine" is an in-home skiing simulator called the Skier's Edge® [US Patent 6,569,064]. This device consists of a carriage mounted to guide rails such that the user is pointed perpendicularly to the direction of motion of the carriage. Additionally there is a series of belts connected from the carriage to the base. The device also comes equipped with numerous attachments for mounting the feet. This allows the user to choose any number of different alpine skiing exercises. The Skier's Edge® is a purely mechanical device, without user input to any kind of electronic interface. In addition, motion is limited to the translational carriage motion along the rail, and any tipping permitted by the foot mounting apparatus chosen. [3-14]

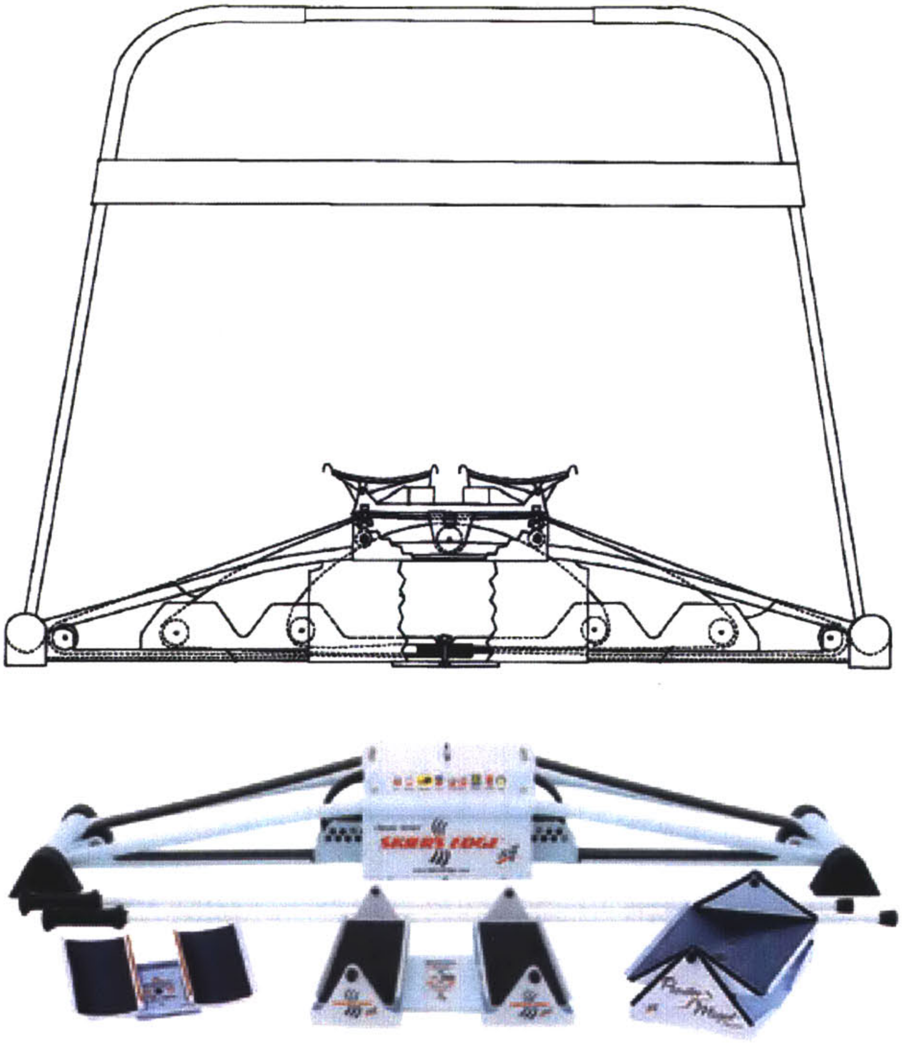


Figure 3-11: Skier's Edge™ [US Patent 6,569,064]

Three other companies: Stamina Products®, NordicTrack®, and FitterFirst® have developed similar products to the Skier's Edge® for the home exercise machine market. Again all of the products involve a series of parallel rails curved downwards. Stamina Products® [US Patent 5,429,567] incorporates both a downhill and cross country element to their skiing exerciser. The cross country element uses two footpads on a flat track, and two long pivoted poles on one end, to serve as the ski poles used in cross country skiing. The curved parallel rails are in between these two flat tracks, with a single carriage. The large bands on the Skier's Edge® are replaced with a series of pulleys. [3-15]

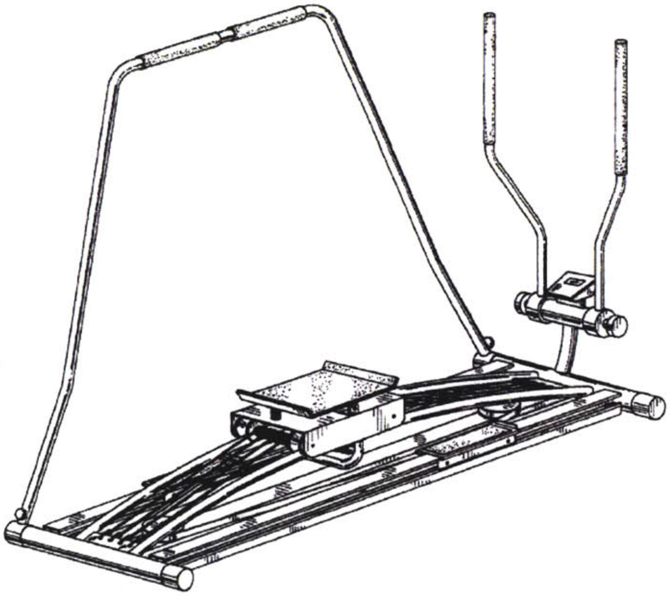


Figure 3-12: Stamina Products™ Skiing Machine [US Patent 5,429,567]

NordicTrack® uses a similar curved track, but with a different carriage configuration. [US Patent 5,374,228] In the NordicTrack® design, a section of "ski" is pivoted from the carriage moving along the curved rails at the rear end of the skis, to a moving pivot at the front end of the skis. The front end of the skis is additionally connected to the curved rails through 2 pivoted lever arms. These lever arms limit the motion of the front ends of the skis, allowing for the sensation of moguls skiing. Roll axis tipping is added to the system through use of pivots on the skis. Unfortunately, using skis in this manner, it is difficult to incorporate different varieties of rotation motions, particularly in the pitch direction. [3-16]

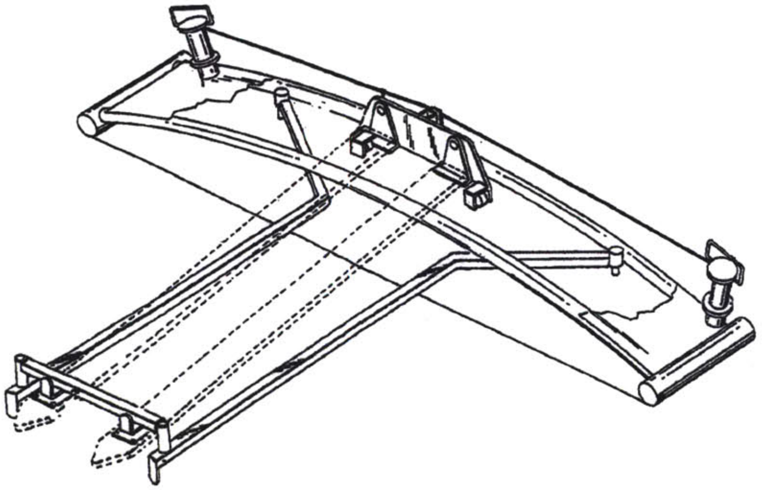


Figure 3-13: NordicTrack™ Skiing Machine [US Patent 5,374,228]

The FitterFirst™ skiing simulator relies almost entirely on the use of a carriage riding over curved rails. The ProFitter™ cross trainer consists of a compact design, without support rails. The carriage rides over the surface of the rails, while the entire support frame is able to rock relative to the ground. The motion along the rails is constrained by stops at the end of travel. [3-17]

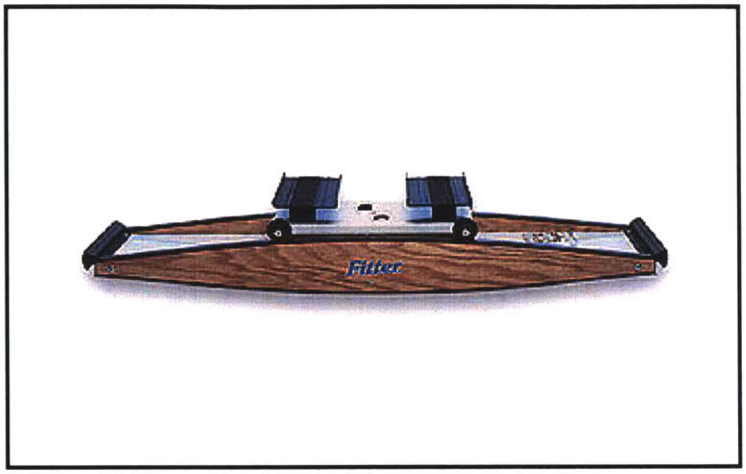


Figure 3-14: ProFitter™ Cross Trainer by FitterFirst

These fully mechanical, in home skiing exercise machines all do a good job of simulating certain elements of downhill skiing. Unfortunately the user is limited to the translational motion of the carriage along the guide rails, and rotational motion based on the configuration of the carriage. The exercise machine market has done considerable development on skiing machines, however snowboarding has been left essentially untouched. The upward curved rails are non conducive to snowboard motion. This creates considerable opportunity to develop a unique design.

The final skiing/snowboarding exercise and training device is known as a “ski deck” [US Patent 5,162,029] Unlike the previous exercise devices, the “ski deck” is not readily available for home use. The conveyor system is expensive, and large, meaning that this device would most likely be found in ski shops and training facilities, where it would see regular use. This simulator is essentially a carpeted conveyor belt angled downwards at approximately 18 degrees. The user wears an actual set of skis or a snowboard, and connects to a harness, free to slide down the length of a rear support bar. The conveyor motion opposes the direction of the downward slope, such that the skis/snowboard slide over the surface. The end effect is that the user is unconstrained by the snowboard, and can do almost any motion that would normally be done on a board. The downside of this device is that the carpet has much greater friction than snow, resulting in a slightly different ride experience. Also, with the conveyor one is limited to only a small width of “slope”, rather than an entire hill, and adding slope features becomes difficult. [3-18]

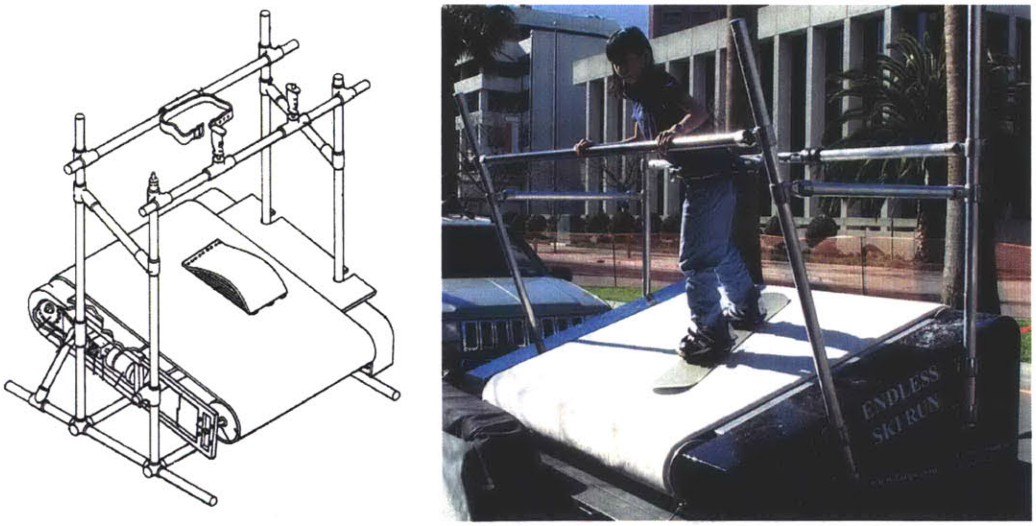


Figure 3-15: Ski Deck [US Patent 5,162,029]

3.2 Haptics and Haptic Devices

For any entertainment based simulator concept, the goal is creating as realistic a user experience as possible. In the case of a snowboard simulator, force feedback could be used to recreate the sensation of bumps and inclines on the mountain slope, or vibration effects of the snowboard riding over an icy surface. This force feedback delves into the complex field of haptics.

Haptics refers to the addition of tactile sensation (touch) to human/computer interactions. Most people are familiar with interacting with a computer visually through a monitor, or aurally through a set of speakers. Haptics provides additional sensations by incorporating the sense of touch. The user connects to the computer through a haptic interface. Haptic interfaces range from something as basic as a joystick or computer mouse, to something as complex as haptic gloves or hexapods. The haptic interface allows the user to input the desired motion. This in turn interacts with the signals from the computer, which send back tactile feedback to the user. This tactile information allows the user to "feel" the object, even though it only exists in the digital domain. [3-19]

The creation of physical space through a digital medium offers a huge amount of potential uses, namely tele-operation and the creation of virtual environments. Tele-operation refers to the remote operation of a device. Remotely operated devices that do not provide tactile feedback leave the operator with only visual (and perhaps audio) clues as to how he/she is accomplishing the task. If the user is trying to fasten a threaded nut, he/she will only be able to see the nut. If haptics are incorporated into the design, the user can remotely feel the nut, and maintain much greater control of the task. This leads to numerous potential applications. The first is remote operation in hazardous environments such as deep sea salvage, nuclear or chemical plant maintenance, and space exploration. The user can maintain a high level of control over their task, while controlling a robot in the safety of their control room. [3-20] The final tele-operation application for haptics is remote surgery. Through highly accurate haptic and visual interfaces, it is possible for a surgeon to remotely perform minimally invasive surgery. [3-21]

Tele-operation uses haptics to create the illusion that some task is being done right in front of the user, despite it actually occurring further away. In this same regard, a computer can be programmed with haptic information, to make a task appear right in front of the user, despite the task not really occurring at all. This looks at haptics as a means of creating virtual environments. An object can be created using sensory information (audio, visual, and haptic), allowing a user to explore the object/ environment. This has many uses in job training, rehabilitation, product design, and entertainment. The virtual environment can be made as realistic as required, but does not risk doing any real world damage. [3-21]

The current state of haptics research has largely been focused on how to improve the realism of haptic interfaces, and on finding new innovative applications for haptics. Most of the major work on improving realism in haptic interfaces has been undertaken at Universities. Researchers in the Robotics laboratory at Stanford University, for example, have looked at various control schemes, and rendering frameworks for tactile display in complex virtual environments. They use a "virtual proxy" which moves unconstrained in the virtual environment until it encounters an obstacle. Through altering the movement of the "proxy" they can create amazingly realistic haptically rendered environments. [3-22] [3-23] Similarly, researchers at Stanford (The Dexterous Manipulation Lab) and Harvard have been gathering tactile/vibrational data in order to develop advanced models of surfaces, incorporating texture, tapping, and puncture effects. [3-24] [3-25] [3-26] [3-27] Through detailed analysis of real world tactile information, and development of advanced control algorithms, haptics is becoming an increasingly powerful means of human, computer interaction.

The application of haptic interfaces becomes a much more interesting topic after development of sufficiently complex haptic rendering capabilities. The first application to look at is the Haptic "Cobot" developed by Faulring, Colgate, et al at Northwestern University. This "Cobot" is primarily for use in tele-operation, and utilizes non-holonomic constraints to create sharp distinctions between allowable and non-allowable motions. The six degree-of-freedom mechanism consists of a parallel mechanism (essentially a hexapod with fixed length struts, and spherical joint bearings), actuated by six linear motors, all attached to a rotating power cylinder. The end result is a robot designed for remote operation in hazardous environments. [3-20]

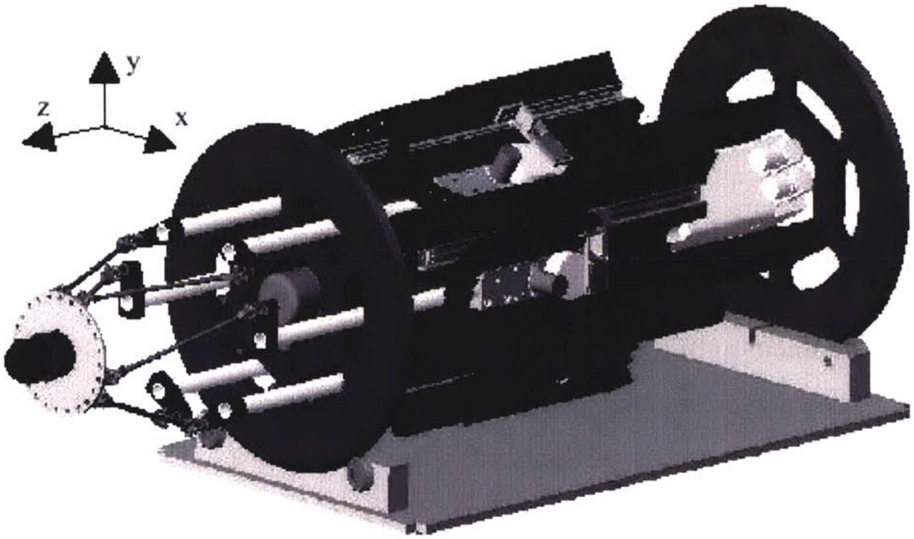


Figure 3-16: Haptic Cobot

Rutgers University has adapted haptics technology for rehabilitation use through their "Rutgers Ankle Rehabilitation System" (RARS) The Rutgers Ankle consists of a parallel mechanism (a Gough-Stewart Platform) connected to a computer. The patient places their foot on the hexapod, and then is given tasks to perform through the haptic interface. By controlling images on a screen through the platform, the patient is able to exercise the ankle in a mentally engaging manner. Furthermore, the simulation is designed to fit the needs of the individual patient, so that they can perform the tasks with an appropriate amount of difficulty, without risk of aggravating the injured ankle. The major advantage of this system is that the patient can rehabilitate their ankle, without the need for constant observation from a therapist. (the Rutgers Ankle can even been installed at home and monitored remotely). [3-28] [3-29]

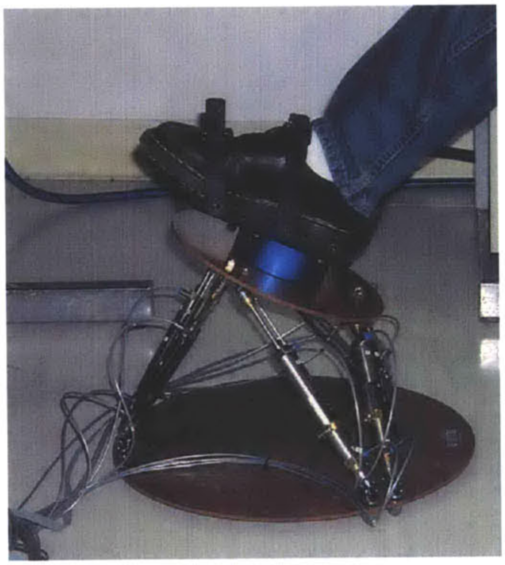


Figure 3-17: The Rutgers Ankle

Haptics devices and technologies are becoming commonplace as researchers gain a better understanding of how to replicate tactile sensations, and implement them in new and innovative ways. Companies such as Immersion®, and Force Dimension™ have sprung up, developing haptic technologies and devices for use in numerous applications. Of particular interest to this project are force feedback gaming devices. Companies including Logitech® and Microsoft® have produced numerous force feedback joysticks, game pads, and steering wheels for use in computer and console gaming. These joysticks contain on board power supplies, and are capable of generating 100+ force sensations. These devices add a new level of realism to gaming, and introduce a new frontier in haptics technology. [3-30] [3-31] [3-32]

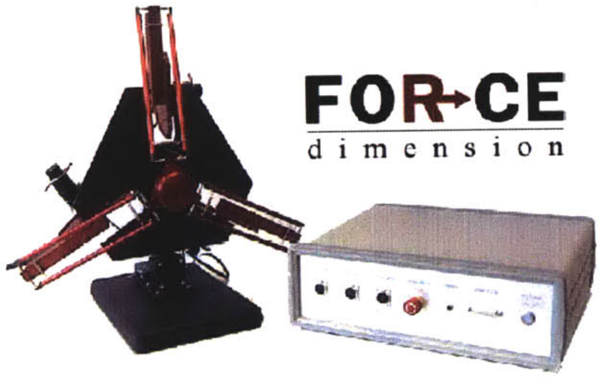


Figure 3-18: Force Dimension 6-dof Delta Haptic Device

Figure 3-19: Microsoft Force Feedback 2 [US Patent 6,531,998]

3.3 Applications of Hexapods and Gough-Stewart Platforms

The final background topic that requires some explanation is that of the parallel mechanisms which can be used to implement the snowboard motion. To create a snowboard simulator for entertainment applications, more degrees of freedom offer a more realistic ride. By choosing a parallel mechanism that has many degrees of freedom, one can more accurately recreate snowboard motion. A Gough-Stewart platform is a six degree-of-freedom hexapod, capable of translation in the *i*, *j*, and *k* directions, and rotation in the pitch, yaw, and roll directions. The platform mounts to the base through 6 variable length struts, typically actuated hydraulically or with linear motors. The struts are mounted to the platform and the base through prismatic (spherical) joints.

Figure 3-20: A Gough-Stewart Platform (PI (Physik Instrumente) M-850)

The origin of the Gough-Stewart Platform as it is today began with Augustine Cauchy's study of the stiffness of the "articulated octahedron" in the 1800's. In 1947, Dr. Eric Gough developed the Gough platform as a tire testing device for Dunlop®. Later, Klaus Cappel independently developed a similar configuration while trying to improve a 6 degree-of-freedom vibration platform for the Franklin Research Institute in 1962. At the exact same time, an engineer by the name of D. Stewart was doing research on an almost identical mechanism, which was to be used as a flight simulator. His work was presented through a paper that appeared in IMechE (British) in 1965. Ultimately, all three men independently developed the variable-length-strut octahedral hexapod. Lack of communication prevented Cappel and Stewart from knowing about Gough's early work at Dunlop. In any case, the Gough-Stewart platform is used in numerous applications including motion simulators, machine tools, and surgical equipment. [3-33]

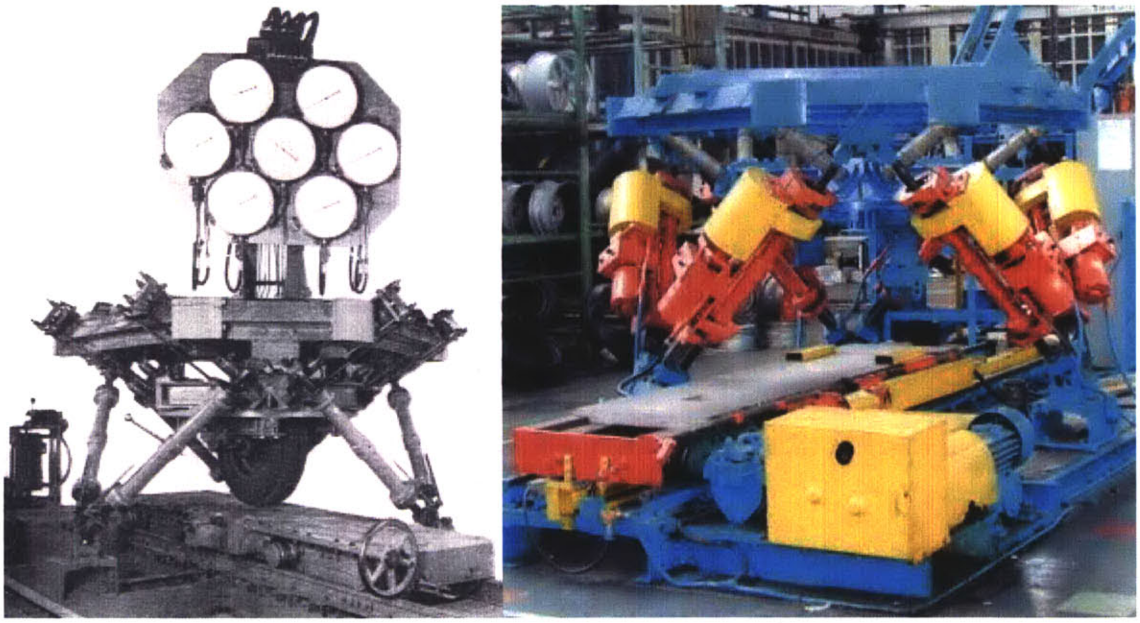


Figure 3-21: The Gough Tire Tester (Before and After)

In the mid-sixties, there arose a need to develop realistic simulators to train pilots which would not jeopardize the plane, the pilots, any passengers, or civilians on the ground. This, in fact, was one of the focuses of engineers like Stewart and Cappel while they were working out the details of their hexapods. The hexapod is great for this application because it recreates many of the tipping and other motion sensations of flight. Companies such as CAE continue to modify this technology with advanced control systems, and visualization to create state of the art flight simulation technology. [3-33]

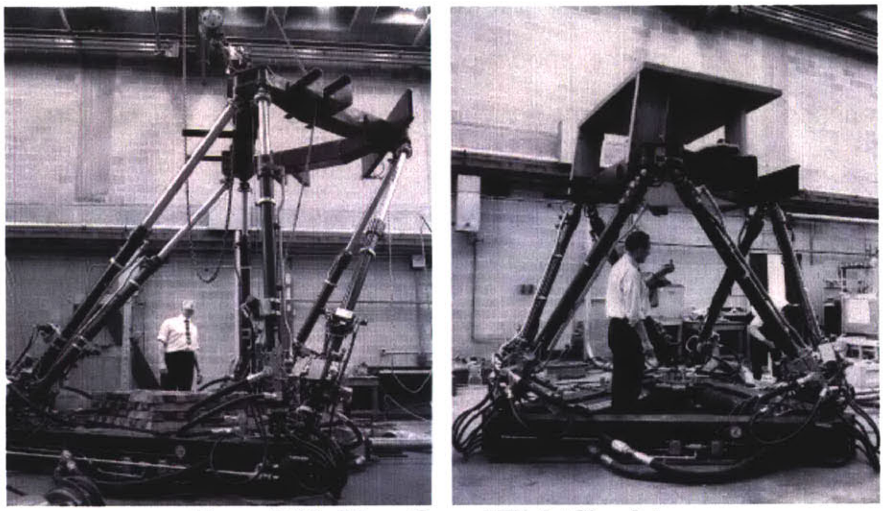


Figure 3-22: Klaus Cappel Flight Simulators

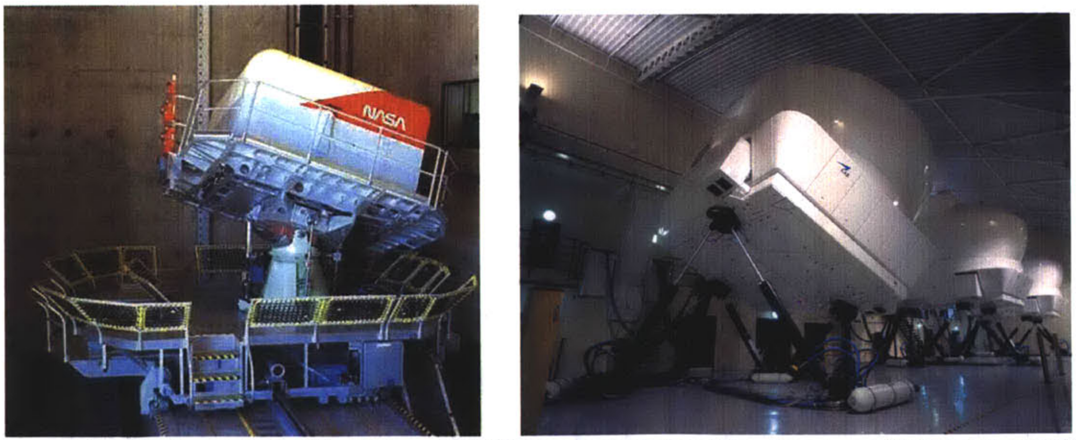


Figure 3-23: Modern Flight Simulators: NASA Vertical Motion Simulator and CAE Embraer 170

The use of this technology in flight simulators led directly to its use in amusement rides. By projecting a movie inside of the "cockpit", the riders inside see the image of motion, coupled with the corresponding motion from the hexapod. This leads to a very realistic sensation of riding a virtual roller coaster, or flying in a virtual fighter jet. The other advantage of such technology is that it is space economical. A simulator takes up a small fraction of the space that even a small roller coaster would take up. This means that it is small enough to fit on a truck and travel with a carnival, or small enough to have multiple simulators at a major amusement park, and still take up less space than most other attractions. (especially where space in an amusement park is at a premium.) The other feature of simulator rides is that they can be reprogrammed. By changing the video, and reprogramming the hexapod motions, a simulator can be used many times over, and constantly upgraded to meet the needs of riders.

Figure 3-24: A Traveling Simulator

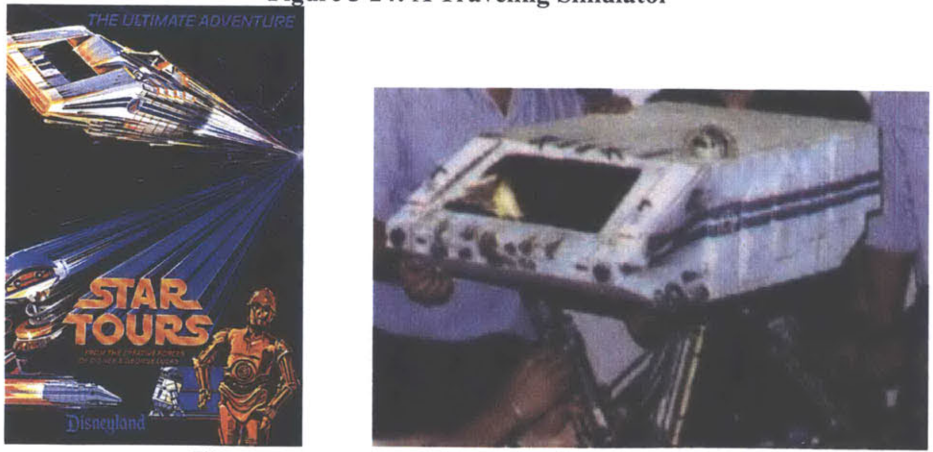


Figure 3-25: Disney's Star Tours Simulator Ride

The next major application for hexapods has been in precision machining. Gough-Stewart Platforms offer a wide range of potential motions. By mounting a machine tool base, tool bit, or Coordinate Measuring device to a hexapod, designers can take advantage of 6 degrees of freedom, and achieve motions and angles that typical multi-axis machines are not capable of. The big problem with these types of machine tools is that they require a different variety of control scheme. To achieve desired platform movement all six variable length struts must constantly be moving. This often results in error motions of at least 25 micron [3-34], which is almost 5 times higher than many multi-axis machines. In addition, the cost of such hexapods is typically higher than those of multi-axis machines (many more moving parts), making Gough-Stewart Platform based machining only appropriate for certain machining applications.

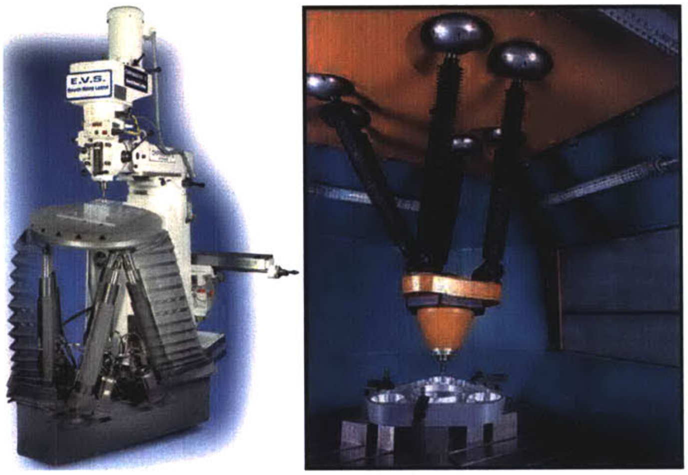


Figure 3-26: Hexel's Hexabot and Tornado 2000 [US Patent 6,196,081]

Figure 3-27: Okuma Cosmo Center PM-600

Figure 3-28: Ingersoll HOH600 [US Patent 5,401,128]

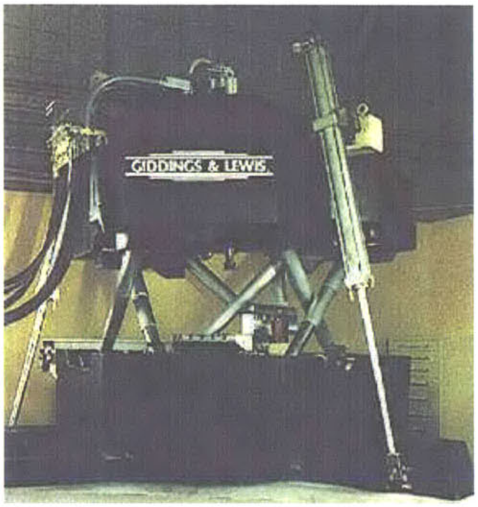


Figure 3-29: Giddings and Lewis Variax [US Patent 5,388,935]

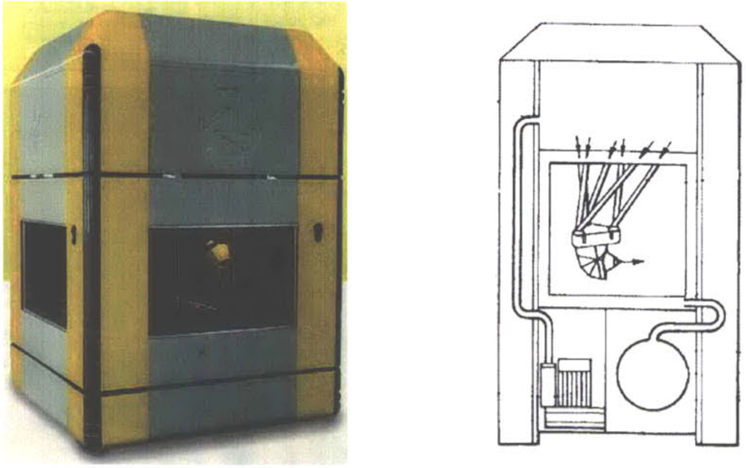


Figure 3-30: Geodetic G500 [US Patent 5,857,815]

The final major application of hexapods is for use as surgical equipment. The wide range of programmable and precise hexapod motions makes hexapods very desirable for performing surgical procedures. A hexapod is capable of motions accurate up to 25 micron (approx 0.001"). With this accuracy, remote or pre-programmed surgery can be performed. Advanced control algorithms can even make it possible to perform tasks as complex as brain surgery, all through use of a hexapod. [3-21]

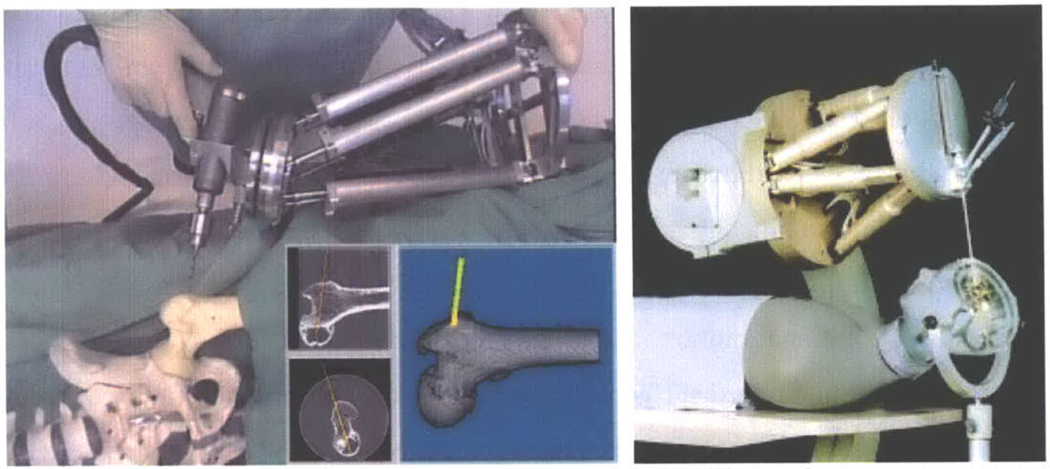


Figure 3-31: CRIGOS Robot and a PI Surgical Hexapod

As shown, there are numerous applications for hexapods ranging from complex surgery all the way to entertainment. Discovering new applications for the technology, however, is only half of the current field of hexapod design. Researchers are constantly looking at parallel mechanisms, and finding better ways to model them. This typically involves looking at the forward or inverse kinematics of hexapods. By developing better analytical models of hexapods, it leads to better control algorithms, and a better understanding of the underlying physics. The other important element of this is finding a better way to handle behavior around singularities. Singularities in hexapod design result in a loss of a degree of freedom or a constraint. In some cases the hexapod motion can be limited to avoid singularity positions, but if the full range of motion is required then methods have to be discovered to handle the singularity.

3.4 Personal Experience

Before considering the strategy for a snowboard simulating device, it is important to look at past personal involvement with related technology. Balance Boards and Exercise Machines are a good starting point.

Balance boards, in general, are a very well defined market. The basic requirements for developing a balance board involve defining a board configuration, with some pivot element underneath. In many households with exercise equipment, a family will buy a balance board because it is easy to store, and can be used for low impact workouts while watching TV. The challenge offered by a balance board depends greatly on the configuration of pivot elements. A large board surface, with a low pivot element offers limited rotational motion, and is easy for beginners to use. More advanced designs, with smaller board surfaces, higher pivots, or multiple/moving pivot locations require a much steeper learning curve to become proficient.

Exercise machines cover a much broader range of potential designs. Most people are familiar with exercise bikes, rowing machines, treadmills, and other such devices. The essential element to machines of this type is to carry out repeated motions to build muscle and stamina. The same rules apply to skiing and snowboarding machines. Using skiing exercisers, like the Skier's Edge®, requires identical repeated motions, designed to work the muscle groups associated with skiing. For a beginner using a device like the Skier's Edge®, the motions are initially jerky, as the ride carriage wants to settle in the two depressions on the ends of the curved rails. After practice, the motion becomes much more natural. For an exercise machine to be successful, it must be intuitive, and require simple motions that are highly repeatable.

Entertainment simulators, by comparison, tend to offer very different ride experiences depending on how information is conveyed to the user. Disney Quest is an indoor interactive amusement park that features simulator technologies of various varieties, which allows for comparisons to be made.

Figure 3-32: Disney Quest Indoor Interactive Amusement Park

The first ride category of entertainment simulators includes typical arcade games. This includes games like SEGA's Snowboard Simulator described earlier. These games utilize a simple user interface, which responds directly with a 2D image on a screen. These simulators provide an enjoyable game experience, but are lacking in realism. The input devices are almost always passive, such that they do not send sensations back to the user (other than simple vibrational feedback). The 2D visual display also is not as engaging as other visualization technologies on the market.

The second category utilizes more involved effects. This category still uses images presented on a screen, but incorporates 3D effects, and feedback sensations. Examples include the ride, "Pirates of the Caribbean: Battle for Buccaneer Gold". In this simulation, the users walk onto the deck of a pirate ship containing cannons and a ships wheel. The users then put on polarized 3D glasses to look at images on a large screen surrounding the deck of the ship. In addition the deck of the ship rocks with the ocean waves. Using a 3D screen allows the user to see the surroundings, while being able to look around the deck of the ship. It provides a very engaging and lifelike experience. Another similar ride is the "Virtual Jungle Cruise" which places users on a raft, mounted on top of sensor lined air bags. The users use oars to stroke the sensor covered surface and indicate direction. The air bags inflate and deflate to simulate the river rapids. In this case the large projected image and the realistic wave motions pull the user into the experience.

Figure 3-33: Pirates of the Caribbean and Virtual Jungle Cruise

The third category of simulator uses VR Visors to achieve the desired effect. The VR Visors transport the users into a virtual world where everything they see is an image in the visor. If the users are holding weapons, they will see the weapon in the virtual world, while holding only a mock interface. The shortcomings of this category of simulators seem to be in the technology. The VR helmets are typically large and bulky, with input cables that restrict head movement. Any misalignment of the helmet results in blurred images, and control system lag leads to a disorienting lapse between actual movement and perceived movement. This, however, can be easily fixed with more recent technology. Kopin® has developed the world's smallest LCD screen, which can easily be mounted in an existing snowboard helmet. This will greatly reduce the size and inertia of the helmet. Faster control systems should also greatly decrease the system lag, resulting in a much better simulation. [3-35]

Figure 3-34: Disney Quest's Ride the Comix

The final category of simulator is the traditional ride simulator. In this type of simulator the users do not offer input to the system. They sit in the simulator module, while the simulator executes preprogrammed images with subsequent motions. This leads to a very coherent ride experience where the images on screen and motions of the module are simultaneous. In addition, the simulator motions can be used to play psychological tricks on the user, by using gravity to create the impression of accelerations in different directions, or using "wash-out" to slowly level out a hexapod, while giving the user the impression of sustained motion. Disney Quest offers Cyberspace Mountain, which is an "interactive" roller coaster simulation. Before the ride, the user chooses the order of ride elements. They then go to a 3 axis simulator module and ride the coaster they have created. Current simulator rides of this type only offer pre-programmed ride experiences, but with faster, less expensive control systems, it may be possible to create fully interactive rides, similar to modern pilot and military training simulators.

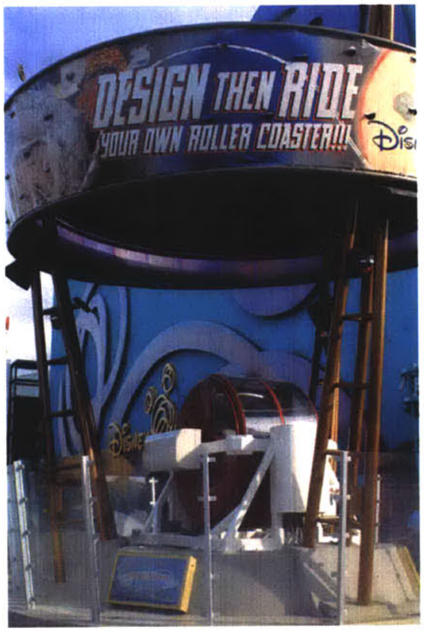


Figure 3-35: Cyberspace Mountain Simulator Module

4 The Physics of Snowboarding

Any attempt to create a snowboard simulating device requires a basic understanding of the underlying snowboard physics. Understanding the problem is a three step process. First, by watching amateurs and professionals, the designer gets a feel for the kind of motions that need to be replicated, and how these motions differ at different skill levels. With these basic motions in mind, the designer then needs to look analytically at the motions, and determine how these motions are generated. Finally, after understanding these motions, the designer should draw on their own snowboarding experience to evaluate potential designs.

The following sections address only the most basic snowboarding motions: straight gliding, traversing, and "carving" a turn. More advanced motions, including the highly complex aerial maneuvers seen in competitive snowboarding, are far more complicated, and not addressed in this level of snowboard simulator. In the design of skis and snowboards, the study of skiing and snowboard mechanics has become a detailed science. For this thesis, however, a simpler approach is taken. Each motion is looked at analytically, but specific equations for snowboard motion are not derived. Many of the motions associated with a snowboard moving down a hill result from inertial forces. A snowboarding simulator, by its stationary nature, removes these inertial forces. Any equations derived from a moving snowboard would have little application to a stationary snowboard simulator. Instead, analysis of snowboarding physics provides insight into the proper board positions, and directions of force application required to generate motion, to create a close facsimile to regular motion. For a more thorough treatment of skiing mechanics, books like John Howe's "Skiing Mechanics" offer an extremely technical analysis of skiing.

4.1 The Snowboard

Before delving into a description of the motions of a snowboarder down a hill, some guidelines must be set for axis conventions on the snowboard. These definitions will carry through to the final snowboard simulator design, to avoid unnecessary confusion.

First three axes must be defined through the snowboard. The *i* axis refers to the line through the long axis of the snowboard. The *j* axis is perpendicular to this, through the central transverse axis of the board. Finally, the *k* axis is the vertical axis through the center of the board. The *i, j,* and *k* axes are rigidly fixed to the board, and serve as the basis vectors for translational motion of the snowboard.

These axes also can be used to describe the three rotational directions. Any rotational motion about the *i* axis is defined as roll axis motion. Similarly, pitch axis motion is any rotation about the *j* axis. Yaw axis motion completes the set, by covering all rotation about the *k* axis. (Figure 4-1)

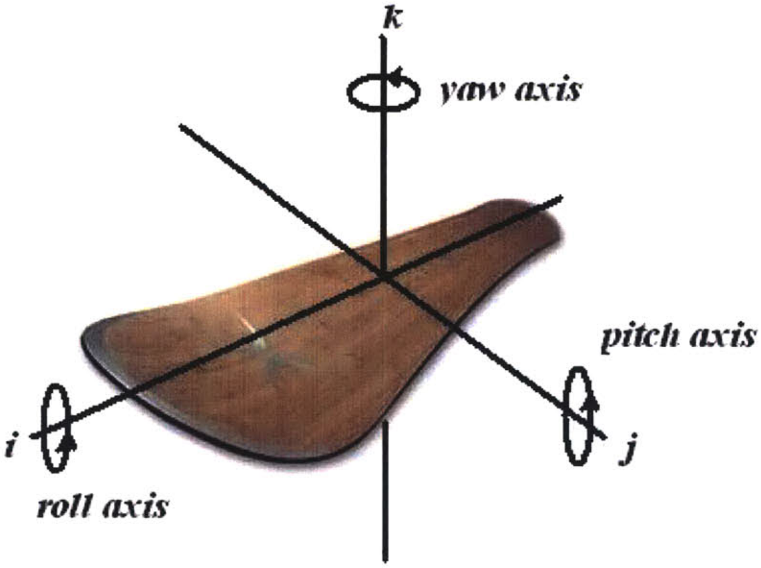


Figure 4-1: Snowboard Axes

4.2 The Basic Motion

When watching amateur or professional snowboarders, there is a common form to how a snowboard moves down a slope. This form consists of three core motions: straight gliding, traversing, and "carving" a turn. Course obstacles, terrain changes, and motion and speed control necessitate the constant turning of the snowboard. The resulting snowboard path is a zigzag pattern, where the snowboarder uses a combination of traversing and straight gliding to progress down the slope, while "carving" turns in between to switch direction (typically to stay within a designated slope path).

The overall path is identical for amateurs and professionals, with several distinctions. Beginning snowboarders require slower speeds to move down a hill. Snowboarding requires hundreds of rapid adjustments for the user to maintain balance. As a result, most beginner snowboard motions consist of far more traversing than straight gliding. This keeps speed low, so that the beginner can spend more time focusing on the next turn, and is not forced into a panic situation at high speeds. As skill increases, several characteristics of the overall path change. Skilled snowboarders move at much higher speeds. Rather than a slow methodical traverse that spans the width of the slope, an experienced snowboarder is used to frequently carving over a much narrower zigzag pattern, with little to no traversing. Professional snowboarders are capable of highly aggressive, yet accurate carved turns, necessary for competitive snowboarding (slalom etc…).

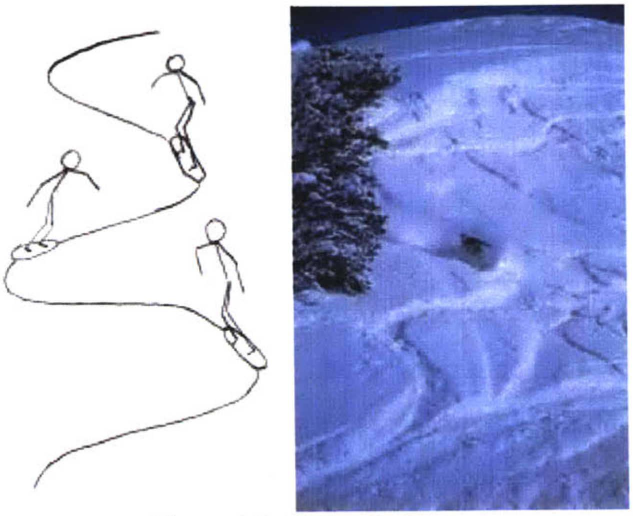


Figure 4-2: Zigzag Pattern

This back and forth "zigzag" pattern is the baseline motion of snowboarding, but added analysis is required to evaluate the individual basic motions to determine how best to incorporate these board motions into a simulator design.

4.3 Straight Gliding

Straight gliding refers to the straight line motion of a snowboarder down a slope. To accurately describe straight gliding, the term fall line must be defined. The fall line is the path with the steepest downward slope (the path with least resistance.) In Howe's "Skiing Mechanics" he illustrates the example of the fall line being the line that a snowball rolling down a hill would follow. [4-1] In straight gliding, the direction of motion is directly down the fall line, with the front end of the board leading the motion..

