DESIGN OF A POOLSIDE ROWING MECHANISM FOR WPI'S CREW TEAM

A Major Qualifying Project Report:

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Abstract

The primary objective of this Major Qualifying Project is to design and manufacture a pool side rowing device for the Worcester Polytechnic Institute Crew Team. The poolside rowing device is a mechanism for achieving balance during rowing. Balance with respect to rowing, requires the rower to accelerate the boat without disrupting its natural motion. In fabricating this rowing device, critical issues such as (i) pool constraints, (ii) ergonomic needs, (iii) standard crew scull layout and (iv) inherent boat instability are accounted for. A prototype is developed by using the machine shop facilities in Higgins and Washburn laboratories. The rowing device will provide the WPI Crew Team the opportunity to practice competitive techniques at minimum cost.

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Chapter 1. Rowing Needs at WPI

Rowing is a sport which depends on the environment. If it is too windy outside or if the body of water is frozen, for example, the team cannot practice. An adequate substitution must be had when teams cannot practice on the water. Land training devices were introduced for this reason, but most lack the feel of the water. This is the reason why indoor rowing tanks were invented. Unfortunately, the typical rowing tank facilities require a large amount of space and money. Currently, the WPI crew team travels to Holy Cross to train at their indoor rowing facilities. For many years, it has been the desire of WPI Athletics to provide our crew team with on-campus water training facilities. We propose creating a device to suspend over the side of Alumni pool which incorporates the ideas of technique and balance training to accurately simulate on-water rowing. With this new device, the team will have more opportunities to practice all-inclusive techniques in an on-campus facility.

The main objectives of this project are listed. It must be dynamically stable to support a 250lb rower safely. It should be economical and corrosion resistant. It needs to position the oar out over the water and be reversible so that the rower can face both directions. A good design incorporates controllable instability for balance training and offers the rower moderate water resistance against the oar blade.

The remainder of this report discusses the design process for developing the poolside rowing mechanism. Chapter 2 addresses the background research necessary to understand each aspect of rowing. We discuss the geometry and physics of rowing, as well as different applications of rowing, from boats to oars to training devices, and an overall view of WPI Crew Team. Chapter 3 discusses the design and fabrication of the mechanism, as

well as recommendations for improvements for further work. Chapter 4 concludes the

report, followed by references and appendices.

Chapter 2. Foundations of Rowing

2. Introduction

Crew, or rowing as it is often called, is a sport typically performed by teams of four or people in a long narrow boat. This boat may have one additional person called a coxswain who steers the boat and encourages the rowers. Each rower has one oar which they hold in both hands and propel through the water while rowing backwards. This basic motion of rowing is called the stroke. The boat should move as quickly and efficiently as possible. Each rower must execute his or her stroke with, power, precision and form. Form, in rowing, is balance and technique. This is often the most important and neglected aspect of rowing. If each rower is not attuned to his or her form, the entire boat will lose its stability

2.1 Geometry of Rowing

Rowing consists of one or more rowers sitting in a boat. Each rower has one oar which moves the boat through the water. Rowing a row boat is much different than rowing in a competitive crew shell.   Comparing a commonly understood row boat with a crew shell, as seen in **Figure 1**, will help illustrate the higher efficiency and force transfer seen in competitive rowing.

Figure 1: Several Crew Shells Racing

In a row boat, as seen in **Figure** 3, the rower sits upright with their legs and back perpendicular to the body of water.   Their motion consists of sweeping their arms in a circular motion to pull the oar blade through the water.   All of the power comes from their arms, shoulders, and backs.   However, in a crew shell, as seen in **Figure 2**, the rower sits on a seat with their legs angled downward. The seat is approximately 2 inches higher than water level. The rower's feet are strapped into shoes which are fixed in the boat with footboards. The seat has wheels and moves on a track so the person can compress their legs to their chest. This position allows the rower push against the footboards, initiating the drive. The 'drive' is the active part of the rowing stroke. The rower rolls backwards with the seat tracks until their legs are fully extended, and they are sitting leaned back at the end of the stroke.