The free body diagram of this motion is extremely basic. In straight sliding gravity is the dominant source of motion. The gravitational force acts through the center of mass of the snowboarder, who is angled on the slope. This gravitation force breaks down into two components, a downward force perpendicular to the slope, and a forward force parallel to the slope, in the direction of motion. This parallel component of the gravitational force is the primary source of downward motion. There are also additional forces acting on the snowboarder. The first of these is the normal force of the snowboard in contact with the ground, which counteracts the vertical component of gravity. The remaining forces are the resistive forces of the snow and the wind. The friction between the snowboard and the snow creates a resistive force at the snowboard. In addition, the force of the wind acting on the moving snowboard provides additional resistance. (Figure 4-3) [4-1]

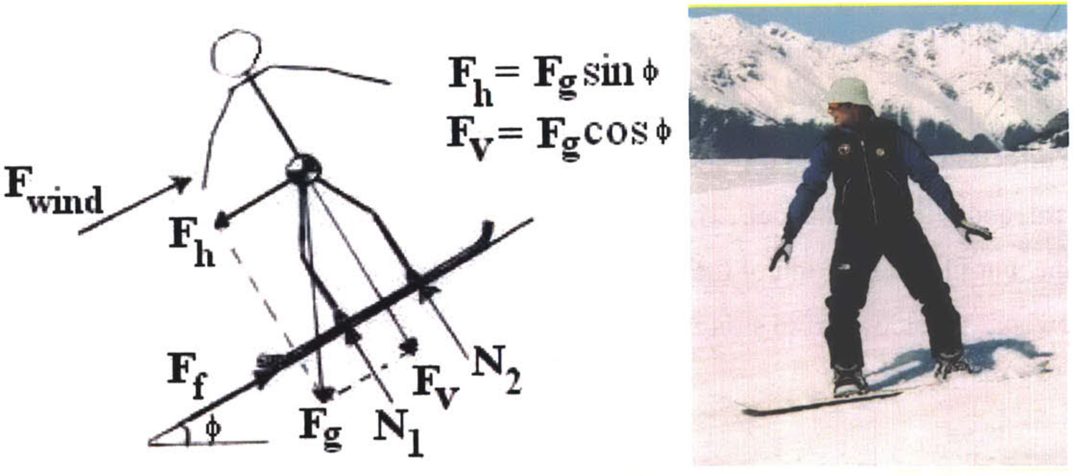


Figure 4-3: Straight Gliding

This gravity driven motion is extremely important in describing the motions of snowboarding, but is not particularly useful in the design of a snowboarding simulator. In a simulator the user will not be experiencing large scale linear motion. The resistive and motive forces will likely not be experienced by the user.

4.4 The Traverse

The traverse motion is another essential element of snowboarding. The term traverse is used to describe straight line motion at some angle to the fall line. When snowboarding, the most direct way to move down a slope is down the fall line because the snowboarder is moving with the component of gravitational force. In the traverse, this is no longer the case. The snowboarder is attempting to move counter to gravity, which results in slower motion, and more complicated dynamics.

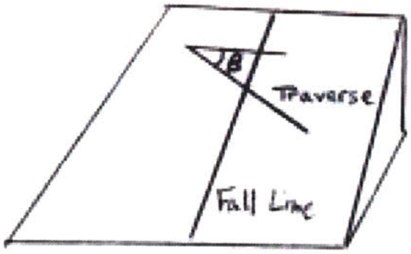


Figure 4-4: Traverse Definition

If the snowboarder is moving at an angle β relative to the fall line, the gravitational force splits into three components rather than two. The first of these forces is the vertical component, perpendicular to the slope (again counteracted by the normal force of the slope). The second of these components is the force parallel to the slope, in the direction of intended traverse motion (resisted by friction between the snow and the board, and wind resistance). The third force is a lateral force, which is parallel to the slope, but in the direction of the fall line. This lateral force is the direction that the snowboard would go if in straight gliding. [4-1]

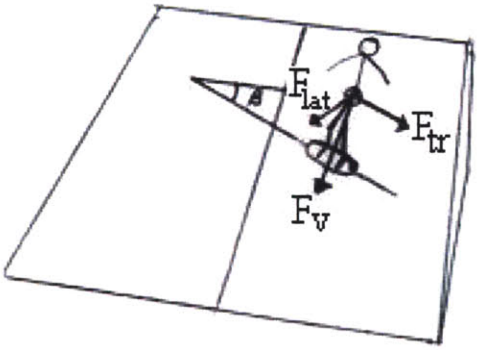


Figure 4-5: Three components of gravity

If this explanation was to be left as it is, there would be one negative effect. The snowboarder would move along the traverse, but would also move laterally down the slope. This does not happen, which means that another force is necessary. This force is called lateral adhesion, and it is due to the edge of the board digging into the slope (about the roll axis). The force of the edge digging into the snow resists the lateral force, so the only motion that occurs is in the intended direction. Unfortunately there is also more going on. Depending on the vertical component of gravitational force perpendicular to the slope, there is a potential for skidding in this lateral direction. By adjusting the angle of the snowboard relative to the slope about the roll axis, this lateral force can be better resisted. This leads to an important discussion of inclination versus angulation. [4-1]

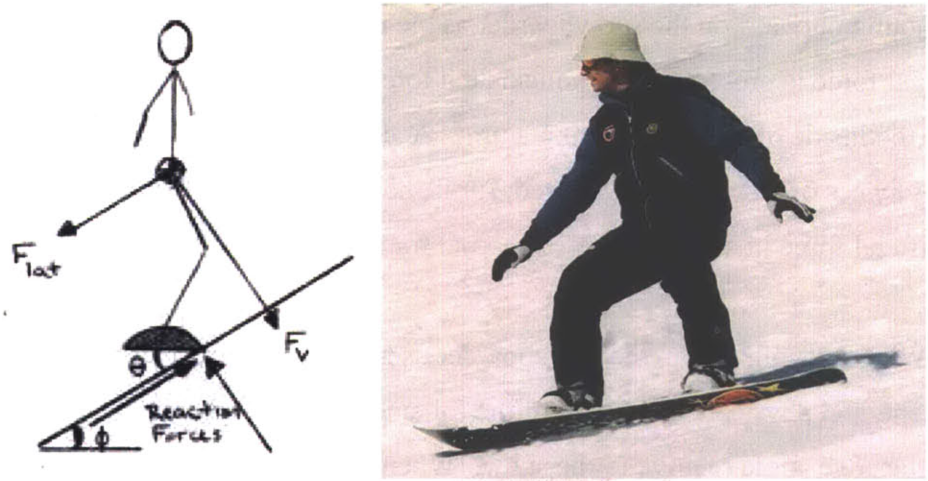


Figure 4-6: The Traverse

Howe's "Skiing Mechanics" defines pure inclination as the body being straight and aligned from both the front and rear views. [4-1] Inclination is essentially the natural lean angle of the snowboarder's center of gravity. The inclination angle on a snowboard is perpendicular to the angle formed between the board edge and the horizontal. [4-2] Angulation, by contrast, refers to some bend in the ankles, knees, or hips. Actual snowboarding employs a combination of both, but angulation is the primary means of the snowboarder altering their roll axis position. [4-1]

The final area of discussion is the location of the snowboarder's center of gravity. For the traverse motion, the snowboarder's center of mass must be over the base of support of the snowboard. Moving along a straight traverse does not offer enough restoring force to prevent the snowboarder from falling. This situation is far different, though, when carving a turn.

4.5 Carving a Turn

In the zigzag motion of a snowboarder moving down a slope, carving a turn is the essential transition element between linear motions (straight gliding and traverses). In the following discussion of carving a turn, the concept of centrifugal force is used. Centrifugal force is a function of snowboarding velocity and the radius of the turn, and is a force acting outward on the snowboarder as the turn is made. In most physics texts, centrifugal force is presented as a nonexistent force. Instead centripetal force acts towards the inside of the circle during a turn. According to Michaud and Duncumb's article "Physics of a Snowboard Carved Turn", however, it is perfectly acceptable to refer to centrifugal force in a body centered inertial frame of reference. [4-2]

When carving a turn, the snowboarder uses a combination of center of gravity adjustment, and physical adjustment of the roll and yaw positions of the snowboard to change the edge angle relative to the snow. When the user is moving at some velocity, they are able to dig in one of their snowboard edges using a combination of inclination and angulation. This edge angle with the snow can range anywhere from 0° to approaching 60°. In addition, snowboards feature a sidecut radius, which is a slightly curved edge, aiding in turning. The radius of the turn is dependent on the sidecut radius of the board, the edge angle of the board with the slope, and the overall speed of the turn. A more severe sidecut radius, a steeper edge angle, or increased speed will decrease the radius of the turn. [4-1] [4-2]

The direction of the turn depends on which side of the board is dug into the ground. The two edges of the snowboard are called the heel side and toe side edges. (Figure 4-7) For a person riding "regular" (who leads with the left foot), carving on the heel side turns left, and carving on the toe side turns right. For a person riding "goofy" (leading with the right foot), these directions are the opposite. Modern snowboards feature a sidecut radius, which aids in turning.

Figure 4-7: Toe Side and Heel Side Carved Turns

Looking at the free body diagram for a typical carved turn, the center of gravity of the snowboarder is out over the base of support of the board. (Figure 4-8) This means that there must be some force which is preventing the snowboarder from falling over. This force is the centrifugal force mentioned before. This force acts outward, balancing out the component of gravitational force which would otherwise throw the snowboarder off. Professional snowboarders are capable of extreme turns (as seen in figure 3-1b), where they use a combination of inclination and angulation to become almost parallel to the slope surface. Though this appears to defy physics, in reality the snowboarder is able to keep their center of gravity as close to the base of support as possible, in addition to moving at a sufficiently high speed, so as to create a large centrifugal force that prevents them from toppling over. [4-1] [4-2]

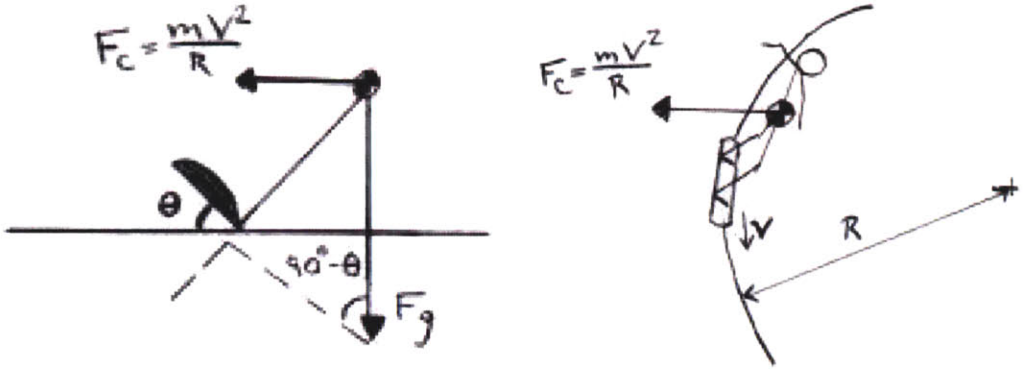


Figure 4-8: A Carved Turn

This centrifugal force provides the biggest challenge to developing a snowboarding simulator. In any simulator concept, the user has no velocity, and there is no turn radius, thus there is no centrifugal force. It is simply not possible to recreate these inertial effects in a simulator. Instead it is the snowboard positions that must be replicated. When holding a traverse, or carving a turn, the snowboarder modifies pitch, yaw, and roll positions of the board to move as desired. In a snowboarding simulator these board positions can be replicated, with some supplemental translational motion to enhance the effect of movement. The body positions when doing these motions may require some alterations, but a strong facsimile of snowboard motion can be replicated.

5 Strategy

After a thorough review of previous patents and designs pertaining to simulation of snowboarding and the physics involved during actual snowboarding, the task now moves to determining what direction to go with the development of a snowboarding simulator. To choose a strategy many different variables must be considered. This requires the establishment of functional requirements, the generation of different strategies to meet these requirements, then a means of organizing and critiquing these ideas in order to choose a desired strategy. The deterministic design process, utilizing a strategy level FRDPARRC table, peer review, and a weighted concept selection chart, becomes an essential tool in selecting the strategy.

5.1 Functional Requirements

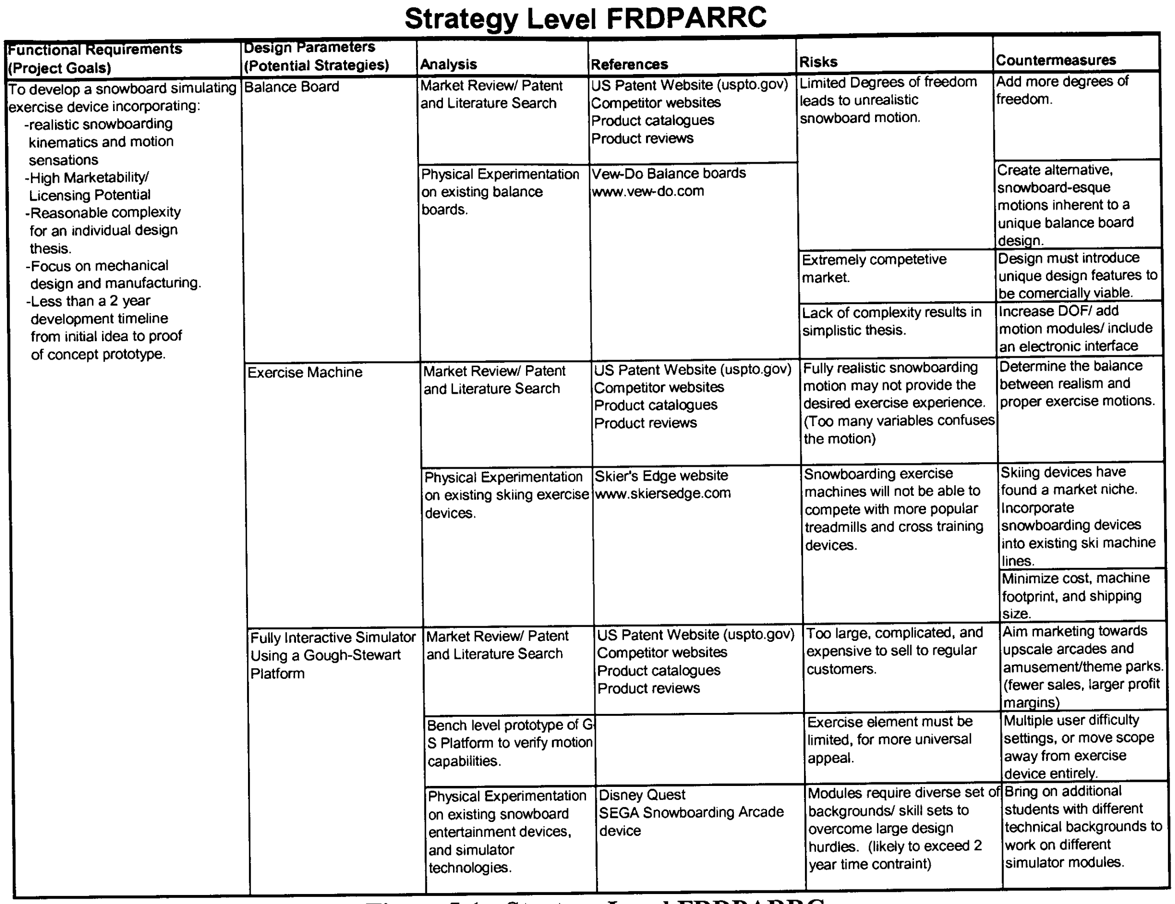
The primary goal in this project is to develop a device that recreates the kinematics and motion sensations associated with snowboarding, such that a user can experience elements of real snowboarding in an indoor setting. From the review of previous literature, it becomes apparent that there are many ways of achieving this primary objective. Depending on the medium selected, a user may be capable of using anywhere from 1 to 6 degrees of freedom. A simple balance board may only offer tipping along one rotational axis, while a fully actuated hexapod could offer full motion in all translational and rotation axes. The desired functional requirement, therefore, is to create as realistic a snowboarding experience as possible. The closer the motions are to actual snowboarding, the better. This, however, is only one of many desired functional requirements for the project.

After successful completion of the basic design, and construction of a working prototype, the goal is to license this product to companies to sell commercially. This makes marketability extremely important. A simple design may be very inexpensive to manufacture, but will have stiff market competition from others with similar simple designs. Extremely complex designs may very accurately reproduce elements of snowboarding, but be expensive to produce and sell. Marketability involves looking at the industry (depending on the strategy being considered) and weighing production cost, market competition, and potential selling volume. A good design is one that will create good profit margins, and have large selling potential, with minimal competition from other designs.

Thesis content is another major consideration. This project is intended to focus primarily on design and manufacturing. Specifically this involves the use of the deterministic design process, design analysis, solid modeling, finite element modeling, bench level experimentation, physical component testing, and manufacturing of a working prototype. Certain design strategies will delve heavily into these subject areas, while others will divert far from this. Some projects, for example, may be reliant on the development of involved analytical models or advanced control algorithms. Though these subject areas provide a great learning experience, they would be a large diversion from the intended project direction.

The final consideration in choosing a project strategy is the time requirement. This project must have a finished proof of concept prototype in less than 2 years time. Though there are many potential strategies which will easily produce a prototype in two years, some pose difficult design challenges that could easily result in years of development work before a prototype can be finished. The goal, therefore, is to choose a strategy that can realistically be completed in the desired timeframe.

In the description of each strategy, many different factors are considered when evaluating the three design strategies. Using the deterministic design process is an effective way of organizing the numerous considerations, and creating a framework within which to evaluate these ideas. A strategy level FRDPARRC table clearly lays out the Functional Requirements, Design Parameters, Analysis, References, Risks, and Countermeasures associated with developing a strategy for designing a Snowboard Simulator. Following the FRDPARRC is a more detailed description of each strategy.



Strategy Level FRDPARRC

Functional Requirements (Project Goals)	Design Parameters (Potential Strategies)	Analysis	References	Risks	Countermeasures
To develop a snowboard simulating exercise device incorporating: -realistic snowboarding kinematics and motion sensations -High Marketability/ Licensing Potential -Reasonable complexity for an individual design thesis. -Focus on mechanical design and manufacturing. -Less than a 2 year development timeline from initial idea to proof of concept prototype.	Balance Board	Market Review/ Patent and Literature Search	US Patent Website (uspto.gov) Competitor websites Product catalogues Product reviews	Limited Degrees of freedom leads to unrealistic snowboard motion.	Add more degrees of freedom.
		Physical Experimentation on existing balance boards.	Vew-Do Balance boards www.vew-do.com		Create alternative, snowboard-esque motions inherent to a unique balance board design.
				Extremely competetive market.	Design must introduce unique design features to be comercially viable.
				Lack of complexity results in simplistic thesis.	Increase DOF/ add motion modules/ include an electronic interface
	Exercise Machine	Market Review/ Patent and Literature Search	US Patent Website (uspto.gov) Competitor websites Product catalogues Product reviews	Fully realistic snowboarding motion may not provide the desired exercise experience. (Too many variables confuses the motion)	Determine the balance between realism and proper exercise motions.
		Physical Experimentation on existing skiing exercise devices.	Skier's Edge website www.skiersedge.com	Snowboarding exercise machines will not be able to compete with more popular treadmills and cross training devices.	Skiing devices have found a market niche. Incorporate snowboarding devices into existing ski machine lines.
					Minimize cost, machine footprint, and shipping size.
	Fully Interactive Simulator Using a Gough-Stewart Platform	Market Review/ Patent and Literature Search	US Patent Website (uspto.gov) Competitor websites Product catalogues Product reviews	Too large, complicated, and expensive to sell to regular customers.	Aim marketing towards upscale arcades and amusement/theme parks. (fewer sales, larger profit margins)
		Bench level prototype of G S Platform to verify motion capabilities.		Exercise element must be limited, for more universal appeal.	Multiple user difficulty settings, or move scope away from exercise device entirely.
		Physical Experimentation on existing snowboard entertainment devices, and simulator technologies.	Disney Quest SEGA Snowboarding Arcade device	Modules require diverse set of backgrounds/ skill sets to overcome large design hurdles. (likely to exceed 2 year time contraint)	Bring on additional students with different technical backgrounds to work on different simulator modules.

Figure 5-1: Strategy Level FRDPARRC

5.1.1 Balance Boards (Strategy 1)

Balance boards offer the simplest solution to simulating the rotational tipping sensations of snowboarding. A balance board, in the most general sense, is a pivoted board that sits on a flat surface, and requires the user to adjust their center of mass to remain balanced on the board. Most boards on the market are capable of 1 to 3 degrees of freedom in the rotational directions, with a few capable of limited motion in a translational direction. This creates the opportunity to develop a 3+ degree of freedom balance board, with the added potential for electronic output. (balance boards move relative to the surface, making electronic input difficult, if not impossible.)

From a kinematics standpoint, a 3+ degree of freedom balance board is good when compared to other balance boards, but lacks the experience of snowboarding. The primary purpose of a balance board is to maintain balance. Though a snowboarder is perpetually trying to maintain balance, a balance board is not capable of providing large translational motions. The effects of carving a turn would be lost when using a balance board, because the user is not able to translate while they are digging into the toe side or heel side (manipulating position about the roll axis). Another consideration is that many of the more complex balance boards currently on the market have developed into sports of their own. People using these balance boards combine skills associated with snowboarding, surfing, and skateboarding to create a new hybrid. While manipulating the board they are able to perform aerial stunts and other complex maneuvers. These maneuvers, however, are a departure from what is capable on a snowboard.

Development of a balance board also provides significant market risk. Balance boards are inherently simple to design and manufacture. This results in a worthwhile design with minimal effort, but also means that others can create designs just as easily. Balance boards are an extremely well developed market, with numerous patents already in existence. If a new design is created, it must be a unique and novel design to warrant a patent, and must not infringe on the claims presented in other related patents. Even if a design is patentable, the task then falls on convincing potential licensers that this balance board is significantly better than other boards already on the market. If the design is licensed, the profit margins are good, but the competition is very tight. Good marketing and a unique design are required have a successful product.

A truly unique balance board design could prove to be highly successful in the marketplace, and create a reasonable representation of some elements of snowboarding. Unfortunately the risk of competitor designs and the simplicity of balance boards in general greatly detract from the appeal of such a strategy.

5.1.2 Exercise Machines (Strategy 2)

Exercise machines offer a much greater opportunity to develop a new, innovative design to simulate snowboarding. This is primarily because of the broader definition of an "exercise machine". Any balance board must contain several key components, namely a board and pivoting elements. An exercise machine, by contrast, refers to any device which requires physical exertion in order to maintain fitness, or increase skill. This opens up the development process to a large number of potential designs.

With this somewhat open ended strategy, it is possible to create numerous different kinematic sensations, depending on the design chosen. This means that the potential exists to create exercise machines capable of motion in 6 degrees of freedom. This, however, is not always desired. Most commercially available exercise machines rely on repeatable motions to maintain the desired physical exertion from the user. Exercise bikes, treadmills, rowing machines, and even skiing machines like the Skier's Edge™ are an illustration of this. People are able to use these exercise machines, and settle into an exercise rhythm. Often they are able to focus their attention on watching television, reading a book, or letting their mind wander. Added degrees of freedom on these devices would only serve to complicate the motion, and make it more difficult for the user to settle into an exercise rhythm. Unfortunately, the freedom of motion necessary for an effective exercise machine lacks much of the realism of actual snowboarding.

Despite this shortcoming, a snowboarding exercise machine has a great deal of appeal from a marketing standpoint. Currently there are several commercially available skiing exercise machines. There are not any snowboarding exercise machines on the market. This creates a wonderful opportunity to fill a market need. Snowboarding is one of the fastest emerging winter sports. In the same way that skiers buy skiing machines to hone their skills when they can not get to a mountain, a snowboarder can buy a snowboarding machine. A snowboarding exercise machine may not sell the same volume as a balance board, but the competition will be much less stiff. A well designed, low cost device will also have the potential for good profit margins. Exercise machines are able to sell at much higher prices than balance boards due to the added complexity, more engaging exercise experience, and more difficult manufacture of components. A design that costs little to manufacture and ship to the customer could still sell at regular exercise machine prices, generating good profits. The outlook for licensing a snowboarding exercise machine is also good. Skiing machine companies are constantly looking to adopt new snowboarding concepts into their product lines. A fully developed snowboarding device has a good chance of being picked up by a company seeking to expand its line.

The development of a snowboarding machine also requires significant mechanical design, analysis, and manufacturing. Most devices of this type are primarily mechanical systems. To achieve the desired kinematics, numerous modules must be designed and then integrated. Each design module requires innovative design and manufacturing work. These designs, by default, include both moving and static elements, requiring a wide array of different mechanical engineering skill sets (primarily focusing on design and manufacturing). A design of this type is also well suited for a 2 year product development cycle. Some new research and testing is required, but the design challenges posed are not so significant that a proof of concept prototype can not be completed in the allotted time.

Exercise machines offer a reasonable tradeoff between a realistic ride experience, market potential, and desired educational experience. Snowboard kinematics may not be as realistic as possible, but a good design has the potential to spread to a very large market segment.

5.1.3 Entertainment Simulators (Strategy 3)

The third and final strategy to consider is the development of full scale, interactive entertainment simulator. The literature search revealed a broad spectrum of these devices. The most basic of these designs were game controllers, which essentially consisted of a balance board with electronic input to a video game system. More involved designs included arcade simulators, which contain motion platforms permitting only rotational motion, again serving as input to a game interface. In this case, however, the goal would be to develop full simulator technologies. This implies that the simulator control system is not just able to receive input from the user manipulating the snowboard, but also send output from the control system back to the user. In addition to the motion system, the user would have access to a visual display through use of virtual reality goggles or screen projection, and audio sensations through use of surround sound speakers. A snowboarding entertainment simulator would offer exciting new possibilities for ride simulation.

In order to create a fully immersive snowboarding environment, a parallel kinematic platform would be necessary. Through use of a Gough-Stewart platform, a snowboard would be capable of movement in all 6 degrees of freedom. (Figure 5-2 shows a bench level prototype of a Gough-Stewart Platform) This allows for freedom of motion in all rotational and translational directions. In addition to this large freedom of movement, a kinematic platform of this type is capable of serving as a haptic interface. Through actuation of the platform struts, it is possible to create a physical slope profile and vibration effects that the user can feel, and interact with. This means that pursuing this strategy would offer an extremely realistic snowboarding experience. Unfortunately, there are also limitations to this strategy. Entertainment simulation technologies are ideally designed to appeal to a large segment of the population. As such, it is difficult to incorporate a large physical component to such designs. An overly taxing simulator does not fit in with traditional simulator technologies, which focus on rider enjoyment and experience, rather than exercise.

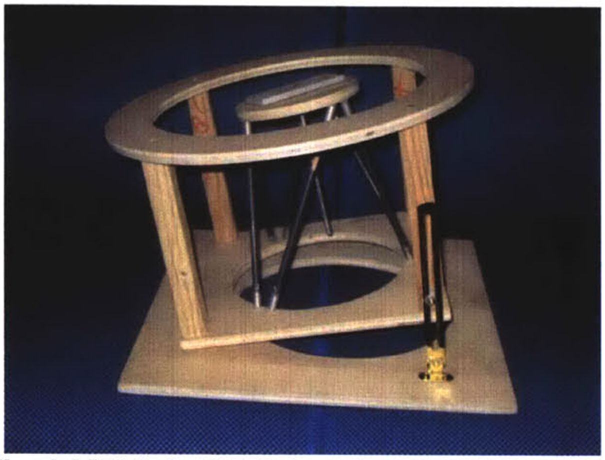


Figure 5-2: Sketch Model of a Gough-Stewart Platform Bench Level Prototype

From a marketing standpoint an entertainment simulator of this type has the potential to be successful, depending upon how it is marketed. A snowboarding simulator offers an incredibly immersive and realistic ride experience. Unfortunately to do this, it prices itself out of the range of regular consumers. First, a ride simulator is large. A Gough-Stewart platform is not easily collapsible, and would have to be sized large enough to hold a full sized adult. With the added safety rails and visual display elements, the resulting simulator footprint would be extremely large. In addition, purchase of a kinematic platform and an audio/visual interface become extremely expensive. The size and monetary cost make it almost impossible for homeowners and small arcades to justify the purchase of a full motion snowboarding simulator. It is much easier for them to purchase smaller, less expensive, less complex simulators. The solution is to target amusement parks, theme parks, and high end video arcades. These types of establishments look for larger simulator rides to provide the user experiences that they can not get at home. The selling volume of these types of simulators is far less, but the profit on a single sale is extremely high. If enough interest is generated among the target customers, an entertainment snowboarding simulator could be very successful.

One potential setback of such an ambitious simulator design is complexity. The proposed simulator strategy involves development of numerous systems. The mechanical system consists of a Gough-Stewart platform, a supporting ride frame, and an amazingly intricate control system capable of processing both input and output in a haptic interface. The visual/audio elements of a snowboard simulator would also tap into this control system. These elements would require development of computer code, a graphic slope interface, and possibly even have to be adapted for use with virtual reality goggles. The final product would require numerous different skill sets, within vastly different disciplines. Additionally, most current simulation devices are either purely input, or purely output devices. Most current haptic devices combine both, but do so on a relatively small scale (on the order of handheld devices, or small motion platforms). Direct user input through an actuated output platform will provide unique, and very difficult design challenges. Ultimately, developing a fully interactive simulator is an extremely tall order for a 2 year thesis project. In reality, a project like this would require a group effort including mechanical engineers working on design and controls, electrical engineers working on the electronic interfaces, and computer programmers to handle the audio/visual interfaces. A significant amount of additional research would also be required to overcome many of the design hurdles associated with control of the simulator.

From a mechanical design standpoint, a ride simulator of this type would also move away from the desired research focus. Undeniably mechanical design would be involved in the development of the ride simulator. The interesting ride kinematics, however, are primarily implemented in the Gough-Stewart platform. Outside of sizing and mounting the motion platform, the remaining mechanical design is in the development of the passive support structure. The bulk of the mechanical engineering work to be done is in the development of the control system. This is not the intended research focus, and is a major deterrent to selecting this strategy.

5.2 Weighted Concept Selection Chart

After carefully outlining each design strategy in the FRDPARRC table, a weighted concept selection chart is needed to sort through the different strategies, and choose the one that best meets the selection criteria. Mirroring the functional requirements established in the FRDPARRC, the selection criteria for the design strategies (in order of importance) include realism, marketability, research focus, design complexity, and project duration.

Strategy Level Weighted Concept Selection Chart

		Strategy		
Selection Criteria	**Weighting**	**Balance Board**	**Exercise Machine**	**Entertainment Simulator**
Snowboard Kinematics/ Realism	5	-1	0/1	1
Marketability	4	-1	1	0/1
Design Complexity	2	-1	1	0/1
Research Focus	3	0	1	-1
Project Duration	1	-1	1	-1
Total Score:		**-12**	**10/15**	**1/7**

Figure 5-3: Strategy Level weighted CSC

The end results show that design of a snowboard simulating exercise machine will best meet the design objectives for this thesis project. Upon review of the strategies, balance boards provided the least amount of appeal. The simplicity of balance boards provide little opportunity for unique development or improvement over the numerous competitor designs, and do not offer the desired educational experience. On the other end of the spectrum, entertainment simulators, though very unique and challenging, require an immense amount of development. The numerous disparate design modules (requiring outside help), and the altered research direction were enough to make this design undesirable. Development of an exercise machine lies directly in between these two extremes. Exercise machines incorporate design, analysis, and manufacturing requirements in line with the research objectives. In addition, this relatively untapped market for snowboard simulation technologies opens the door for potential licensing of the finished product. Design of a snowboard simulating exercise device has the best potential for success.

6 Concept

At the strategy level, an exercise machine best meets the overall project goals for the snowboarding simulator device. Unfortunately the term exercise machine is rather broad. An exercise machine is any device that requires physical exertion to develop or maintain fitness or increase skill. The goal of the concept phase is to again establish functional requirements which are used to generate concept ideas. A FRDPARRC Table is again used to organize these ideas, and a weighted concept selection chart is used to select the chosen concept to be split into modules.

6.1 Functional Requirements

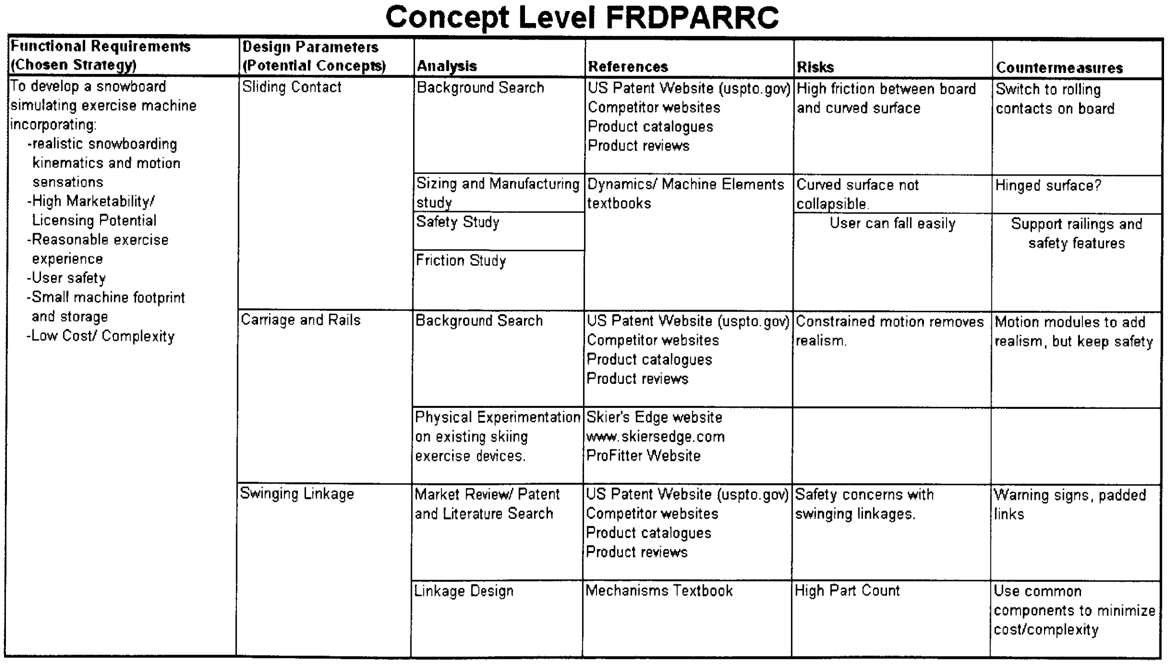
The initial functional requirements are based on the chosen design parameter for the strategy level. Therefore the primary functional requirement of the concept level is to develop an exercise machine that simulates the motions of snowboarding. The specific design must be targeted towards individual snowboarding enthusiasts for pubic or home gyms. More specific elements of the functional requirements require added explanation.

As an exercise machine, the overall motion and exercise potential are extremely important to consumers. When looking at most exercise machines, there are repeated motions which are used to build endurance and increase proficiency. For this device, 3 degree of freedom tipping (technically a balance board) would be insufficient in offering any variety of endurance training. Some form of translation is also needed for the resulting exercise to be meaningful. It is up to concept generation to find ways of introducing translational motion, with elements of rotational motion to create a realistic snowboard motion, which also provides a desirable exercise experience.

As a commercially available device, it is also desirable for the exercise machine to be safe, and user friendly. This means that any chosen design must not be so extreme that it causes potential harm to the user. Inherently unstable designs, or designs with extreme motions are not desirable in a chosen concept.

Size is another critical element to any commercial exercise machine. If a user is going to purchase an exercise machine, it has to be of reasonable size to fit in a typical home gym. Concept ideas, therefore, can't contain motions which require incredibly large support structures. Further discussions on sizing and storage of the machine occur in later levels of the project, but in the concept stage it is important to properly consider sizing.

The final area of consideration is cost and complexity. Exercise machines must be affordable for consumers to purchase the machine. Though the final cost details are not worked out until later stages of detailed design, there are certain concerns that should be considered at the concept level. For example, adding motors and electronics to a design adds cost and complexity. If these elements are needed in the design, then the added cost can be justified. If not, the concept ideas should avoid using them. In the end, eliminating high cost options at the concept level greatly simplifies work during the detailed design phase, to trim expense off the final design. After defining all the functional requirements, a concept level FRDPARRC can be constructed, where the following concept ideas are laid out as design parameters.



Concept Level FRDPARRC

Functional Requirements (Chosen Strategy)	Design Parameters (Potential Concepts)	Analysis	References	Risks	Countermeasures
To develop a snowboard simulating exercise machine incorporating: -realistic snowboarding kinematics and motion sensations -High Marketability/ Licensing Potential -Reasonable exercise experience -User safety -Small machine footprint and storage -Low Cost/ Complexity	Sliding Contact	Background Search	US Patent Website (uspto.gov) Competitor websites Product catalogues Product reviews	High friction between board and curved surface	Switch to rolling contacts on board
		Sizing and Manufacturing study	Dynamics/ Machine Elements textbooks	Curved surface not collapsible.	Hinged surface?
		Safety Study		User can fall easily	Support railings and safety features
		Friction Study			
	Carriage and Rails	Background Search	US Patent Website (uspto.gov) Competitor websites Product catalogues Product reviews	Constrained motion removes realism.	Motion modules to add realism, but keep safety
		Physical Experimentation on existing skiing exercise devices.	Skier's Edge website www.skiersedge.com ProFitter Website		
	Swinging Linkage	Market Review/ Patent and Literature Search	US Patent Website (uspto.gov) Competitor websites Product catalogues Product reviews	Safety concerns with swinging linkages.	Warning signs, padded links
		Linkage Design	Mechanisms Textbook	High Part Count	Use common components to minimize cost/complexity

Figure 6-1: Concept Level FRDPARRC

6.1.1 Sliding Contact Curve (Concept 1)

The first attempt at creating an exercise machine looks at using a "snowboard" in sliding contact over a curved surface. In this approach, the user wears a low friction, snowboard-esque assembly on their feet. While gripping the side support bars, they are able to generate snowboard like motion by sliding along the curved surface. This provides translational motion along the curved surface, in addition to giving the user complete freedom of rotation. (Figure 6-2)

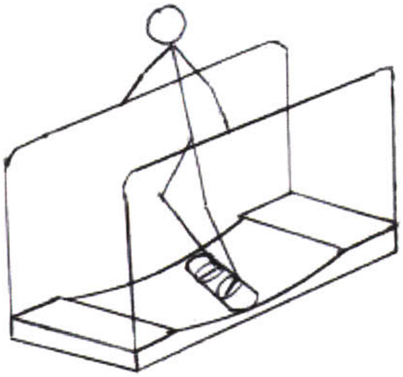


Figure 6-2: Sliding Contact Concept

This design provides mixed results in terms of ride motion and exercise experience. Users using this design are able to tip the board in the same ways that they are able to tip a snowboard. Generating motion, however, is totally different. The user starts in a low stable position on the sliding surface. Unlike snowboarding, there is not a downward slope to generate motion. Instead the user must use their arm strength to generate the initial motion. The friction between the board and the surface also has the potential to be quite high, making the ride motion more difficult. Creating rolling contact between the board and surface can improve this, but in the end, the arms do most of the work trying to overcome the friction of the board.

Safety is an issue in this design. In this concept the user's feet are strapped to the board, but the board is not constrained to the surface. The result is that the user has great freedom of movement, but a higher potential for injury. There is nothing to prevent the board from going over the edge of the curve, or twisting so that the long axis of the board is parallel to the ride motion. This configuration also does nothing to prevent the user from falling and injuring themselves on the machine.

The size of the machine is also not necessarily desirable. Due to the unconstrained motion of the board relative to the surface, the curved surface must be reasonably large. This creates a storage concern. A large curved surface may occupy the same footprint as other designs, but it can not be collapsed to a smaller size.

This sizing concern also translates to the overall cost of the machine. Fabrication and material cost of a large, low friction curved surface has the potential to be expensive. Anything that drives up cost could result in greatly reduced marketability of the final design.

6.1.2 Carriage and Rails (Concept 2)

The sliding contact approach offers great freedom of movement, but is undesirable from a safety, sizing, and cost standpoint. The carriage and rails approach has a similar ride motion, but with added constraints which increase overall ride safety. In this approach a curved rail or rails are used, with a carriage riding along in rolling contact with the rails. On this carriage angular motion modules can be added to introduce the desired rotational sensations. In addition a support frame is required for user support. The output motion consists of the user moving back and forth along the rails, while adjusting angular position to change direction of force application and thus the direction of the carriage. (Figure 6-3)

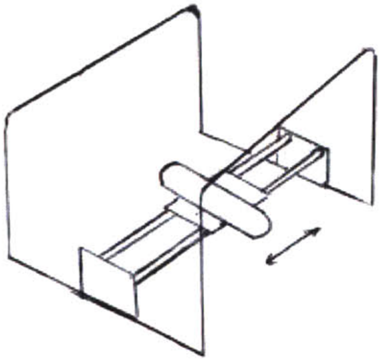


Figure 6-3: Carriage and Rails Concept

From an exercise and ride motion standpoint, the carriage and rails approach is very similar to the sliding contact approach. The rider is able to move back and forth translationally, while having freedom of rotation. The difference is that the motions of the carriage and rails approach are constrained. Using a sliding contact approach the user can move in any direction they desire. The motions of the carriage and rails approach are dictated by the rails, and the angular motion modules. This lack of motion is not necessarily a bad thing. In exercise machines, repeatable motions are important for building proficiency and increasing performance. The constrained motions of a carriage and rails approach are far more repeatable than the free form motion of sliding contacts.

Safety is also increased considerably in this design. In this design the user does not need to be physically strapped to the motion platform. Instead the entire platform is constrained. This makes it impossible for the carriage to go over the edge, or otherwise fall off the curved track. There is still a risk of failing off the ride carriage, or being hit or pinched by the moving carriage, but this can be alleviated through proper design of a support frame and other safety features.

The size of this design is typical of many commercially available exercise devices. This concept can be built almost entirely of bars and tubes, resulting in use of a relatively small amount of material, and a high probability of being collapsible for easy storage.

Simple manufacture and reasonable material use result in potential for a low cost design. This approach is very similar to many of the skiing exercise machines already on the market. This means that a design like this will easily fit into the existing product lines of numerous companies, greatly improving the likelihood of licensing the product. This design appears to have a high probability of success.

6.1.3 Swinging Linkage (Concept 3)

The third and final concept is using linkages to create a swinging motion, replicating the curved surface of the sliding contact concept. Here large radius swinging links create the translational curve of motion, while an angular motion module adds the desired rotational element. Through adjusting both weight, and direction of force application, the user can move back and forth along the motion path. A support frame serves as both handholds for the user, and as a mounting point for the linkages. (Figure 6-4)

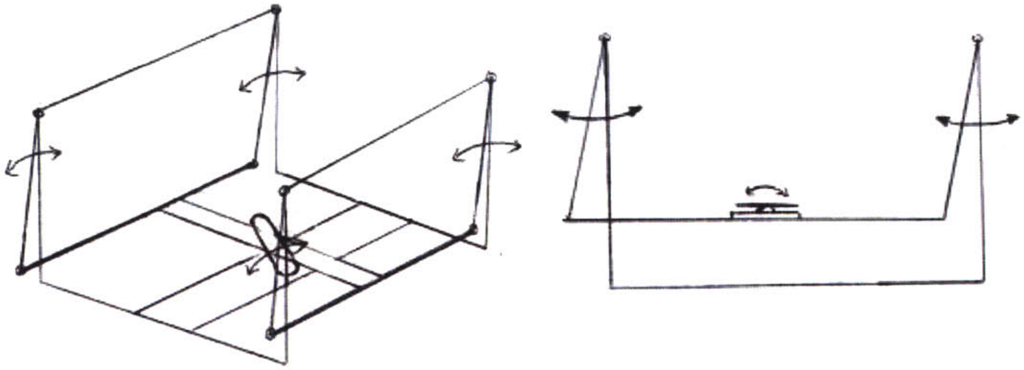


Figure 6-4: Swinging Linkage Concept

The motion path of this concept is similar to that of the carriage and rails, consisting of constrained translational motion, with added rotational motion. In the hanging approach however, the motion is far faster. The swinging motion of the linkage is met with little resistance, as opposed to the carriage and rail concept, which has friction between the carriage wheels and the rails. Some resistance is more desirable, but in this case the output motion is still acceptable. The exercise experience is also essentially equal to the carriage and rails approach.

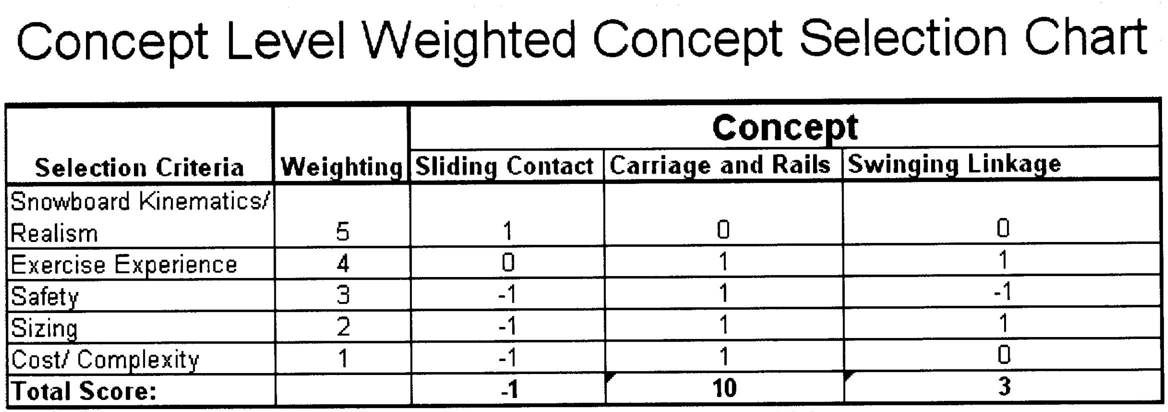
This concept features large swinging bars, moving at a high speed relative to stationary support rails. This offers significant risk from a safety standpoint. Users or bystanders run the risk of getting pinched between the links and the supports, or getting hit by the swinging platform. It is also possible to exceed the intended motion range of the linkage, throwing the user.

The size of this concept is comparable to the carriage and rail concept. The only potential difference is any additional space and structure required for the swinging platform. The collapsibility of this design appears more complex. The various linkages used in this design require a higher part count and complexity in the assembly. Further design, however, can simplify and improve the assembly process for the user.

Cost-wise, the higher part count is the only drawback to pursuing this design over others. Additional parts require added material and assembly, and detract from the appeal of the design.

6.2 *Weighted Concept Selection Chart*

After careful review of the concept level FRDPARRC Table, the Carriage and Rail concept is selected. This design offers an appropriate constrained motion, which has the fewest safety concerns. The footprint for this design is similar to numerous existing exercise machines. Similarly, common components and simple manufacturing offer the potential to produce this design very inexpensively compared to other concepts. The common elements in the design also closely match the designs in existing skiing exercise machine lines, increasing the probability of licensing the design. The sliding contact approach offers reasonable ride motions, but has numerous safety, sizing, and cost concerns which make it non ideal. The swinging linkage approach has many positive traits, but the safety issues with swinging elements make the design undesirable. The carriage and rail approach best meets the functional requirements, and is the chosen design for module level development.



Concept Level Weighted Concept Selection Chart

Selection Criteria	Weighting	Concept		
		Sliding Contact	Carriage and Rails	Swinging Linkage
Snowboard Kinematics/ Realism	5	1	0	0
Exercise Experience	4	0	1	1
Safety	3	-1	1	-1
Sizing	2	-1	1	1
Cost/ Complexity	1	-1	1	0
Total Score:		**-1**	**10**	**3**

Figure 6-5: Concept Level weighted CSC

7 Modules

The first step in the detailed design of the proposed snowboarding exercise device is the establishment of all system modules. The basic simulator concept revolves around the layout of a curved track and ride carriage. This provides the basis for the exercise motion, and establishes the Most Critical Module (MCM) for the design. Second in importance to this is the support frame which prevents the rail base from sliding relative to the ground, and provides an adjustable set of handrails for user stability. Additional angular motions are provided to the user through modules added onto the ride carriage. In a commercially available snowboarding exercise machine there would be numerous angular motion modules available (providing a combination of pitch, yaw, and roll). However, because of the importance of roll axis motion to "carving" a basic turn, the roll axis module is the most important angular motion module for a proof of concept prototype.

Snowboard Exercise Machine Modules

1. Carriage and Track (MCM)
2. Support Frame
3. Angular Motion Module (Roll Axis)

Each of the above modules must undergo the deterministic design process on the Module level. For each module, FRDPARRC Tables and weighted Concept Selection Charts are again used to sort through the numerous module designs. Once a module design is chosen, the true detailed design work can begin. The following sections review the different modules, showing the idea generation and selection process, the detailed design of each module (including layout, component selection, analysis and testing), and the creation of the finished module prototypes.

7.1 Carriage and Track

The basic motion of the proposed snowboarding exercise device is implemented through the motion of a ride carriage along a curved track. After review of snowboarding physics, the basic motion that a user makes down a mountain slope is typically a zigzag pattern, where the snowboarder alternates between "carving" on the heel side and toe side of the snowboard. In order to replicate such a motion, back and forth translational motion is required. The simplest starting point to facilitate the design of the rails is to look at skiing exercise devices that use similar rail and carriage systems.

Figure 7-1: Zigzag motion of a snowboarder down a slope

7.1.1 Track Selection

The Skier's Edge design is a logical starting point for looking at rail configurations. In the basic Skier's Edge layout, parallel rails are curved downwards. (Figure 7-2) The carriage moves along the rails, attached to large elastic bands for resistance. When a Skier's Edge is used as intended (with both feet facing forward, perpendicular to the carriage motion), this configuration is a very good approximation of skiing down a mountain slope. At the extremes of motion, the user adjusts their weight and direction of force application such that they can overcome the central rise to reach the other side. The results are quite different when the user removes the foot pedals on the Skier's Edge, and turns their feet to be parallel to the carriage motion. The user finds themselves stuck in the low points on the ends of the track. Instead of simply adjusting their center of mass and direction of force application, the user is required to brace themselves on an external hand rail, and bend precariously over the end of the track to generate force in the right direction to overcome the high point of the track. The resulting motion is sporadic, jerky, and incredibly dangerous. Rails curved downwards in this configuration are not conducive to snowboarding, but provide a basis for the design of an appropriate rail configuration.

Figure 7-2: Full Skier's Edge with foot pedals removed for bench level test

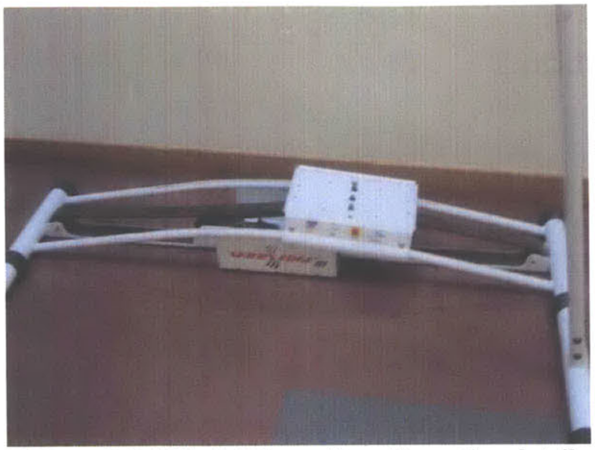


Figure 7-3: Skier's Edge rail configuration detail

The ProFitter design could similarly be modified for snowboarding. The ProFitter rail configuration, in this case, would consist of two sets of curved rails, one set with ends pointed downwards to mount the carriage, and a mirror set having ends pointed upwards for the rocking motion. (Figure 7-4) This design runs into similar problems to the previous configuration. Adding a snowboarding carriage to this rail configuration has the same inherent instability of the previous configuration, but also introduces much more dangerous instability. Now the user no longer has rails to grab hold of, and the base is now moving relative to the floor. The resulting motions prove even more dangerous, while offering little potential advantage.

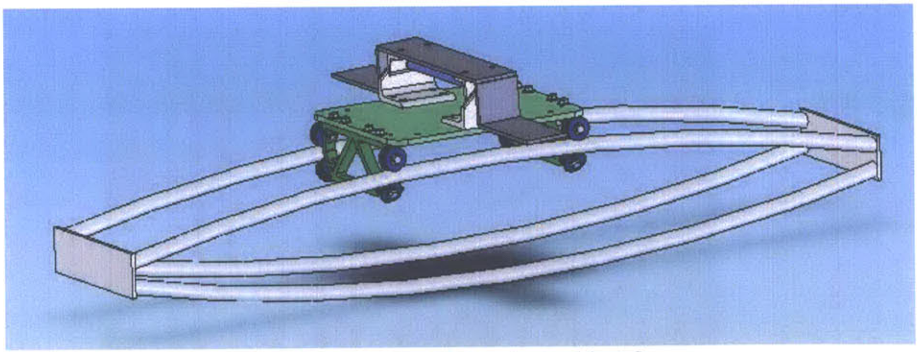


Figure 7-4: Carriage mounted on a rocking frame

The solution to this problem lies in reciprocity. Rails curved downward do not work, so the simplest solution is to invert the rails so that they curve upwards. Now instead of being stuck on the low ends, the ride carriage settles into the low, stable region in the center of the track. Through tipping about the roll axis of the ride carriage the user can adjust the direction of force application, and begin to generate the momentum required to maintain the back and forth motion. Instead of relying on elastic bands to supplement the motion, gravity, which costs less, can be used instead. The resulting motion is not dissimilar from the motions of a child using a playground swing. On each end of the motion, the user is required to adjust their position along the roll axis. On a swing the user adjusts the location of their center of mass. On inverse rails the user adjusts the direction of force application by pivoting about the motion platform. The upward curves on each end, coupled with the range of motion on the roll axis module closely resemble the 0-60° of roll axis tip when snowboarding down a hill.

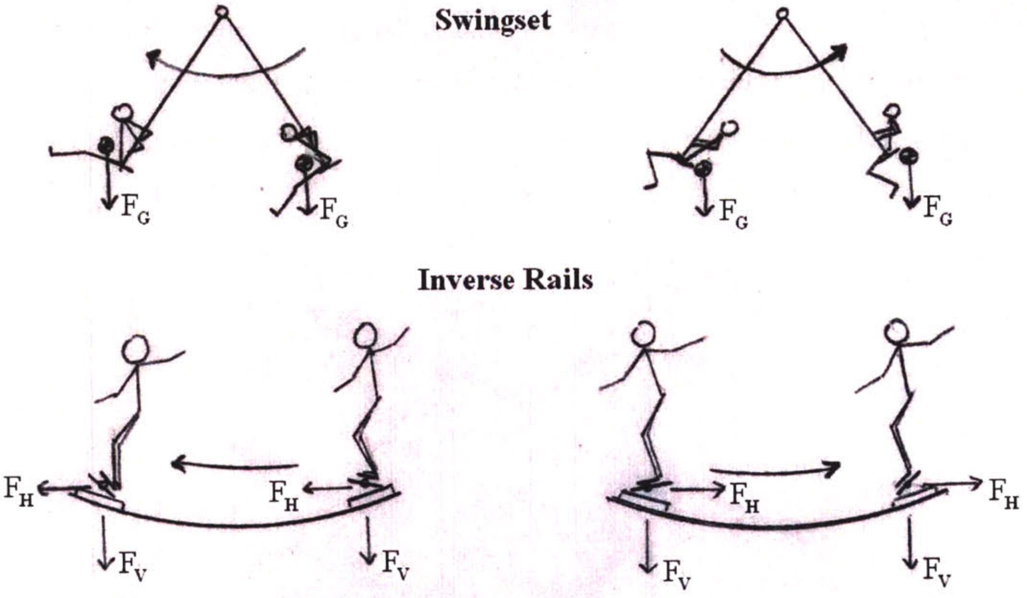


Figure 7-5: Swing set versus Inverse Rail

Using the idea of the upwards curve, the only remaining rail design decisions pertain to the quantity and shape of the rails. This requires establishment of a new set of functional requirements, the most important of which is stability. Stability in the rails requires that the carriage move along the track with minimal wobble, and no chance of derailment or failure. The carriage moves along the track with the attached "snowboard" mounted perpendicularly to the direction of motion. When a user stands on the motion platform, their feet straddle the rails, pointed parallel to the carriage motion. In this position they will be able to generate moments in the pitch, yaw, and roll directions. As such, the spacing must be wide enough to maximize resistance to the moments generated by the user.

Two of these moments can be compensated for by adjusting the spacing of the wheels on the carriage. The first of these, roll axis moment, is of the least concern. In the roll axis direction, the user is able to apply their entire body weight to roll axis motion. The maximum moment arm on the roll axis, however, is only half the width of the "snowboard" platform (approximately 6 inches). This relatively small moment is then resisted by the vertical forces of the carriage wheels in contact with the long axis of the rails. The second, yaw axis moment, has a larger moment arm equal to half the distance of the foot to foot spacing on the snowboard (approximately 9-12 inches). Luckily, the magnitude of the force is much less due to the fact that the user can not use their full body weight. Any yaw axis moments are resisted by the horizontal forces of the carriage wheels in contact with the long axis of the rails.

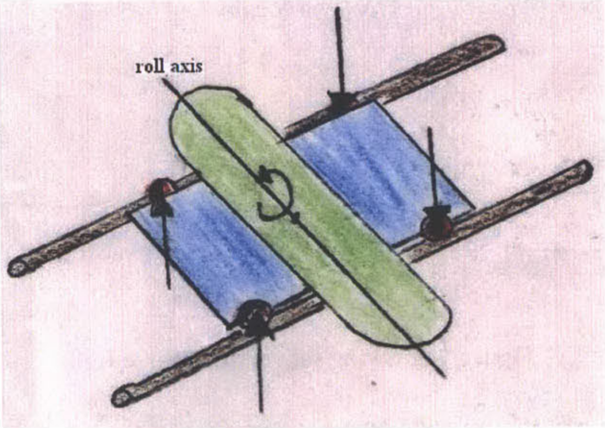


Figure 7-6: Roll Axis Moment and Reaction Forces

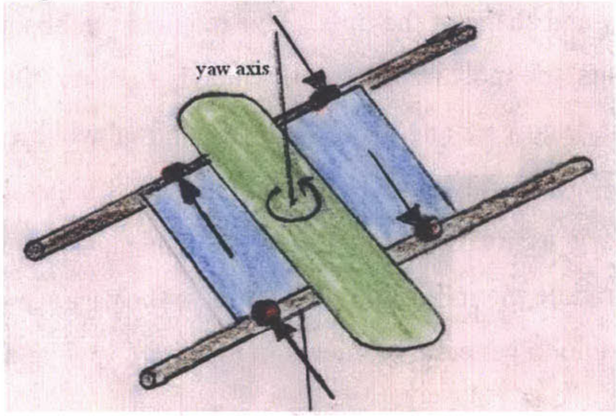


Figure 7-7: Yaw Axis Moment and Reaction Forces

Pitch axis moments, by comparison, are much larger, and specifically relate to the design of the rails. The moment arm in the pitch direction is again half the foot-to-foot distance of the user (9 – 12 inches). The user is able to apply their full body weight, creating a much larger moment. Resistance to this moment is handled by the vertical forces of the carriage wheels. The difference is that the spacing between the reaction forces is dependent on the spacing or width of the rails, rather than the spacing of the carriage wheels. Insufficient rail spacing/width could result in large forces being transmitted to the rails, or cause disengagement or even failure in the carriage wheels. Rail width and spacing becomes a critical element of proper stability.

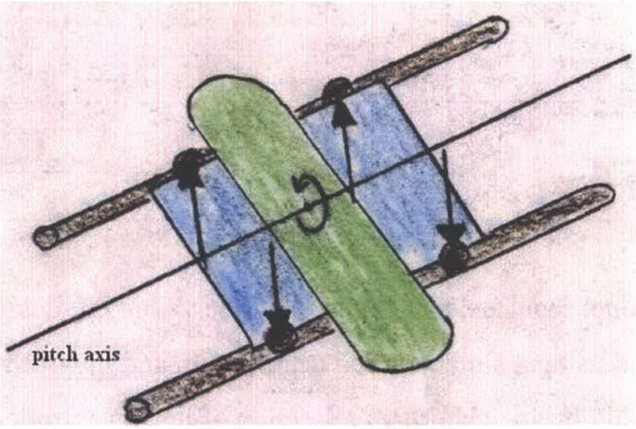
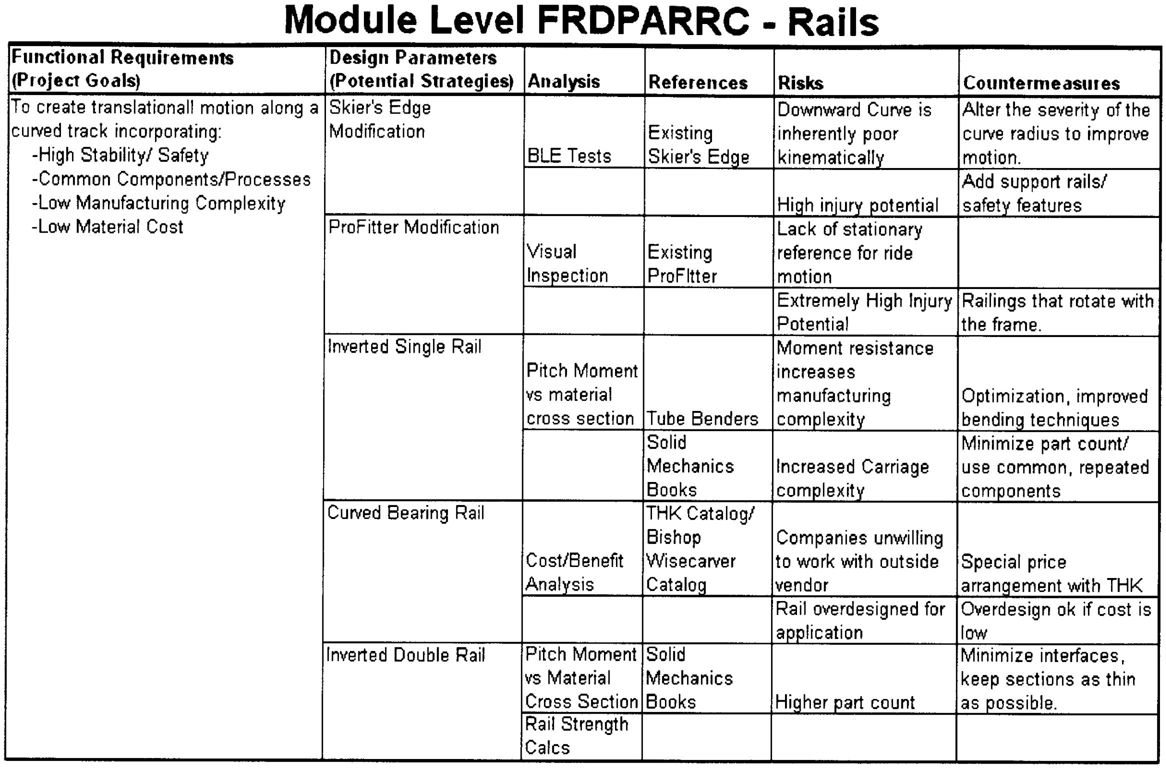


Figure 7-8: Pitch Axis Moment and Reaction Forces

The remaining functional requirements consider the manufacturing of both the prototype and commercial models. In the design of a commercially available snowboarding exercise machine, consumers are going to look for an inexpensive, safe, light weight, user friendly design that meets their exercise requirements. Companies looking to license these technologies typically look for similar attributes, in addition to designs that will fit in well with their existing product lines. The goal then is to minimize the material cost and manufacturing complexity, while incorporating parts and manufacturing processes that are in line with current competitive technologies. This minimizes the fabrication effort at the prototyping stage, and results in a more marketable final product.



Module Level FRDPARRC - Rails

Functional Requirements (Project Goals)	Design Parameters (Potential Strategies)	Analysis	References	Risks	Countermeasures
To create translationall motion along a curved track incorporating: -High Stability/ Safety -Common Components/Processes -Low Manufacturing Complexity -Low Material Cost	Skier's Edge Modification	BLE Tests	Existing Skier's Edge	Downward Curve is inherently poor kinematically	Alter the severity of the curve radius to improve motion.
				High injury potential	Add support rails/ safety features
	ProFitter Modification	Visual Inspection	Existing ProFItter	Lack of stationary reference for ride motion	
				Extremely High Injury Potential	Railings that rotate with the frame.
	Inverted Single Rail	Pitch Moment vs material cross section	Tube Benders	Moment resistance increases manufacturing complexity	Optimization, improved bending techniques
			Solid Mechanics Books	Increased Carriage complexity	Minimize part count/ use common, repeated components
	Curved Bearing Rail	Cost/Benefit Analysis	THK Catalog/ Bishop Wisecarver Catalog	Companies unwilling to work with outside vendor	Special price arrangement with THK
				Rail overdesigned for application	Overdesign ok if cost is low
	Inverted Double Rail	Pitch Moment vs Material Cross Section	Solid Mechanics Books	Higher part count	Minimize interfaces, keep sections as thin as possible.
		Rail Strength Calcs			

Figure 7-9: Module Level FRDPARRC - Rails

These functional requirements generated three viable rail designs, the first using a single rail, the second using a single curved bearing rail, and the third using two parallel rails. In the single rail design, a short, wide section of tube is extruded and bent to the desired radius. A square, hollow cross section with rounded corners is chosen for the tube because of its relative simplicity and light weight. This single rail can then have “T” supports welded beneath it for support. (Figure 7-10) This design is appealing in that it consists of only one curved extrusion, and requires only a simple ride base. It does, however, have its drawbacks. In order to minimize the effects of pitch axis moments acting on the track, it has to be wide. Unfortunately, with thin walls, a large cross section can prove difficult to bend. A larger section area may also use more material than a multi-rail configuration. Another consideration is how to constrain the carriage to the rail. Ideally the carriage can be constrained through use of identical wheels to minimize the machines required for production. In certain configurations this is possible (Figure 7-11, Configuration 4), but results in difficult mounting of the wheels on the carriage. Other, more logical wheel configurations require two or more different wheel shapes. (Figure 7-11, Configuration 1-3)

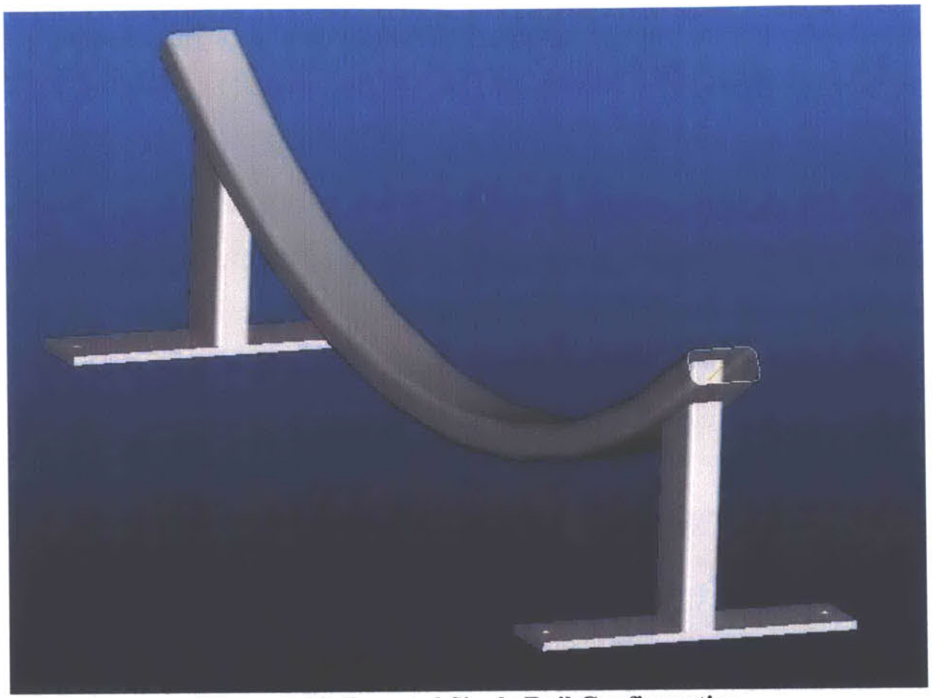


Figure 7-10: Inverted Single Rail Configuration

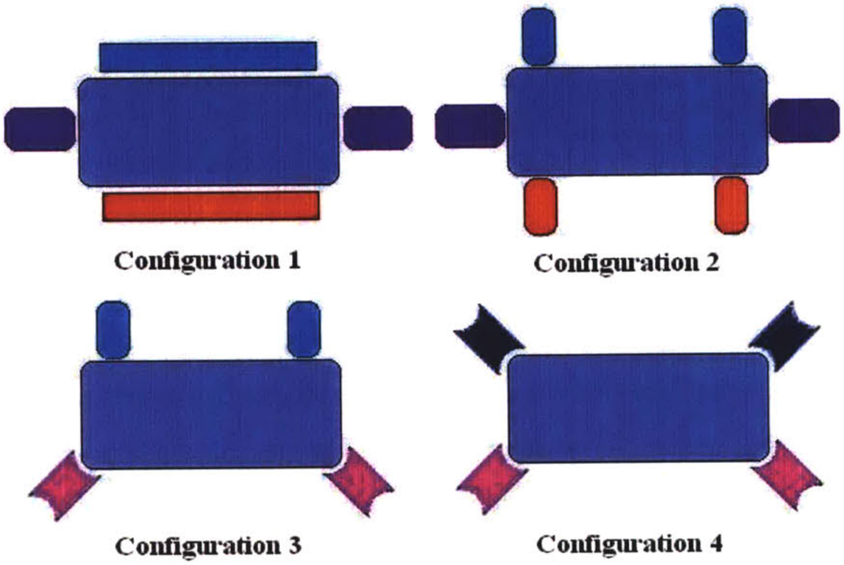


Figure 7-11: Single Rail Carriage Wheel Configurations

Another approach to using a single rail is to look at using an existing curved bearing rail. The bearing company THK currently makes a circular-shaped bearing guide, known as the R-Guide Type HCR. (Figure 7-12) This curved bearing rail is capable of withstanding large forces and moments in all directions. The bearing rail also comes equipped with a specially designed carriage, which utilizes four rows of recirculating balls in a precision-ground raceway, resulting in an incredibly smooth motion. [7-1] Modification of this bearing rail would require mounting of the rail ends to a support structure. Because the bearing rail is purchased as is, additional manufacturing of the prototype for the rail and carriage would be at an absolute minimum. The issue with using such a bearing rail is that it is a stock item intended for precision applications. The force and moment resisting characteristics are highly desired, but the high precision motion is unnecessary for this application. Companies considering licensing this product want to keep cost at a minimum. The design becomes more enticing to an existing equipment company if they can see the product fitting in with the manufacturing processes used on their existing machines, such as using bent rails and a carriage with rollers.

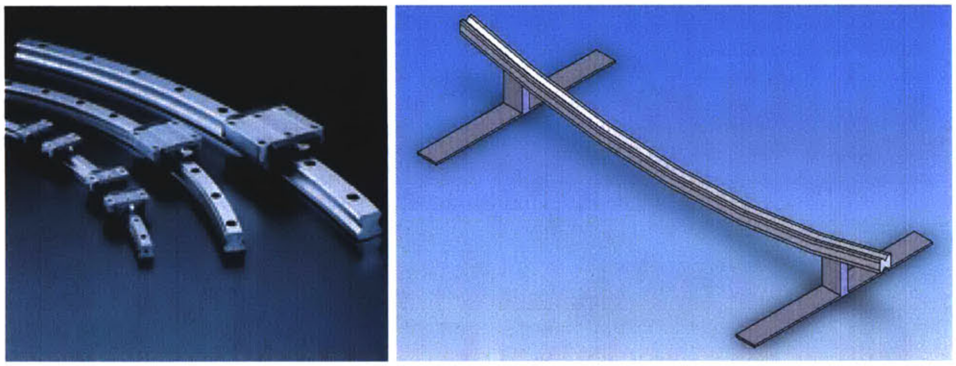
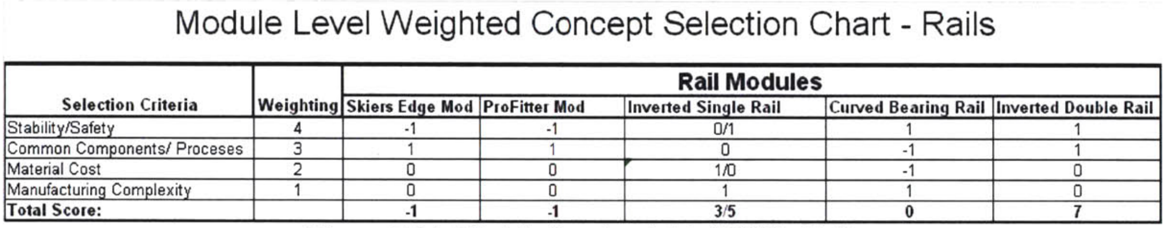


Figure 7-12: THK R-Guide Type HCR Curved Bearing Rail and Curved Bearing Rail Base

Using two parallel rails can eliminate many of the problems associated with the single rail approaches. For a parallel rail design, circular sections can be used. Circular sections are relatively straightforward to bend using commercially available roll benders, and can be mounted a wide distance apart. Two rails mounted apart also have compliances such that motion in the pitch direction is achieved “for free”. This results in a more complicated rail base, but also creates good resistance to the pitch axis moments, and doesn’t require any material in between the parallel rails. This parallel configuration also introduces numerous options for fully constraining the carriage to the track using only one type of wheel. The other advantage to circular tubing is that it is used by almost every exercise machine on the market, including almost all of the skiing exercise machines. The skiing machine companies also make carriage wheels designed for rails with circular cross sections. With this design it would be a simple matter to order carriage wheels to create a prototype carriage. The resulting exercise machine would be one that naturally fits in with the companies existing product line, and uses many common components and processes.

Figure 7-13: Inverted Double Rail Configuration



Module Level Weighted Concept Selection Chart - Rails

Selection Criteria	Weighting	Rail Modules				
		Skiers Edge Mod	ProFitter Mod	Inverted Single Rail	Curved Bearing Rail	Inverted Double Rail
Stability/Safety	4	-1	-1	0/1	1	1
Common Components/ Proceses	3	1	1	0	-1	1
Material Cost	2	0	0	1/0	-1	0
Manufacturing Complexity	1	0	0	1	1	0
Total Score:		**-1**	**-1**	**3/5**	**0**	**7**

Figure 7-14: Module Level weighted CSC - Rails

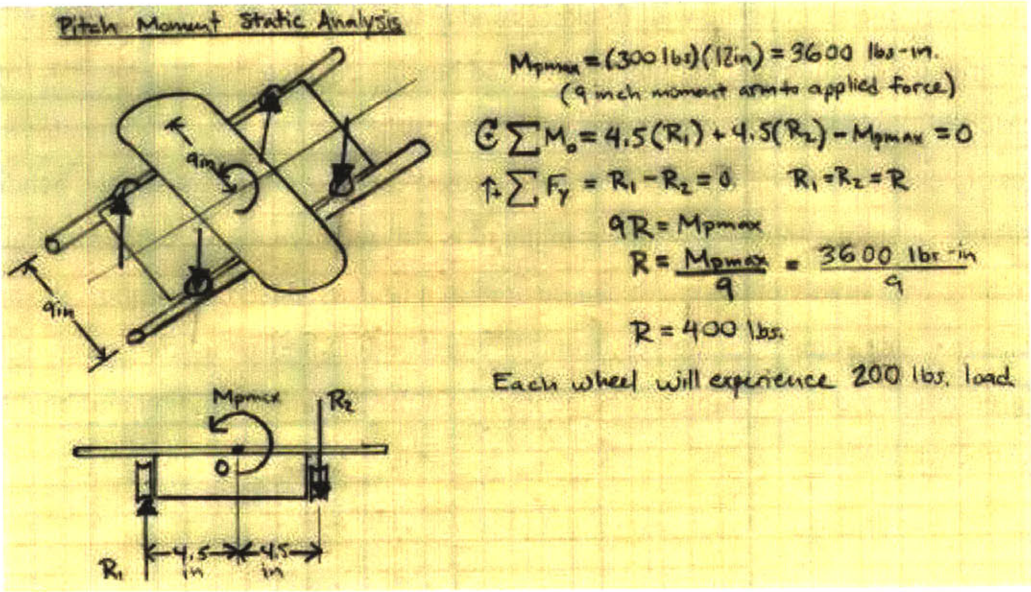
Using a weighted concept selection chart for the rail modules reveals that parallel inverted rails best meet the functional requirements for the rail configuration. The stability issues associated with modifying existing rail configurations put them at an early disadvantage. The decision, then, is between using a single or double rail. A double rail system is stable, and uses identical components to the existing skiing exercisers. The inverted single rail configuration can vary greatly depending on how it is implemented. Using a smaller cross section greatly simplifies manufacturing complexity and material cost, but is slightly less stable. A larger cross section increases the stability, but adds a significant amount of material. In addition, a single rail configuration has a much more compact rail base. Using a single curved bearing rail is great for a prototype, but the high cost of a precision curved bearing rail may be too much. The double rail design is the most desirable, but it seems likely that elements of the single rail base could be incorporated into the commercially available design to reduce material cost and manufacturing complexity.

7.1.2 Track Detailed Design

Once it is decided that a parallel inverted double rail is the best option for the rail design, detailed design is required to bring this module from the conceptual stages to a working prototype stage. For this particular module this involves the solid modeling and analysis of the rails, and the mounting of the rails to the rail frame.

The first major decision regarding the rails is the rail material. In this case steel is the obvious choice. The rails and support frame are structurally important to the design, and must be made of strong and wear resistant, yet inexpensive material. This leaves rail placement, cross section, and shape as the only remaining variables.

The spacing of the rails is critical to machine stability. When a user mounts the ride platform in a snowboarding stance, they will be able to exert large pitch moments through their body weight acting over a relatively large moment arm. Resistance to this moment occurs through the vertical reaction forces acting between the carriage wheels/ rail interface across the parallel track. If the spacing of the rails is wide, then the required reaction forces are smaller (Moment = Force * Moment Arm), and the rails are better able to resist the applied moment. If the rails are closer together, the resulting reaction forces are larger, and have potential to do damage to the machine. In the end a gap of 9 inches is chosen for the parallel rails. This decision is made based on the availability of the Skier's Edge carriage. By choosing a 9 inch gap, the existing Skier's Edge carriage can be immediately used to verify rail performance. Running a basic static analysis for an applied pitch moment shows that the reaction forces on the rails are reasonable for the most extreme case of a 300 pound person putting their entire weight on the end of a 12 inch moment arm.



$M_{pmax} = (300\text{ lbs})(12\text{in}) = 3600$ lbs-in.
(9 inch moment arm to applied force)

$\circlearrowleft \sum M_o = 4.5(R_1) + 4.5(R_2) - M_{pmax} = 0$

$\uparrow + \sum F_y = R_1 - R_2 = 0 \qquad R_1 = R_2 = R$

$9R = M_{pmax}$

$R = \frac{M_{pmax}}{9} = \frac{3600\text{ lbs-in}}{9}$

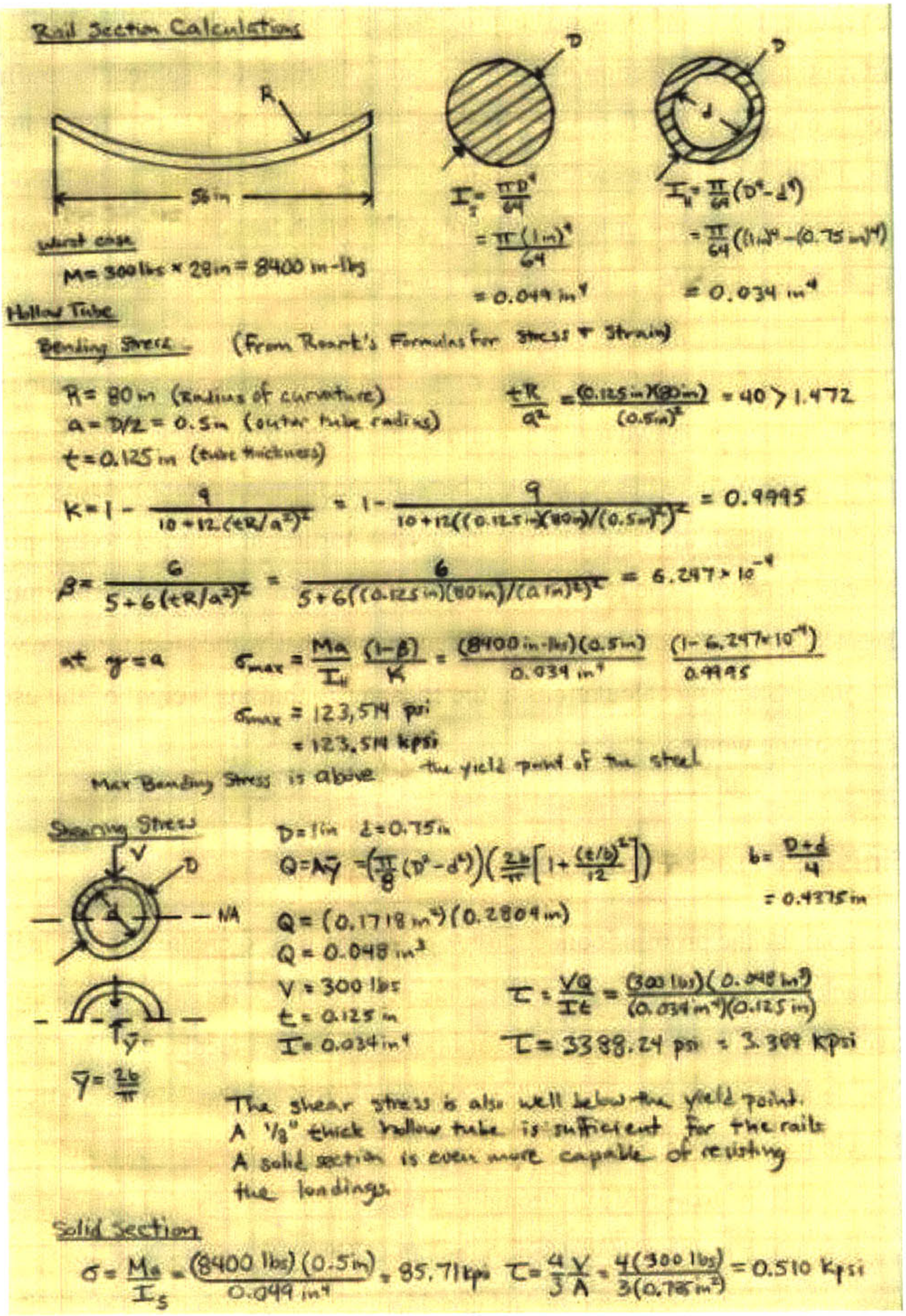
$R = 400$ lbs.

Each wheel will experience 200 lbs. load

Figure 7-15: Pitch Moment Static Analysis

The reaction forces calculated above are the worst case loading scenarios for the rails, and serve as a basis for the design of the rail cross section. One of the reasons for choosing a round section, is so exercise machine manufacturers can use existing carriage wheels and manufacturing processes. In this case the only requirement for the circular cross section is that it works with existing carriage wheels. The wheels used on the Skier's Edge machine (which can be purchased individually), require use of a 1 inch outer diameter rail.

The choice between using a solid or hollow rail is a tradeoff between manufacturing and design considerations. A solid rail has a much thicker section (resulting in a larger moment of inertia), and will support a much higher load than a hollow section. This thicker section, though it requires more force to bend, will also have fewer complications during bending (bending hollow tubing can result in buckling of the tube wall). The disadvantage to using a solid section is that a large thickness may not be necessary for the application. A solid section is heavier and more expensive than a hollow section, however, for a proof of concept prototype it makes sense to use a solid section, because it is best suited to carrying large loads, and can be easily bent to a large radius. Because only one prototype is created, the higher cost and weight is acceptable. For the commercial design, hollow tubing might be preferable. Calculations must be done to determine appropriate wall thickness and material properties in order to minimize the material used, while maintaining proper load bearing characteristics (Figure 7-16). In this case a 300lb load on the center of a 1/8" tube results in a 123 kpsi bending stress. This easily exceeds the yield stress of regular steel. A solid section reduces the bending stresses considerably, though a stronger material is still required. A variety of hydraulic steel tubing with high yield strength can be used in a finished design to support the user. Exercise machine companies are very familiar with bending hollow tubing, meaning that for a production product; tubing can be bent without the unwanted binding and buckling of the tube wall.



Rail Section Calculations

worst case

$M = 300\,\text{lbs} \times 28\,\text{in} = 8400\,\text{in-lbs}$

$I_s = \frac{\pi D^4}{64} = \frac{\pi (1\,\text{in})^4}{64} = 0.049\,\text{in}^4$

$I_H = \frac{\pi}{64}(D^4 - d^4) = \frac{\pi}{64}((1\,\text{in})^4 - (0.75\,\text{in})^4) = 0.034\,\text{in}^4$

Hollow Tube

Bending Stress (From Roark's Formulas for Stress + Strain)

$R = 80\,\text{in}$ (Radius of curvature)

$a = D/2 = 0.5\,\text{in}$ (outer tube radius)

$t = 0.125\,\text{in}$ (tube thickness)

$\frac{tR}{a^2} = \frac{(0.125\,\text{in})(80\,\text{in})}{(0.5\,\text{in})^2} = 40 > 1.472$

$$K = 1 - \frac{9}{10 + 12(tR/a^2)^2} = 1 - \frac{9}{10 + 12((0.125\,\text{in})(80\,\text{in})/(0.5\,\text{in})^2)^2} = 0.9995$$

$$\beta = \frac{6}{5 + 6(tR/a^2)^2} = \frac{6}{5 + 6((0.125\,\text{in})(80\,\text{in})/(0.5\,\text{in})^2)^2} = 6.247 \times 10^{-4}$$

at $y = a$

$$\sigma_{max} = \frac{Ma}{I_H}\frac{(1-\beta)}{K} = \frac{(8400\,\text{in-lbs})(0.5\,\text{in})}{0.034\,\text{in}^4}\frac{(1 - 6.247 \times 10^{-4})}{0.9995}$$

$\sigma_{max} = 123{,}514\,\text{psi}$

$= 123.514\,\text{kpsi}$

Max Bending Stress is above the yield point of the steel

Shearing Stress

$D = 1\,\text{in}$ $d = 0.75\,\text{in}$

$Q = A\bar{y} = \left(\frac{\pi}{8}(D^2 - d^2)\right)\left(\frac{2b}{\pi}\left[1 + \frac{(t/b)^2}{12}\right]\right)$

$b = \frac{D+d}{4} = 0.4375\,\text{in}$

$Q = (0.1718\,\text{in}^2)(0.2804\,\text{in})$

$Q = 0.048\,\text{in}^3$

$V = 300\,\text{lbs}$

$t = 0.125\,\text{in}$

$I = 0.034\,\text{in}^4$

$\tau = \frac{VQ}{It} = \frac{(300\,\text{lbs})(0.048\,\text{in}^3)}{(0.034\,\text{in}^4)(0.125\,\text{in})}$

$\tau = 3388.24\,\text{psi} = 3.389\,\text{kpsi}$

$\bar{y} = \frac{2b}{\pi}$

The shear stress is also well below the yield point.
A 1/8" thick hollow tube is sufficient for the rails
A solid section is even more capable of resisting
the loadings.

Solid Section

$\sigma = \frac{Ma}{I_s} = \frac{(8400\,\text{lbs})(0.5\,\text{in})}{0.049\,\text{in}^4} = 85.71\,\text{kpsi}$ $\tau = \frac{4}{3}\frac{V}{A} = \frac{4(300\,\text{lbs})}{3(0.785\,\text{in}^2)} = 0.510\,\text{kpsi}$

Figure 7-16: Rail Section Calculations

The bend radius for the rails is a more subjective design category. The bend radius of the track is dependent on two factors, geometry and the resulting ride motion. A horizontal rail length of 56 inches and a vertical rail height of 6 inches were originally chosen for the rails, based on the geometry of other skiing exercise machine designs. A corresponding rail bend radius of 80 inches was selected because it closely matched these geometric requirements, and provided approximately a 30° end slope for realistic snowboard motion. The selection of this bend radius is ultimately subject to testing of the finished prototype. Smooth, natural snowboard motion indicates that the radius is acceptable. Frequent collisions with the rail ends, or difficult carriage propulsion due to the end slope being too large or too small indicate the need for redesign of the rails. An 80 inch bend radius provides a good starting point for testing out the motion.

The design of the rail frame is part of the support frame module. The mounting of the rails to the rail frame, however, is extremely important to the track module. In the design of the carriage, there has to be room beneath the rails to accommodate constraint wheels. For this reason, the spacing from the lowest portion of the track to the ground must be at least 3 inches. The mounting height must account for both this minimum lower clearance, and the 9 inch spacing between rails. Finally, the steel rails are welded to the rail frame. Shearing calculations at the ends verify that the weight of the user will not break any of the welds.

7.1.3 Finished Track Prototype

The goal for the proof of concept track prototype was to create a functional section of track that can verify exercise machine performance. As such, it was imperative that the track be completed very quickly, for immediate design feedback. This meant that much of the detailed design, which is absolutely imperative for the commercially available device, was not used in the proof of concept prototype. Instead quick calculations were done to verify rail strength. Then, using the basic rail dimensions, bend radius, and spacing, a frame was welded to the rails. The end prototype is not as ergonomic as the commercial version (and considerably heavier), but it is incredibly effective in testing out the concept, and verifying that it is an appropriate motion.

The first step in building the proof of concept prototype was to bend the rails to the appropriate 80 inch bend radius. In the detailed design of the rails, given the 1 inch outer rail diameter, it was found that a hollow tube with a 1/8" inch wall thickness, made out of hydraulic tubing with a high yield strength could handle the loads exhibited by a 300 lb person. Using the solid bar provides appropriate strength, and easy and quick manufacture. Bending a solid bar was a less risky approach. With that decision made, two lengths of 1 inch diameter steel round bar stock were placed between rollers, and curved to an 80 inch bend radius. The bar was then cut off to a horizontal length of 56 inches.

The prototype rail frame was designed to simply mount the rails at the right spacing and height. It was created by using quarter inch angle bar, with steel end bars. Two segments of quarter inch steel angle bar were cut to lengths of 56 inches. On each end, a section of steel flat stock was welded to the angle bars to space them 10 inches apart (to mount the rails at 9 inches apart). Then two vertical segments were welded on each end, so that the rails could be mounted at the proper height. At this stage the rails were added, and MIG welded into place on the vertical strips. The finished frame was finally coated with primer to prevent oxidation. (Figure 7-17) The resulting frame, though heavy, is perfect for testing the inverted rails and verifying performance.

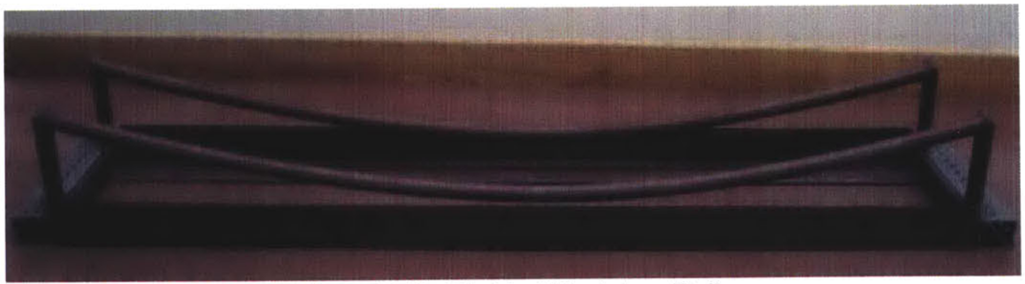


Figure 7-17: Finished Prototype Rails

7.1.4 Carriage Selection

Fabrication of the prototype track provided an easy transition into the design of the ride carriage. In the detailed design of the track, the rail diameter, and spacing of the parallel rails were decided on based on the dimensions and spacing of the carriage wheels used in the Skier's Edge. This meant that when the prototype rails were completed, the existing Skier's Edge carriage could be used immediately to test carriage motion along the rails. When this was done, the resulting motion was a smooth, curved motion from one end of the track to the other, indicating that the rail design worked as desired. The challenge arrived when adding a snowboarding interface to the existing carriage.

In order to create an exercise machine that simulates snowboarding, it is essential to require a snowboarder's stance when using the machine. Unfortunately this requires that the user's feet be placed on either end of the snowboard between 18 and 24 inches apart, effectively straddling the central curved track. To test this out, a simple set of foot pedals was added to the Skier's Edge carriage. (Figure 7-18) The Skier's Edge model in the lab contains only 4 wheels, positioned above the track. When a user attempted to mount the snowboard, they would apply the force of their body weight onto one of the foot pedals, outside of the base of support of the 4 wheels. The large resulting moment was enough to lift the entire opposite side of the ride carriage, derailing it. This meant that an entirely new carriage was required which fully constrained the carriage to the track.

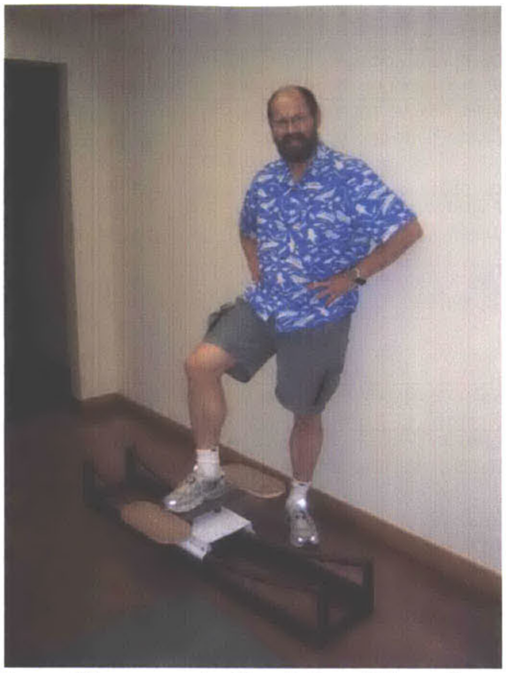
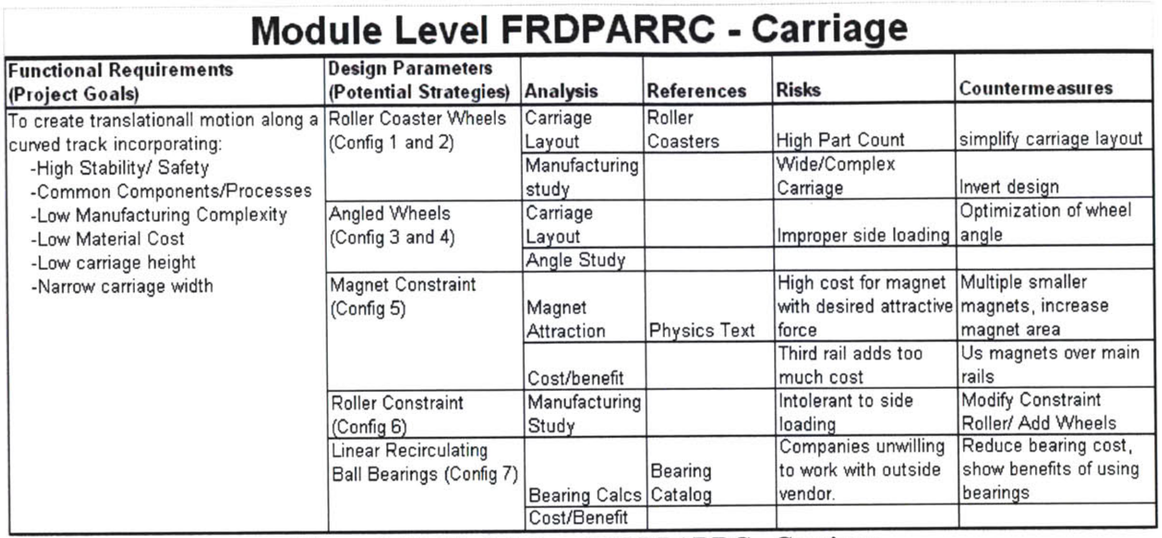


Figure 7-18: Professor Slocum and a Bench Level Experiment on the carriage

By definition, full carriage constraint requires that the ride carriage be able to resist all applied forces and moments except in the direction of intended motion. The carriage must resist horizontal and vertical transverse loading, in addition to the pitch, yaw, and roll moments described before. The first step in fully constraining the carriage is to determine a wheel layout which provides horizontal and vertical reaction forces to the transverse loading. The spacing of the wheels will then be determined to best resist the generated moments. In addition to the placement of the wheels, it is also necessary to consider the wheel type, material cost, manufacturing complexity, and size/height of the resulting configurations, when developing functional requirements.



Module Level FRDPARRC - Carriage

Functional Requirements (Project Goals)	Design Parameters (Potential Strategies)	Analysis	References	Risks	Countermeasures
To create translationall motion along a curved track incorporating: -High Stability/ Safety -Common Components/Processes -Low Manufacturing Complexity -Low Material Cost -Low carriage height -Narrow carriage width	Roller Coaster Wheels (Config 1 and 2)	Carriage Layout	Roller Coasters	High Part Count	simplify carriage layout
		Manufacturing study		Wide/Complex Carriage	Invert design
	Angled Wheels (Config 3 and 4)	Carriage Layout		Improper side loading	Optimization of wheel angle
		Angle Study			
	Magnet Constraint (Config 5)	Magnet Attraction	Physics Text	High cost for magnet with desired attractive force	Multiple smaller magnets, increase magnet area
		Cost/benefit		Third rail adds too much cost	Us magnets over main rails
	Roller Constraint (Config 6)	Manufacturing Study		Intolerant to side loading	Modify Constraint Roller/ Add Wheels
	Linear Recirculating Ball Bearings (Config 7)	Bearing Calcs	Bearing Catalog	Companies unwilling to work with outside vendor.	Reduce bearing cost, show benefits of using bearings
		Cost/Benefit			

Figure 7-19: Module Level FRDPARRC - Carriage

Through concept generation, seven different wheel layouts were developed. (Figure 7-21) The first layouts took their inspiration from steel roller coaster cars. In a roller coaster, there are three sets of wheels. (Figure 7-20) The load wheels are responsible for carrying the weight of the roller coaster car over the track. The stop wheels, also referred to as the up-stop wheels, are mounted beneath the steel track in order to prevent derailment. The third set of wheels is known as the guide or side friction wheels. These wheels are in place to resist side loadings and maintain wheel alignment on the track.

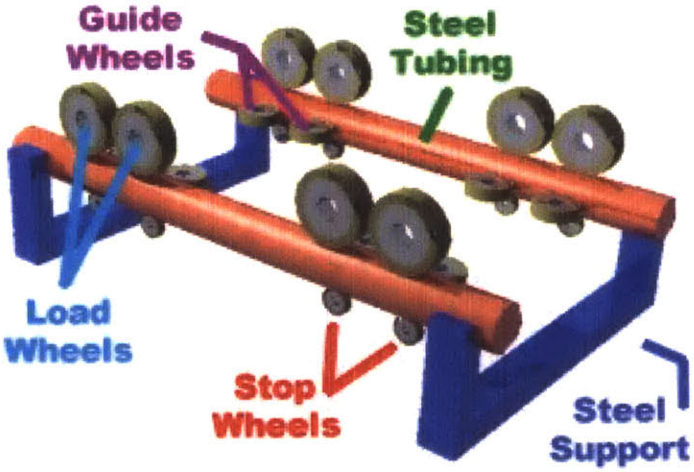
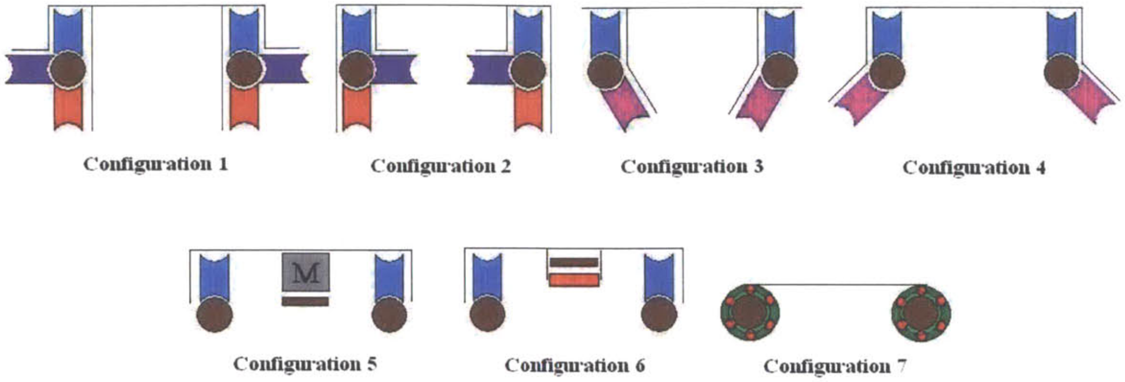


Figure 7-20: Roller coaster wheel configuration



Configuration 1
Configuration 2
Configuration 3
Configuration 4
Configuration 5
Configuration 6
Configuration 7

Figure 7-21: Carriage wheel configurations

Configurations 1 and 2 directly model the wheel configurations used in steel roller coasters. Here, the concave wheels used in most commercial skiing exercise machines can be easily utilized. In these two layouts, the load and up-stop wheels are located above and below the rails. The only difference between the two is the location of the guide wheels, where configuration 1 has guide rails on the outside, and configuration 2 has guide rails on the inside. This layout is inherently stable. The problem is that the curved wheels are not inexpensive. Both of these carriages require a total of 12 wheels (6 on each end). The layout of the wheels also leads to complicated wheel mounting on the carriage frame. Modification of these designs must be done to maintain stability, while reducing cost.