The two body positions of competitive rowing are called the 'catch' and the 'finish'. The 'catch' happens when the legs are fully compressed to the chest, and the oar is just entering the water at the bow, or back of the boat. The 'finish' happens when the legs are down, the rower is leaning backward, and the oar is just coming out of the water at the stern, or front of the boat. The movements between the catch and finish are the 'drive' and the 'recovery'. The 'drive,' as described above, is performed when the oar is in the water. The 'recovery' is performed when the oar is out of the water. This movement is performed as the rower repositions the oar from the stern to the bow, and brings their knees up to their chests.

Figure 2: Crew Scull

Figure 3: Row Boat

As you can see, most of a rower's power comes from their legs as opposed to a person rowing a row boat. Through descriptions of the catch, drive, finish and recovery, we realize the need to understand how to apply these to a stationary device that is protruding over the side of a pool.

2.2 Physics of Rowing

Rowing is based around physics, with most forces taken from the rower. The rower acts as an intermediary between the boat, oar and water. When the blade is squared in the water, the rower pushes their legs down while carrying the blade along with them and forces are felt. The force from the feet (F_H) as seen in **Figure 4**, is transmitted and acts as the force of the hands on the oar, which is transmitted to the water. The water moves, as does the boat, via the rower. The point along the slide which creates the most power is when the shins are perpendicular to the water. Body positioning greatly influences the power transmission effectiveness. These are the reasons why coaches strive to achieve perfect form in their rowers.
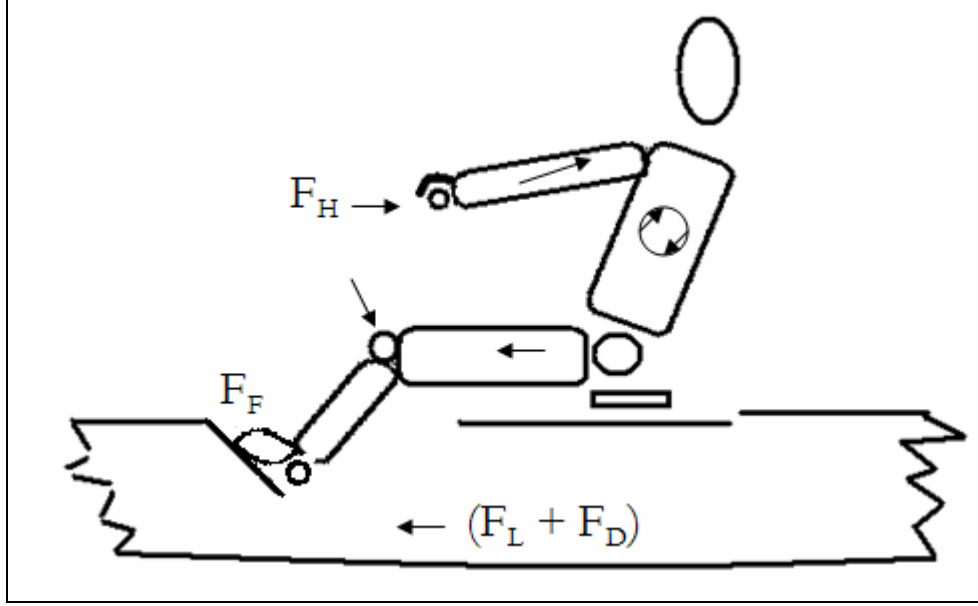
Figure 4: Internal Forces Schematic

2.2.1 Summation of Forces

Acceleration and velocity are important quantities to consider when talking about rowing. Measuring the displacement over the water and knowing the mass of all necessary bodies, allows the rowing forces to be calculated.

$$F = m * a \qquad \int a = v \, dx \qquad \iint a = s \, d^2x$$

In order for a boat to accelerate, the forces causing the acceleration must be greater than any of the opposing forces. Thus the force of the foot stretchers (F_F), is equal to the force exerted on the handle (F_H), and the force of the blade on the water (F_B), must be greater than the drag forces (F_D) and the force of the water on the blade (F_L).

$$F_F = F_H = F_B > (F_L + F_D)$$

If this condition is not met, the boat will not accelerate. When starting with a = 0, v = 0, and this condition not being met, the boat will be stationary.

Rowing is an action-reaction sequence. Before a stroke is taken, forces are in equilibrium, thus the relative velocity of the boat to the water is equal to zero. However,

after the stroke is taken, the boat is accelerating forward, which creates an equal and opposite reaction of the water moving in the negative direction with the same velocity. In Figure 5, we see how the boat is in equilibrium before the stroke, and after the stroke acceleration occurs for the water and the boat, as seen in **Figure 5**. According to Newton's second law, the total momentum must remain constant.
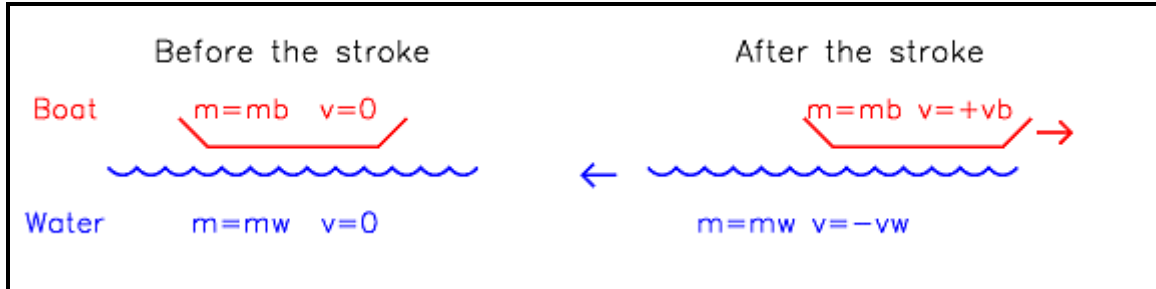
Figure 5: Stroke Dynamics [6]

2.2.2 Boat Specific Forces

From different manufacturers such as Vespoli, Resolute, and WinTech, we know the weights of different classes of boats. **Table 1** shows the specifications for Resolute, eight person boats.

Table 1: Boat Weights [12]

Hull	Length Over-All	Height	Weight of Boat	Beam	Weight of Rower
Heavy 8+	54' 11";	15"	207-211 lbs	29"	195-215 lbs
Mid-Wt. 8+	8 54' 1"	14.63"	200-205 lbs	25.25"	165-195 lbs
Light 8+	53' 5";	14.4"	200-208 lbs	27.6"	135-165 lbs

We will utilize the information for a "Resolute z8 mid-weight" boat. We will utilize 200 pounds as our mass. Forces can be measured in a few ways from the boat. They can be measured by the feet with a sensor, by the bending of the oar shaft, or the forces exerted on the face of the blade (see **Figure 6**), or also at the focal point of the oarlock where forces can be measured by the pin and the oarlock.
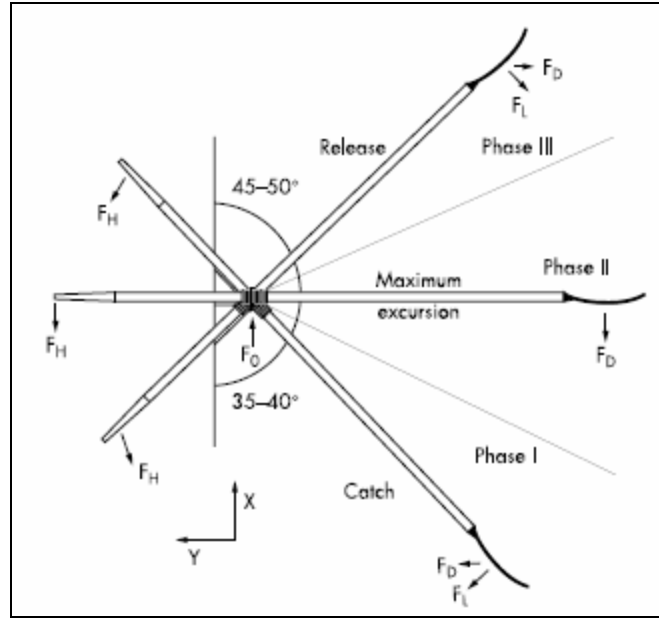
Figure 6: Forces on the Oar

So for our case:

$$\sum F = F_F - F_D - F_L = (200 + m_{Rower}) * a$$

The force at the feet can be assumed to be constant for one person, assuming that all other outside conditions are kept constant. In this regard, the drag forces will also be constant [6]. The force of the water on the blade is close to the force the blade exerts which is equal to the force of the foot stretchers. The mass of the rowers and coxswains, collectively, is m_{Rower}. This can be assumed constant by assuming the average weight to be 155lbs, and the weight of the coxswain to be 110lbs. Thus the total weight would be 8*155 + 110 = 1350.