Mounting the curved wheels at an angle is an extremely viable method of simplifying the design, without sacrificing stability. In this case the lower angled wheels are a substitute for the up-stop and guide wheels. This reduces the total wheel count from 12 down to 8. In addition, the mounting of the angled bars is far simpler making it possible to create the carriage body out of a single piece of metal. A final bonus to using configuration 3, is that it fits in between the rails, resulting in a compact, but effective design.

The remaining three configurations involve more "out of the box" thinking. The first of these, configuration 5, utilizes identical load wheels to the previous layouts. The difference is that it uses a magnet to maintain carriage/rail contact. The powerful central magnet is attracted to a third steel rail, in between the main rails. This presents several problems. The first is that a powerful magnet can be expensive, and might require a licensing company to look to an outside vendor. The second is that a third rail adds a lot of weight, cost, and complexity to the design. This can be potentially remedied by using multiple magnets on the main rails in order to remove the central rail, but this does little to reduce the cost of using magnets in the design.

Configuration 6 is essentially a purely mechanical version of the magnet concept. Instead of using a magnet on a central rail, a roller is used to constrain the carriage. Unfortunately this offers little improvement over its predecessor. Using this approach, the undesired third rail is still necessary, in addition to a different type of roller to the regular concave wheels. This means that additional machines are needed for production. The final drawback of this approach is that it does not adequately constrain horizontal transverse motions. This design leaves a lot to be desired compared to the others.

The final wheel layout uses linear recirculating ball bearings to fully constrain the carriage to the track. In this setup, four linear ball bearings are attached to a carriage, such that the mounting can accommodate linear misalignment due to the bearings moving along a curved track. The advantages of this design are that the linear ball bearings provide resistance in all directions, require relatively simply manufacturing to build a carriage body, and allow the top of the carriage platform to be essentially on level with the track, lowering the user's center of mass by 2 to 3 inches over the other layouts. The problem with using linear ball bearings is that most exercise machine companies will have to seek outside sources to obtain (or even design) such bearings. Many companies are unwilling to do this, especially if it is cheaper and equally as effective to use regular carriage wheels.

Module Level Weighted Concept Selection Chart - Carriage

		Carriage Layouts						
Selection Criteria	**Weighting**	**Config 1**	**Config 2**	**Config 3**	**Config 4**	**Config 5**	**Config 6**	**Config 7**
Stability	4	1	1	1	1	0	0	1
Common Components	3	1	1	1	1	0	0	-1
Material Cost	2	-1	-1	1	1	-1	0	-1
Manufacturing Complexity	2	-1	-1	0	0	-1	-1	1
Size/Height	1	-1	0	0	-1	0	0	1
Total Score:		**2**	**3**	**9**	**8**	**-4**	**-2**	**2**

Figure 7-22: Module Level weighted CSC - Carriage

Weighted concept selection reveals that configuration 3 best meets the design requirements for the wheel layout. Using the curved wheel layout with inward angled wheels reduces the number of wheels required, fits in between the main rails, keeps the user at a reasonable height above the rails, and is manageable to design and construct. This layout is therefore the focus of detailed design.

7.1.5 Carriage Detailed Design

Detailed design of the carriage requires selection of the carriage wheels, proper placement of these wheels to match the chosen layout, and verification that the carriage can endure all applied loadings without failure. For the design of the prototype carriage, the goal is to create a quick, but well designed carriage for immediate testing. At the same time, commercial solutions must be developed, so that the carriage can be manufactured efficiently and inexpensively in a production version.

The selection and design of the carriage wheels is extremely simple. In the module selection, a configuration was chosen that uses carriage wheels from the Skier's Edge exercise machine. The Skier's Edge wheel assembly consists of a plastic molded carriage wheel (which conforms to a 1 inch diameter rail), 2 rotational ball bearings, and a bolt acting as a support shaft, properly spaced with washers, and locked down with a nut with a nylon ring insert. (Figure 7-23) The ball bearings used in the design are able to withstand high radial loads, and have a long running life. (Figure 7-24) Though these carriage wheel assemblies are designed for identical use in the Skier's Edge machines, it is important to run bending and shear calculations on the support bolt, to verify that the carriage wheels can withstand the weight of a user.

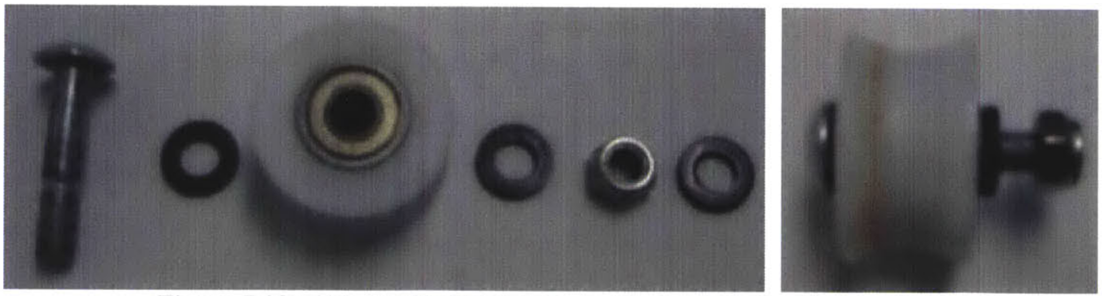
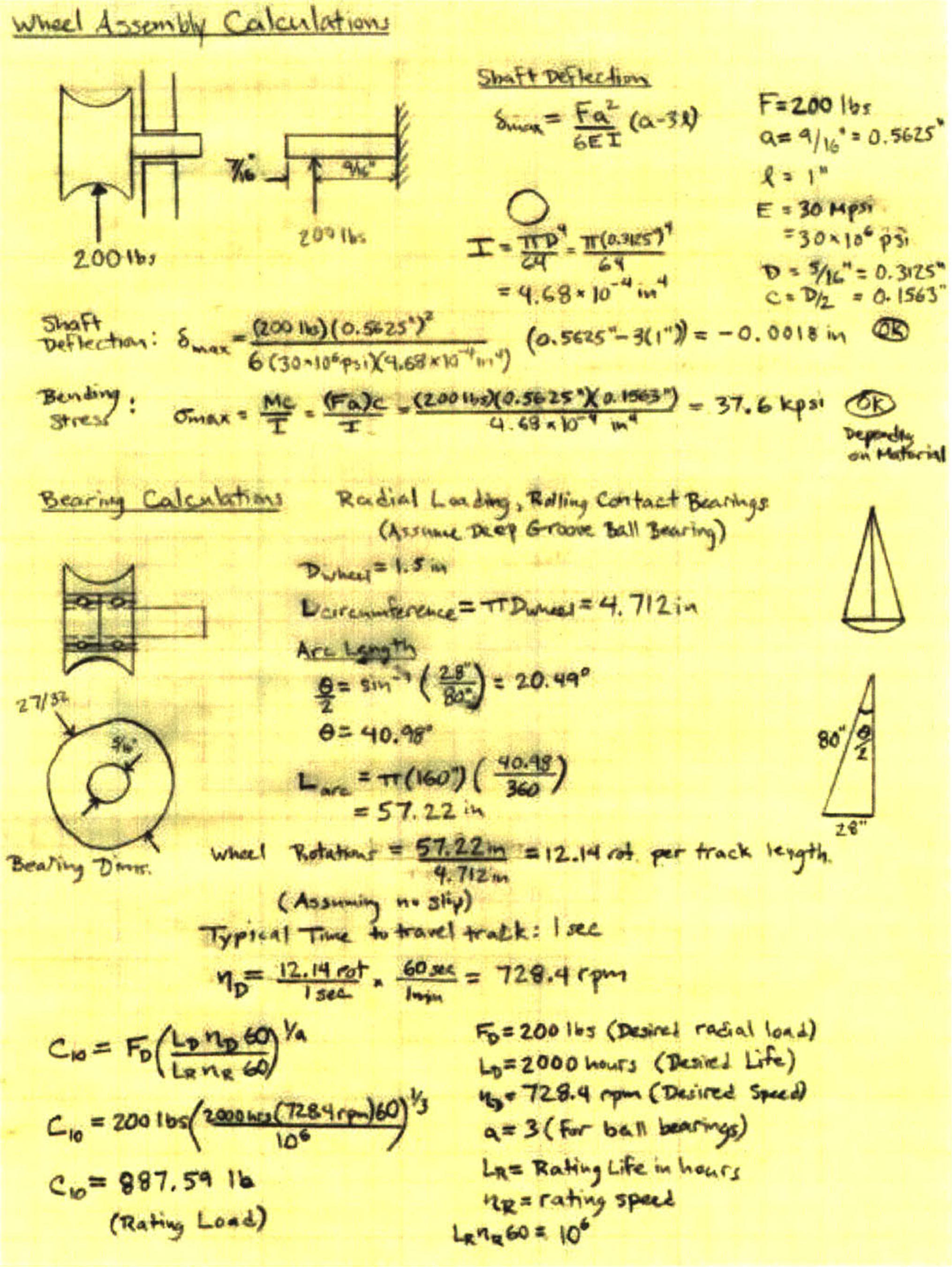


Figure 7-23: Skier's Edge Wheel Assembly (exploded and assembled)



Wheel Assembly Calculations

Shaft Deflection

$$\delta_{max} = \frac{Fa^2}{6EI}(a-3l)$$

$F = 200$ lbs
$a = 9/16" = 0.5625"$
$l = 1"$
$E = 30$ Mpsi
$= 30 \times 10^6$ psi
$D = 5/16" = 0.3125"$
$c = D/2 = 0.1563"$

$$I = \frac{\pi D^4}{64} = \frac{\pi (0.3125")^4}{64} = 4.68 \times 10^{-4}\ in^4$$

Shaft Deflection: $\delta_{max} = \frac{(200\ lbs)(0.5625")^2}{6(30\times10^6 psi)(4.68\times10^{-4} in^4)}(0.5625" - 3(1")) = -0.0018$ in OK

Bending Stress: $\sigma_{max} = \frac{Mc}{I} = \frac{(Fa)c}{I} = \frac{(200\ lbs)(0.5625")(0.1563")}{4.68\times10^{-4}\ in^4} = 37.6$ kpsi OK

Depending on Material

Bearing Calculations

Radial Loading, Rolling Contact Bearings
(Assume Deep Groove Ball Bearing)

$D_{wheel} = 1.5$ in

$L_{circumference} = \pi D_{wheel} = 4.712$ in

Arc Length

$$\frac{\theta}{2} = \sin^{-1}\left(\frac{28"}{80"}\right) = 20.49°$$

$$\theta = 40.98°$$

$$L_{arc} = \pi(160")\left(\frac{40.98}{360}\right) = 57.22\ in$$

Wheel Rotations $= \frac{57.22 in}{4.712 in} = 12.14$ rot. per track length.
(Assuming no slip)

Typical Time to travel track: 1 sec

$$n_D = \frac{12.14\ rot}{1\ sec} \times \frac{60\ sec}{1\ min} = 728.4\ rpm$$

$$C_{10} = F_D\left(\frac{L_D n_D 60}{L_R n_R 60}\right)^{1/a}$$

$$C_{10} = 200\ lbs\left(\frac{2000\ hrs(728.4\ rpm)60}{10^6}\right)^{1/3}$$

$C_{10} = 887.59$ lb
(Rating Load)

$F_D = 200$ lbs (Desired radial load)
$L_D = 2000$ hours (Desired Life)
$n_D = 728.4$ rpm (Desired Speed)
$a = 3$ (for ball bearings)
L_R = Rating Life in hours
n_R = rating speed
$L_R n_R 60 = 10^6$

Figure 7-24: Bearing Calculations

To arrange the carriage wheels in the same configuration as in the chosen wheel layout, a geometric analysis has to be done. The spacing of the load wheels must be at the same distance as the spacing of the rails. This means that the width of the carriage mount must be set so that the middles of the wheels are exactly 9 inches apart. The lower angled wheels act as both the up-stop wheels and the guide wheels. The appropriate angle of these wheels is dependent on the loadings. As previously discussed, the vertical forces are most dominant because the user is able to apply their entire body weight in the vertical direction. This means that the chosen angle should have a higher component of reaction force in the vertical direction, than in the horizontal. Mounting the angled wheel at 30° from the horizontal produces a much larger component of resistance in the vertical direction. To properly design the wheel mounts, the 30° angle must be placed such that the distance from the angle vertex, to the mounting holes is equidistant, and that both sets of wheels are in contact with the rail. (Figure 7-25)

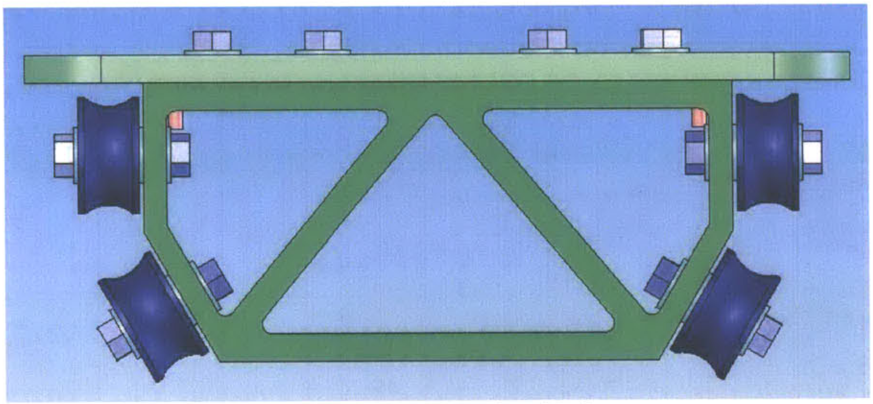


Figure 7-25: Carriage End

In the detailed design of the rails, rail spacing was important for resisting the applied pitch moments. In the same way, wheel spacing is critical for resisting roll and yaw moments. To select the rail spacing, the Golden ratio of 1.618 was used as a guideline. This means that for a 9 inch rail spacing, that a 14.5 inch wheel spacing would be appropriate. In the design, this value was rounded down to 14 inches for simplicity. With established wheel positions, there are options for several different carriage configurations.

Design of the prototype carriage requires a sturdy design that can quickly verify carriage performance, and allow for later modifications. In this case a design is desired that can be easily made using local machine shop resources. The most simplistic carriage design, for this purpose, consists of 2 wheeled end brackets mounted to a top plate for the proper wheel spacing. The end brackets are required to mount the wheels in the appropriate wheel layout. The bracket thickness must be large enough to accommodate the 5/16" wheel shaft bore, with enough material around the hole to maintain structural stability. In this case a ½" aluminum plate is sufficient. The cross section of the end plates requires triangular cross bracing for structural stability. The resulting section can then be produced with an abrasive waterjet cutter or a CNC Milling machine. With the finished cross sections, the mounting holes on the sides must be clearance holes for the wheel shafts. The top edge of the end bracket requires four 5/16" threaded holes for attaching the end brackets to the top carriage plate. (Figure 7-26)

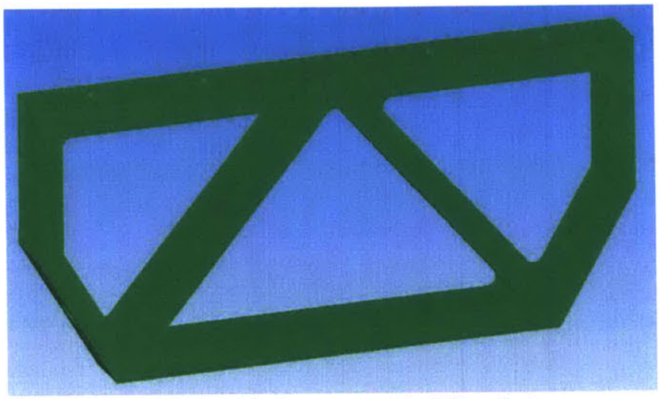


Figure 7-26: Prototype End Bracket

The top plate is simply a rectangular plate with rounded edges and can similarly be made out of aluminum (3/8" thick). Two rows of four 5/16" clearance holes are needed to attach the end brackets to the top plate at each end (using bolts threaded into the end brackets). In addition two 3/16" holes are added at each end, to accommodate spring pins. These spring pins are added in order to align the bracket end with the top plate end. The resulting geometry perfectly aligns the end brackets with the top plate ends. By making the top plate 11 inches wide it also overhangs the wheels on either side of the carriage protecting the user from the moving wheels. After assembly of the basic carriage, additional holes can then be drilled for the mounting of angular motion modules. (Figure 7-27)

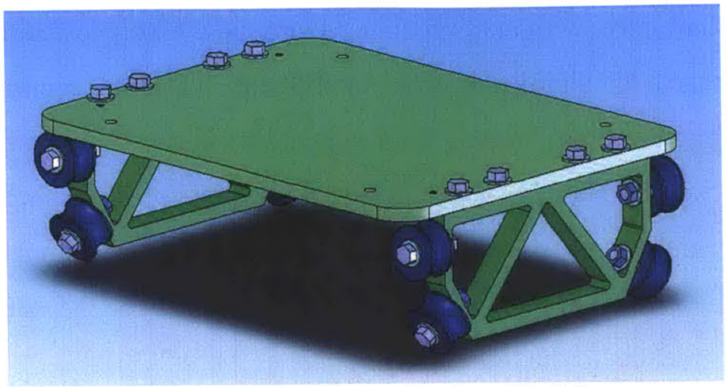


Figure 7-27: Prototype Carriage Module

The resulting prototype carriage is capable of supporting large loads, and accommodating numerous different test sections.

7.1.6 Finished Carriage Prototype

Fabrication of the finished carriage prototype was an incredibly simple process. This process began by calling the Skier's Edge Company, and ordering 8 wheel assemblies. (this being the primary reason that the machine was designed to work with common components). This step removed much of the machining difficulty in the prototype, and left only the brackets and top plate to be manufactured.

The end brackets were primarily machined using an abrasive waterjet cutter. A 2D drawing of the end bracket was extracted from ProEngineer, and opened in OMAX to create a waterjet cutting profile. After this, a ½" thick aluminum plate was loaded into the waterjet, and cut to the desired cross section. The completed end brackets were then drilled using a milling machine. The holes on the sides were drilled to 5/16" clearance holes to accommodate the wheel shafts. The holes on the top edge of the bracket were drilled and tapped to accommodate 5/16" bolts.

The top plate was also created on the waterjet. For the top plate, the water jet was used for both the outer edge and the holes. Four 5/16" clearance holes were waterjetted along each end to accommodate the bolts used to fasten the end brackets to the top plate. In addition, two 3/16" holes were waterjetted at each end for alignment spring pins. After the top plate was removed from the waterjet, spring pins were inserted into the 3/16" holes using an arbor press.

The assembly of the carriage must be done in the correct order to properly constrain the carriage to the rails. First, the four load wheel assemblies were attached to the end brackets by putting the wheel shaft through the vertical side clearance holes, and locking it with a locking nut. Next, the top plate was bolted to each end bracket, using 5/16 bolts and washers, threaded into the brackets. The semi assembled carriage was then lowered onto the track. Finally, the remaining wheel assemblies were fastened into place through the angled side clearance holes. This last step proved a little difficult, because the high ends of the curved wheels to do not want to easily fit into place under the rails (though with some manipulation, the wheels fit into place.). Once everything was secure, the carriage and rails were ready for testing. (Figure 7-28 and 29)

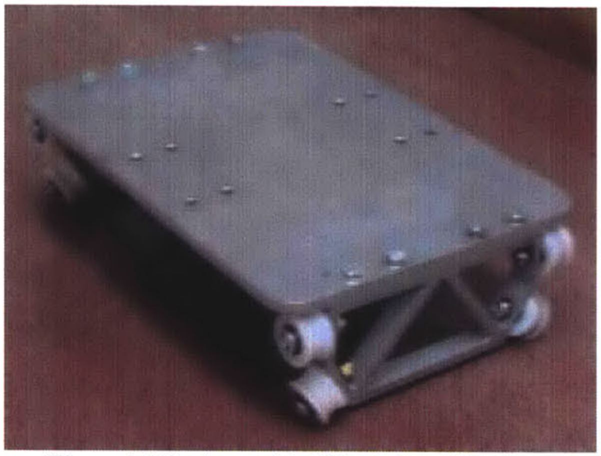


Figure 7-28: Assembled Prototype Carriage

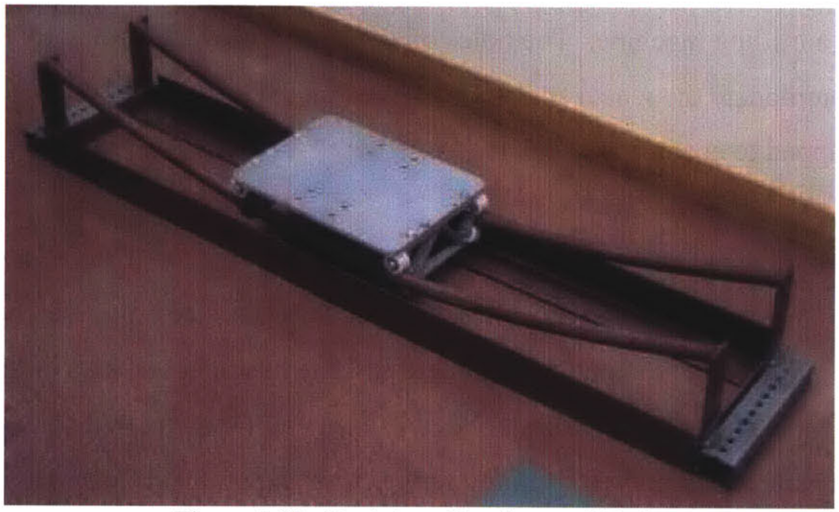


Figure 7-29: Prototype Carriage and Rails

Testing on the full carriage and rail assembly verified that the design produced a smooth inverted motion. Unfortunately, due to lack of a support frame, the design could not yet be mounted by a user. Instead, forces were applied on the carriage from external loading. When a large downward force was exerted on the machine, the load wheels would remain in contact, while the angled wheels were disengaged. When a large pitch moment was applied, one side of the carriage would remain with load wheels in contact with the rails, while on the other side the lower angled wheels engaged. This indicated that there were slight material deflections between the carriage and rails, but that all in all the carriage performed as designed. Addition of the support frame was no necessary to determine the ride feel.

7.2 Support Frame

Second in importance to the design of the carriage and rails, is the design of the support frame for the snowboarding exercise machine. When a user is on the exercise machine, they are moving their entire body weight back and forth along the carriage track. This generates a tremendous amount of momentum. When this occurs, safety is of the utmost importance. A person moving with a lot of momentum can badly injure themselves or others if they become unstable. A support frame is required to provide stability and support to the user, and if an accident happens, be designed in a way to minimize injury. The frame is also what dictates the overall machine footprint, meaning that collapsibility, storage, size, weight, and ease of assembly must be taken into account.

7.2.1 Support Frame Selection

Stability and safety are by far the most important functional requirements for the design of the support frame, but still require some explanation. Stability and safety most noticeably refer to the prevention of injury to the user. It is almost as important that the user feels secure and comfortable using the machine. This is essential for the user to want to purchase the machine and use it on a regular basis. All load forces exerted on the exercise machine have the potential to slide, wobble, tip, or even destroy the entire machine. Sliding and machine wobble are both undesirable effects, but ones that can be acceptable in small amounts. Tipping and mechanical failure are far more disastrous, and have the potential to cause serious injury.

Sliding refers to any translational motion relative to the floor. Sliding on the large scale results in user instability, and the potential for the frame "kicking out" from underneath the user (which could do damage to the machine, the surrounding area, or the rider). Sliding on the small scale is unwanted, but not nearly as dangerous. Luckily most of the unwanted sliding is managed easily by selecting a wider machine base, and high coefficient of friction rubber to serve as the interface between the machine and the floor.

Machine wobble is any small scale rotational motion of the machine relative to the floor, or parts relative to each other. These small scale motions in the carriage are typically due to lack of proper constraint and tolerance gaps in the frame interfaces. This is again a problem that can be easily addressed through proper design and constraint of the carriage.

Tipping is a much more serious concern. Tipping of the carriage means that a large majority of the machine base tilts about a pivot and lifts relative to the floor. Small tip will throw the user off balance (potentially off the machine entirely), and return to the stable position. Larger tip can be so severe that the machine falls over, throwing the user, or trapping them beneath the machine. In both cases there is complete instability of the machine and an extremely high probability that the user will fall and sustain injury.

Even more dangerous is the potential of mechanical failure in the support frame. For a component to fail, there must be a large enough loading to cause failure. In an exercise machine, almost all of the larger load forces are applied by the user. In most cases this means that the user is applying a high load to maintain stability. The resulting failure causes the user to lose support and fall on top of the machine. The probability of injury is extremely high, and even if the user escapes serious injury, they are left with a broken machine that will either be grudgingly sent for repair, or thrown out entirely.

The machine size is the other critical element to the design of the support frame. In most homes and gyms, space is very limited. This means that consumers have to carefully consider what is going to go in their limited space. A fully assembled snowboarding exercise machine will be large by necessity (taking into account the length of travel required for realistic snowboard motion). Most users can not permanently donate space to an exercise machine, and manufacturers can not afford to store or ship a fully assembled machine. This necessitates incorporating collapsibility, storage, and ease of assembly into the design of the module. The design should be capable of fitting easily into a 2'x2'x6' box, so that it can be stored and shipped at a bare minimum of expense, and conveniently stored in a basement, garage, or closet. The assembly and disassembly of the machine should also be as quick and painless as possible. This requires a straightforward, intuitive assembly plan, and a minimum of required assembly tools and parts.

Module Level FRDPARRC - Frame

Functional Requirements (Project Goals)	Design Parameters (Potential Strategies)	Analysis	References	Risks	Countermeasures
To provide a support frame incorporating: -User Stability/ Safety -Common Components/Processes -Low Manufacturing Complexity -Low Material Cost/ Part Count -Reasonable Machine Footprint -Easy Collapsibility/ Storage	Aerial Support Harness	Tension Analysis	Climbing equipment	Requires external mounting	Instead of external mountings, use support columns
				Users unwilling to wear harness	Fall back on belt system.
	Stationary Handrails	Stability analysis	Parallel Bars	Large machine footprint	Cut to single stationary rail
			Solid Mechanics Books	Height/ Width increase could add unnecessary cost.	Height/ Width adjustment can be removed, or limited
	Moving Handrails	Stability analysis		high cost for proper kinematic output	Fall back on stationary railing.
		Kinematic analysis	Mechanisms Text Book	Moving rail lacks stiffness in axial direction along the rails.	Damp railing motion

Figure 7-30: Module Level FRDPARRC - Support Frame

To fulfill these functional requirements, three designs were considered. The first design uses an aerial support harness. In this design a user is suspended by an adjustable support harness above the track. The ropes for this harness can be mounted in several ways. First, it can be physically attached to the ceiling using eye bolts. Second, it can be hung from large uprights on the machine corners, using regular rope. Third, it can be mounted on shorter uprights, using elastic cords. (Figure 7-31) In the connected harness the user is incapable of falling to the ground. Instead they are able to use the exercise machine as intended, and if they fall, the slack in the harness disappears, preventing injury. The advantage to using this approach is that the harness leaves the user's hands free, which is much closer to actual snowboarding. The disadvantages are numerous. Mounting the ropes from the ceiling requires drilling holes. Many consumers, especially those living in apartments, can not do this. Using uprights is not much of an improvement, given that large amounts of material and assembly are needed to elevate the rope mounts. Finally, using a harness is more complicated than the design needs to be. A simple self contained device with hand rails allows a user to instantly mount and use the machine, without having the hassle of putting on a harness.

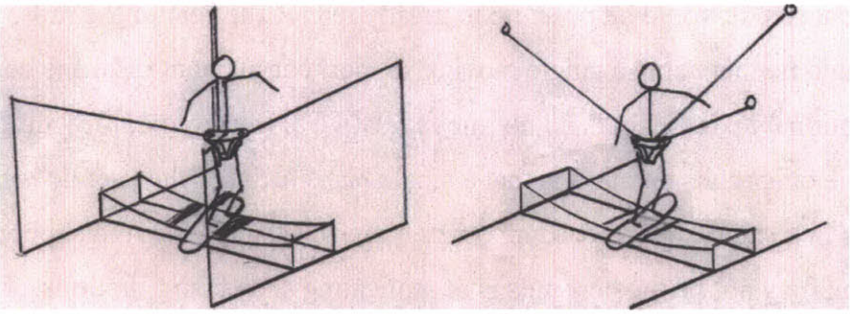


Figure 7-31: Aerial Support Harness Designs

The second design is far more traditional: a set of stationary parallel bars mounted on either side of the carriage track. In this approach the user is able to brace themselves on the bars to their right and left (parallel to the track). By making the rails height and width adjustable, the user can adjust the rails so that their arms are in a semi-natural snowboarding position. With practice it could be possible to balance without the use of the rails. This approach appears to be an effective and very simple means of adding stability, though use of two rails could add size and expense to the overall design. (Figure 7-32)

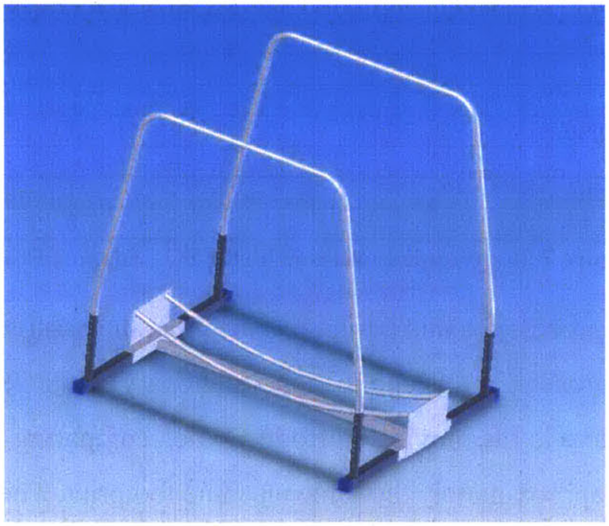


Figure 7-32: Support Frame with Parallel Support Structure

The third approach considers use of an active single support bar that moves with the user. This design would involve a single bar mounted perpendicularly to the track, constrained to move with a prescribed motion along with the track. This motion constraint could be handled either through use of linkages (possibly connected directly to the moving carriage), or through use of a custom track. Depending on the motion constraints chosen, it would be possible to greatly reduce the cost of the rails. The only problem would be that using a single moving support bar may not offer the desired support. Stationary parallel bars do not move relative to the ground, providing added stability. The other consideration is that a single bar in front of the user does not put the user's hands in a natural snowboarding orientation. The single moving support bar has its merits, but may not be the best means of replicating snowboard motions. (Figure 7-33)

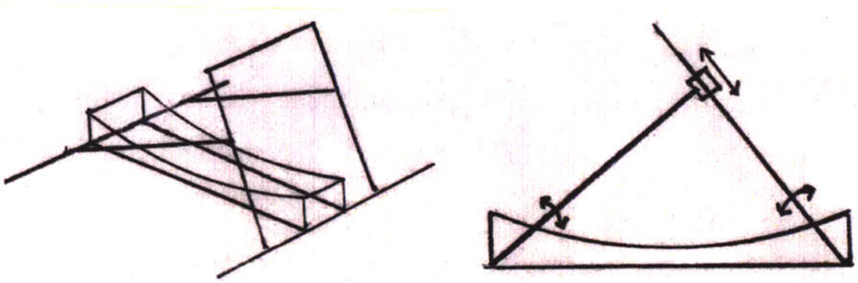
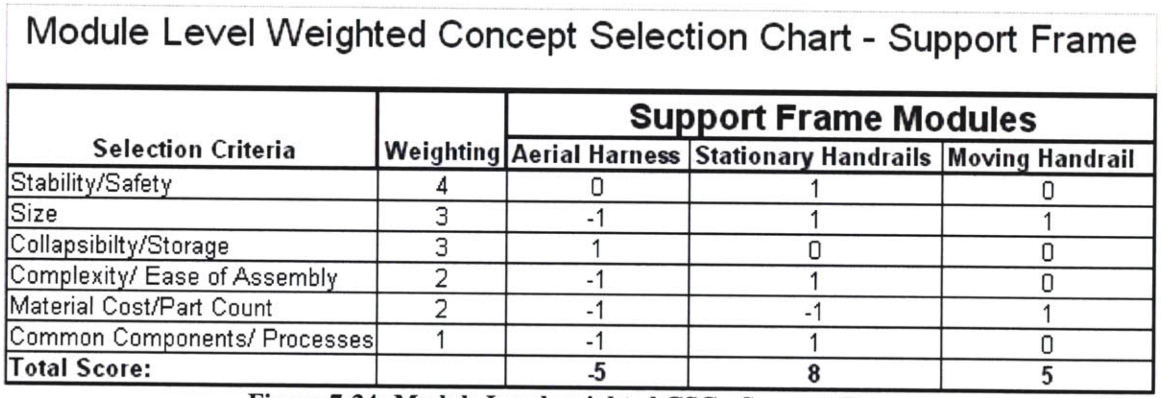


Figure 7-33: An Active Rail Design



Module Level Weighted Concept Selection Chart - Support Frame

Selection Criteria	Weighting	Support Frame Modules		
		Aerial Harness	Stationary Handrails	Moving Handrail
Stability/Safety	4	0	1	0
Size	3	-1	1	1
Collapsibilty/Storage	3	1	0	0
Complexity/ Ease of Assembly	2	-1	1	0
Material Cost/Part Count	2	-1	-1	1
Common Components/ Processes	1	-1	1	0
Total Score:		**-5**	**8**	**5**

Figure 7-34: Module Level weighted CSC - Support Frame

The selection process for this design revealed that the passive parallel support bars were the best approach for this application. Stationary bars offer the user a greater sense of stability relative to the moving platform. When comparing the size of the designs, all occupied approximately the same machine footprint. The moving handrail theoretically uses less material than the stationary handrail, but occupies the same overall space as two parallel rails. The collapsibility and ease of assembly are also favorable to the stationary approach. The moving handrail design is complex, with multiple moving parts. This makes the design less intuitive to the user, and more difficult to assemble. The stationary design has a set of handrails, rather than just one, but the assembly on each handrail is identical, greatly simplifying the process. Stationary handrails provide a stable, comfortable framework for users to use the exercise machine without fear of injury.

7.2.2 Support Frame Detailed Design

Design of the steel support frame required the largest amount of engineering work. The goal of the detailed design was to create a stationary parallel support system that provided stability to the user, while being easily collapsible and ergonomic. This process required a great deal of design work, supported by analysis to verify stability and frame strength.

After purchase, there are several different configuration "states" in which the snowboarding exercise machine can exist. The most basic of these is fully collapsed for storage. In this state, the machine footprint must be minimized. The biggest element of the entire machine is the track and carriage assembly, which can not be reduced in size. The remaining support bars, then, should be designed to fit alongside the rails, creating a minimum footprint. The next state, the fully assembled state, requires that the footprint be as wide as is feasible (to prevent sliding and tipping), with adjustable handrails for user comfort. The third state is a semi assembled state for advanced users. As users become increasingly adept at balancing on the motion platform, they may feel the need to remove the handrails. In this case the wide support base is still needed, but because the risk of falling is higher, all dangerous elements of the frame (bar mounts etc..) must be removed to eliminate any chance of impalement on the frame.

The rail frame is the logical starting point for the design of the support frame. The decision of where to mount the rails was decided in the detailed design of the track. The specific layout of the rail frame and how it connects to the larger support frame still requires discussion. The rail frame already contains the two parallel curved rails of the track, and two endplates to mount the rails at the appropriate height and spacing. Additional structural members, which do not bear transverse loading, are necessary to maintain the end constraints of the rails. Using a single rail for this introduces the potential for twisting about the single rail, or having the carriage slam into the support bar. Instead, two sections of 1.5" square tubing with 1/16" wall thickness, positioned just outside of either rail, create a stable end condition without risk of collision with the carriage.

The rail frame also must provide a connection for transverse support bars which increase the overall machine footprint. In this case there are two different mounting approaches: U brackets or sockets. The U bracket approach simply uses two inverted U's beneath the rail frame (lined with foam for a press fit), to connect to two single, full length transverse square tubes. (Figure 7-35) This allows for quick removal of the rail frame from the transverse bars, by simply removing locking pins and lifting the entire assembly. Fewer parts, though they are larger, also result in simpler assembly and storage. The biggest problem is that using an open section (the inverted U) results in a complete lack of torsional stiffness, creating instability in the ride frame. The inverted U was used in the prototype frame, illustrating this instability. The socket approach utilizes nestable square tubing (inserted and pinned to eachother), and eliminates torsional instability by closing the section. (Figure 7-36) The only drawbacks are that now 4 half length transverse tubes are needed, instead of 2 full length tubes. This adds several extra steps to the assembly, and creates more "clutter" in the storage of the device.

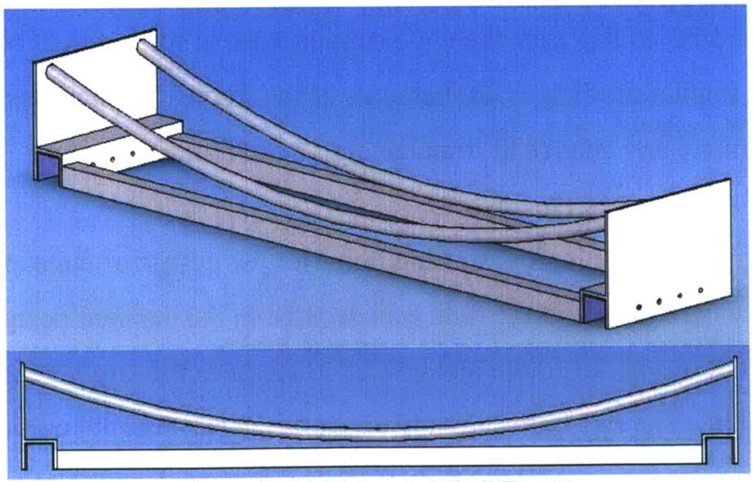


Figure 7-35: U Bracket Rail Frame

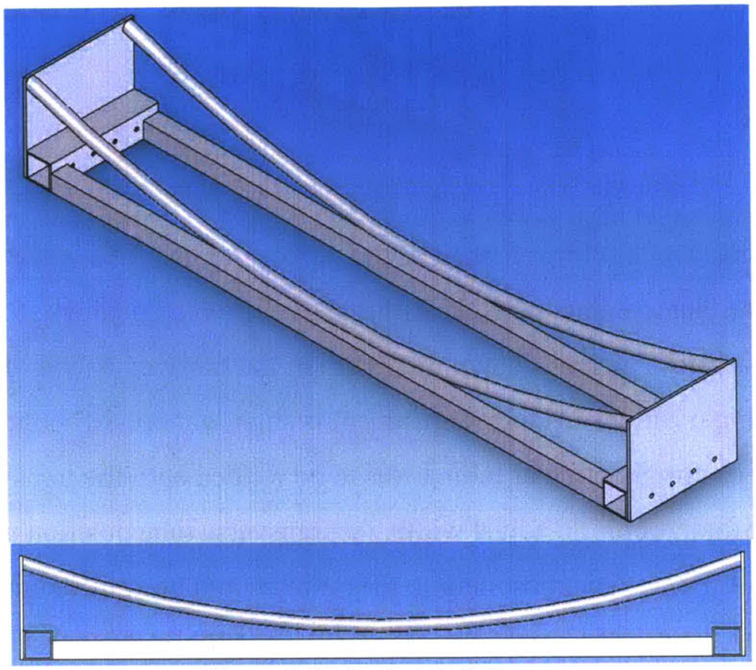


Figure 7-36: Socket Rail Frame

The transverse tubes on either end of the track are necessary to expand the machine footprint, in order to resist sliding and tipping of the machine. The transverse bar is a 4 foot length of 2 in square steel tubing with an 1/8" wall thickness, and holes down the length for connecting it with the rail frame and railing mounts. Each transverse tube has an end cap and high friction rubber pad at each end. The end cap is a safety precaution which covers the sharp edges at the end of the tube. The high friction pad's purpose is twofold. First, it resists sliding of the machine relative to the floor. Second, the pads at each end provide discrete contact points, such that the machine can sit on an uneven surface and not wobble. In the U bracket approach, a single length of transverse tube can be used at each end. For the socketed approach, these lengths must be cut in half. (Figures 7-37 and 38)

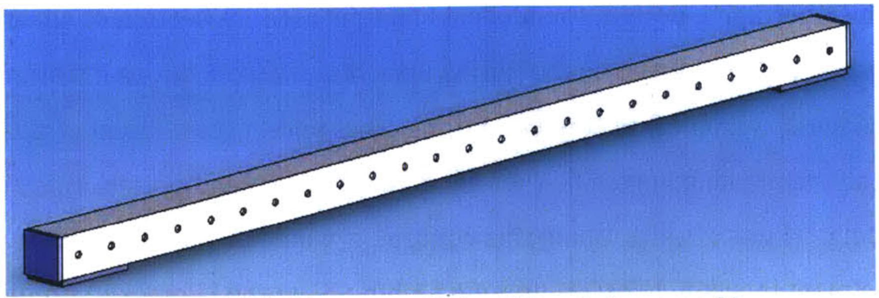


Figure 7-37: Transverse Tube (U bracket approach)

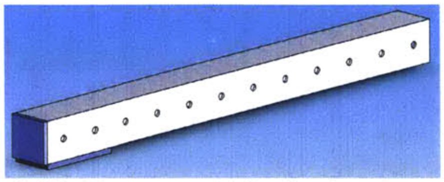


Figure 7-38: Transverse Tube (socketed approach)

The railings are the final element of the support frame. Ideally the goal for the railings is to have them height and width adjustable. Width adjustment, for this configuration, is easy. The holes down the length of the transverse tube offer numerous different mounting positions. Height adjustment is slightly more difficult. Originally a nestable section of upright circular tubing was to be welded onto the transverse tubes in the socketed configuration. To adjust width, the transverse tube position was adjusted relative to the rail frame. To adjust height, the railing could be adjusted in the upright circular section to the desired height. (Figure 7-39) The problem was that if the railings were removed, the upright sections remained, creating an impalement hazard. Instead, a simpler solution was found, removing the option of height adjustment.

Figure 7-39: Railing Configuration with undesirable height adjustment

In this alternative design, round steel tubing is used. A section of square U bracket is welded directly beneath the railing uprights. These sections of railing then have tapered ends, which connect with a railing crosspiece. The U bracket is then lined with foam, so that it can be press fit over the transverse tube and pinned at the desired railing spacing. (Figure 7-40) Using this concept, it would also be possible to bring back height adjustment by using telescoping round tubing, with the U bracket mounting strategy. This, however, adds parts and assembling complexity to the design. Selection of an appropriate average mounting height effectively removes the need for a height adjustment option.

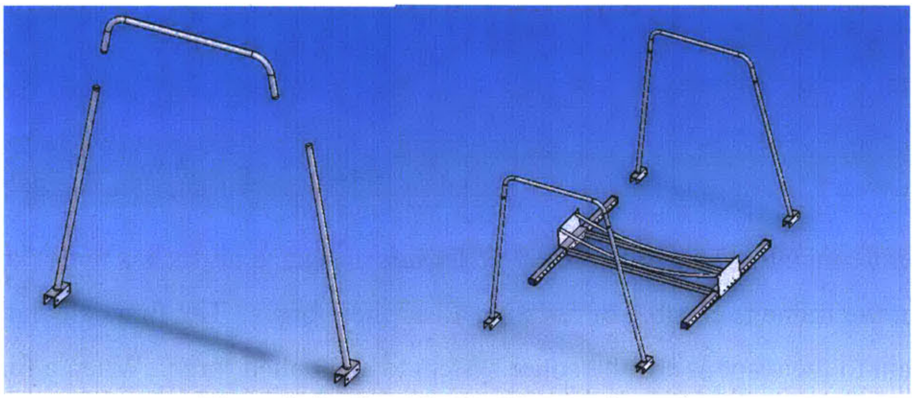


Figure 7-40: Simplified Railing configuration

Combining these various chosen elements renders the completed support frame. For the prototype the U bracket approach is used for the rail frame. The collapsibility of this approach is particularly desirable. The transverse tubes, railing uprights, and railing crosspiece are all long, and store in a narrow storage envelope. (Figure 7-41) Unfortunately the lack of torsional resistance requires that the socketed approach be pursued for a production model. The collapsibility of this approach is still good, it is just more labor intensive than the other approach. Users, however, will appreciate the added stability of the design. (Figure 7-42)

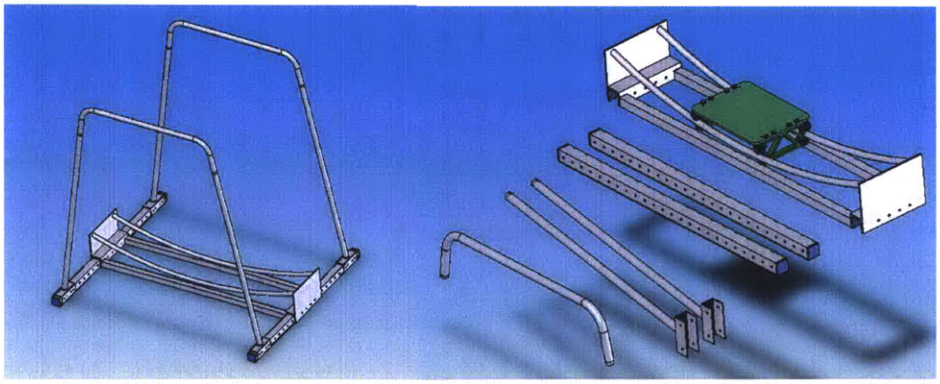


Figure 7-41: U bracket Approach (Assembled and Disassembled for Storage/Shipping)

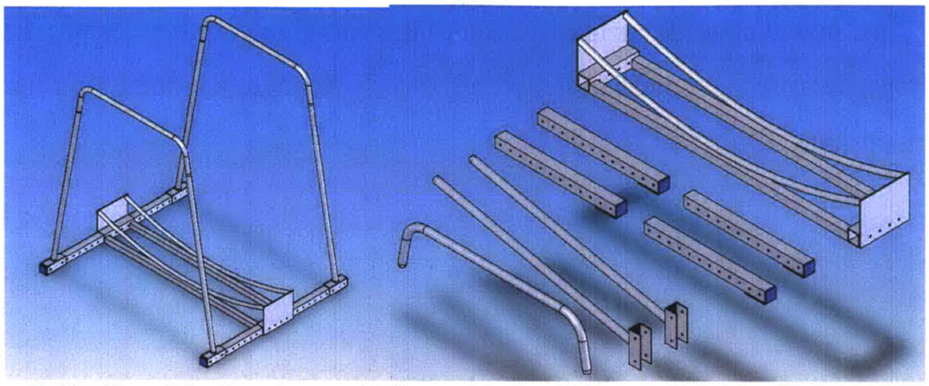
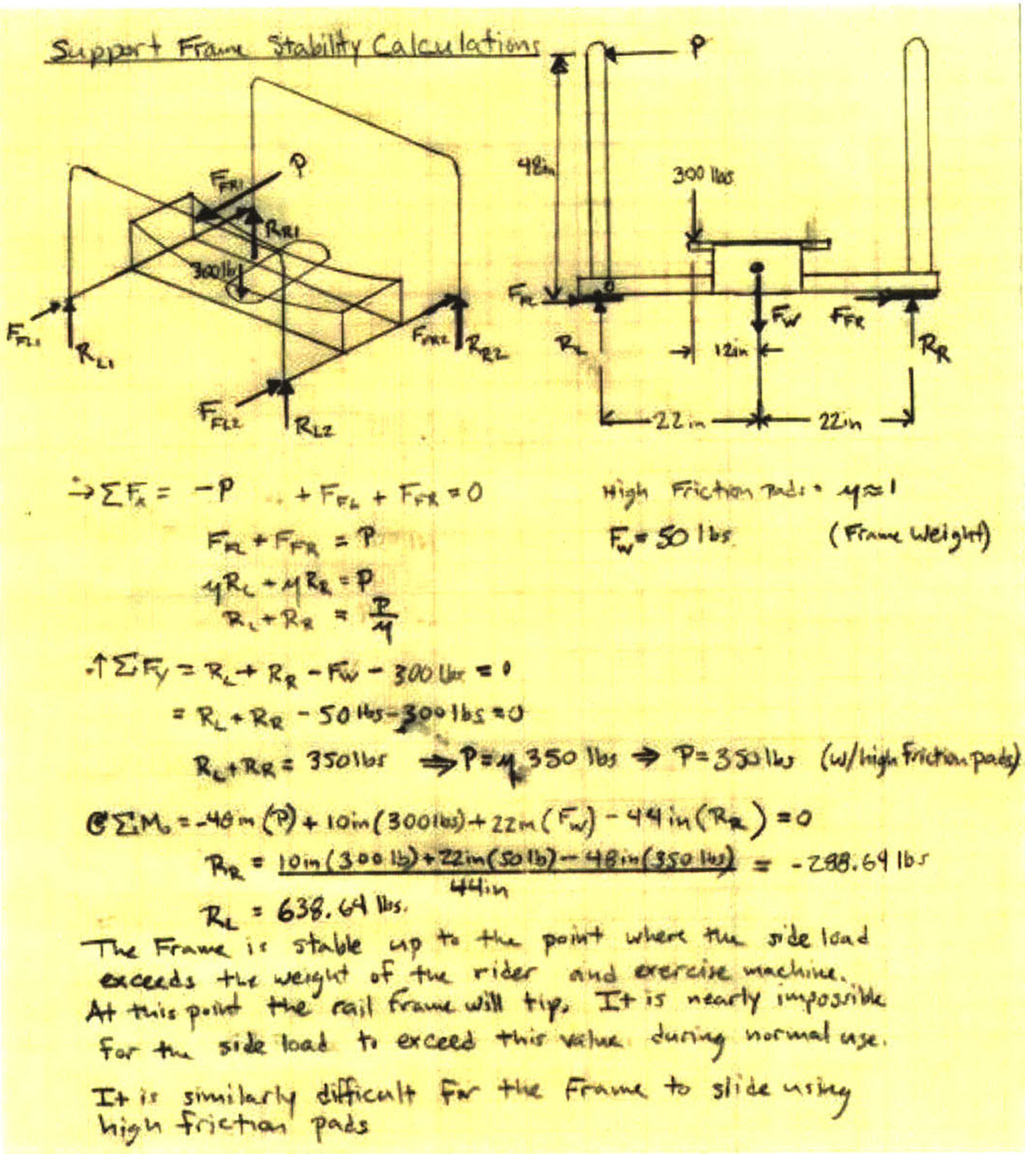


Figure 7-42: Closed Section Approach (Assembled and Disassembled for Storage/Shipping)

Before manufacturing the prototype for this design, analysis has to be done to ensure that the frame is capable of resisting all applied forces. The first calculations to be done pertain to the response of the entire system to an applied force. When a force is applied, the system will either tip or slip. Given the wide footprint of the base, this design will experience sliding far before it experiences any tip. With high friction pads underneath the transverse tubes, even the sliding is eliminated. The attached analysis shows that the design is able to resist large forces, with minimal sliding.