In rowing, various devices exist, that will measure stress and thereby deflection, see **Figure 7**. This deflection translates into a force applied to the water. This force in turn creates a measurable acceleration. Another way is to measure the velocity of the boat over a

set distance and calculate the acceleration from that. Various studies have been conducted to both accurately measure and model the forces and how they are applied [13]. Several important observations can be drawn to help crews optimize their velocity, and in turn win races.
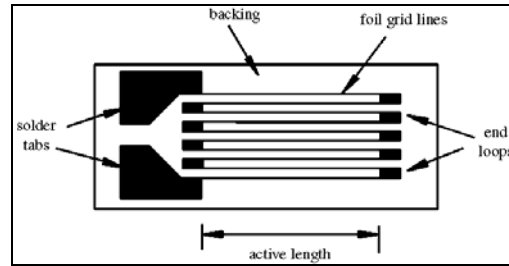
Figure 7: Strain Gage

"To reduce force pattern differences more effective rowing training should be performed at high force output. [5]" Differences in individual rowers force patterns mean a lack of optimized rowing. "During relaxation periods immediately after the intensive rowing intervals, smoothness is at its worst." [5] Lack of smoothness translates into drag, hindering the boat. Conversely, times of high smoothness occurred at those periods of high stroke rate, high force output, as seen in **Figure 8**.
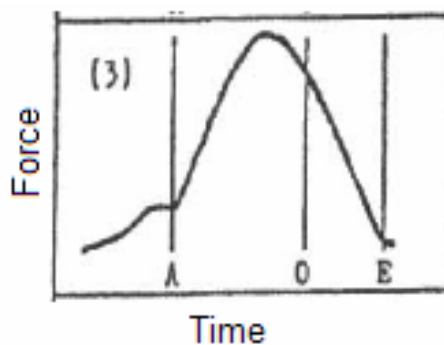
Figure 7: Blade Force Diagram

The speed of the water is directly proportional to the speed of the boat. In order for a boat to move with the maximum possible acceleration through the water, all rowers must

exert equally high forces onto the blade. Imbalance of force is wasted effort because it breaks the optimal distribution of force in the intended direction into components, with one component being to turn the boat. So this is a compounded problem, because now the coxswain is forced to correct by turning the crew back onto course.

As is seen in the lift and drag section, the majority of the leverage from the oar blade is gained through the middle ¾ of the drive [1]. The maximum force is applied between A (the catch) and O (the perpendicular position of the oar) and before E (the finish) (**Figure 8**).

2.2.3 Buoyant Forces

A boat must be able to float independent of propulsion. Thus buoyancy is a main condition that must be met. In order for this phenomenon to occur, the buoyant forces must be greater than the gravitational force which creates weight. In an eight person boat, there are nine individuals contributing to weight, as well as the physical boat, oars, and any extraneous objects. Figure 8 shows the various ways in which a boat may stay upright.
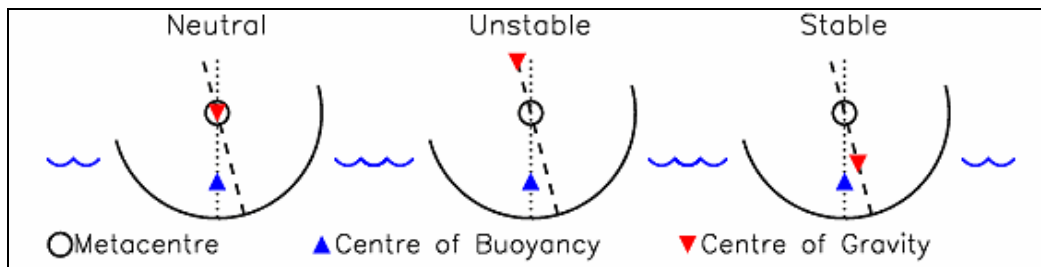
Figure 8: Buoyancy Diagram [6]

In order for a boat to float, the sum of the gravitational forces must equal the sum of the buoyant forces. However, because there are nine different shaped people, the gravitational center of the boat is complicated to find. With new advancements in technology, the weight of a boat has significantly decreased; boats at one time were made

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from wood. These advancements have led to the development of composite materials and plastics that are much lighter and stiffer, and support weight better.