Support Frame Stability Calculations

$$\rightarrow \sum F_x = -P + F_{FL} + F_{FR} = 0$$

$$F_{FL} + F_{FR} = P$$

$$\mu R_L + \mu R_R = P$$

$$R_L + R_R = \frac{P}{\mu}$$

High Friction Pads: $\mu \approx 1$

$F_w = 50 \text{ lbs}$ (Frame Weight)

$$\uparrow \sum F_y = R_L + R_R - F_w - 300 \text{ lbs} = 0$$

$$= R_L + R_R - 50 \text{ lbs} - 300 \text{ lbs} = 0$$

$$R_L + R_R = 350 \text{ lbs} \Rightarrow P = \mu\, 350 \text{ lbs} \Rightarrow P = 350 \text{ lbs}$$ (w/high friction pads)

$$@ \sum M_o = -48\text{in}(P) + 10\text{in}(300\text{lbs}) + 22\text{in}(F_w) - 44\text{in}(R_R) = 0$$

$$R_R = \frac{10\text{in}(300\text{ lb}) + 22\text{in}(50\text{ lb}) - 48\text{in}(350\text{ lbs})}{44\text{in}} = -288.64 \text{ lbs}$$

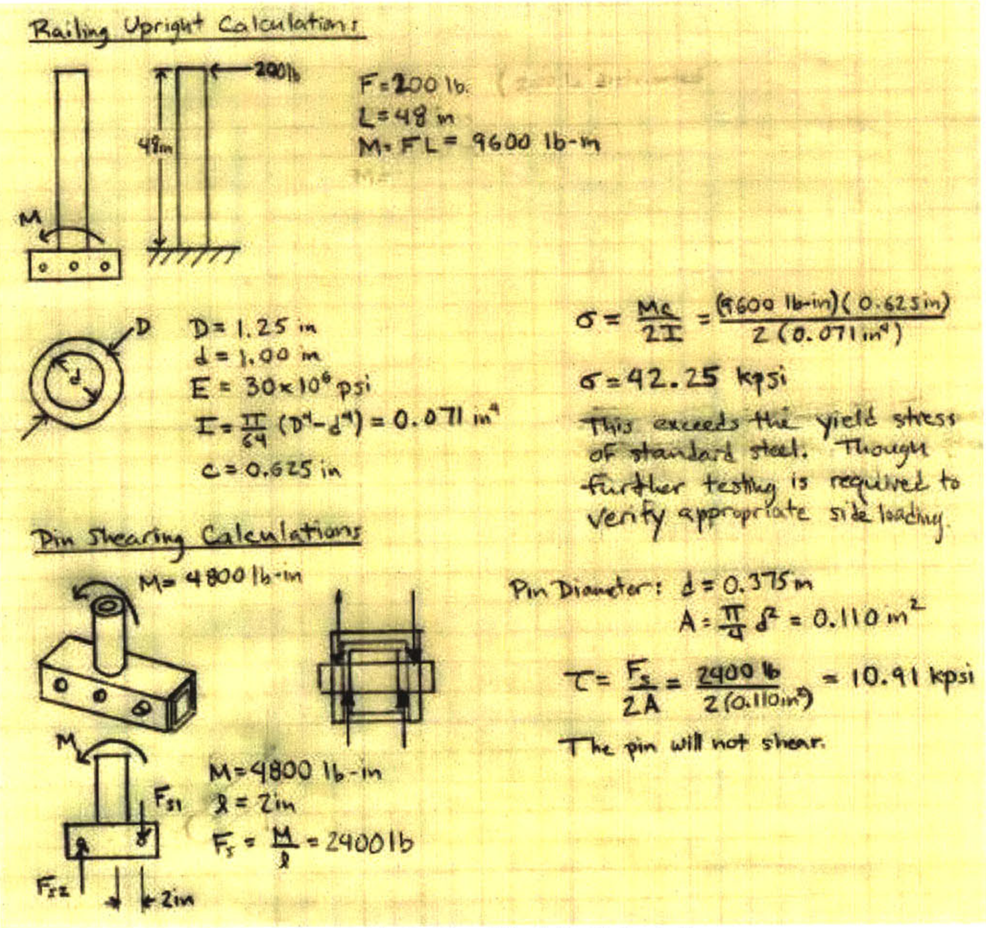
$$R_L = 638.64 \text{ lbs.}$$

The Frame is stable up to the point where the side load exceeds the weight of the rider and exercise machine. At this point the rail frame will tip. It is nearly impossible for the side load to exceed this value during normal use.

It is similarly difficult for the Frame to slide using high friction pads

Figure 7-43: Stability Calculations

The other trouble spot in the design is the reaction at the point where the railings meet the transverse tubes. If a user were to put their full body weight against the railing crosspiece, a tremendous moment would be generated at the railing base. If the load was high enough, it could potentially cause failure in the support pins, the mounting holes, or the interface between the railing upright and the U bracket. Careful analysis shows that with a railing wall thickness of 1/8", and 3/8" diameter support pin, that a 200 lb force will exceed the yield stress of standard steel. The 200 lb force, however, is questionable. If a person were to fall, their entire bodyweight would not be exerted in side loading. If the side load is decreased to 100 lbs, the resulting bending stress (21.2 kpsi) is reduced beneath the yield point.



Railing Upright Calculations:

$F = 200$ lb.
$L = 48$ in
$M = FL = 9600$ lb-in

$D = 1.25$ in
$d = 1.00$ in
$E = 30 \times 10^6$ psi
$I = \frac{\pi}{64}(D^4 - d^4) = 0.071$ in^4
$c = 0.625$ in

$$\sigma = \frac{Mc}{2I} = \frac{(9600 \text{ lb-in})(0.625 \text{ in})}{2(0.071 \text{ in}^4)}$$

$\sigma = 42.25$ kpsi

This exceeds the yield stress of standard steel. Though further testing is required to verify appropriate side loading.

Pin Shearing Calculations

$M = 4800$ lb-in
$\ell = 2$ in
$F_s = \frac{M}{\ell} = 2400$ lb

Pin Diameter: $d = 0.375$ in
$A = \frac{\pi}{4} d^2 = 0.110$ in^2

$$\tau = \frac{F_s}{2A} = \frac{2400 \text{ lb}}{2(0.110 \text{ in}^2)} = 10.91 \text{ kpsi}$$

The pin will not shear.

Figure 7-44: Railing Upright Calculations

Now that the analysis shows that the frame should work as desired, the support frame can be manufactured, and the basic machine motion can be fully tested.

7.2.3 Finished Support Frame Prototype

During the development of the rail prototype a simple base is constructed to mount the rails at the proper height and spacing. This rail frame is appropriate for rapid testing of the rails, though its design is not ideal for integration with other modules. Given the time constraints of the project and the desire to keep the design inexpensive, it is more practical to use the existing inverted rail frame rather than manufacturing a new integrated frame. Outfitting the existing frame offers identical functionality, though it lacks the aesthetic quality of an integrated design.

Due to the ease of assembly, the open section (U bracket) approach is initially chosen for the rail frame. In this configuration, the open sections are part of the rail frame, and fit directly over two 4 ft length sections of steel square stock. To create this, nestable square tubing is used. 2-1/4" and 2" nestable square tubes are purchased, with 5/16" holes down the length of the tube. For the U brackets, two sections of the 2-1/4" tube are cut to a 10 inch length, and the bottom edge of the tube is removed with a band saw. The ends of the existing rail frame are then ground and sanded to remove all primer and paint. The U brackets can then be welded onto each end of the rail frame.

The transverse bars are similarly simple. The 2" square tubes are available in 4ft lengths, which is the desired length of the transverse bars. After ordering the bars, rubber skid pads can be added with simple adhesive.

The railings are a little more challenging. The railings in the detailed design are custom bent to angles designed for the distance between the transverse bars. By necessity, the U brackets are mounted further apart on the prototype. In the prototype, many changes may need to be made to adjust the height and width of the railings. Creating custom bent railings requires that a section of tube be placed into a pipe bender, and bent to the proper angle. This process is not easy to reverse, if design changes need to be made. A simpler solution is available.

Galvanized electrical conduit is frequently used in wiring, and consists of a thin walled circular steel tube, with a zinc coating. Though most electrical conduit is sold in straight sections, most hardware stores offer 90° bends to move conduit around corners. There are also conduit connectors, which fit over sections, and clamp down on the conduit with set screws. By purchasing sections of conduit and connectors, vertical railings can be created, using 90° sections to connect to a horizontal crossbar. This removes the need to bending (greatly facilitating prototyping), and is easily adapted for different heights and configurations. The high part count, which would be a detriment for a commercial machine, is desirable because it produces a functional prototype with relatively minimal effort.

Figure 7-45: Standard 90 Degree Bend Electrical Conduit and Set Screw Connectors

After purchasing conduit, 4 vertical sections are cut such that the crossbar railing height is 56 inches. At the same time, four 6 inch lengths of the 2-1/4" square tubes are cut to length, and cut on the band saw to remove the bottom edge, creating U brackets. In order to weld the galvanized conduit onto the U brackets, first the weld site on the galvanized tube is thrown on a belt sander to remove the outer zinc coating on the pipe. The cleaned steel surfaced is then welded together to create the uprights. Two horizontal sections are then cut to bridge the gap between the transverse bars. The finished parts are then assembled on the exercise machine.

Figure 7-46: Welded Upright for Prototype Railing

To assemble the support frame, first the transverse bars are thrown underneath the rail frame and rigidly attached with bolts. The four uprights are then placed at even spacing from the rail frame, using 2 bolts with wingnuts to clamp the U brackets of the uprights to the transverse bars. The railings are then completed by using the conduit connectors and set screws to attach and lock down the 90° bends and horizontal crossbars. (Figure 7-47)

Figure 7-47: Full Prototype Support Frame

Using the completed frame provides a relatively stable frame to hold while using the machine, though it also reveals the inherent problems of using open section. When applying forces along the long axis of the frame, there is considerable play in the frame. This is primarily due to the lack of torsional stiffness inherent to the open sections in the design. Switching to a socketed approach, in addition to more solid clamping of the brackets to the frame will greatly cut down on the play along the long axis. In addition, there is similar play in the transverse direction caused by tolerance stack ups in the bolt holes and gaps between the brackets and the frame. Padding the inside of the brackets creates a press fit that will also greatly reduce this problem. For the purpose of a proof of concept prototype, the resulting support frame provides enough stability to effectively test the ride motion of the exercise machine.

7.3 Angular Motion Module

On a snowboard the user is capable of tipping the board in the pitch, yaw, and roll directions to manipulate their decent down a hill. For a commercially available snowboarding exercise machine, though, the user will want the ability to activate or deactivate degrees of freedom that may not be desired when working specific muscle groups. It is therefore important to develop different modules which incorporate different combinations of angular motions. For a base level machine (or a proof of concept prototype), the first desired motion is to simulate "carving" down a mountain slope. The basic carving motion requires a combination of roll axis and yaw axis motion. Through further simplification, roll axis motion can be used to largely simulate the motion of a snowboarder down a hill. By using a stacked axis approach, more degrees of freedom can be added, as deemed appropriate by the user.

7.3.1 Angular Motion Module Selection

As with many previous modules, stability and safety are the most important functional requirements for a successful angular motion module. Addition of an angular motion module introduces new degrees of freedom to the user, outside of the normal translational motion of the carriage along the track. This creates a more realistic snowboard motion, but also adds instability to the system. For this reason, it is important to ensure that the ride platform has a default stable position, so that users can safely mount and dismount the platform. The lower the user's center of mass is the better.

Also, the motions must be appropriately limited, so that angular motions are not rapid, potentially throwing the user off balance.

Realistic snowboard motion is also of critical importance in the design of this module. If an angular module is incorporated into the exercise machine, the resulting motion must have a similar feel to doing that same motion on a mountain slope. A simple pivoted platform with a bearing may move to the same positions as a snowboard, but without proper resistance, a pivoted platform can never feel like manipulating a snowboard through snow. By incorporating linear or nonlinear reaction forces into the angular motions, the feel (and stability) of the module can be greatly improved.

Part count, material cost, size/portability, complexity, and ease of assembly also play an important role in the design of this module. Ideally numerous different angular motion modules will be available for purchase, offering an entire range of different motions and exercises for different muscle groups. For this to be convenient, the modules will have to be light weight, simple, and easily swapped out for a different module. From a manufacturing standpoint, these modules must be designed for inexpensive manufacture, so they can be offered to the consumer at a minimum price.

Concept generation yielded a wealth of potential methods for incorporating an angular motion module into the design of the exercise machine. Initial concepts aimed at including pitch, yaw, and roll axis motions into the design. Several of these designs offered 3 degree of freedom rotation without use of springs. To incorporate resistance elements into the 3 degree of freedom concepts, linear and nonlinear springs were incorporated into the design. As the project evolved, it was discovered that a 3 degree of freedom approach is not necessarily desirable. Instead, using a stacked axis approach best met the needs of the design. A roll axis module provides a reasonable approximation of carving a turn. After demonstrating successful roll axis motion, the entire module can then be "stacked" on top of a yaw axis module, adding another degree of freedom.

Module Level FRDPARRC - Angular Motion

Functional Requirements (Project Goals)	Design Parameters (Potential Strategies)	Analysis	References	Risks	Countermeasures
To provide localized angular motion incorporating: -User Stability/ Safety -Realistic Snowboard Motion -Common Components/Processes -Low Manufacturing Complexity -Low Material Cost/ Part Count -Portabiliy -Easy Collapsibility/ Storage	3 DOF Springs	Stiffness Analysis	Machine Elements Textbook	Off center loads on a single row of springs creates buckling.	Add springs out of plane
		Stability Analysis		A person on top of springs is inherently unstable.	Lower foot height below springs.
	3 DOF Hanging	Stability Analysis	Statics Textbook	Repeated Impacts on mounting bracket.	Pad the brackets, or limit hanging motion.
	3 DOF Ball Transfer	Stability Analysis/ Bearing Selection	Bearing Catalogs	Constraints to prevent separation, also prevent desired motion	Can the design function with separation possible
	3 DOF 3D Nonlinear Springs	Stiffness Analysis/ Testing	Jian Li's Thesis	Research required for end conditions and transtion to 3D. Time intensive	Preliminary tests to indicate design potential before selection.
	Roll Axis 2D Nonlinear Springs (stackable)	Stiffness Analysis/ Testing	Jian Li's Thesis	Research required for end conditions. Time intensive	Preliminary tests to indicate design potential before selection.
	Roll Axis Axle w/ springs/foam (stackable)	Stifness Analysis/ Testing	Machine Elements Textbook	Roll Axis motion only may lack some motion sensations.	Initially use roll axis, add yaw if needed.

Figure 7-48: Module Level FRDPARRC - Angular Motion

The first angular motion module considered uses 2 valve springs (typically used in engines), connected directly between the motion platform and the carriage. (Figures 7-49) The spring orientation in this configuration is such that a user is capable of limited motion in all three angular directions. Due to the simplicity of the design, a bench level prototype was built to test the feel of the tipping sensations, and try the module using the Skier's Edge platform on the inverted rails. (Figure 7-50) Though the tipping responses had the right feel and resistance for snowboarding, the module was incredibly unstable. The height of the platform elevates the user's center of mass by several inches. If the user's weight moves outside of the base of support for the springs, the entire motion platform tips, throwing the user off.

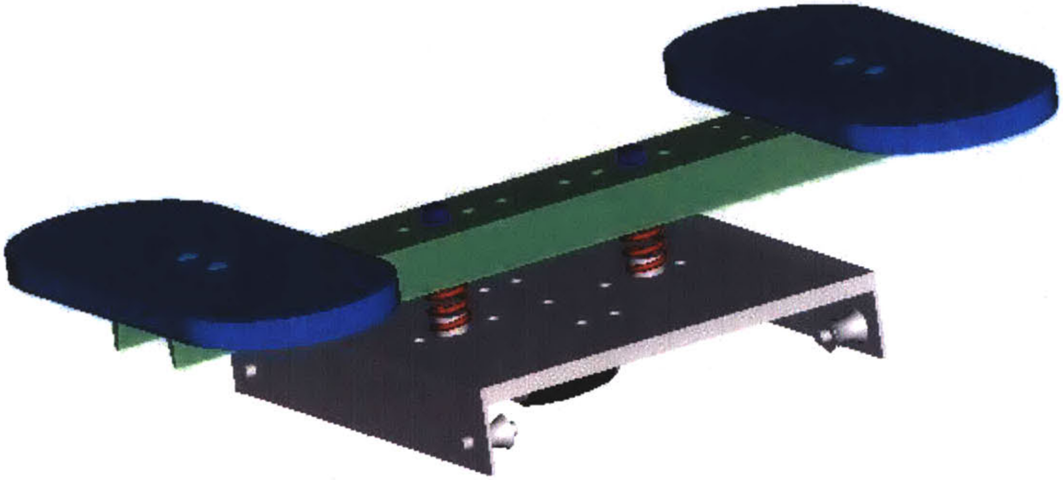


Figure 7-49: Angular Motion Spring Design

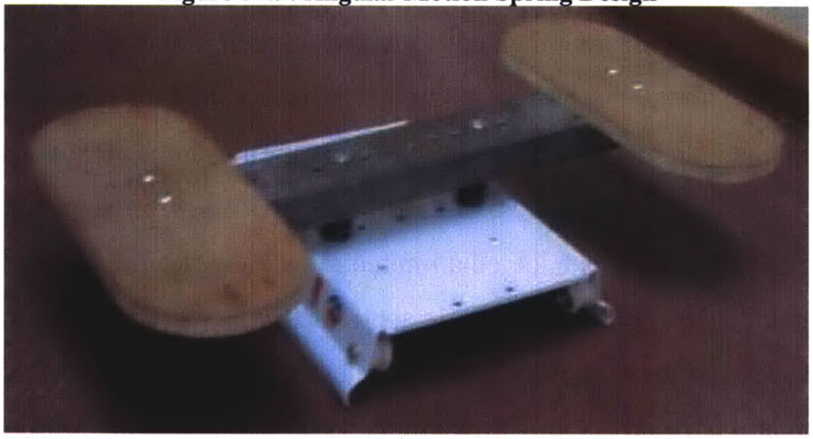


Figure 7-50: Angular Motion Spring Bench Level Test

The next design was one of several 3 DOF motion concepts without using springs. In this design a motion platform was designed to hang beneath a mounted bracket. (Figure 7-51) The hanging platform allowed pitch, yaw, and roll axis motion. The problem is that it was incredibly unstable. There was no way to add resistance forces to any of the motions. When a user tried to step on the motor mount, one end would tip all the way down until it collided with the carriage, while the other end would elevate high into the air. Even if the user could mount the platform, collisions would regularly occur. Any motions in the pitch or yaw directions would cause the platform to hit the carriage or the sides of the bracket. This design adds very unrealistic and unstable motion to the exercise machine, and almost hurt the thesis advisor.

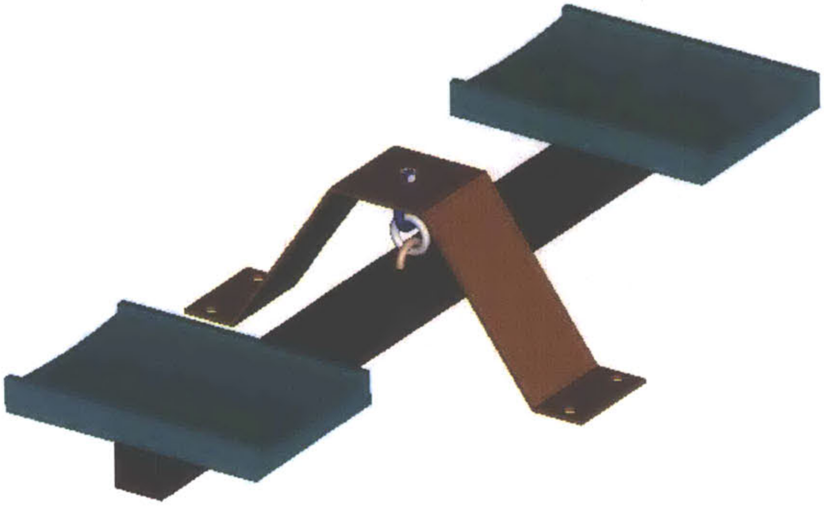


Figure 7-51: Angular Motion Module with Hanging Platform

A second non-spring approach considered the use of a ball transfer under a hemispherical shell. In this design, a ball transfer was mounted on a high mount, underneath a hemispherical shell. The shell had foot mounts all around its edge, allowing the user to tip the shell, such that the ball transfer maintained rolling contact with the shell. The resulting kinematics allowed a limited range of motion in the pitch and roll directions, and a full 360 degrees of motion about the yaw axis. In this configuration, it was extremely difficult to provide resistance to these tipping motions. A resistive element (like foam) can surround the lower circumference of the shell (aiding in stability), but this does little to prevent any upward forces from knocking the shell off of the ball transfer. This concept is similarly unstable, and has a higher part count and manufacturing complexity. (Figure 7-52)

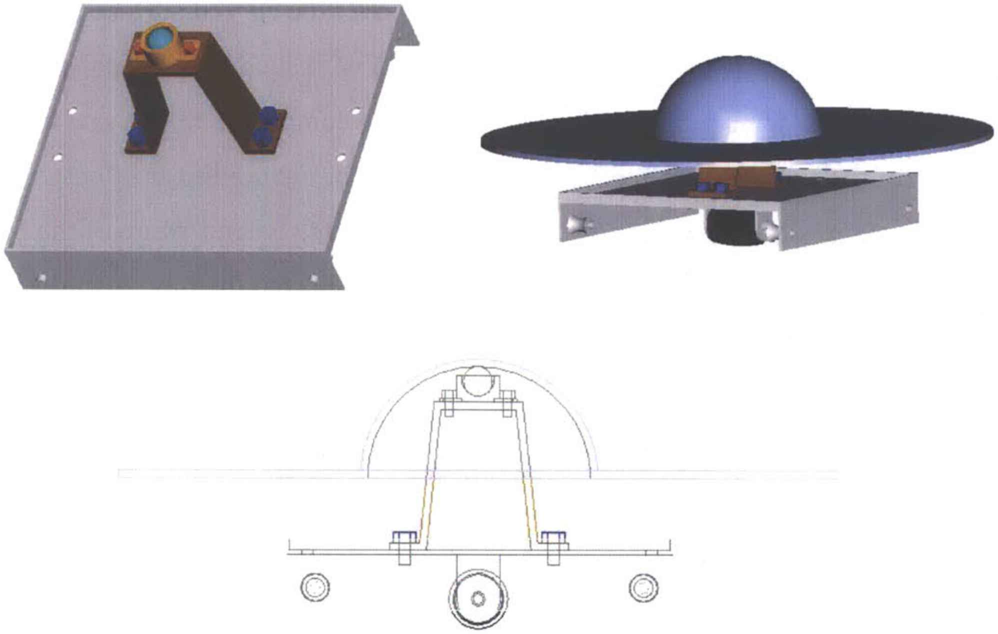


Figure 7-52: Angular Motion Module using a ball transfer and hemispherical shell

The previous two designs showed very poor stability when not using springs. This meant that the remaining designs needed to incorporate some form of spring to provide the proper resistance. Linear springs are readily available, and can easily be incorporated into numerous designs. Exploration of nonlinear springs led to research previously done in the lab on nonlinear zipping effect by Jian Li. [7-2] In this research, when a strip of metal is bent over a curved surface, a zipping effect occurs along the interface, shortening the length of the cantilever, and increasing stiffness. Different forms of linear and nonlinear springs provide many options for the modules.

Modification of Jian Li's nonlinear zipping effect to 3D led to the development of many different module designs, all using hemispherical shells as a 3D curved surface. Of these designs, two are potentially viable. The first of these is the literal conversion of a metal strip over a 2D curved surface, to a spider-like plate of cantilevered strips over a 3D curved surface. (Figures 7-53 to 55) If the nonlinear spring theory could be verified in 3D, the resulting motion would produce resisted motion in the pitch and roll directions, with the possibility of adding yaw axis motion. As the user applies their weight to the motion platform, the cantilevered strips would "zip" over the curved surface, increasing stiffness in the desired direction. The biggest problem with such an approach is that the manufacturing and assembly of the module is relatively complicated. The end constraints on each arm of the spider-like plate have to be specific for the nonlinear effect to happen. (Research is requires to fins the appropriate end constraints) Manufacture of the 3D surface and the spider plate would also be far more complicated than the manufacture of other less involved designs.

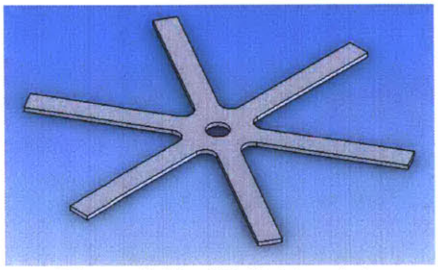


Figure 7-53: 3D Spiderplate

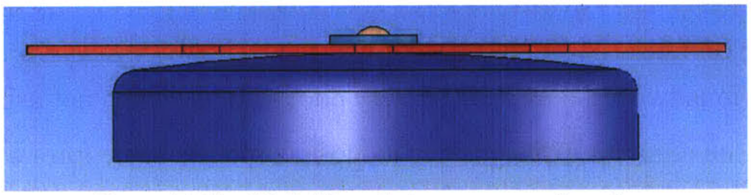


Figure 7-54: 3D Spider-plate over curved surface

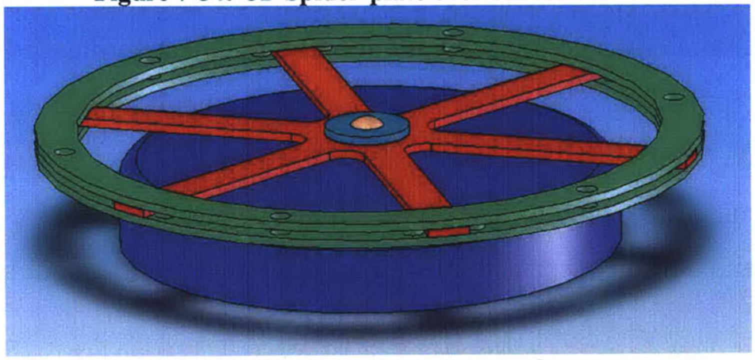


Figure 7-55: 3D Nonlinear Spring Concept

The second 3D nonlinear spring approach uses reciprocity on the previous module concept. Instead of using a motion platform connected to cantilevered strips over a stationary 3D surface, the motion platform is put in direct contact with a slotted 3D surface. By cutting slots in the 3D surface, curved cantilevers are created around the entire perimeter. Tipping of the motion platform lowers the contact point of the platform with the curved cantilever, shortening the cantilever length, and increasing stiffness. This design removes the spider plate, lowering the part count, but does not necessarily remove any complexity. The design also requires testing to verify functionality. (Figure 7-56)

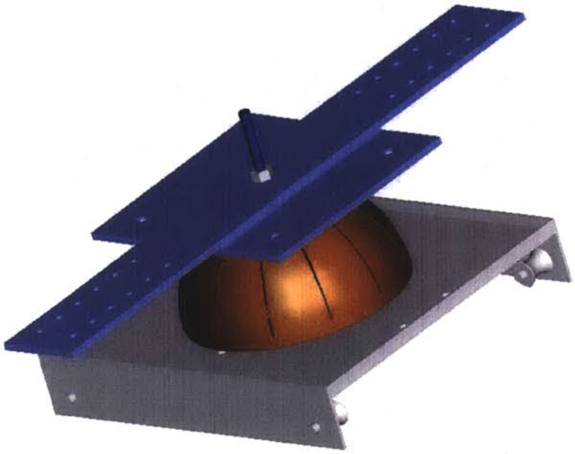


Figure 7-56: 3D Nonlinear Spring Design using curved cantilevers

The origins of the stacked axis approach started with testing done on Jian Li's nonlinear spring theory in the 2D case. A simple 2D test apparatus was created to gather force versus displacement data to verify a nonlinear response. (Figure 7-57) At the same time, the carriage, rail, and support frame prototypes were assembled and being experimented with. After using the machine without an angular motion module, it was decided that pitch motion is unnecessary to achieve realistic snowboarding results. Instead, roll axis motion is essential to "carving" a turn, and yaw axis motion adds even more realism. For the proof of concept prototype it is less risky to implement roll axis motion first, and add yaw axis motion later. This allows the roll axis module to go through an isolated design process, where the module is proven effective, before adding complexity.

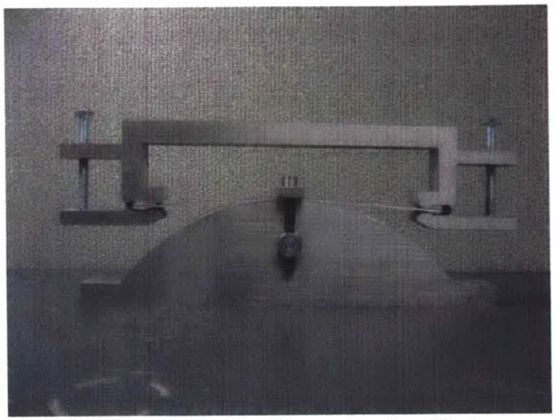


Figure 7-57: Nonlinear Spring Test

The first purely roll axis module was an extension of the 2D test configuration for the nonlinear springs. By extending the length of the curved surface and plate, a long nonlinear spring is created. This will make the angular motion increasingly stiff as the board is rotated about the roll axis. This design has a constraint problem with the mounting. A board mounted to the metal sheet is able to move in the direction of the long axis of the board. Proper constraint of the end clamps is also extremely important. The zipping effect can result in slipping of the metal sheet relative to the clamp. Any slipping in the module can result in major stability issues. With careful constraint, and added testing, this design could be worked into a viable roll axis module. (Figure 7-58)

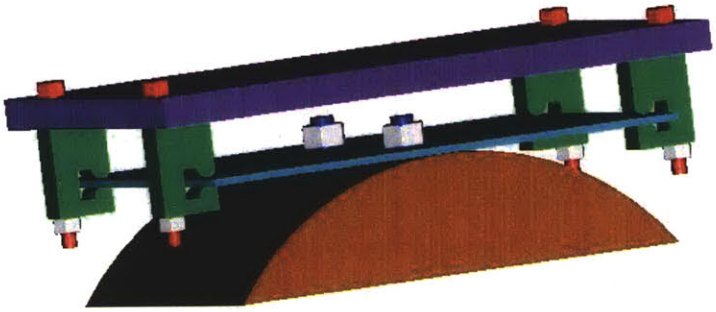


Figure 7-58: Roll Axis Module with nonlinear "zipping" effect

The final roll axis concept achieves the desired motion with a simple axle, supplemented by nonlinear (or linear) springs under each side of the platform to provide resistance. Testing was done on a snowboarding game controller that uses only an axle

(Figure 7-59). The axle provides remarkable stability in all directions except for the roll axis. Addition of springs on either side of the axle provides the resistance required for realistic snowboarding feel. The choice of springs is also extremely varied. On the most basic level, linear compression springs or a foam block could be used. For nonlinear response, nonlinear compression springs (with a varying coil diameter), or a custom foam cross section could be used. Some testing is required for the nonlinear springs, but otherwise this is a very stable, safe design. (Figure 7-60)

Figure 7-59: Snowboarding Game Controller

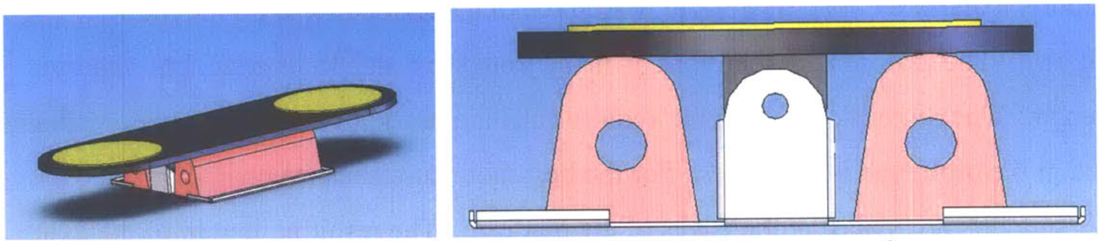
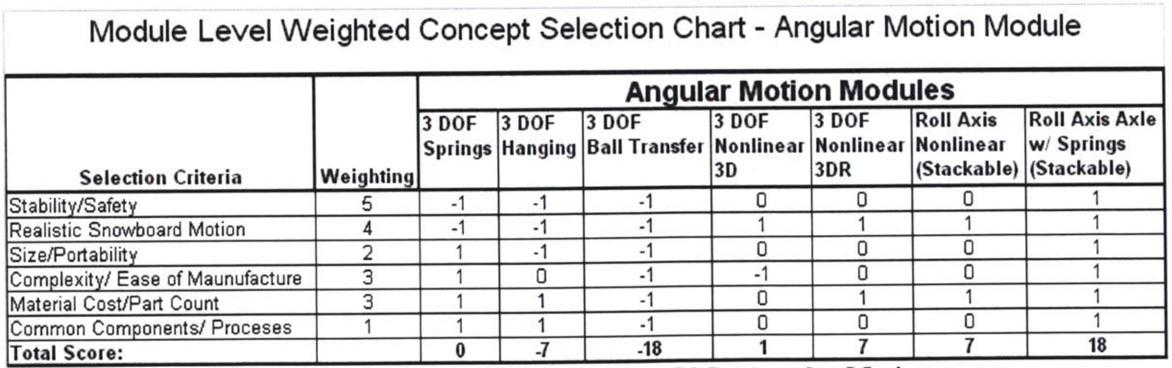


Figure 7-60: Roll Axis Module using axle and foam cross section



Module Level Weighted Concept Selection Chart - Angular Motion Module

Selection Criteria	Weighting	Angular Motion Modules						
		3 DOF Springs	3 DOF Hanging	3 DOF Ball Transfer	3 DOF Nonlinear 3D	3 DOF Nonlinear 3DR	Roll Axis Nonlinear (Stackable)	Roll Axis Axle w/ Springs (Stackable)
Stability/Safety	5	-1	-1	-1	0	0	0	1
Realistic Snowboard Motion	4	-1	-1	-1	1	1	1	1
Size/Portability	2	1	-1	-1	0	0	0	1
Complexity/ Ease of Maunufacture	3	1	0	-1	-1	0	0	1
Material Cost/Part Count	3	1	1	-1	0	1	1	1
Common Components/ Proceses	1	1	1	-1	0	0	0	1
Total Score:		**0**	**-7**	**-18**	**1**	**7**	**7**	**18**

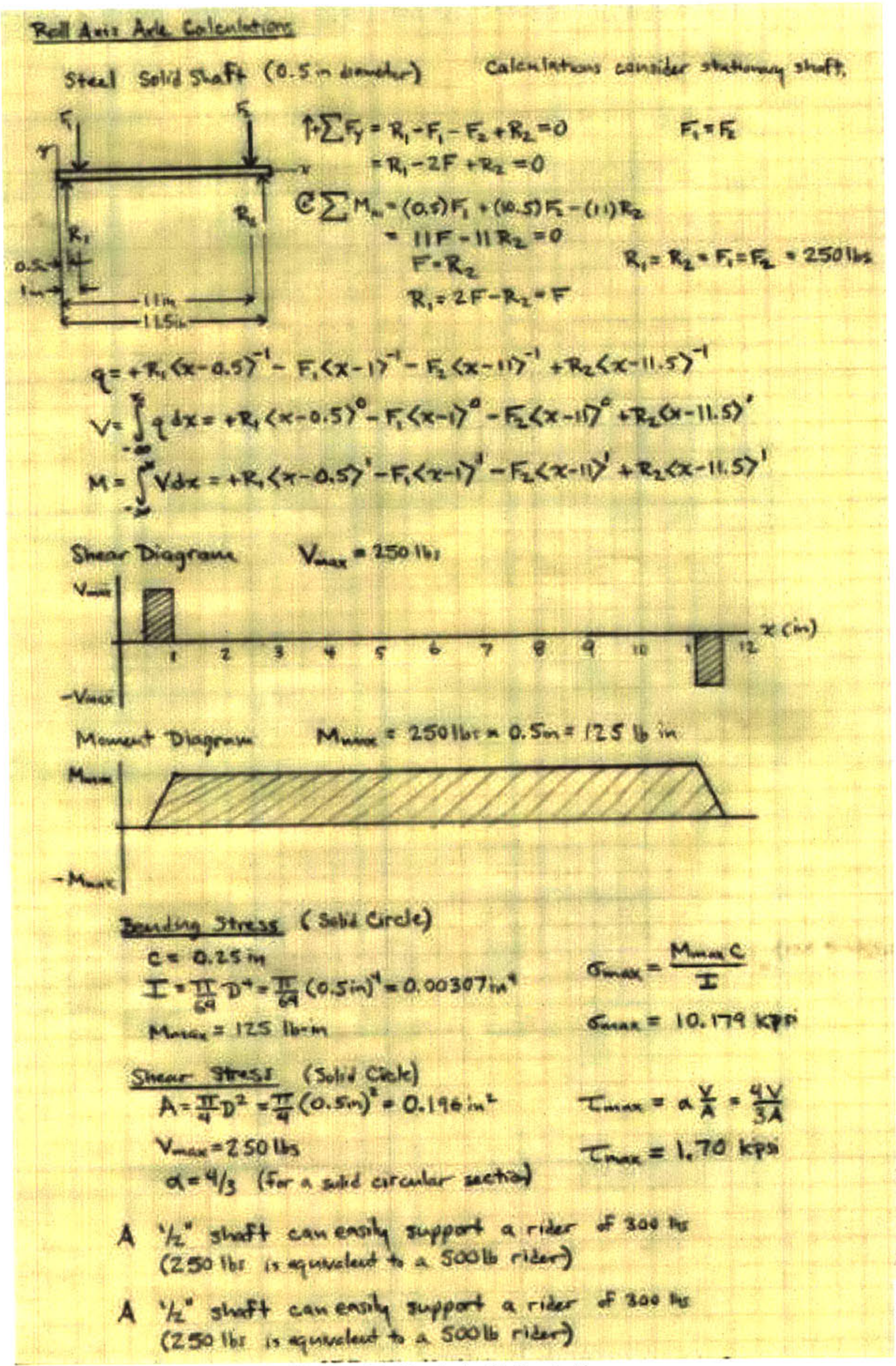
Figure 7-61: Module Level weighted CSC - Angular Motion

The weighted concept selection chart shows that the Roll axis module incorporating an axle with support springs is the best approach for the angular motion module. Using an axle requires simple components and tooling to produce a prototype. The resulting module is incredibly stable, and allows validation of just the roll axis module, before other modules are added. The only elements that potentially require testing are the spring elements providing resistance to the roll axis motion. These tests, however, will be extremely straightforward compared to validation of the more complex nonlinear spring theory. Using this module offers a high probability of success, in a short amount of time.

7.3.2 Angular Motion Module Detailed Design

The chosen roll axis module must accurately recreate roll axis motion, in addition to being strong enough to support the shifting weight of a user. The resulting detailed design focuses on the proper placement and selection of the module components, and verification that these components are able to reproduce the desired snowboard kinematics.

The roll axis motion for the chosen module design relies on an axle, and axle supports to carry the load of a 300lb person rocking back and forth on the motion platform. The axle design, therefore, is made from steel, due to its excellent material strength. The dimensions of the bar require calculation. The existing top plate width used in the prototype is 11 inches. For the best moment resistance characteristics, the axle supports are placed at the edges of the platform. The resulting length of the axle, then should be slightly longer than the width of the top plate. One foot of axle is chosen, to provide a half inch of material on either end, to keep options open for constraining the shaft to the supports. Given the length, the proper diameter of this axle is then found through stress calculations for both bending and shear. (Figure 7-62) A ½" steel rod is more than sufficient to support the weight of the carriage.



Roll Axis Axle Calculations

Steel Solid Shaft (0.5 in diameter) Calculations consider stationary shaft.

$+\uparrow \sum F_y = R_1 - F_1 - F_2 + R_2 = 0$ $F_1 = F_2$

$= R_1 - 2F + R_2 = 0$

$\circlearrowleft \sum M_{R_1} = (0.5)F_1 + (10.5)F_2 - (11)R_2$

$= 11F - 11R_2 = 0$

$F = R_2$ $R_1 = R_2 = F_1 = F_2 = 250\text{ lbs}$

$R_1 = 2F - R_2 = F$

$$q = +R_1\langle x-0.5\rangle^{-1} - F_1\langle x-1\rangle^{-1} - F_2\langle x-11\rangle^{-1} + R_2\langle x-11.5\rangle^{-1}$$

$$V = \int_{-\infty}^{x} q\,dx = +R_1\langle x-0.5\rangle^{0} - F_1\langle x-1\rangle^{0} - F_2\langle x-11\rangle^{0} + R_2\langle x-11.5\rangle^{0}$$

$$M = \int_{-\infty}^{x} V\,dx = +R_1\langle x-0.5\rangle^{1} - F_1\langle x-1\rangle^{1} - F_2\langle x-11\rangle^{1} + R_2\langle x-11.5\rangle^{1}$$

Shear Diagram $V_{max} = 250\text{ lbs}$

Moment Diagram $M_{max} = 250\text{ lbs} \times 0.5\text{in} = 125\text{ lb in}$

Bending Stress (Solid Circle)

$c = 0.25\text{ in}$ $\sigma_{max} = \frac{M_{max}c}{I}$

$I = \frac{\pi}{64}D^4 = \frac{\pi}{64}(0.5\text{in})^4 = 0.00307\text{ in}^4$

$M_{max} = 125\text{ lb-in}$ $\sigma_{max} = 10.179\text{ kpsi}$

Shear Stress (Solid Circle)

$A = \frac{\pi}{4}D^2 = \frac{\pi}{4}(0.5\text{in})^2 = 0.196\text{ in}^2$ $\tau_{max} = \alpha\frac{V}{A} = \frac{4V}{3A}$

$V_{max} = 250\text{ lbs}$ $\tau_{max} = 1.70\text{ kpsi}$

$\alpha = 4/3$ (for a solid circular section)

A ½" shaft can easily support a rider of 300 lbs
(250 lbs is equivalent to a 500lb rider)

A ½" shaft can easily support a rider of 300 lbs
(250 lbs is equivalent to a 500lb rider)

Figure 7-62: Axle Calculations

The supports for the steel axle must be equally as robust, to support large loadings. For this design, aluminum angle bar is selected to serve as a lower angle bracket. Aluminum bar is not as strong as steel, but its light weight and high machineability makes it desirable for a prototype. The size of the angle bar is dependent on the geometric requirements for snowboard motion, and the structural requirements for the desired loading. To sweep out the desired path, a 2-1/2" axle mounting height is sufficient for a board section to bend to a reasonable angle, without collision with the top plate. (Figure 7-63) A 3 inch angle arm provides enough space to drill the hole, and leave sufficient material around the hole. In addition, for the board section to rotate without colliding with the mounting bracket, the corners are removed on the angle brackets. The thickness of the angle arms is found through calculation. (Figure 7-65) A 3/8" angle thickness provides enough of a support to resist the applied loads.

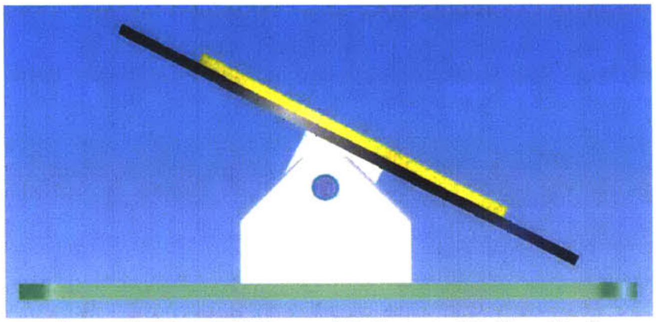


Figure 7-63: End View of Roll Axis Motion Study

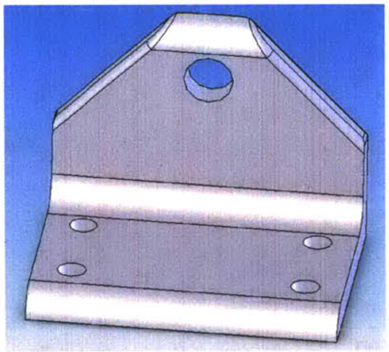
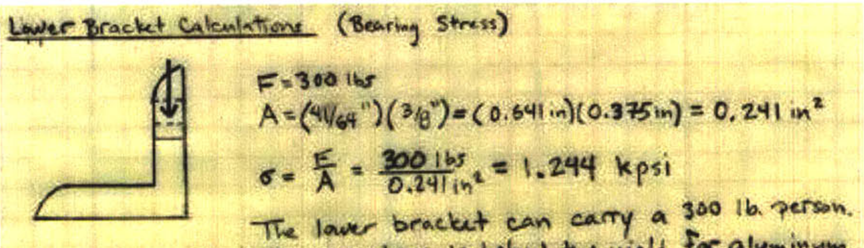


Figure 7-64: Lower Angle Bracket



Lower Bracket Calculations (Bearing Stress)

$F = 300\ \text{lbs}$

$A = (41/64")(3/8") = (0.641\ \text{in})(0.375\ \text{in}) = 0.241\ \text{in}^2$

$\sigma = \frac{F}{A} = \frac{300\ \text{lbs}}{0.241\ \text{in}^2} = 1.244\ \text{kpsi}$

The lower bracket can carry a 300 lb. person.
The max stress is below the yield for aluminum.

Figure 7-65: Lower Bracket Calculations

The lower angle bracket is bolted to the top plate using four 3/8" nuts and bolts for each bracket, to avoid twist of the brackets relative to the top plate (requiring 3/8" clearance holes). The interface between the axle and the bracket must allow for rotation, requiring a rotary bearing. Doing a simple PV calculation reveals that nylon bushings are sufficient for this application. (Figure 7-66) The calculations show that under extreme load, the bushings will survive to over 2000 hours. For the casual user, this is essentially infinite life. For an exercise machine in a gym, replacement parts would be available if needed. After referring to available bearings in a catalog (McMaster-Carr), a nylon bushing is selected that is designed to accommodate a ½" rod. This bushing must be mounted with the thrust end on the inside portion of the bracket, to provide proper resistance to axial loadings.

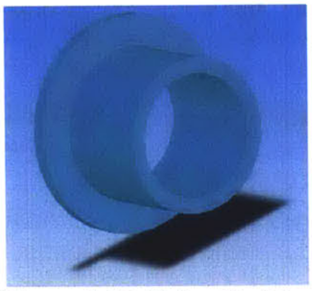
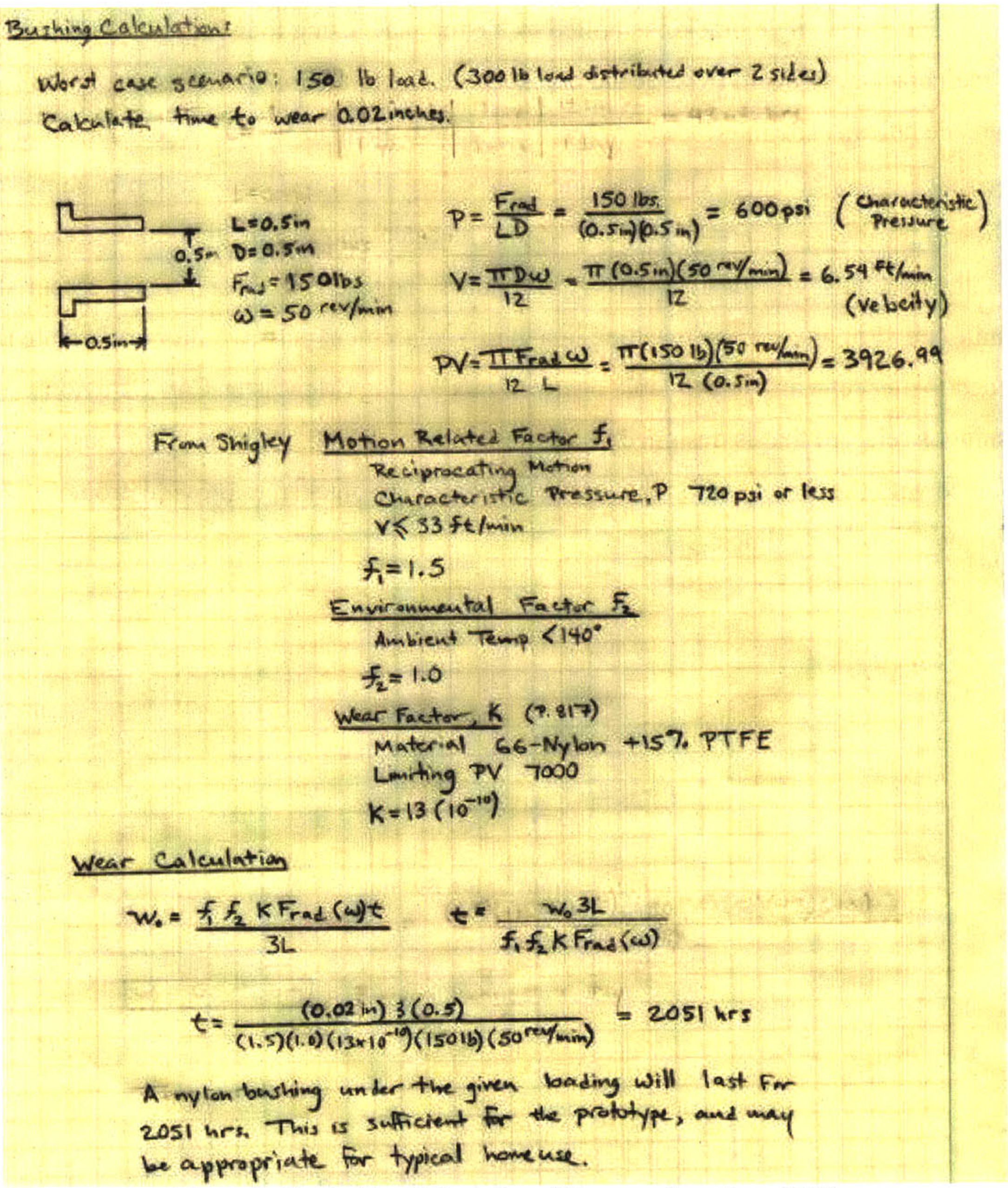


Figure 7-66: Nylon Bushing



Bushing Calculations:

Worst case scenario: 150 lb load. (300 lb load distributed over 2 sides)

Calculate time to wear 0.02 inches.

L=0.5in

D=0.5in

F_{rad}=150lbs

ω = 50 rev/min

$$P = \frac{F_{rad}}{LD} = \frac{150\text{ lbs.}}{(0.5\text{in})(0.5\text{in})} = 600\text{psi} \quad \left(\begin{matrix}\text{Characteristic}\\ \text{Pressure}\end{matrix}\right)$$

$$V = \frac{\pi D\omega}{12} = \frac{\pi(0.5\text{in})(50\text{ rev/min})}{12} = 6.54\text{ ft/min} \quad \text{(velocity)}$$

$$PV = \frac{\pi F_{rad}\,\omega}{12\ L} = \frac{\pi(150\text{ lb})(50\text{ rev/min})}{12\ (0.5\text{in})} = 3926.99$$

From Shigley **Motion Related Factor f_1**

Reciprocating Motion

Characteristic Pressure, P 720 psi or less

$V \leqslant 33$ ft/min

$f_1 = 1.5$

Environmental Factor f_2

Ambient Temp <140°

$f_2 = 1.0$

Wear Factor, K (P. 817)

Material 66-Nylon +15% PTFE

Limiting PV 7000

$K = 13(10^{-10})$

Wear Calculation

$$w_0 = \frac{f_1 f_2 K F_{rad}(\omega)t}{3L} \qquad t = \frac{w_0 3L}{f_1 f_2 K F_{rad}(\omega)}$$

$$t = \frac{(0.02\text{ in})\,3\,(0.5)}{(1.5)(1.0)(13\times10^{-10})(150\text{lb})(50\text{ rev/min})} = 2051\text{ hrs}$$

A nylon bushing under the given loading will last for 2051 hrs. This is sufficient for the prototype, and may be appropriate for typical home use.

Figure 7-67: Bushing Calculations (Wear numbers from [7-3])

A second interface is required between the axle and the motion platform to correctly transmit the rotational motion. To keep the design simple, an upper angle bracket is developed, again using aluminum angle bar and nylon bushings. The angle bar required for the upper brackets can be much smaller than for the lower bracket. This is primarily due to the geometry of the motion. The larger lower angle bracket has a long angle arm, with trimmed corners. These features allow a much shorter arm length on the upper angle brackets. Instead, a 1-1/2" angle arm can be used, with a wall thickness of

¼", while part strength is maintained. (Figure 7-69) The resulting angle bars only need to be trimmed to a length of 3 inches (the width of the motion platform), and drilled in order to mount two 3/8" bolts, and a nylon bushing. The nylon bushing used in the design is identical to the bushing used on the lower angle bracket, which again meets the PV requirements for the bushing.

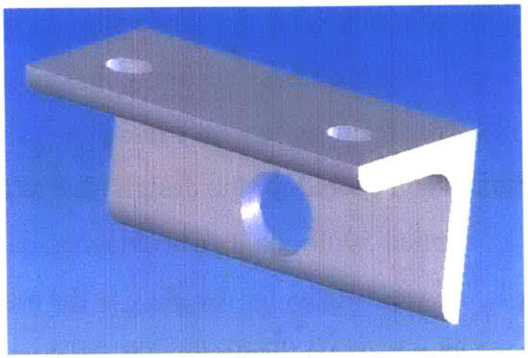
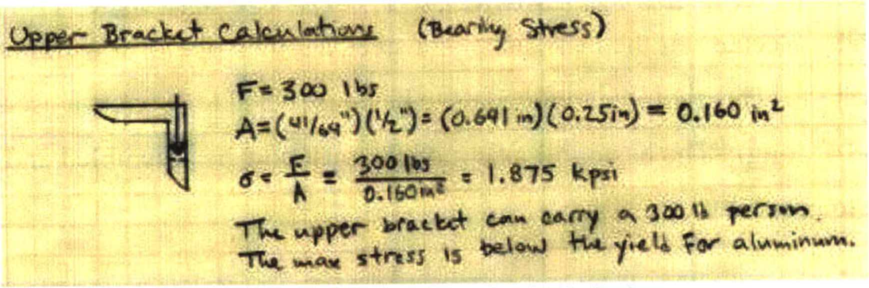


Figure 7-68: Upper Angle Bracket



Upper Bracket Calculations (Bearing Stress)

$F = 300$ lbs

$A = (41/64")(1/2") = (0.691 \text{ in})(0.25 \text{in}) = 0.160 \text{ in}^2$

$\sigma = \frac{F}{A} = \frac{300 \text{ lbs}}{0.160 \text{in}^2} = 1.875$ kpsi

The upper bracket can carry a 300 lb person.
The max stress is below the yield for aluminum.

Figure 7-69: Upper Bracket Calculations

The remaining section of the core roll axis module is the motion platform itself. Initial sketches of the roll axis module show it with a snowboard like platform. (Figure 7-70) The assumed default position for the motion carriage is sitting horizontally, on top of some form of spring/foam (with the reaction forces above the pivot). This configuration is only semi-stable. At the exact top of the motion, the design is stable, however, even the smallest angular offset makes the entire board unstable, and it tips (until it collides with the carriage, or is stopped by the spring element). Inversion is used on the design to fix the problem. If the location of force application is beneath the pivot, the configuration becomes inherently stable in the default position. This relocation is carried out by lowering the ends on either side of the motion platform. The resulting shape looks like a 2D form of "top hat".

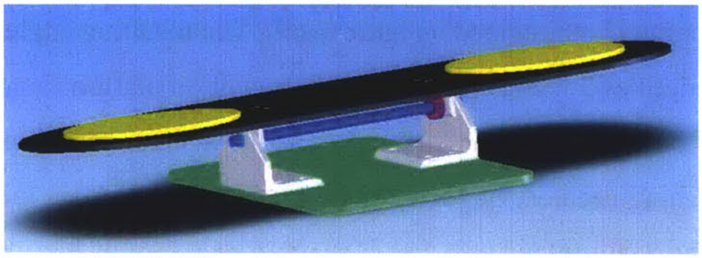


Figure 7-70: Semi-Stable "Snowboard" Configuration

The "top hat" configuration maintains the same motions as the "snowboard" approach, but lowers the user's center of mass, resulting in a more comfortable exercise experience. The design of the platform starts with stress and deflection analysis. Again, the weight of a 300lb person is considered for the design (due to dynamic loading, calculations are run with an applied 500lb load). The attached calculations show that a ¼" thick steel plate exceeds the yield stress for the plate at the maximum dynamic loading. For a proof of concept prototype the design will hold up the smaller loads of an average user. In a commercial version a composite is necessary to withstand the large dynamic loads. Because of the high density of steel, a 3 inch platform width is used to minimize weight. This requires foot pedals to be constructed to support a users feet (6" wide by 12-14" long). The basic roll axis module must now be assembled and properly constrained to prevent motion.

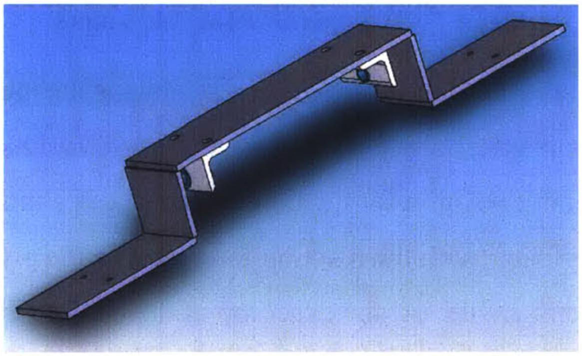
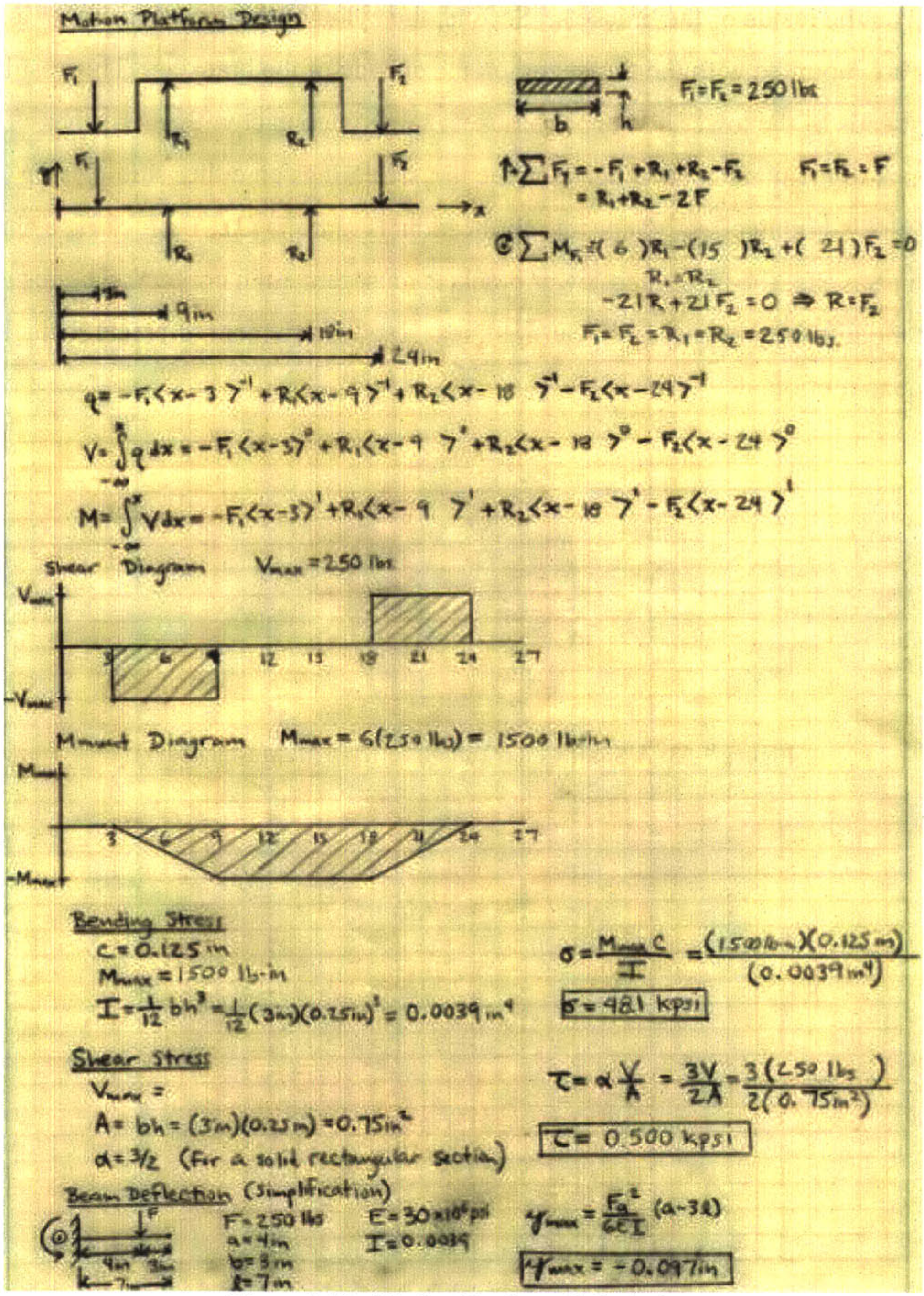


Figure 7-71: "Top Hat" Configuration (with upper angle brackets)



Motion Platform Design

$F_1 = F_2 = 250$ lbs

$\uparrow + \sum F_y = -F_1 + R_1 + R_2 - F_2$ $F_1 = F_2 = F$

$= R_1 + R_2 - 2F$

$\circlearrowleft \sum M_{R_1} = (6)R_1 - (15)R_2 + (21)F_2 = 0$

$R_1 = R_2$

$-21R + 21F_2 = 0 \Rightarrow R = F_2$

$F_1 = F_2 = R_1 = R_2 = 250$ lbs.

$$q = -F_1\langle x-3\rangle^{-1} + R_1\langle x-9\rangle^{-1} + R_2\langle x-18\rangle^{-1} - F_2\langle x-24\rangle^{-1}$$

$$V = \int_{-\infty}^{x} q\,dx = -F_1\langle x-3\rangle^{0} + R_1\langle x-9\rangle^{0} + R_2\langle x-18\rangle^{0} - F_2\langle x-24\rangle^{0}$$

$$M = \int_{-\infty}^{x} V\,dx = -F_1\langle x-3\rangle^{1} + R_1\langle x-9\rangle^{1} + R_2\langle x-18\rangle^{1} - F_2\langle x-24\rangle^{1}$$

Shear Diagram $V_{max} = 250$ lbs

Moment Diagram $M_{max} = 6(250 \text{ lbs}) = 1500$ lb-in

Bending Stress

$c = 0.125$ in

$M_{max} = 1500$ lb-in

$I = \frac{1}{12}bh^3 = \frac{1}{12}(3\text{in})(0.25\text{in})^3 = 0.0039\text{ in}^4$

$\sigma = \frac{M_{max}c}{I} = \frac{(1500 \text{ lb-in})(0.125 \text{ in})}{(0.0039\text{ in}^4)}$

$\boxed{\sigma = 48.1 \text{ kpsi}}$

Shear Stress

$V_{max} =$

$A = bh = (3\text{in})(0.25\text{in}) = 0.75\text{in}^2$

$\alpha = 3/2$ (For a solid rectangular section)

$\tau = \alpha\frac{V}{A} = \frac{3V}{2A} = \frac{3(250 \text{ lbs})}{2(0.75\text{in}^2)}$

$\boxed{\tau = 0.500 \text{ kpsi}}$

Beam Deflection (Simplification)

$F = 250$ lbs $E = 30 \times 10^6$ psi

$a = 4$ in $I = 0.0039$

$b = 3$ in

$l = 7$ in

$y_{max} = \frac{Fa^2}{6EI}(a - 3l)$

$\boxed{y_{max} = -0.097\text{in}}$

Figure 7-72: Motion Platform Calculations

When assembled, the lower angle brackets are rigidly attached to the carriage top plate, while the upper angle brackets are rigidly attached to the motion platform. Proper constraint requires that only rotation about the roll axis be allowed. The largest motion that can occur outside of the roll axis rotation is axial translation along the axle. To prevent this, first, the thrust end of the nylon bushings on the lower angle brackets is mounted on the inside of the brackets. Second, the nylon bushings on the upper angle brackets are mounted with the thrust end on the outside of the brackets. This results in the thrust ends of the lower and upper brackets being in contact with each other. The final step is to maintain contact between the thrust bearings on either side. Using ½" shaft collars is highly effective for this application. (Figure 7-73). By locking a shaft collar on each end, the upper and lower brackets must remain in contact. The resulting roll axis module only requires a linear/nonlinear response element to create realistic resistance to motion.

Figure 7-73: A Shaft Collar (obtained from McMaster-Carr)

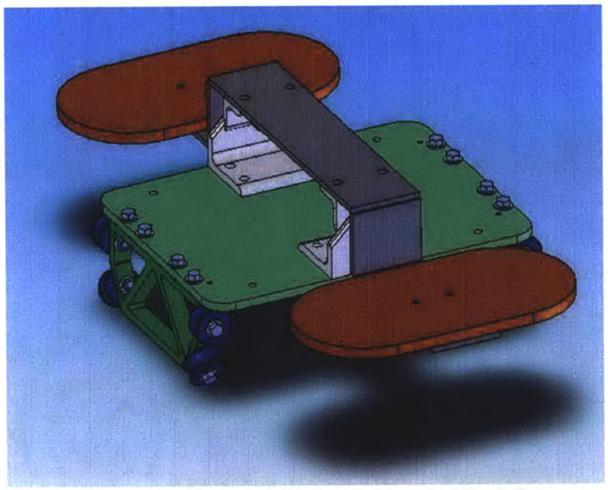


Figure 7-74: Prototype Roll Axis Module

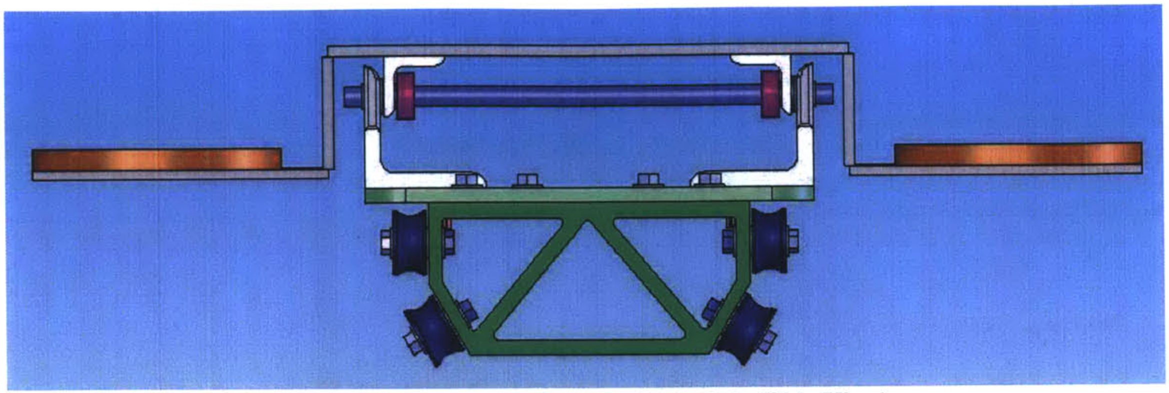


Figure 7-75: Prototype Roll Axis Module (Side View)

Early studies on nonlinear zipping effect show promise in introducing nonlinear response to the roll axis motion. The difficulties in maintaining end constraints, however, require looking into other ways of achieving nonlinear effect. Two prominent ideas emerge during development. The first idea is to use springs with an increasing coil diameter. The second idea is to use a custom cross section of foam. Given the low cost, and ease of manufacture of foam, foam is the logical starting place.

Determination of the ideal cross section for nonlinear response can be handled in several ways. Typically finite element methods can be used as an initial measure of response. In this instance, however, due to an ample supply of foam and access to a soft materials tester, it is far less time intensive to quickly cut samples, and obtain force-deflection curves. For these trials, 9 sample sections are cut to varying cross sections, and tested on a TA XT plus Texture Analyzer. (Figure 7-76) To simulate the actual loading on each sample, a large flat section is used to apply load to the top of the foam. The resulting force versus deflection curves are then compared to determine which has the best response.

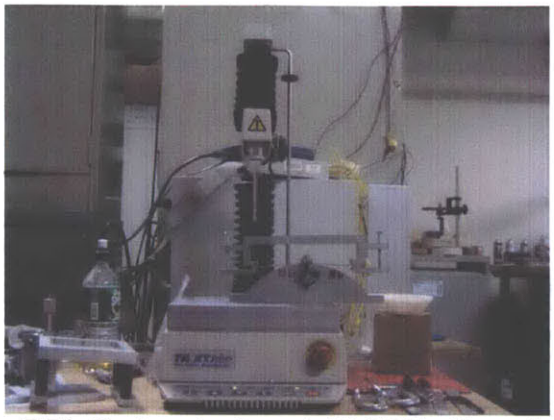
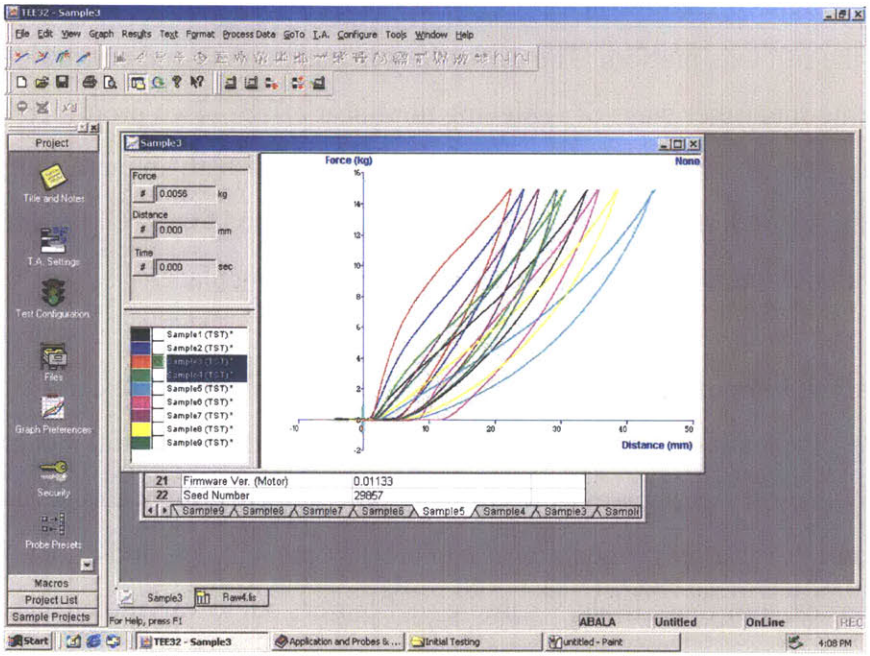


Figure 7-76: Texture Analyzer (with 2D Nonlinear Spring)



Force # 0.0056 kg

Distance # 0.000 mm

Time # 0.000 sec

21	Firmware Ver. (Motor)	0.01133
22	Seed Number	29857

For Help, press F1

Figure 7-77: Force versus Deflection Test Results

After review of the various deflection curves, a trapezoidal shape is selected. The force versus deflection curve provides excellent nonlinear response. (Figure 7-78) This design is modified further to round the edges, and put a hole through the middle. (Figure 7-79) The resulting design is then placed into a finite element model to look at stress distribution for a vertical load, and an angled load. (Figure 7-80) The only remaining step is to design the moment bars, which will apply the proper force to the foam sections.

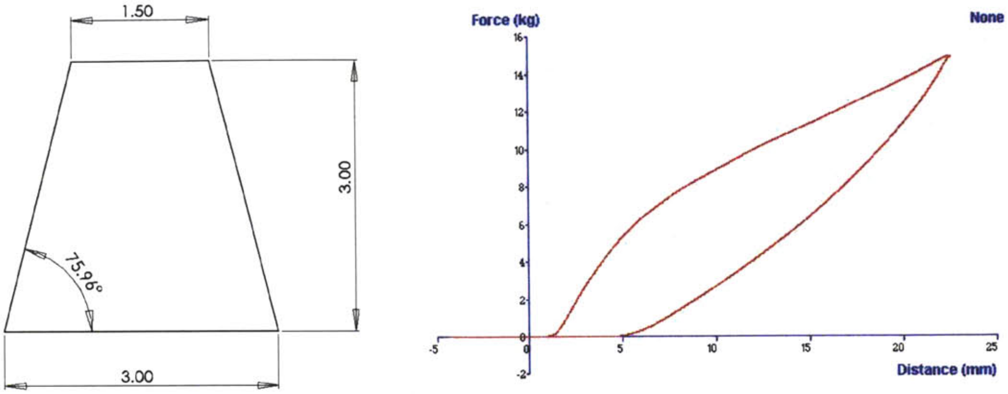


Figure 7-78: Selected Trapezoid and Force versus Deflection Curve

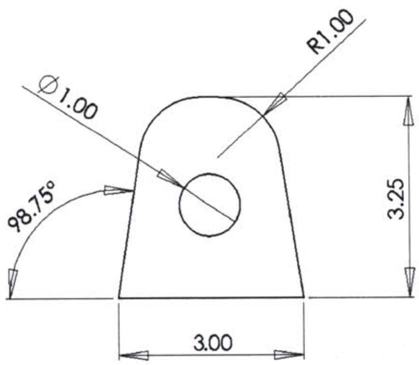


Figure 7-79: Trapezoidal Redesign

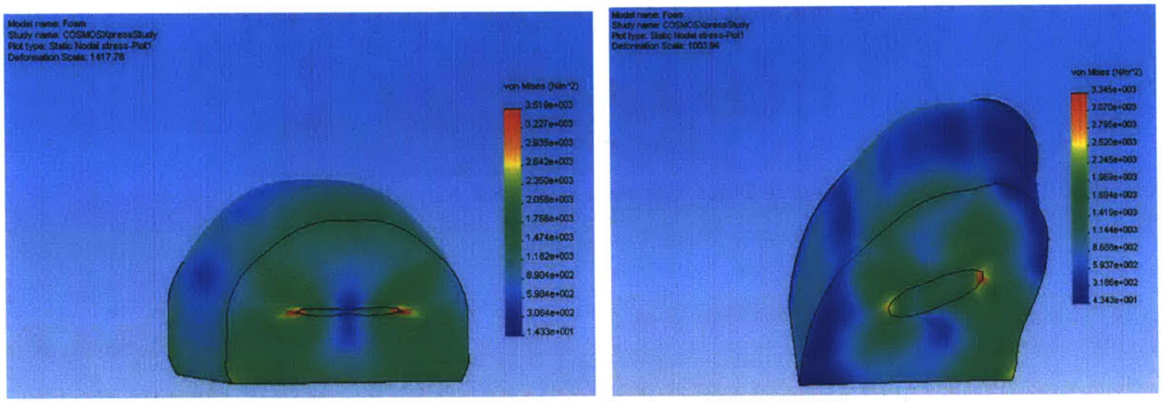


Figure 7-80: FEA Stress Distributions (COSMOSXpress)

The purpose of the moment bars is to take user rotation about the roll axis, and create a contact force with the foam on one side or the other. For a commercial version, the moment bars can be worked directly into the design of the motion platform. For a prototype, it is more desirable to keep things modular, so changes can be made later. With that in mind, the bolts used to connect the upper brackets with the motion platform are ideal for mounting the moment bars. Quarter inch thick steel flat stock can be welded together (Figure 7-81)) to create the contact. The finished module offers some resistance to the roll axis motion, providing user stability when initially mounting the platform. The arrangement also is considerably better than if the foam were mounted beneath a snowboard like platform. In this configuration the foot pedals are underneath the foam contacts, such that the axle carries much of the user's weight, and only the roll axis moment deflects the foam.

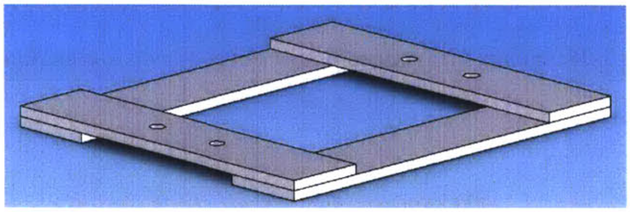


Figure 7-81: Moment Bars

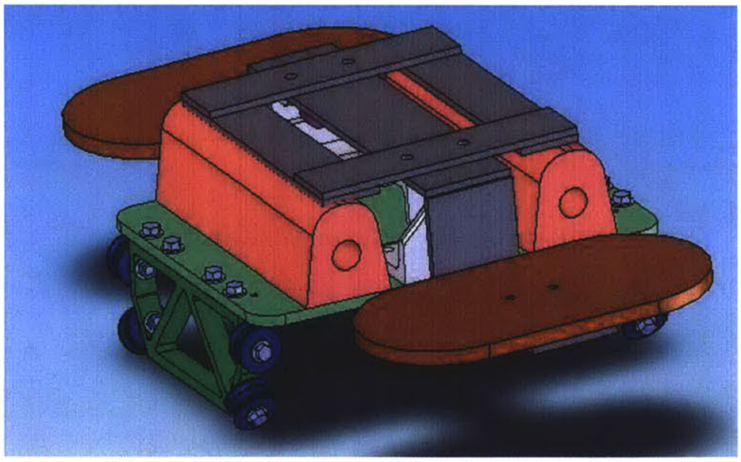


Figure 7-82: Carriage with Roll Axis Module

7.3.3 Finished Roll Axis Module Prototype

Though the commercial version of a roll axis module is easily made in a fully automated process, it proves difficult to make as a prototype. Instead, the prototype design is much more easily constructed using more typical machine tools. The first step in this process is to modify the top plate of the carriage for a roll axis module. Using the bolt pattern decided on during the detailed design process, additional holes must be put into the plate. Though a waterjet was originally used to place holes in the top plate, it is not the best choice for a second pass, due to poor alignment capability. A CNC Milling machine obtains much better, faster results.

The aluminum angled brackets require holes for both the mounting bolts and the nylon bushings. To machine the large 3" aluminum angle bar, it is first cut into two 4 inch lengths. For the holes a milling machine is again used. The coordinate measuring capabilities of a standard digital readout allow for the holes to be drilled in one part, and then substituted out for an identical part, for quick turnaround on the brackets. For the mounting bolts, a 3/8" clearance hole is drilled. For the nylon bushing a 41/64" drill is used to drill a close clearance hole to the outer diameter of the bushing. After the holes are drilled, the corners on the vertical arm are removed to accommodate for the rotating platform. These brackets are then smoothed on a belt sander and bolted to the top plate with 3/8" bolts.

The 2" aluminum brackets are machined in an identical manner. After cutting the brackets to two 3 inch lengths, each bracket is drilled with two 3/8" clearance holes for mounting bolts, and one 41/64" hole for mounting a nylon bushing.

After cutting a ½" diameter steel rod to a 12 inch length, the base components are ready for assembly on the carriage top plate. Assembly starts with the lower angle brackets already mounted to the top plate. At this stage the longer length ½" nylon bushings are placed in each 41/64" hole, with the thrust end of the bushing on the inside of the bracket. The axle is now inserted through one of the angle bars. With the axle half inserted, the remaining components can be inserted onto the structure. First, the shorter length ½" nylon bushings are inserted into the smaller brackets with the thrust end on the outside of the brackets. One of these brackets is placed on the steel axle, such that the thrust end of both bracket bushings meet. Next the two locking collars are inserted onto the shaft, followed by the second smaller bracket (with the thrust ends meeting, this time on the other side). Finally the shaft can be fully inserted through the other bracket.

The next piece to be constructed is the motion platform on which the user stands. In the detailed design, a top hat-like design was decided on. To create this, sections of ¼" thick, 3" inch wide steel are cut to the proper lengths. These sections are then MIG welded into the proper configuration. (Prototype bending using heat would have resulted in large inaccurate bend radii but would be preferable for production) After completing the welding, a milling machine is again used to drill the 3/8" clearance holes for mounting the motion platform to the roll axis base, and the ¼" clearance holes for mounting the foot pedals (made out of wood, using a jigsaw). The foot pedals are first bolted to the metal platform using ¼" bolts with shallow rounded heads, so the user can stand over the bolts. Finally, the finished motion platform is bolted to the smaller angled brackets with 3/8" bolts, and the locking collars are squeezed against each side of the assembly, and locked into place on the shaft.

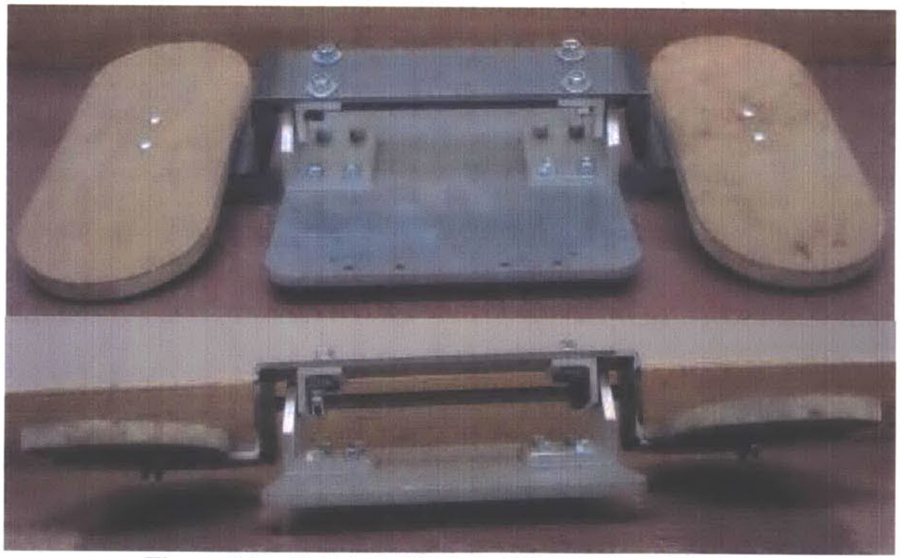


Figure 7-83: Roll Axis Module without Foam Element

Figure 7-84: Prototype Carriage with Roll axis module

The moment bars are created in an identical manner to the motion platform. A power hacksaw is used to cut 2” by ¼” bar stock to the proper lengths (9 inch and 10.25 inch respectively). The mounting holes for the bolts are then drilled into the 9 inch bar segments on a milling machine. The pieces are then welded together in the proper configuration, and the finished assembly is bolted onto the rest of the module.

Figure 7-85: Prototype Carriage with Complete Roll Axis Module

The finished roll axis module features a default stable position, and good roll axis motion with a nonlinear resistance force. Reattaching the finished top plate with roll axis module completes the proof of concept prototype, and allows for full scale tests of the overall exercise machine motion.

8 Finished Design

8.1 The Proof of Concept Prototype

The proof of concept prototype is the first real test to verify the performance of the snowboarding exercise machine. Through combination of the proof of concept modules in Chapter 7, the resulting prototype is a very close approximation to a commercially available version. The results of prototype testing reveal how closely the design meets the functional requirements of the machine, but more importantly, they uncover trouble spots that need to be addressed in subsequent prototypes, and ultimately in the commercially available version. (Figures 8-1 and 2)

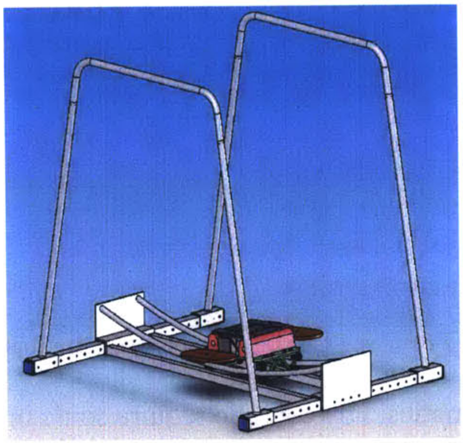


Figure 8-1: Full Prototype Assembly (CAD)

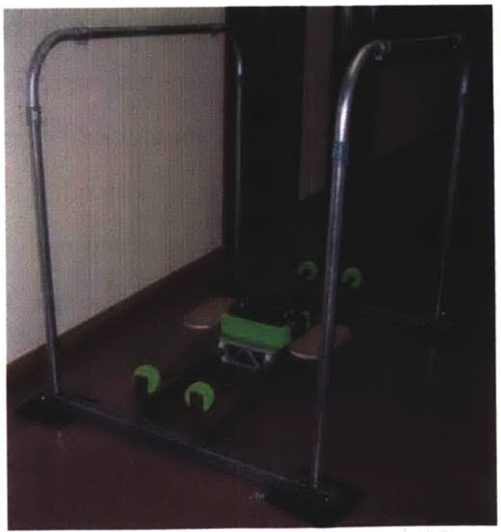


Figure 8-2: Full Prototype Assembly

The most important functional requirement for the design of the exercise machine is that it provides an accurate representation of snowboarding kinematics. The core motions selected for the design were the back and forth translational motion over the inverted curve, and the roll axis tipping to simulate "carving" a turn. Testing of this design indicates that this effect is achieved. Through a combination of tipping along the roll axis, and using the side hand rails, the user is able to rock back and forth along the rails. The resulting motion along the track is smooth.

Figure 8-3: Prototype Carriage and Rails (with foam bumpers)

The prototype kinematics, however, do require some improvement. The first issue is the length of the track. Initial test runs on the 56" long track resulted in the user picking up momentum, and repeatedly slamming into the rail ends. Adding sections of padding at the rail ends softens the impact, but does not solve the problem. The final rail design must be modified to extend the length of the track or decrease the radius at the ends to avoid impacts, and prevent serious damage. The other kinematic shortcoming is the lack of yaw axis motion. Earlier, it was discussed that both roll axis and yaw axis motion are required for carving a turn, though roll axis motion is dominant. Snowboarders attempting to use the exercise machine have the tendency to attempt turning in the same way that they would on a snowboard. Unfortunately with only roll axis motion, the carriage resists any motion about the yaw axis. Even limited yaw axis motion requires a new module design. Roll axis is a wonderful indicator of performance for the prototype, but a new angular motion module is required for the finished product.

Safety and stability is also of utmost importance. Users (especially beginners) require sturdy handrails to balance while using the simulator. The parallel stationary handrails appear to meet these needs. Holding onto the handrails provides stability, while keeping the user's arms in a somewhat natural snowboarding stance. There are several aspects of the railing prototype that are not desirable. Open sections were used to connect the rail frame and railings to the transverse bars. The lack of torsional stiffness in these sections results in unwanted rotation in the axial direction for the rail frame, and unwanted axial and transverse rotation of the railings. For the rail frame it is a simple matter to switch the open section to a closed section, but for the railings, geometric constraints (padding, etc) make it difficult to switch over to a closed section. Tightening down the wingnuts on the open section, however, significantly improves stability. Adding foam to the inside of the U bracket (creating a press fit) similarly reduces both axial and transverse wobble. The second problem with the prototype is the multiple railing sections. Each railing is made from 9 separate pieces, rather than 3. On occasion these sections are able to come loose, which is disastrous for the user. Luckily, sections like this would never be used in a commercial model, so this problem is limited to only this particular prototype.

The frame as a whole appears highly resistant to slipping, tipping, frame wobble, and failure. During use the wide frame is sufficient to prevent tipping and sliding. This can be further improved by adding high friction rubber pads underneath the ends. Wobble is also not a huge concern, outside of the previous problems associated with the railings. The carriage and motion platform also offer promising results. When a user boards the machine, they apply their entire bodyweight on one side of the motion platform, creating a very large moment. The motion platform and rails experience minimal deflection, no different than the deflections experienced boarding a regular snowboard. More importantly, the machine does not tip when a user applies their bodyweight in this way. By incorporating rounded corners, and padding into the final commercial design, the finished snowboarding exercise machine will be incredibly stable, safe, and user friendly.

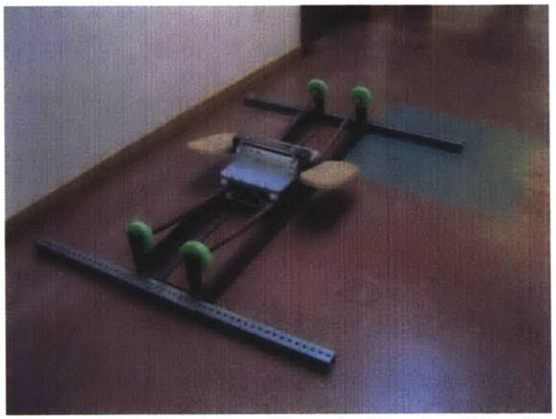


Figure 8-4: Prototype Base (without railings)

The final major design topic addressed by testing of the proof of concept prototype is assembly and collapsibility. Though the design and manufacture of the prototype is different from that of the finished design, the resulting assembly is functionally equivalent. The assembly process for the prototype is extremely straightforward. The rail frame contains two open sections of the larger 2-1/4" nestable square tubing. These open sections fit directly over the transverse bars, and attach into place with bolts. The open sections on the railings attach in an identical manner. The more involved elements of the prototype assembly are the upper railing sections, and the roll axis module. Ideally the railings are to be made in three pieces, with tapered ends to connect the sections. Currently, conduit connectors with set screws are used to attach the railing segments together. Removing the extra parts will simplify the assembly. Similarly, the roll axis module in the prototype is a collection of parts assembled to the top plate. This involves complicated assembly for the prototype. Luckily, for a consumer version, the roll axis module would be a pre-assembled unit that bolts onto the carriage.

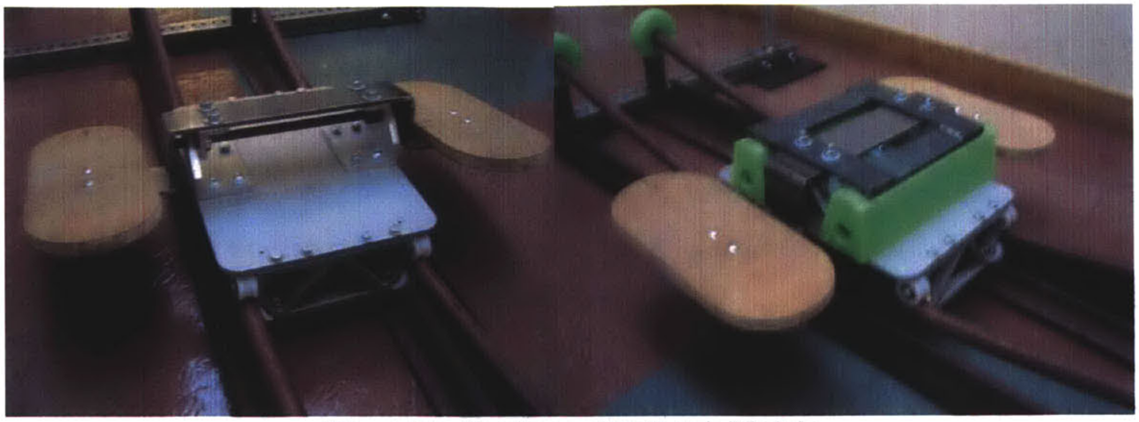


Figure 8-5: Carriage and Roll Axis Module

Collapsibility is also acceptable for the prototype module. The components of the assembly break down into long thin elements that fit easily into a long narrow box. This leads to easy storage for consumers.

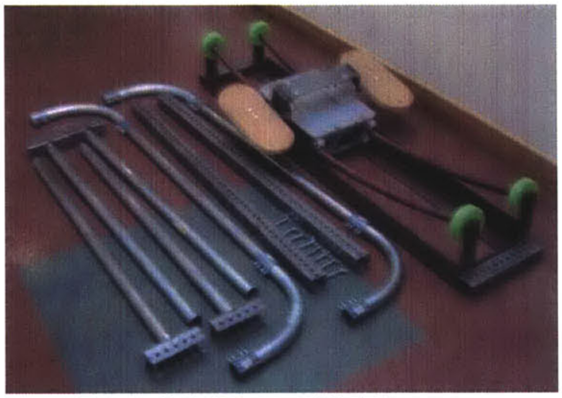


Figure 8-6: Disassembled Prototype

The overall results of the proof of concept prototype show that, for the most part, everything in the design works as it should. The trouble points discussed above can now be fixed, and incorporated into the final consumer design.

8.2 Finished Snowboarding Exercise Machine Design

The finished version of the Snowboarding Exercise machine uses the initial detailed design and fabrication work done on the proof of concept prototype as the basis for a machine that will be commercially viable. Ultimately the transition from proof of concept prototype to finished design is a collaboration between the designers, product testers, and the company licensing the product. A working proof of concept prototype establishes that the machine will work, but from that point a great deal of design is required to overcome the hurdles of bringing a product to market. As this project currently stands, it has successfully reached the proof of concept prototype level. The design is now ready to be shown to licensing companies to try to generate enough interest to bring the product to the next level. A finished design can not be settled on until this happens, though it is possible to describe several possibilities for what the finished design could look like.

Testing of the prototype rails revealed that though the inverse curve of the rails is great for the ride motion, but that the length and end conditions of the rail are inappropriate. To eliminate the repeated impacts on the end of travel, it is necessary to extend the track, and increase the slope at the ends. Figure 8-7 shows one possible implementation of this configuration. In this design the rail length is extended by approximately 10 inches, with greatly increased slope on the ends. This design would certainly remove any concerns with impacts on the ends, though it adds material, while keeping the same complex rail frame. It is, however, possible to incorporate the track length and end conditions into a simpler rail frame.

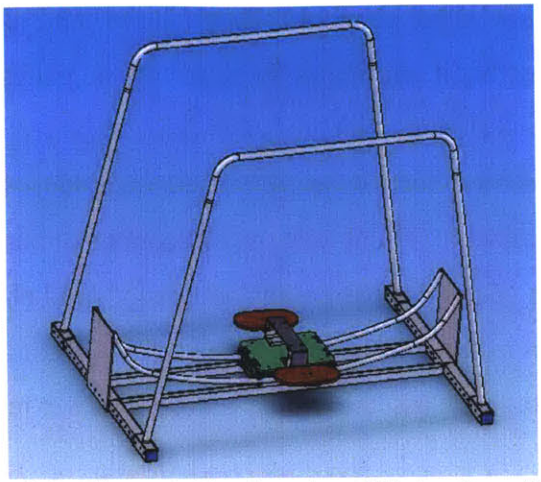


Figure 8-7: Elongated track and modified end conditions.

A separate concern with the overall ride motion is that for some snowboarders, the large degree of travel when carving on the heel side is unrealistic to actual snowboarding. A solution to this problem is to introduce asymmetric rails. Toe side motion is acceptable, while heel side motion is too spread out. If one side of the track is shortened, and the end slope is increased, it is possible to fix this problem, while not worrying about impacts on a shorter track. (Figure 8-8)

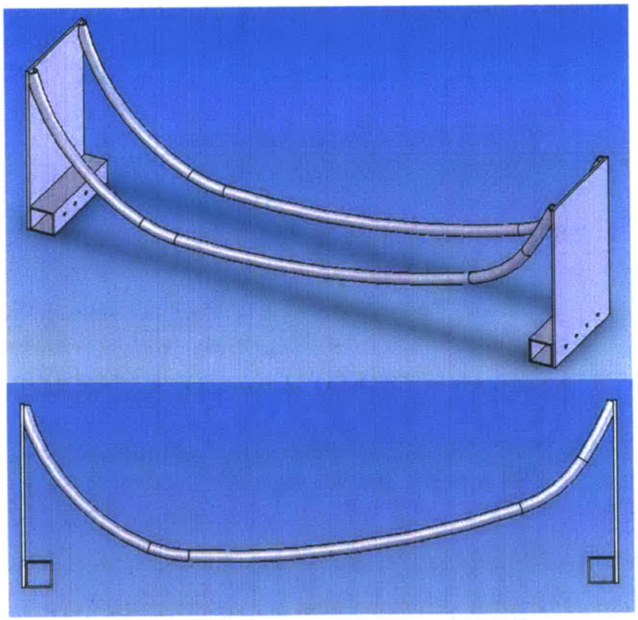


Figure 8-8: Asymmetric Curved Rails

Currently the rail frame has two long crossbars, in addition to 2 end plates that meet the rails at a sharp angle (creating a safety concern.) This design can be simplified considerably by "removing" these elements. Through the bending process, hollow tubing can be bent in such a way that it eliminates the need for end plates, replacing the sharp angle, with a rounded bend radius. The crossbars can also be removed. There will be some resulting side deflection, but not large enough to provide a safety risk. The resulting design only consists of 2 bent rails, and 2 sections of nestable square tubing. (Figure 8-9) The resulting design is extremely lightweight, and eliminates a large part of the manufacturing process. It also incorporates the added length and end slope into the design, and does not change the assembly process. (Figures 8-9 to 11)

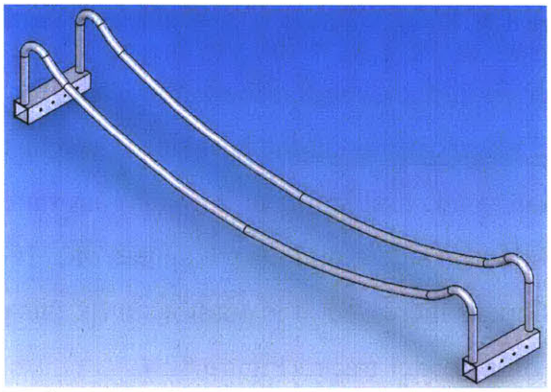


Figure 8-9: Curved Rail Frame (Isometric)

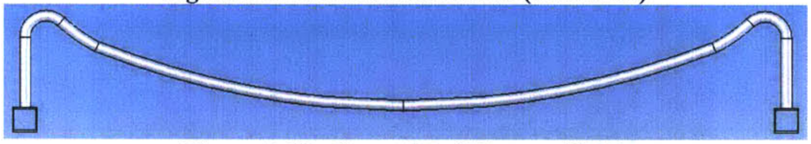


Figure 8-10: Curved Rail Frame (Side)

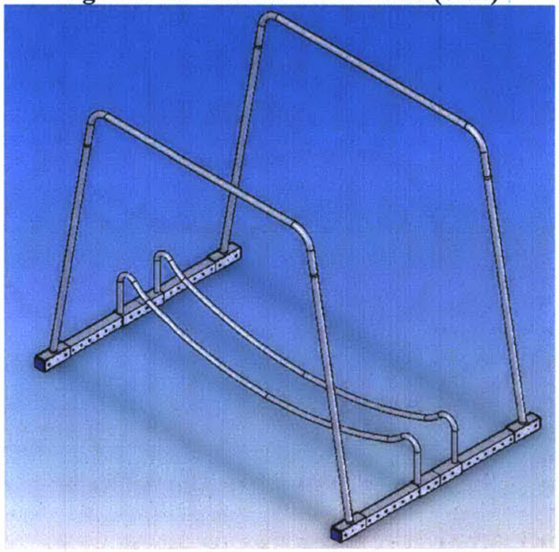


Figure 8-11: Support Frame with Curved Rail Frame

The carriage design in the prototype provides a solid base while moving along the rails, but unfortunately is not at all practical from a manufacturing standpoint. The thick aluminum sections and the numerous parts in the assembly are not desired. Instead it is easier to use thin sections of 0.1" steel. Using a 2 step bend process, it is possible to bend a single sheet of steel into the proper shape to fully constraint the wheels. In this configuration, the sheet is able to deflect, but if two sheets are stamped with an end pattern and welded into place, it eliminates this problem, but still gives the user access to the undercarriage to replace/ adjust the carriage wheel assemblies. The exposed wheels in this configuration can be covered with the angular motion base attached to the top of the carriage.

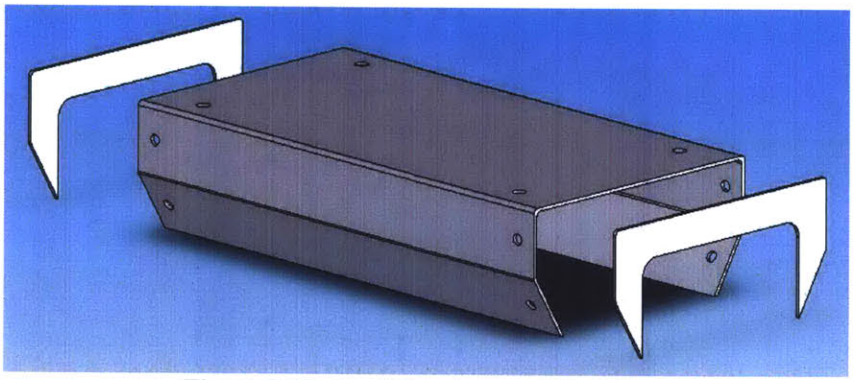


Figure 8-12: Bent Carriage and Endplates

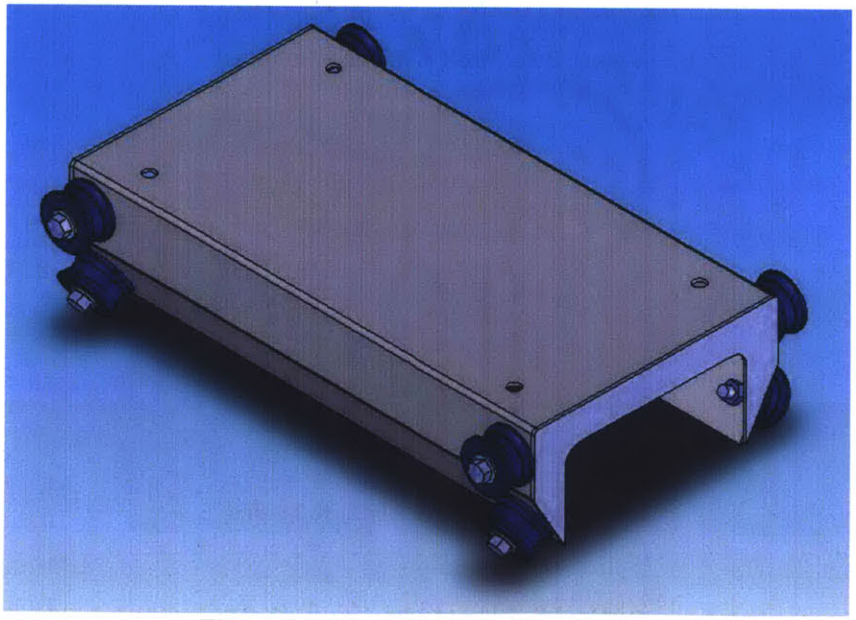


Figure 8-13: Bent Steel Carriage Design

The roll axis module prototype has similar problems. The goal for a finished design is to have the angular motion modules easily removable, as a single unit. As it is, the module is a collection of separate parts. Again, 0.1" sheet steel can be used. Figure 8-14 shows a potential bend pattern for a roll axis module. By first bending the triangular tabs on the two upright sections, then bending up the uprights, and welding the tabs on the triangular sections into the base slots, a very sturdy, monolithic roll axis base can be created. By making this base wider than the carriage, it can overhang the wheels, protecting the user from moving components. This overhang does run the risk of deflecting at the overhang, though ribbed sections could easily and inexpensively be welded onto the carriage to support these loads.

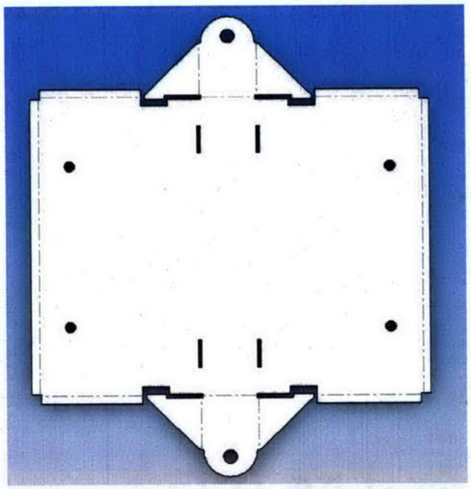


Figure 8-14: Roll Axis Base Unfolded

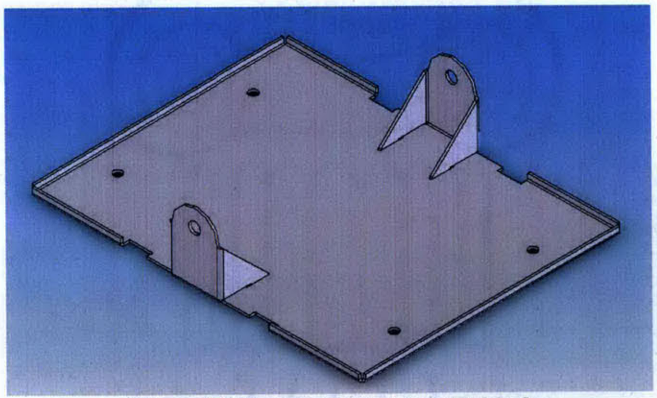


Figure 8-15: Roll Axis Base Folded

This new roll axis base allows for simple mounting of the roll axis, using bushings and lock nuts on either end (to constrain the shaft without using shaft collars). The angled brackets used in the prototype are replaced with rounded steel sections, to avoid impact with the upright support ribs. In addition, the motion platform in the commercial design is greatly simplified. Composites are required to meet the load bearing needs of the platform. Instead of welding separate segments together, materials can be individually bent, then injected with material to greatly increase platform strength. The moment bars can also be integrated into a single unit with the motion platform. This configuration leaves ample space to place foam, and results in an all around simpler design.

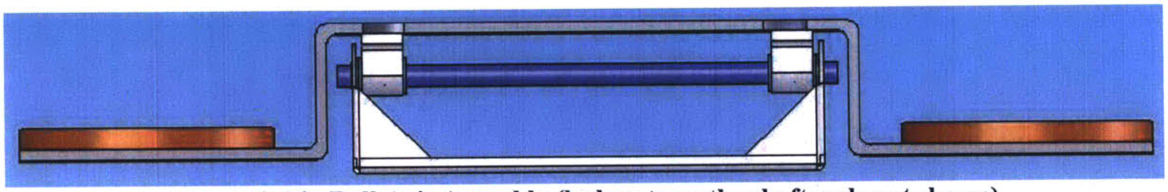


Figure 8-16: Roll Axis Assembly (lock nuts on the shaft ends not shown)

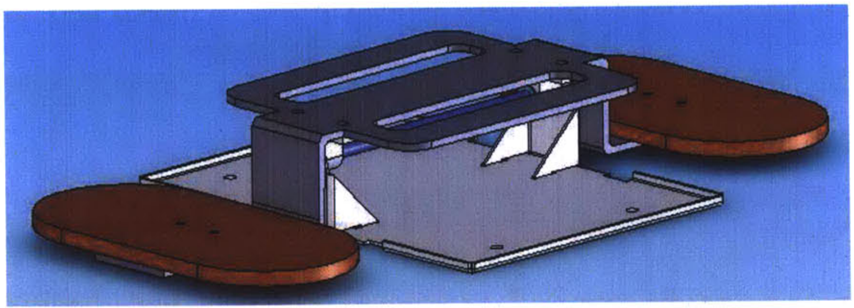


Figure 8-17: Roll Axis Module (without foam)

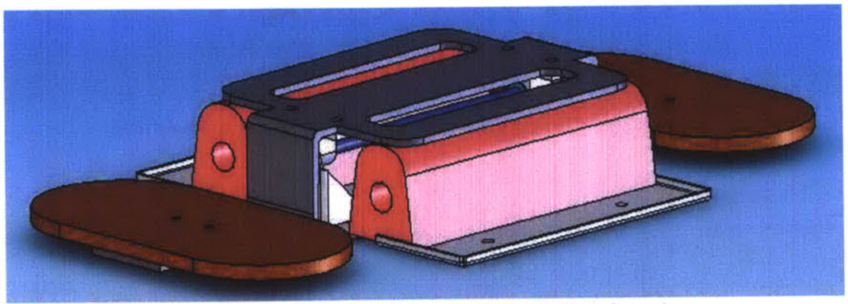


Figure 8-18: Roll Axis Module (with foam)

The finished roll axis module attaches onto the carriage as a single unit, and can easily be replaced with different angular motion modules. (Figures 8-19 and 20) Combining the full carriage assembly with the support frame provides a good indication of what the finished, commercially available design will look like. (Figure 8-21) The motions of the finished design are an improvement over the proof of concept prototype, and require the same amount of assembly time. Other significant improvements in the design are the lighter weight, greatly simplified machining, and fewer parts. The final design of the exercise machine relies on polling market testers, and working with the licensing company, but many of these ideas will definitely be incorporated into the final design.

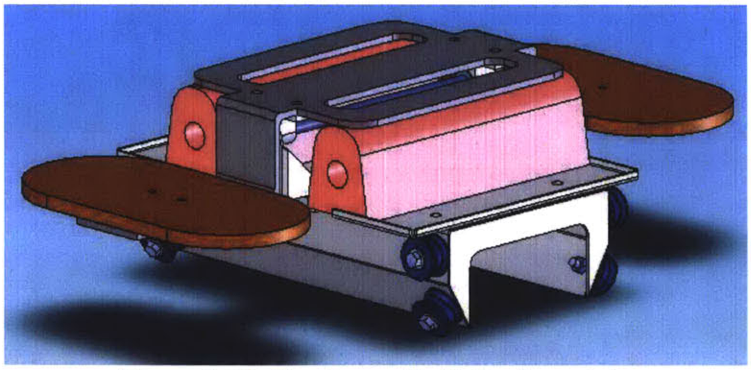


Figure 8-19: Carriage with Roll axis module

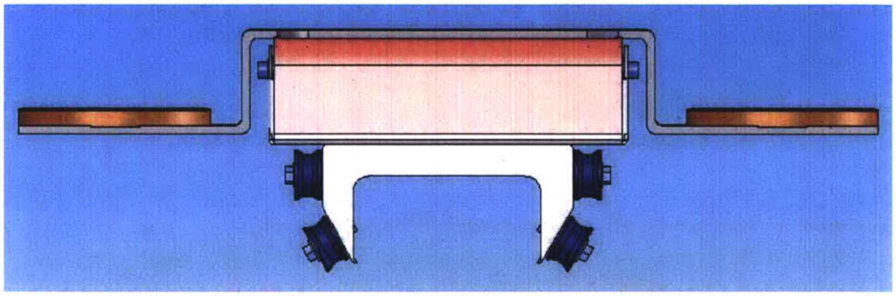


Figure 8-20: Carriage with Roll axis module (side view)

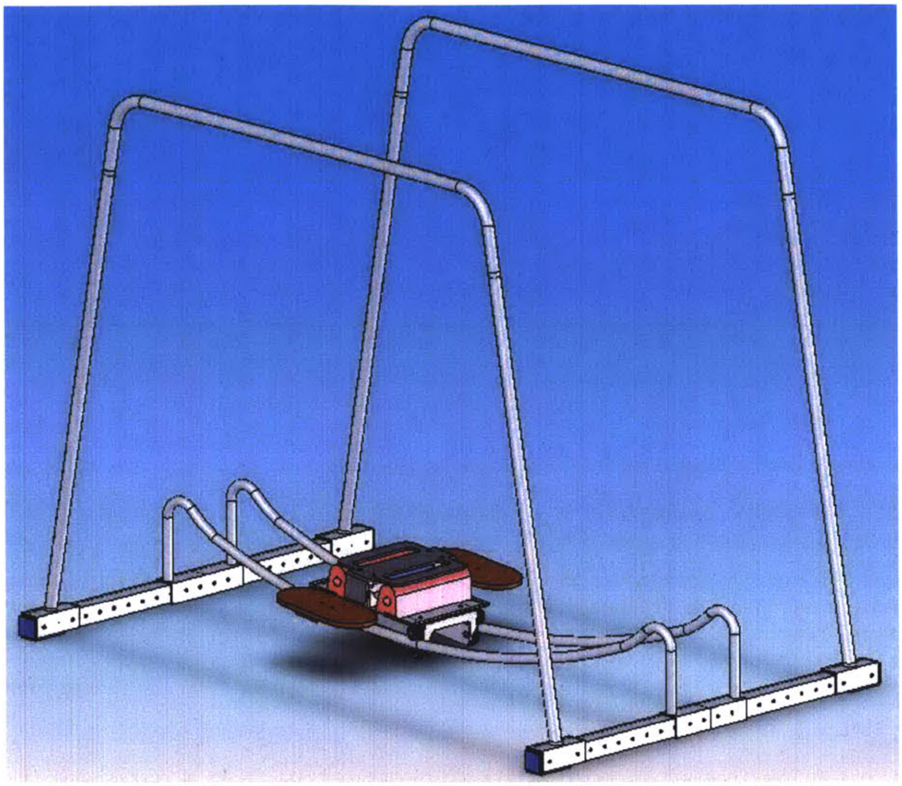


Figure 8-21: Final Proposed Snowboard Simulating Exercise Machine

9 Criteria for Success and Future Work

9.1 Criteria for Success

The completion of the proof of concept prototype and the detailed design naturally lead to discussions of how to measure success for the project. The ultimate success or failure of this exercise machine ties back to the fulfillment of the functional requirements. At the most basic level, the goals of the project are to create a device that realistically simulates the motions of snowboarding, offers a reasonably complex, individual mechanical design project which can be completed in a two year time span, and has a high potential for future licensing and marketing.

The measure of realism in the ride motion relies on market testing with a broad spectrum of potential users. In these tests, avid snowboarders are most desired, because of their ability to compare the ride motion with their own snowboarding experiences. Novices, however, offer valuable opinions on how easy it is to use the machine with no prior snowboarding knowledge. The user feedback is a necessary step in identifying what works, and what needs to be improved before the design becomes a viable product.

Thus far numerous test runs have been conducted with users ranging from beginners to seasoned snowboarding instructors. Though these initial runs only consist of a limited sample size, many important points have emerged. Users find the inverse rails to be effective in replicating a basic snowboard motion, though some have questioned the length and slope conditions of the rails. In addition, the foam inserts resisting the roll axis motion provide roll axis tipping much closer to carving through snow. A common concern is the railing height and placement. Ideally height and width adjustment can be added for the user to customize their preferred configuration. Beginners also experienced a fast learning curve in adapting to the carriage and roll axis motion along the rails. The results thus far have been overall positive, though the true measure of how realistic the motion is will depend on more extensive and controlled market tests on later design prototypes.

The academic element to the design of the snowboarding simulator has also been very successful. When selecting this approach to simulating snowboard motion, the goal was to focus on the mechanical design of the system. The resulting design provided numerous design challenges, all within the desired scope of the project. The complexity of the design was also perfect for a 2 year master's thesis project. In this time it was very feasible to take a typical course load, and still finish the detailed design and proof of concept prototype in the allotted time. The upcoming marketing of the design, and subsequent development of advanced prototypes also offers the potential for a fantastic learning experience.

The final major project goal is also the most complicated to address. Licensing of the snowboard exercise machine requires a solid design, positive market feedback, and a little bit of luck in finding a company willing to adopt and license the finished product. Again functional requirements come into play. For a design to even be considered, it must have excellent kinematics, be safe and stable, easily assembled and stored, inexpensive to produce, and as non invasive as possible. Evaluation again goes back to the users. Testers can provide valuable feedback on how well the design meets these needs. Unfortunately, even a great design may never become a commercial reality, if it cannot find the right audience. In this case user feedback is a good measure of how marketable the product is, but the only true measure of success is actually finding a company to license the product.

After considering these criteria, the Snowboard Exercise Machine has the potential to be very successful. As a project, the design offers a wonderful learning experience, in addition to creating a prototype that has thus far been extremely well received, despite small suggestions for improvement. Future success will be highly dependent on the results of market testing, and the licensing of the design by a company.

9.2 Future Work

This thesis marks the completion of the proof of concept prototype, and the first round of detailed design, but it is only the first phase of the much larger development cycle for the Snowboarding Exercise Machine. The evolution of the design from this stage to commercial reality requires a great deal of addition work.

The completion of the proof of concept prototype is a critically important milestone in the attempt to license the design in that it is the first hardware that allows people to physically test the exercise machine. The first step after this is to protect the design by filing for a patent (in this case a provisional patent). Once the idea is protected, the design must be presented to the outside world. This includes large scale testing of the prototype to identify design issues, and to generate positive feedback about the machine. In addition, a press release is needed to start the licensing campaign with companies. After doing a thorough search of potential licensing companies, the top candidates will be selected, and presented with the press release as a basis for initiating dialogue. The companies' response to the press release will determine the next phase of the project.

If a company expresses serious interest in the design, one of two things will happen. First, if the company wishes to purchase the idea for their own development, then the idea can be sold outright. In a second alternative, strong interest makes it worthwhile to create a second phase prototype. In this second phase, many of the ideas discussed in section 8.2, in addition to modifications based on user feedback can be used to create a better product, closer to a commercially viable design. Further work with the licensing company will result in more product testing, and hand catering the design to the manufacturing processes used by the licensing company.

If companies do not express interest in the design, but funds can be found, the second phase prototype can be created without company support. This second phase prototype may be more appealing to companies that previously were not interested.

In the end the snowboard simulating exercise device has the potential to be highly successful. If the design is popular, there will be much more work to complete, but the end result will be worth the long hours put into creating a robust, well designed machine.

10 Acknowledgements

I would like to take this opportunity to thank those that helped to make this project possible. First and foremost I would like to thank my advisor, Professor Alex Slocum, whose enthusiasm, brilliance, and love for design made this entire project more enjoyable than I ever could have imagined.

Next, I would like to thank Marc Graham and David Freeman, my lab mates in the Precision Engineering Research Group, who served as my peer reviewers, and provided me with much appreciated assistance in the design and testing of the proof of concept prototype. Similarly, I would also like to thank Alexandra Nelson, who worked on the project as an undergraduate researcher, and was responsible for the testing of roll axis module foam sections on the soft materials tester.

On the administrative side of the project, I would like to thank Maureen Lynch, who made sure that everything in the project ran smoothly.

The actual construction of the proof of concept prototype required the assistance of many different individuals. First I would like to thank Bob Gertsen, Joe Cronin, and Bob Nuttal in the MIT Pappalardo Lab, Gerry Wentworth in the LMP shop, and Ken Stone in the MIT Hobby shop, for their manufacturing input. In addition I would like to specifically recognize Mark Belanger in the LMP shop, who helped me to fabricate many of the carriage components, and Steve Haberek in the Pappalardo Lab, who did all of the welding on the support frame, carriage, and roll axis modules. I would also like to thank Bill Miskoe of Iron Dragon in New Hampshire, who was responsible for creating the rails and rail frame.

Finally, I would like to thank my dad Richard, my mom Althea, and my brother Charlie for their unflinching support through this entire process. They are the reason that I work so hard, and continue to strive for success.

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Figure 3-1b: US Olympic Snowboarder Chris Klug obtained from http://www.courier-journal.com/cjsports/news2002/02/16/klug.jpg

Figure 3-2: Eggenberger's Snowboard Simulator obtained from [3-5]

Figure 3-3a: Moscarello's Vew-do Balance Board obtained from [3-6]

Figure 3-3b: Moscarello's Vew-do Balance Board obtained from http://www.vewdo.com/

Figure 3-4: Corcoran's Blancing Board obtained from [3-7]

Figure 3-5: Fitter First BoarDRock obtained from http://www.fitter1.com/boardrock.html

Figure 3-6: Romero's Rehabilitation Board obtained from [3-9]

Figure 3-7: McGuiness' Surfing Simulator obtained from [3-10]

Figure 3-8: Fitter First Balance Boards obtained from http://www.fitter1.com/rocker-board-20-beginner.html

Figure 3-9a: SEGA Boarding Arcade obtained from [3-12]

Figure 3-9b: SEGA Boarding Arcade courtesy of Richard Vanderpoel

Figure 3-10a: Catapult Game Controller obtained from [3-13]

Figure 3-10b: Catapult Game Controller obtained from http://www.soulride.com/products/catapult.html

Figure 3-11a: Skier's Edge obtained from [3-14]

Figure 3-11b: Skier's Edge obtained from http://www.skiersedge.com/

Figure 3-12: Stamina Products Skiing Machine obtained from [3-15]

Figure 3-13: Nordic Track Skiing Machine [3-16]

Figure 3-14: ProFitter Lateral Cross Trainer obtained from http://www.fitter1.com/pro-fitter.html

Figure 3-15a: Ski Deck obtained from [3-18]

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Figure 3-17: The Rutgers Ankle obtained from http://www.caip.rutgers.edu/vrlab/projects/ankle/img/mech_dev_with_force_sensor3.jpg

Figure 3-18: Force Dimension 6-dof Haptic Device obtained from http://www.forcedimension.com/products/files/delta6dof.pdf

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Figure 3-20: Gough-Stewart Platform obtained from http://www.hexapods.net/hexapod.htm

Figures 3-21: The Gough Tire Tester obtained from http://www.parallemic.org/Reviews/Review007p.html courtesy of Mike Beeson, Dunlop Tyres

Figure 3-22: Early Cappel Flight Simulators obtained from http://www.parallemic.org/Reviews/Review007p.html courtesy of Klaus Cappel

Figure 3-23a: NASA Vertical Motion Simulator obtained from http://www.ecse.com/flight_sim.htm

Figure 3-23b: CAE Embraer 170 Flight Simulator obtained from http://www.cae.com/en/newsroom/img/gallery/mshsim.jpg

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Figure 3-25a: Star Tours Poster Obtained from http://www.disneylandpostcards.com/tlst4.jpg

Figure 3-25b: Star Tours Conceptual Model obtained from http://members.lycos.nl/ultimatedisneyfan/maquettes_van_disneyland_park.htm

Figure 3-26a: Hexel Hexabot obtained from http://www.hexel.com/hexabot.htm

Figure 3-26b: Hexel Tornado 2000 obtained from http://www.ifw.uni-hannover.de/robotool/pages/maschinen_pages/hexelTornado2000.html

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Figure 3-28a: Ingersoll HOH600 obtained from http://www.ingersoll.com/assets/images/hexapod.jpg

Figure 3-28b: Ingersoll HOH600 hexapod obtained from http://metalworking.com/DropBox/_2002_retired_files/Ingersoll-shop-1-hexapod-mill.jpg

Figure 3-29: Giddings and Lewis VARIAX obtained from http://www.ifw.uni-hannover.de/robotool/pages/maschinen_pages/giddingsVARIAX.html

Figure 3-30a: Geodetic G500 obtained from http://www.ifw.uni-hannover.de/robotool/pages/maschinen_pages/geodeticG500.html

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Figure 3-31a: CRIGOS Robot obtained from http://www.parallemic.org/Reviews/Review003.html courtesy of K. Radermacher and G. Rau, Helmholtz-Institut Aachen, Germany

Figure 3-31b: PI (Physik Instrumente) Surgical Hexapod obtained from http://www.physikinstrumente.de/primages/pi_m850_med_i4c_o_eps.jpg

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Figure 3-33a: Disney Quest's Pirates of the Caribbean obtained from http://www.gamasutra.com/features/20010706/game.jpg

Figure 3-33b: Disney Quest's Virtual Jungle Cruise obtained from http://www.pocketvenus.net/disneyparks/wdw/photos/downtowndisney/dqjunglecruise.jpg

Figure 3-34: Disney Quest's Ride the Comix obtained from http://www.pocketvenus.net/disneyparks/wdw/photos/downtowndisney/dqridethecomix.jpg

Figure 3-35: Disney Quest's Cyberspace Mountain obtained from http://www.wdwinfo.com/Photos/DisneyQuest2/images/152-5279_IMG.jpg

Figure 4-1: Snowboard, modified from source image found at http://www.caymag.com/wp-content/images/snowboard.jpg

Figure 4-2b: Carved Slope, obtained from
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Figures 4-3b, 4-6b, 4-7a, 4-7b: Pictures of Oli Sebbar, Snowboarding Instructor at Alpe d'Huez. Pictures obtained from: http://www.masterclass.f9.co.uk/images

Figure 7-1: Snowboarder, obtained from Canadian Mountain Holidays Website
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Figure 7-12a: THK HCR Bearing Rail and Carriage obtained from
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Figure 7-20: Roller Coaster wheels obtained from
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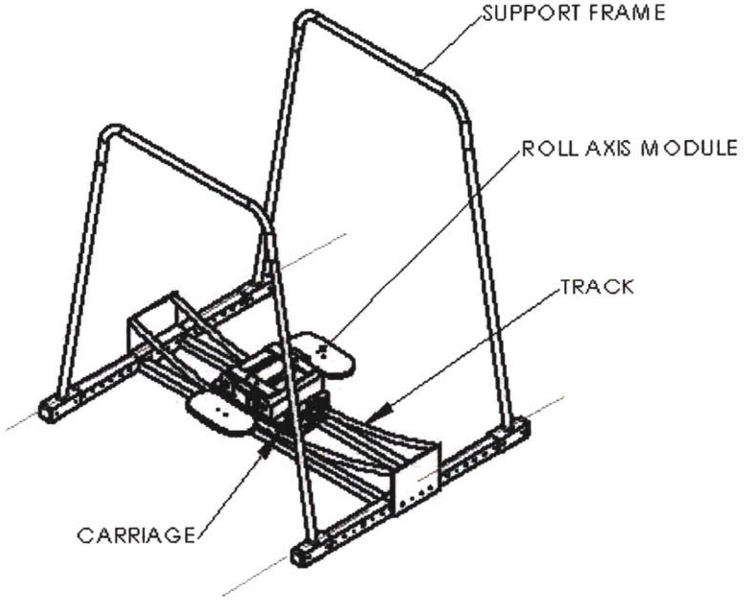
12 Appendix: Engineering Drawings



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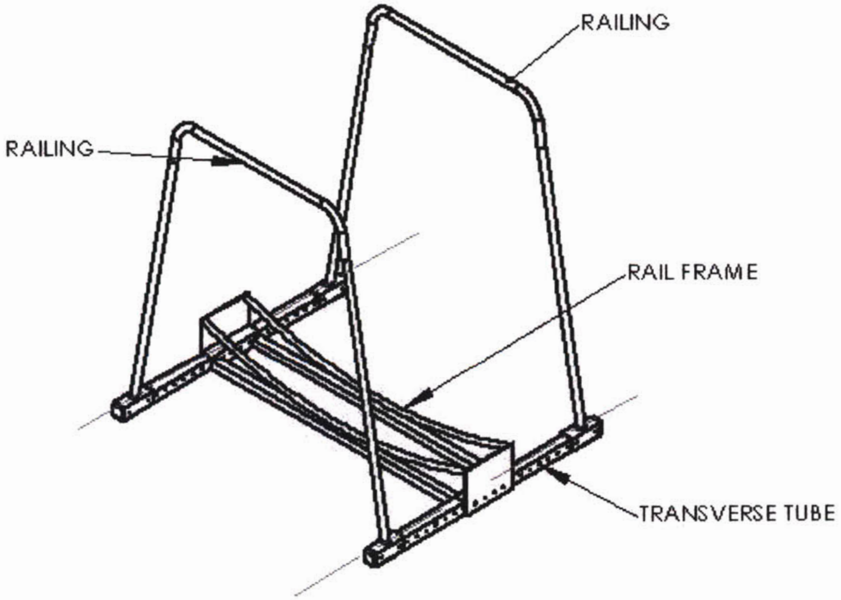

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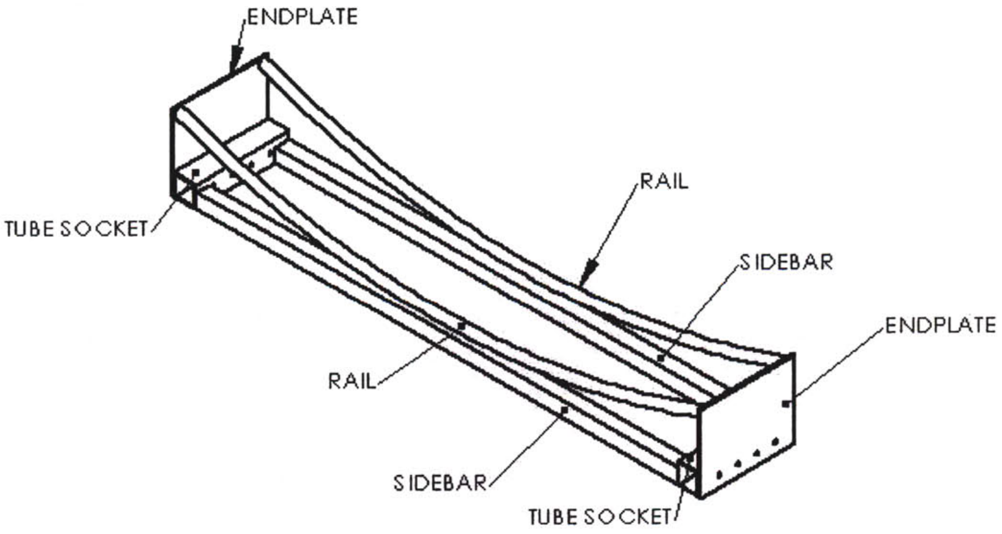

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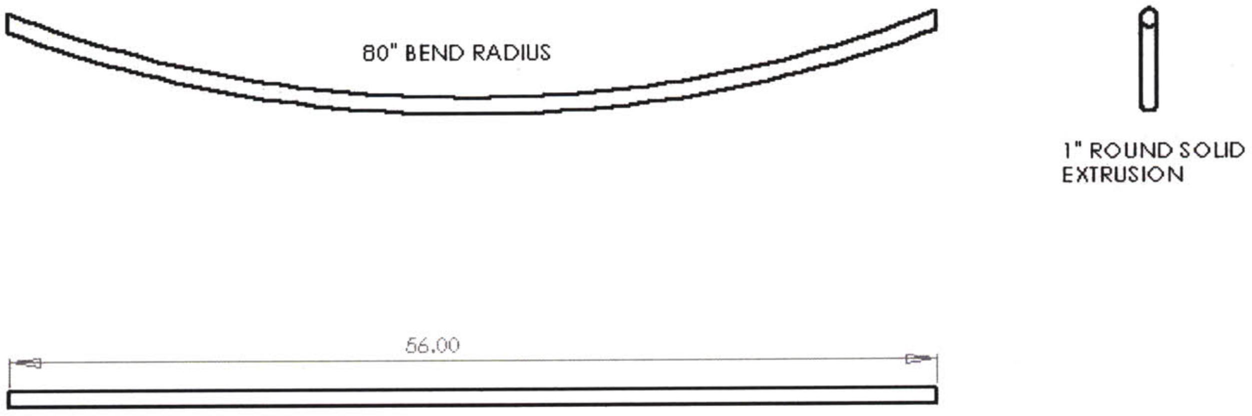

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Rail

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SHEET 1 OF 1

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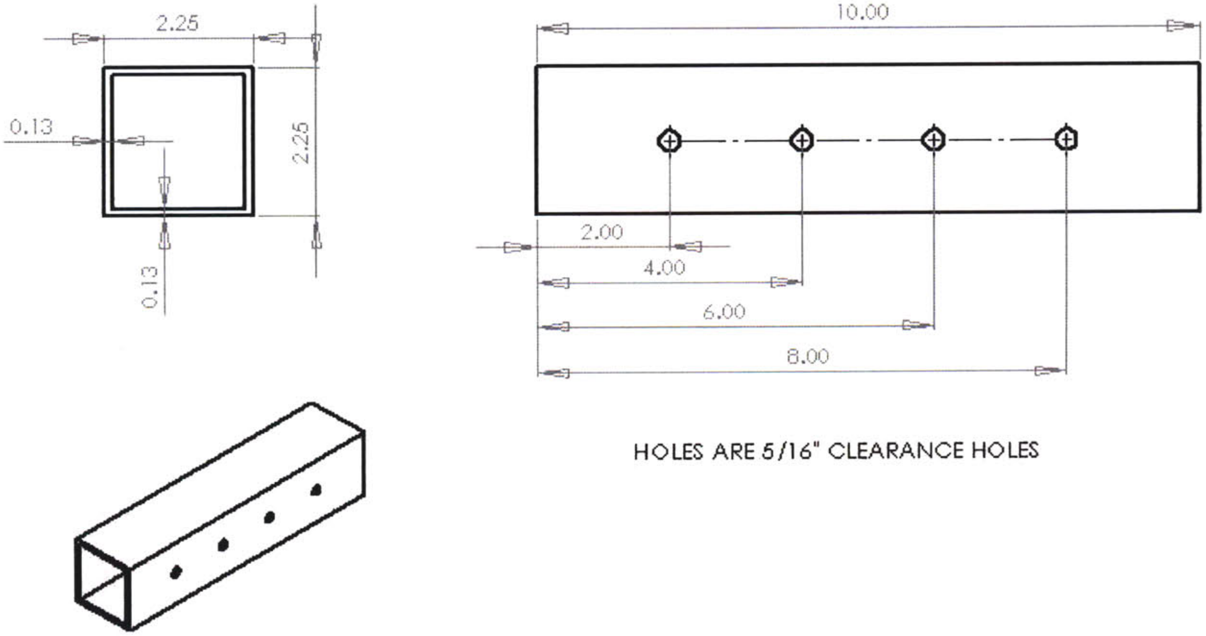

HOLES ARE 5/16" CLEARANCE HOLES

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NEXT ASSY
USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
STEEL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	IAV	4/15/04
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

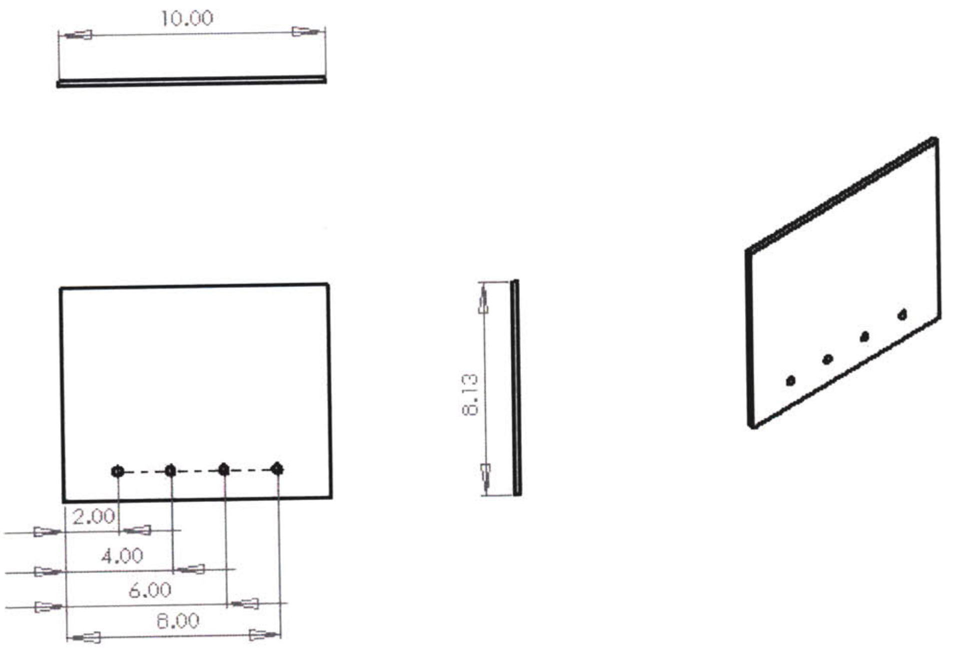
MIT PERG LAB

TITLE:

Railbase Sockets

SIZE A
DWG. NO. Rail Base Square socketed
REV

SCALE: 1:2 WEIGHT: SHEET 1 OF 1



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

INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
STEEL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	IAV	4/15/04
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

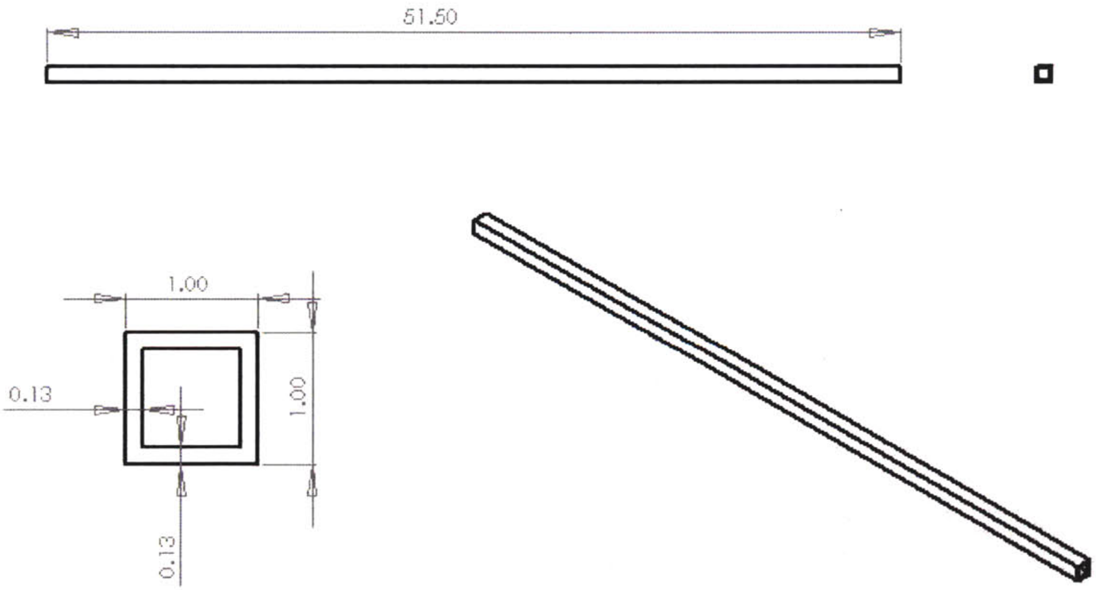
COMMENTS:

MIT PERG LAB

TITLE:

Railbase Endplate

SIZE
A
DWG. NO.
Rail Base Plate socketed
REV
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1



PROPRIETARY AND CONFIDENTIAL THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF MIT PERG LAB. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF MIT PERG LAB IS PROHIBITED	NEXT ASSY	USED ON	UNLESS OTHERWISE SPECIFIED: DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ± INTERPRET GEOMETRIC TOLERANCING PER: MATERIAL STEEL FINISH	
	APPLICATION		DO NOT SCALE DRAWING	

	NAME	DATE
DRAWN	IAV	4/5/06
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

MIT PERG LAB

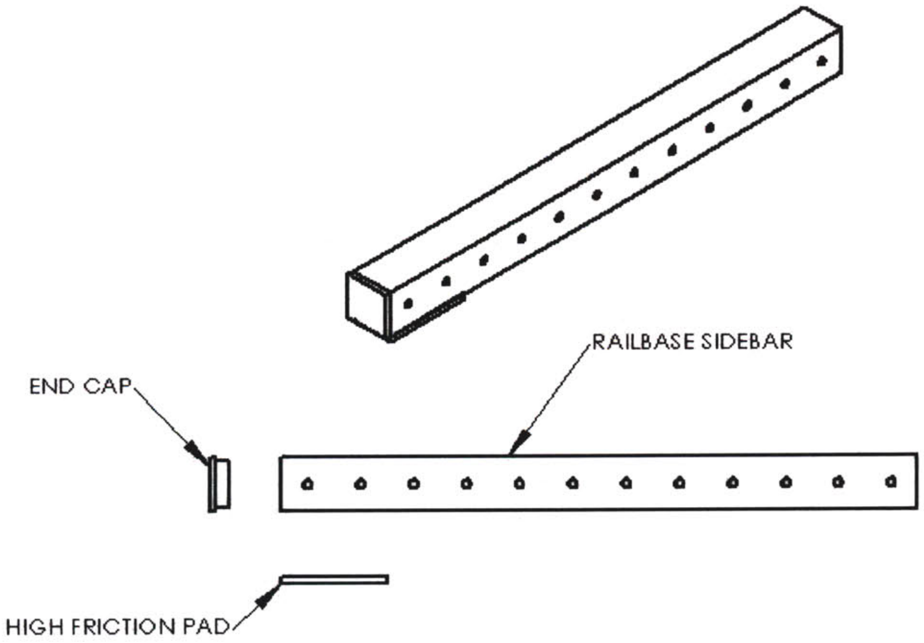
TITLE:

Railbase Sidebar

SIZE	DWG. NO.	REV
A	Rail Base SideBar socketed	

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



MIT PERG LAB

TITLE:

Sidebar Assembly

	NAME	DATE
DRAWN	IAV	4/15/04
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

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

NEXT ASSY
USED ON
APPLICATION

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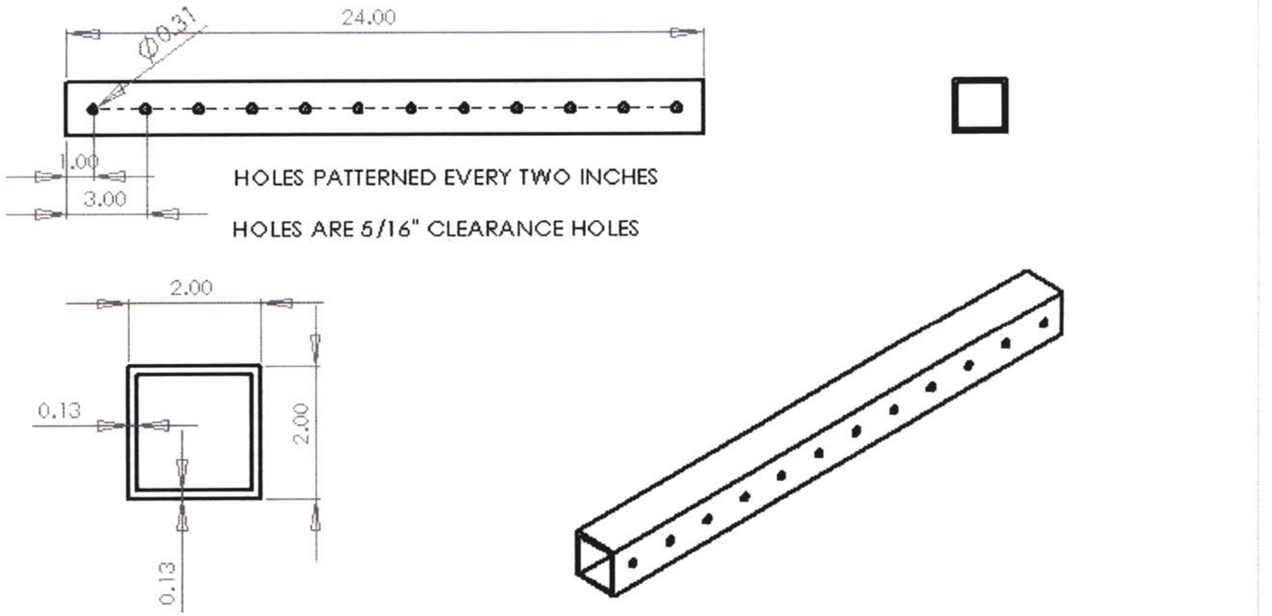
SIZE A
DWG. NO. Rail Base SlideBar Assy socketed
REV

SCALE: 1:5 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



HOLES PATTERNED EVERY TWO INCHES

HOLES ARE 5/16" CLEARANCE HOLES

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

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
STEEL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	IAV	4/15/04
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

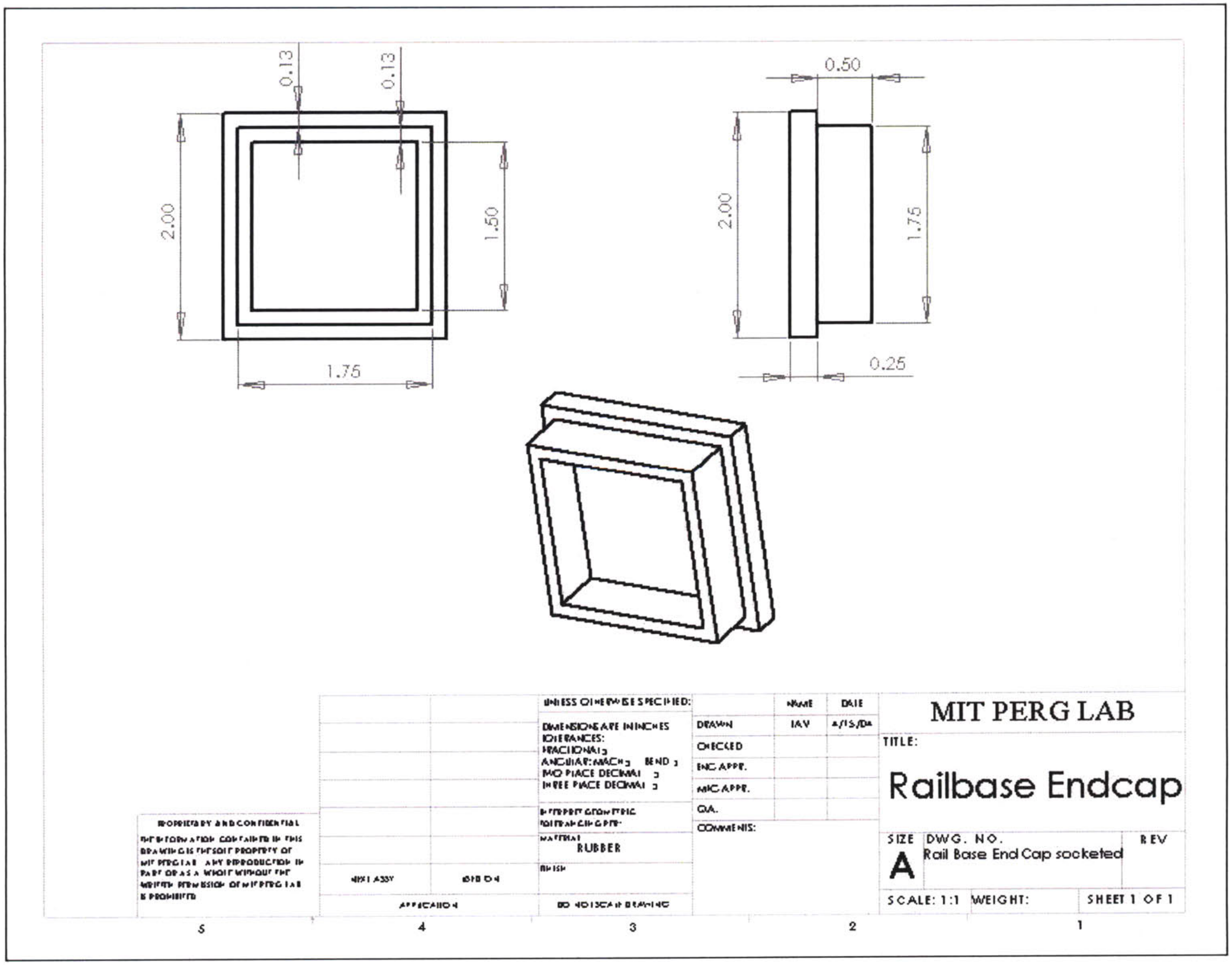
MIT PERG LAB

TITLE:

Railbase Sidebar

SIZE A | DWG. NO. Rail Base Slide Bar socketed | REV

SCALE: 1:5 | WEIGHT: | SHEET 1 OF 1


0.13
0.13
2.00
1.50
1.75
0.50
2.00
1.75
0.25
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
RUBBER
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
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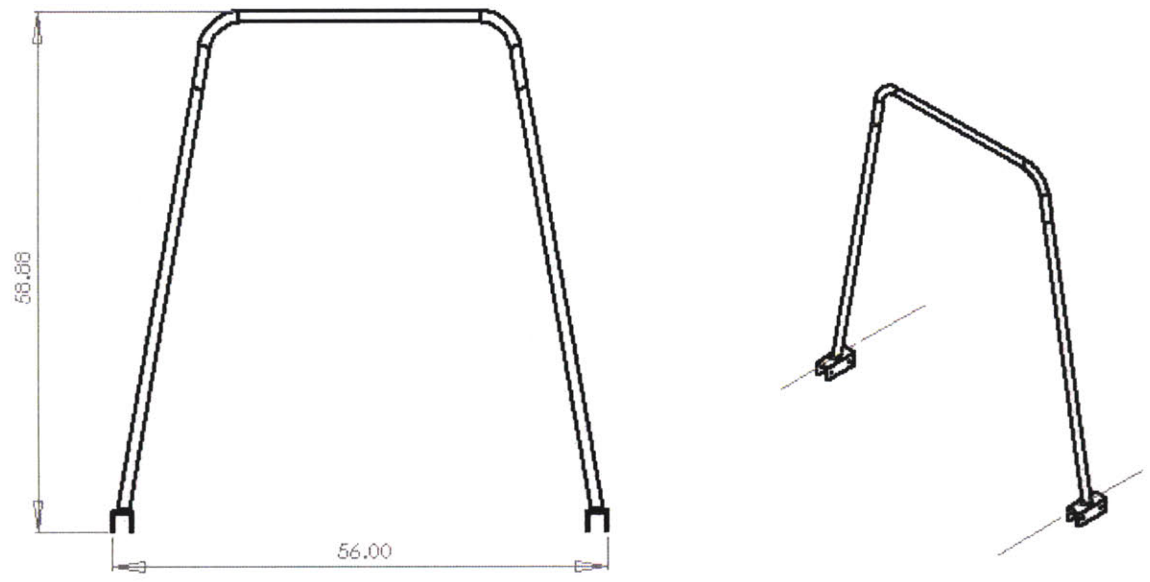
NAME
DATE
DRAWN
IAV
4/15/04
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MIT PERG LAB
TITLE:
Railbase Endcap
SIZE
A
DWG. NO.
Rail Base End Cap socketed
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



MIT PERG LAB

TITLE:

Support Railing

	NAME	DATE
DRAWN	IAV	3/5/05
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

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

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
STEEL

FINISH

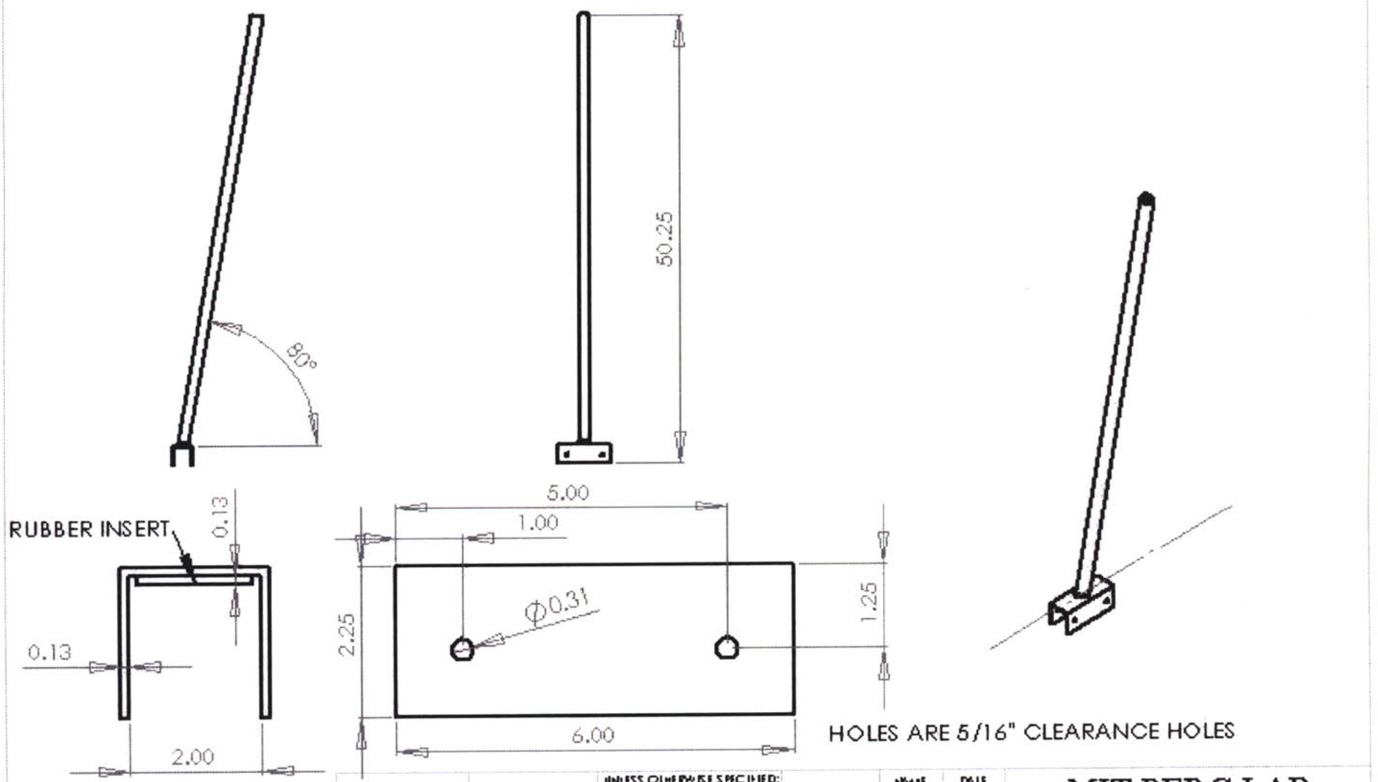
DO NOT SCALE DRAWING

NEXT ASSY | USED ON
APPLICATION

SIZE A
DWG. NO. FullRailing AssyPhase2
REV

SCALE: 1:1
WEIGHT:
SHEET 1 OF 1

5 4 3 2 1



HOLES ARE 5/16" CLEARANCE HOLES

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USED ON
APPLICATION

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

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
STEEL

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	IAV	3/5/06
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

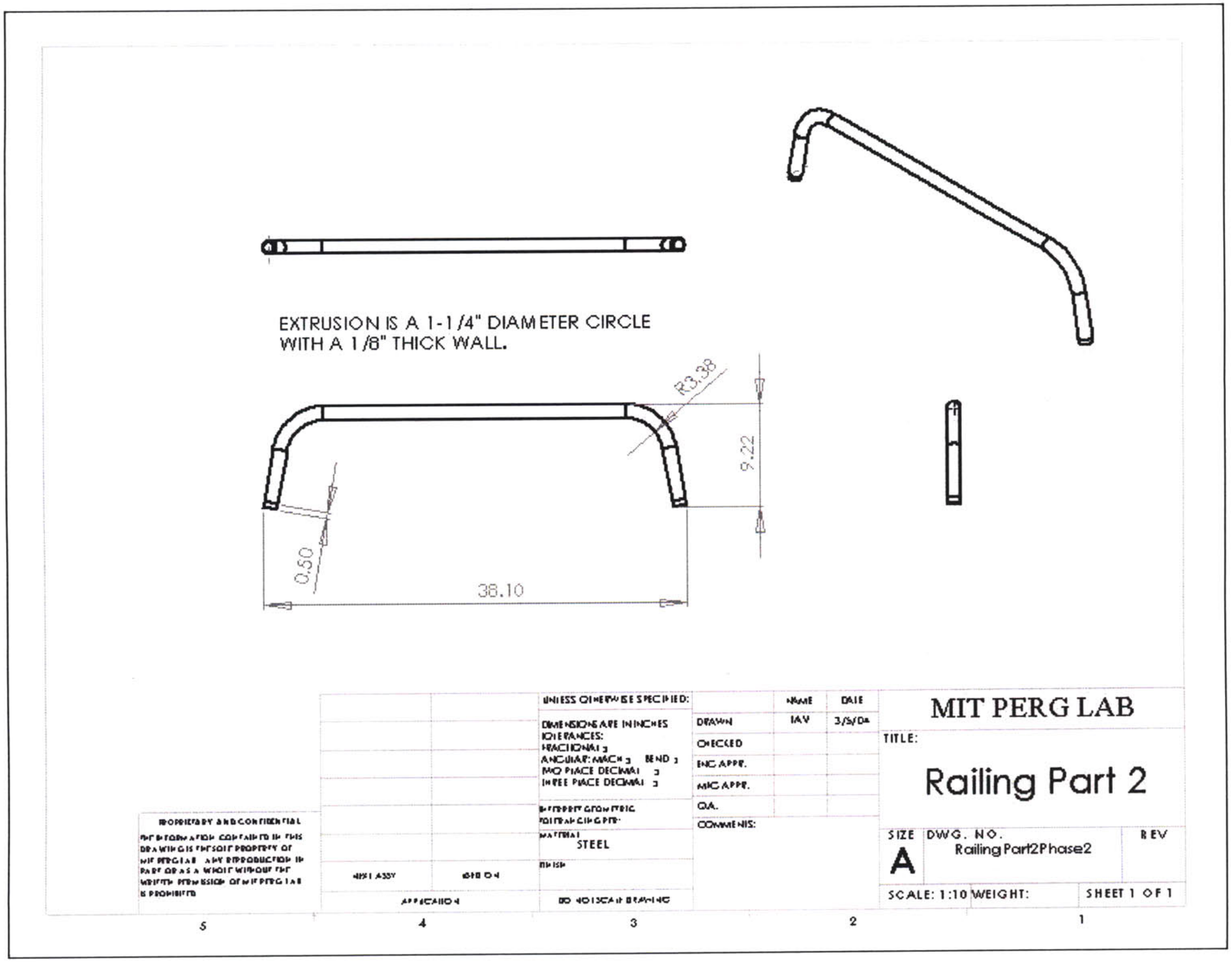
MIT PERG LAB

TITLE:

Railing Part 1

SIZE A
DWG. NO. RailingAssyPart1socketed
REV

SCALE: 1:20 WEIGHT: SHEET 1 OF 1



EXTRUSION IS A 1-1/4" DIAMETER CIRCLE
WITH A 1/8" THICK WALL.

MIT PERG LAB

TITLE:

Railing Part 2

	NAME	DATE
DRAWN	IAV	3/5/04
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

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

INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
STEEL
FINISH
DO NOT SCALE DRAWING

NEXT ASSY
USED ON
APPLICATION

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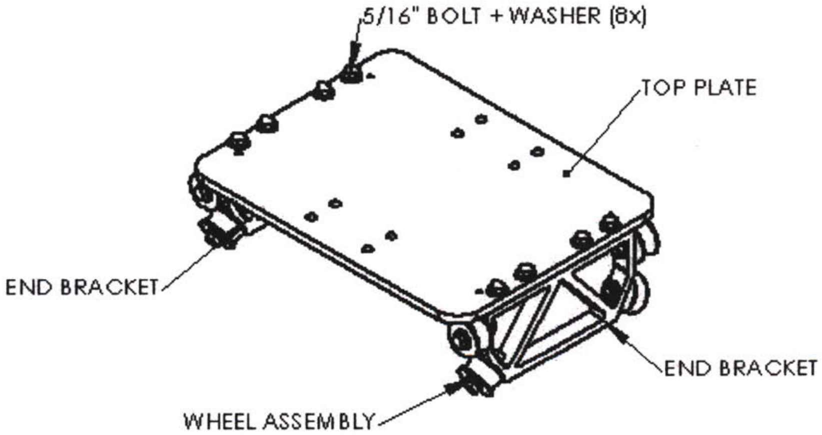
SIZE A
DWG. NO. Railing Part2Phase2
REV
SCALE: 1:10
WEIGHT:
SHEET 1 OF 1



WHEEL ASSEMBLY CONTAINS:
1 WHEEL
1 5/16" CARRIAGE BOLT
3 5/16" WASHERS
1 5/16" NUT W? NYLONG INSERT

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NEXT ASSY	USED ON
APPLICATION	

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	IAV	7/6/06
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

MIT PERG LAB

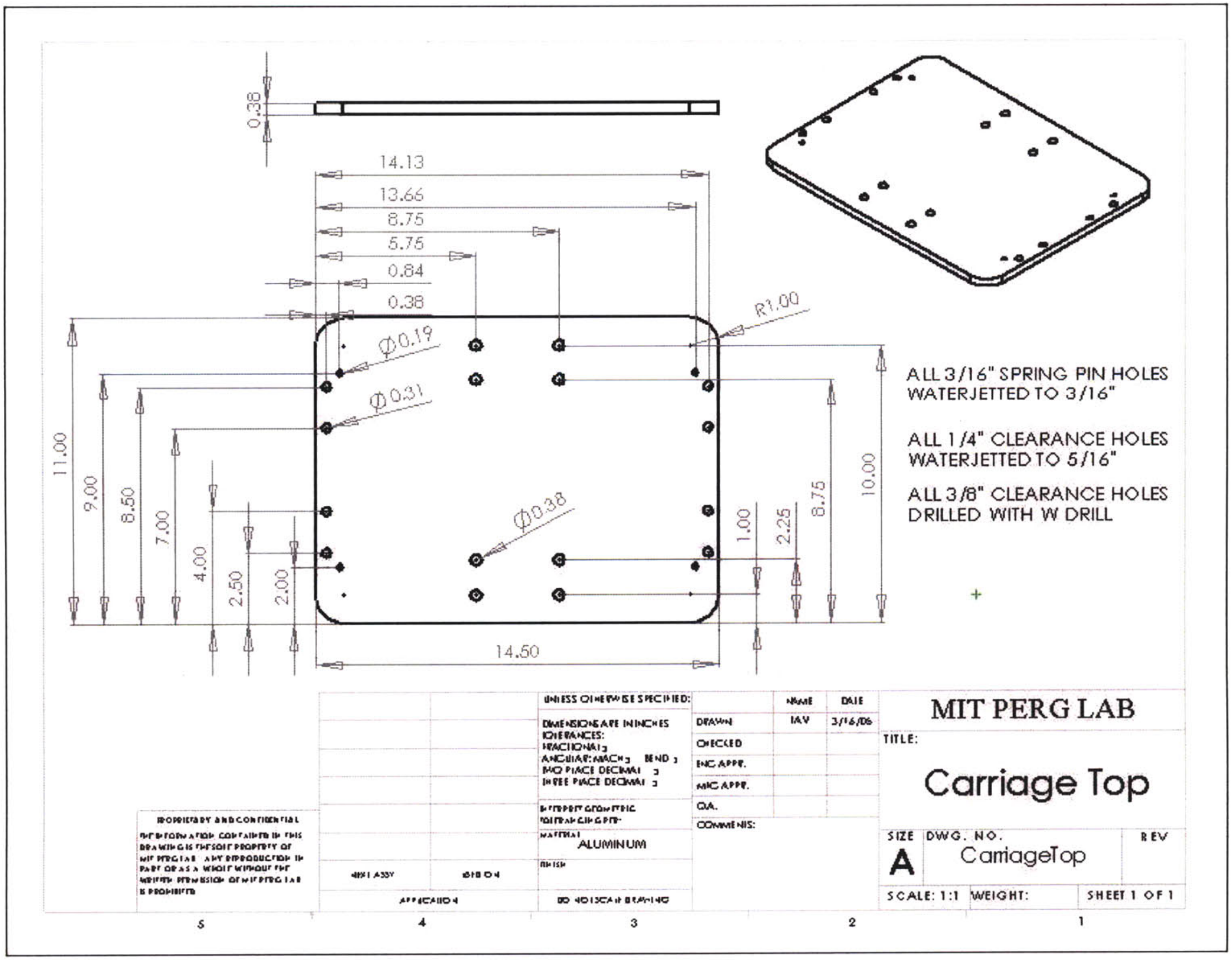
TITLE:

Carriage

SIZE	DWG. NO.	REV
A	CarriageAssy	

SCALE: 1:5 WEIGHT: SHEET 1 OF 1

5 4 3 2 1


0.38
14.13
13.66
8.75
5.75
0.84
0.38
R1.00
Ø0.19
Ø0.31
Ø0.38
11.00
9.00
8.50
7.00
4.00
2.50
2.00
1.00
2.25
8.75
10.00
14.50
ALL 3/16" SPRING PIN HOLES WATERJETTED TO 3/16"
ALL 1/4" CLEARANCE HOLES WATERJETTED TO 5/16"
ALL 3/8" CLEARANCE HOLES DRILLED WITH W DRILL
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ALUMINUM
FINISH
DO NOT SCALE DRAWING
NEXT ASSY
USED ON
APPLICATION
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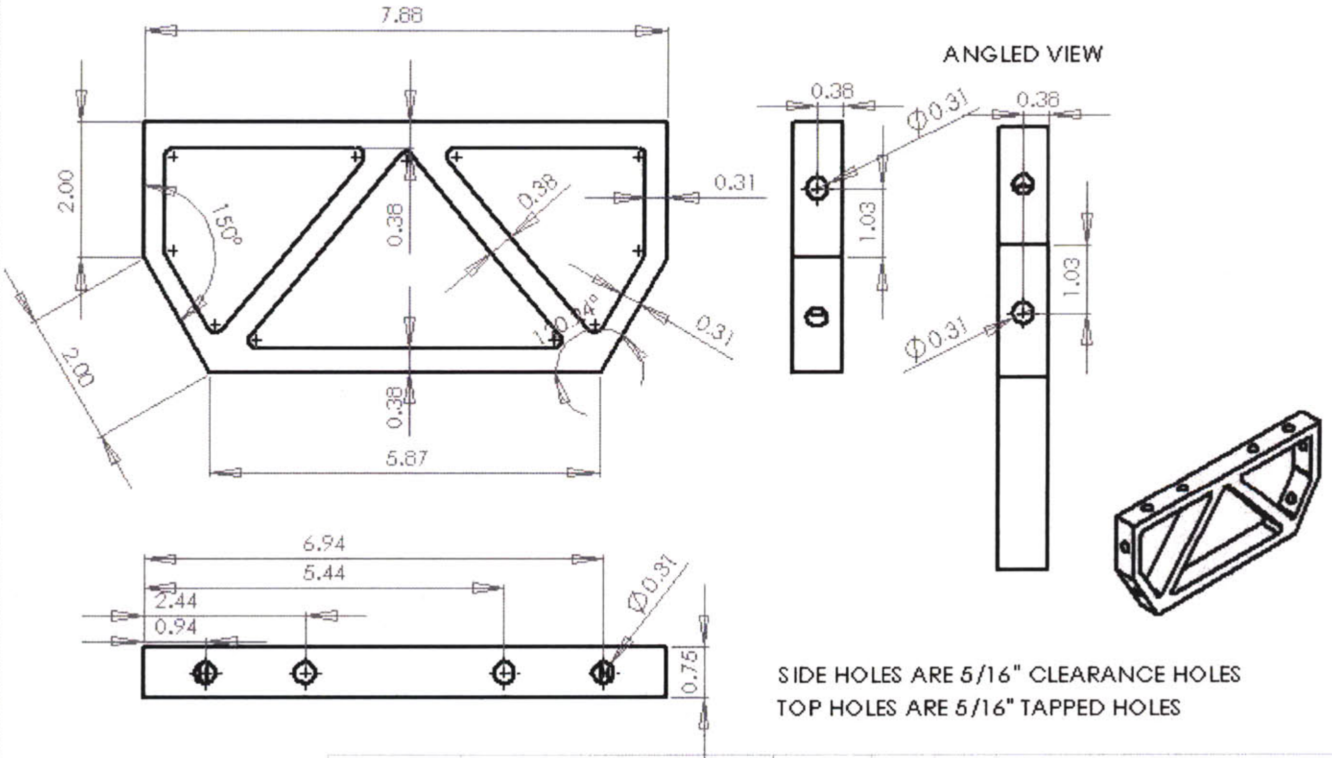
NAME
DATE
DRAWN
IAV
3/16/06
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MIT PERG LAB
TITLE:
Carriage Top
SIZE
A
DWG. NO.
CarriageTop
REV
SCALE: 1:1
WEIGHT:
SHEET 1 OF 1
5
4
3
2
1



SIDE HOLES ARE 5/16" CLEARANCE HOLES
TOP HOLES ARE 5/16" TAPPED HOLES

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NEXT ASSY	USED ON
APPLICATION	

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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ALUMINUM
FINISH
DO NOT SCALE DRAWING

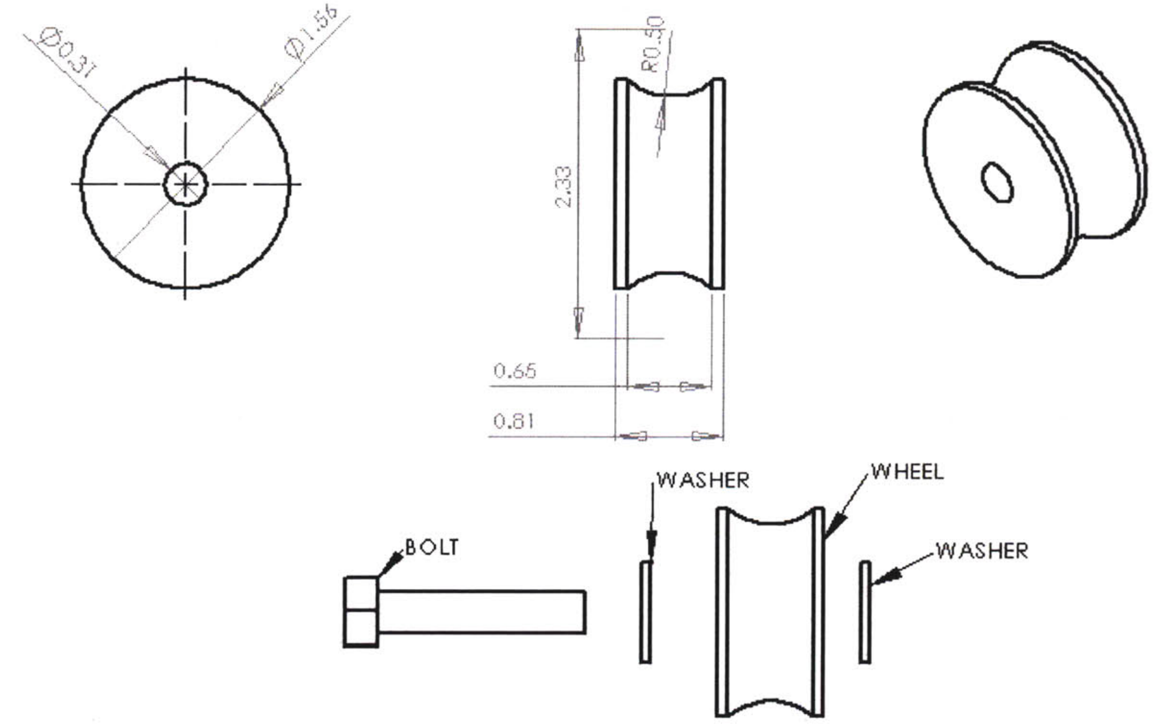
	NAME	DATE
DRAWN	IAV	8/20/04
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

MIT PERG LAB

TITLE:
Carriage End

SIZE A
DWG. NO. CarriageEnd
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1

5 4 3 2 1



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

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
NYLON

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	IAV	6/10/04
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

NEXT ASSY
USED ON
APPLICATION

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MIT PERG LAB

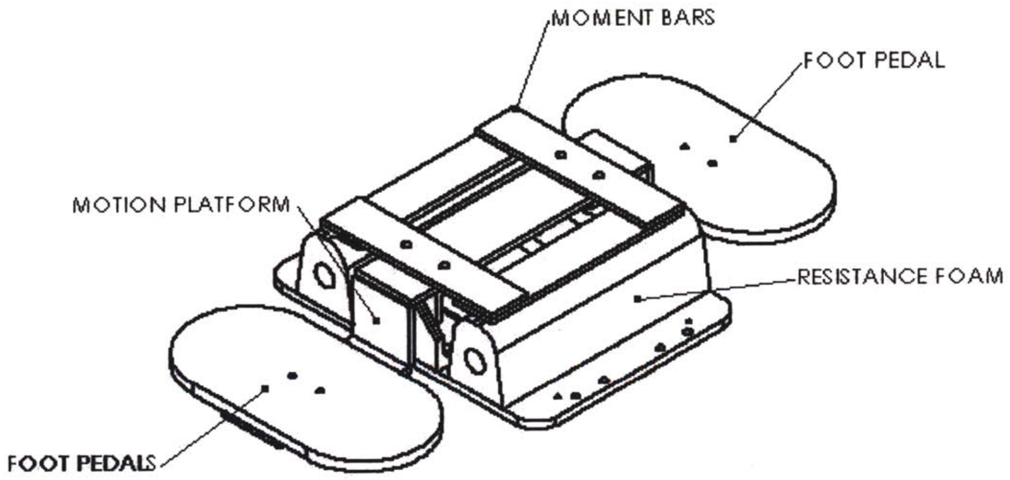
TITLE:

Carriage Wheel

SIZE A
DWG. NO. CarriageWheel_real
REV

SCALE: 1:1
WEIGHT:
SHEET 1 OF 1

5 4 3 2 1



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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	IAV	4/27/06
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

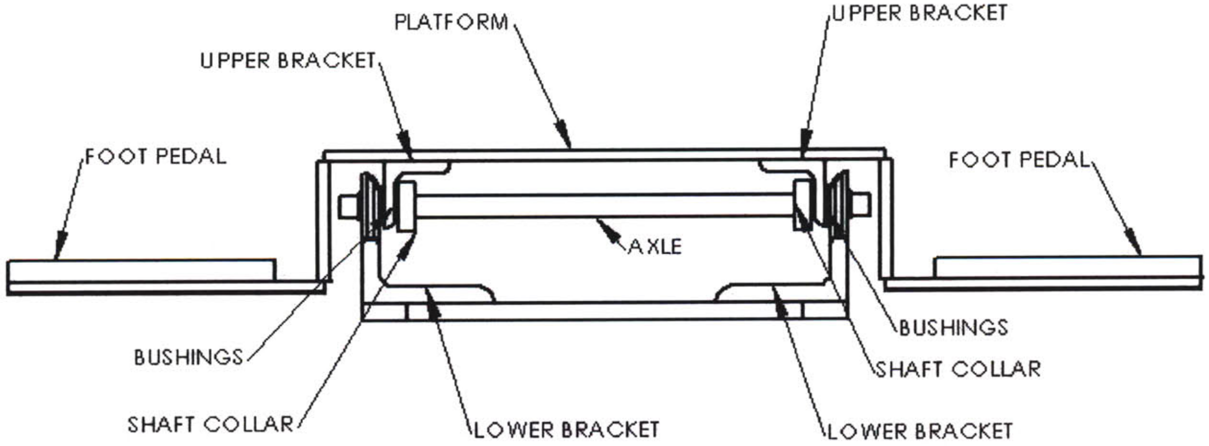
MIT PERG LAB

TITLE:

Roll Axis Module

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

5 4 3 2 1



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NEXT ASSY	USED ON
APPLICATION	

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TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	IAV	4/4/05
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

MIT PERG LAB

TITLE:

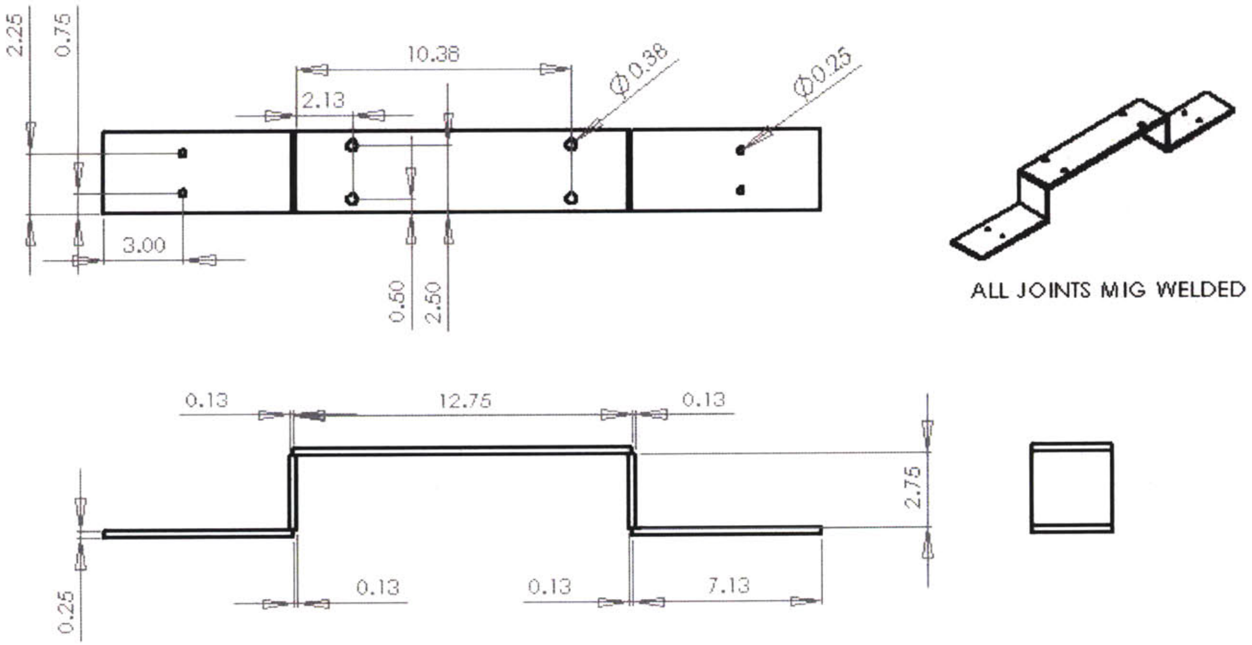
Roll Axis Assembly

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

5 4 3 2 1

ALL 3/8" CLEARANCE HOLES DRILLED WITH W DRILL

ALL 1/4" CLEARANCE HOLES DRILLED WITH F DRILL



ALL JOINTS MIG WELDED

UNLESS OTHERWISE SPECIFIED:

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

INTERPRET GEOMETRIC
TOLERANCING PER:

MATERIAL
STEEL

FINISH

DO NOT SCALE DRAWING

NEXT ASSY | USED ON

APPLICATION

	NAME	DATE
DRAWN	IAV	4/20/06
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

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MIT PERG LAB

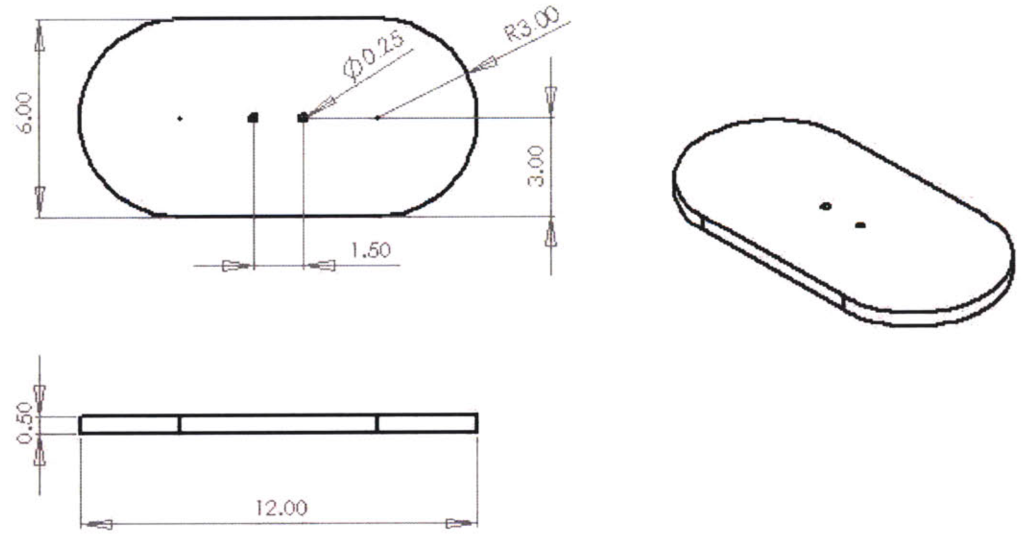
TITLE:

Platform

SIZE A
DWG. NO. Board3fullassy
REV

SCALE: 1:5 WEIGHT: SHEET 1 OF 1

5 4 3 2 1



1/4" CLEARANCE HOLES DRILLED WITH F DRILL

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DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL WOOD
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	IAV	4/11/06
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

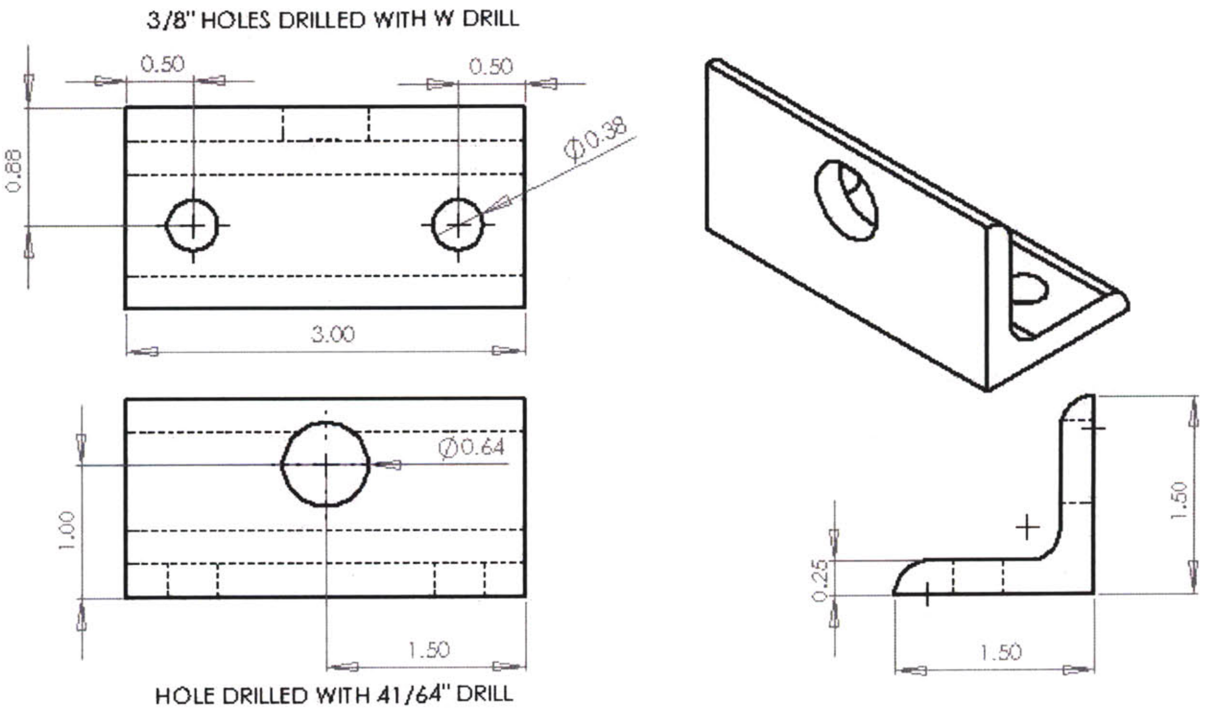
MIT PERG LAB

TITLE:

Foot Pedal

SIZE A
DWG. NO. Rollaxisfootpedal
REV
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1

5 4 3 2 1



3/8" HOLES DRILLED WITH W DRILL

HOLE DRILLED WITH 41/64" DRILL

MIT PERG LAB

TITLE:

UPPER BRACKET

UNLESS OTHERWISE SPECIFIED:		NAME	DATE
DIMENSIONS ARE IN INCHES TOLERANCES: FRACTIONAL ± ANGULAR: MACH ± BEND ± TWO PLACE DECIMAL ± THREE PLACE DECIMAL ±	DRAWN	IAV	4/4/05
	CHECKED		
	ENG APPR.		
	MFG APPR.		
INTERPRET GEOMETRIC TOLERANCING PER:	Q.A.		
MATERIAL ALUMINUM	COMMENTS:		
FINISH			
DO NOT SCALE DRAWING			

NEXT ASSY	USED ON
APPLICATION	

SIZE A

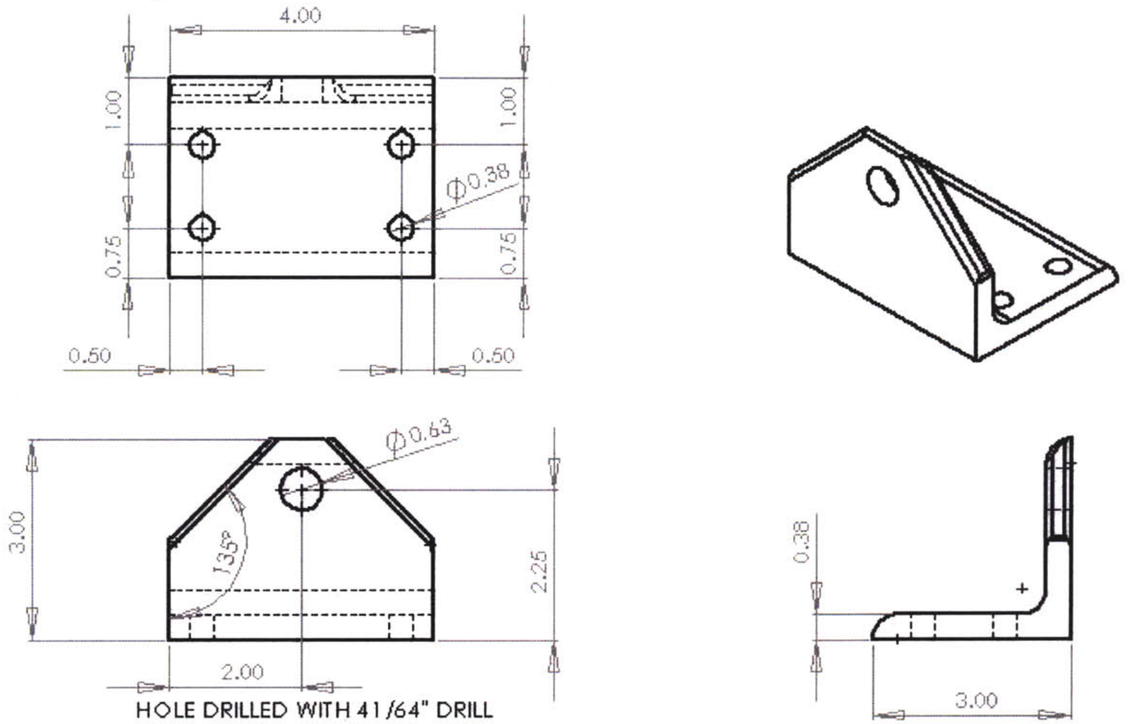
DWG. NO. Upper Bracket

REV

SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1

3/8" HOLES DRILLED WITH W DRILL



HOLE DRILLED WITH 41/64" DRILL

MIT PERG LAB

TITLE:

Lower Bracket

	NAME	DATE
DRAWN	IAV	4/4/06
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
ALUMINUM
FINISH
DO NOT SCALE DRAWING

NEXT ASSY USED ON
APPLICATION

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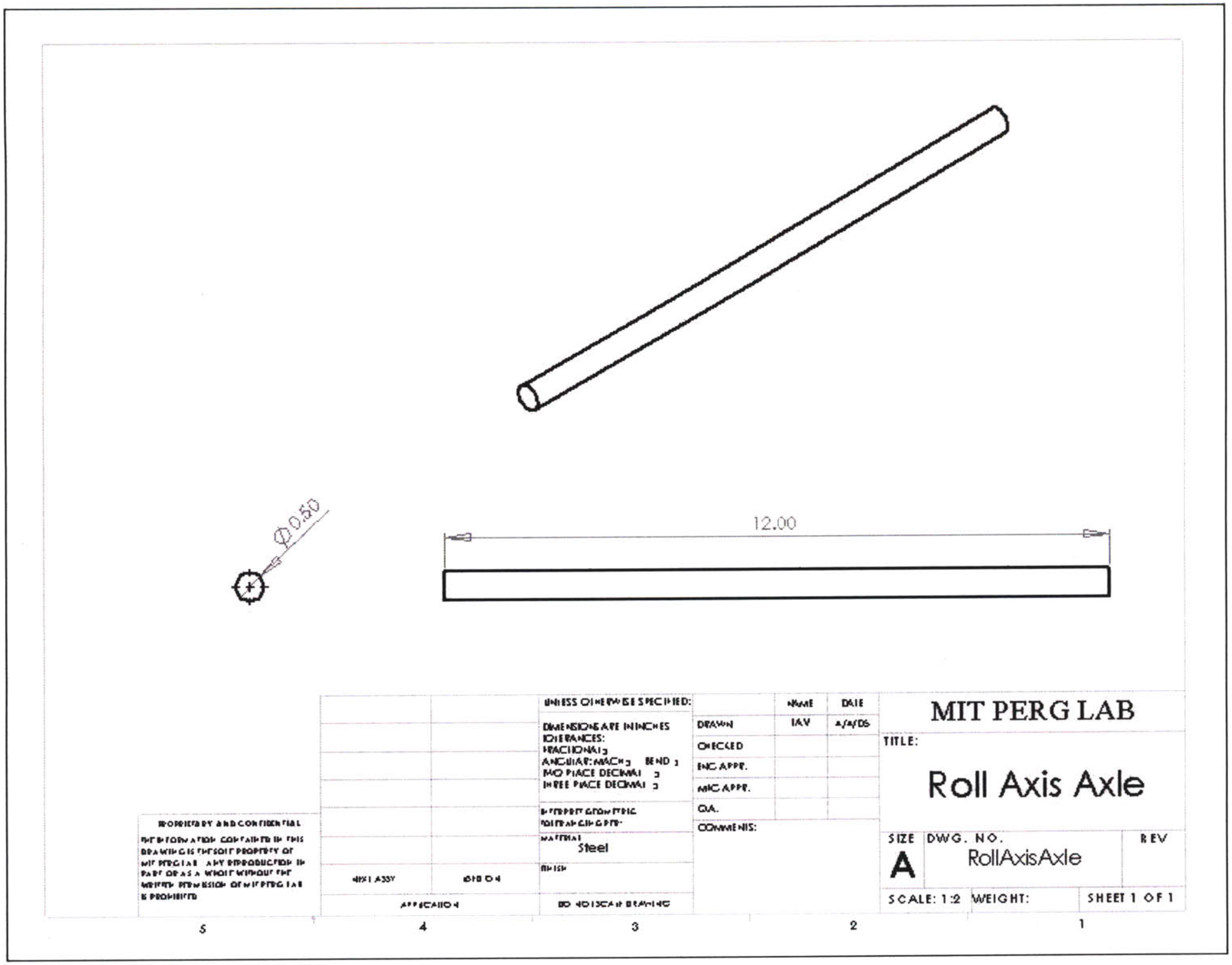
SIZE A
DWG. NO. RollAxisAngleBar
REV
SCALE: 1:1 WEIGHT: SHEET 1 OF 1

5 4 3 2 1


Ø0.50
12.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±
ANGULAR: MACH± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
Steel
FINISH
DO NOT SCALE DRAWING
NAME
DATE
DRAWN
IAV
4/4/05
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
MIT PERG LAB
TITLE:
Roll Axis Axle
SIZE
A
DWG. NO.
RollAxisAxle
REV
SCALE: 1:2
WEIGHT:
SHEET 1 OF 1
NEXT ASSY
USED ON
APPLICATION
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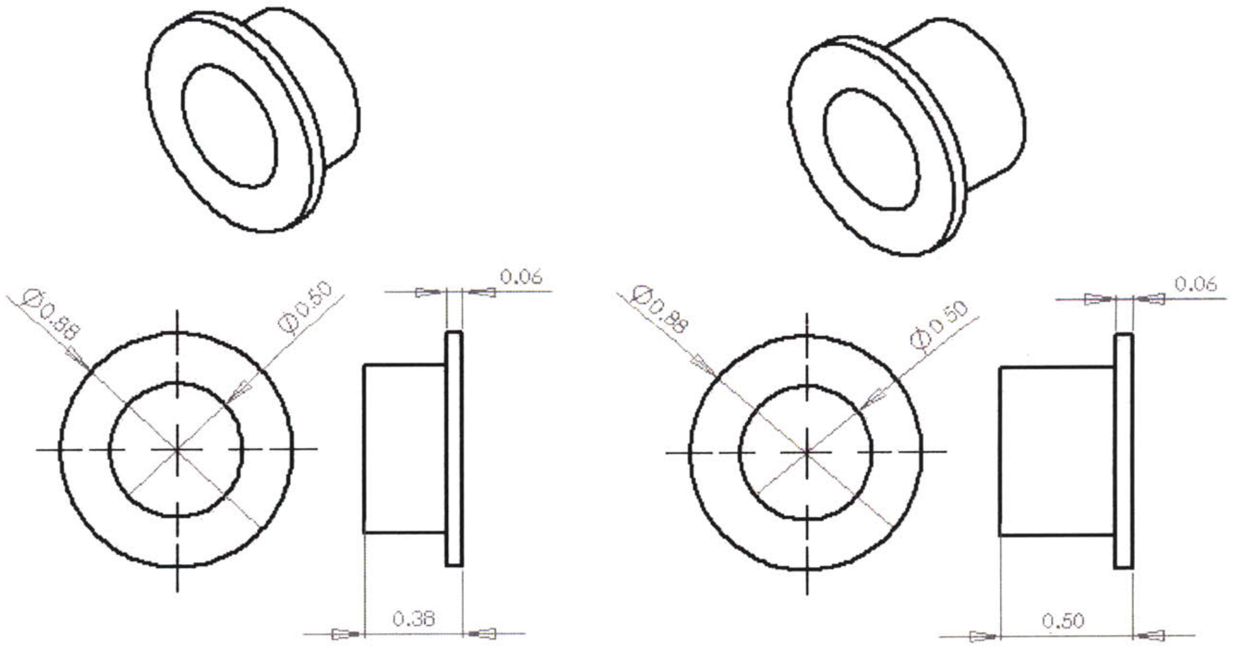
5
4
3
2
1



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NEXT ASSY USED ON
APPLICATION

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

INTERPRET GEOMETRIC
TOLERANCING PER:
MATERIAL
NYLON
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	IVA	4/4/05
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

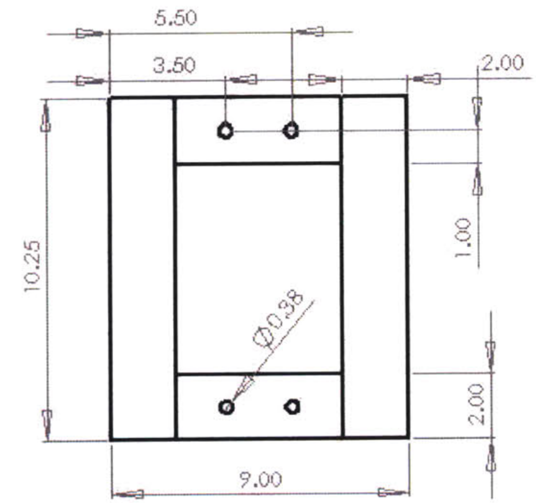
MIT PERG LAB

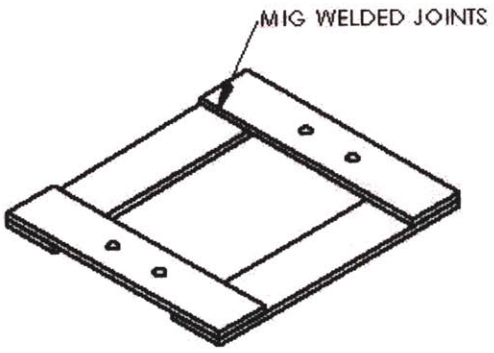
TITLE:

Bushings

SIZE A
DWG. NO. 1-2in3-8longNylonBushing
REV
SCALE: 2:1
WEIGHT:
SHEET 1 OF 1

5 4 3 2 1





3 /8" CLEARANCE HOLES DRILLED WITH W DRILL

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NEXT ASSY
USED ON
APPLICATION

UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL
STEEL
FINISH
DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	IAV	4/27/06
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

MIT PERG LAB

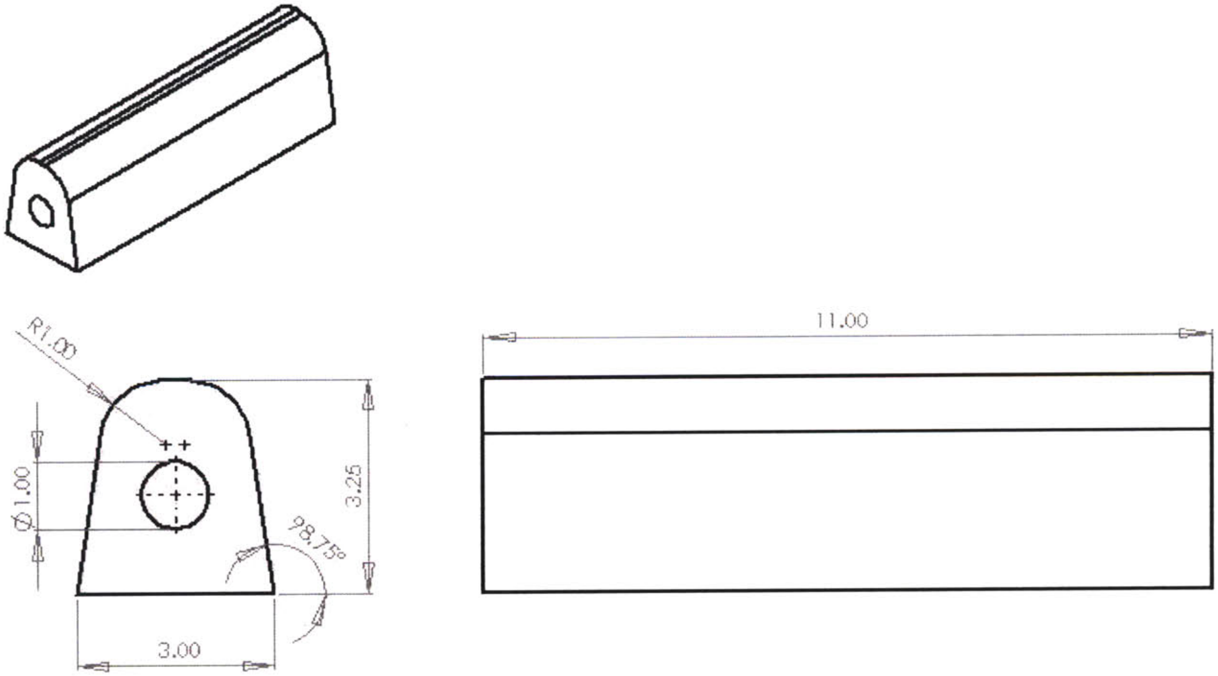
TITLE:

MOMENT BARS

SIZE A
DWG. NO. Board3fullassy
REV
SCALE: 1:5
WEIGHT:
SHEET 1 OF 1

5 4 3 2 1

S758-101



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NEXT ASSY | USED ON

APPLICATION

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

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
Polyethylene Foam

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	TAV	3/3/05
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		
COMMENTS:		

MIT PERG LAB

TITLE:

Foam

SIZE	DWG. NO.	REV
A	Foam	

SCALE: 1:2 WEIGHT: SHEET 1 OF 1

5 4 3 2 1