Buoyant forces are taken into account for the oar. If the oar is sitting in the water, it will stay floating and stationary. This is again because the sum of the forces acting on the blade equal zero. However, these forces are not enough when the boat is going at full speed to keep the blade from digging deep in the water, or washing out. Thus the rigger is set at a pitch or angle to obtain buoyancy [5] and prevent rowers from digging deep or washing out. When an oar is sitting stationary in the water without anyone holding on to it, the pitch is what determines its depth [5]. This is where a coach believes the optimal height to pull an oar through the water is at. However it can be changed. Pitch ranges between zero and ten degrees [5]. The optimal is around five, but changes depending on a rowers' technique, and what a coach thinks is optimal positioning. The greater the angle, the lower the oar is in the water, and thus creates the effect of digging in the water. The lower the angle the higher out of the water the oar will sit, and thus will not be able to grab as much water. Depending on what type the boat is will give a good idea as to what angle to set each person's pitch at, but a coach will usually start out at five degrees [5].

The pitch can be changed by different techniques depending on the type of rigger. The most common method is putting a different plastic insert in the oarlock [5]. On some boats though, it can be changed by rotating part of the back stay, and changing its respective length. Pitch and buoyancy are important in a shell, but will also play a major roll in tanks so as to keep the feel, height and depth concurrent with rowing in a boat [5].

2.2.4 Oar Blade Forces

There are many forces which must act upon the blade in order for a boat to move. As seen in **Figure 6**, forces occur at the focal point, the face of the blade, and the oar handle. The force on the handle is created by the hands pulling the blade through the water during the drive. The forces on the face of the blade consist of the driving force, F_D, and the turning force, F_L. The focal point is located at the oarlock. On the blade there is a drag force from the water. In order for the boat to move, the blade can not be caught by the speed of the water [6]. Thus the blade must move faster than the speed of the water. This is accomplished by the driving force being greater than any drag or opposing force.

$$v\_blade > v\_water$$

$$F\_driving > F\_drag + F\_other$$

The blade creates an arc, which is approximately ninety degrees. For optimization, the blade should stay in the water the entire length of the arc.

The forces a person exerts include those that drive the boat. There is a force between the handle and the hands, and also the feet and foot stretchers. There is also a weight contributed to the total mass of the system, but for the time being we will ignore this. The force of the hands on the handle will be denoted by F_H. The force of the feet on the foot stretchers will be denoted by F_F.

The rower plays the vital role in the overall force application. The oar blade in the water has no effect acceleration wise on the boat without the rower transferring energy from one medium to the next. Starting with the boat, the rower exerts a force predominantly parallel to the gunwale of the boat as seen in **Figure 9**.

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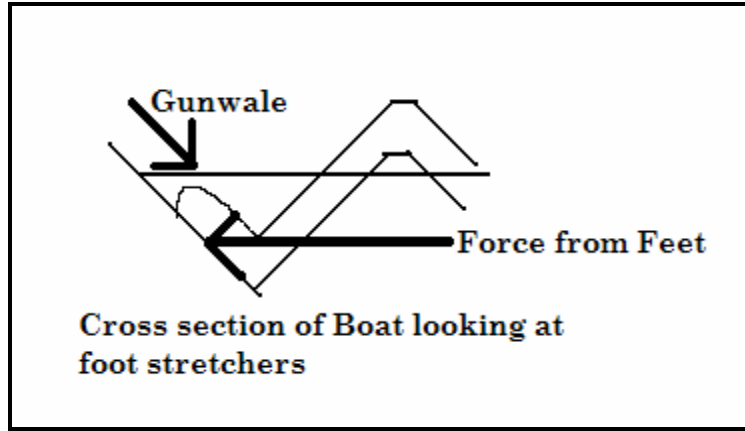
Figure 9: Leg Force on Boat

The muscles of the legs force the knees down parallel to the gunwale and displacing the seat and torso. The force on the handle now is produced by the swing through the body. Lastly the arms pull against the oar handle, with most of the point of contact being in the fingers. The displacement of the oar handle is radial about the oarlock (see **Figure 6**). The resulting acceleration of the boat is opposite to the direction the rower faces (see **Figure 5**).

$$F_H = - F_F$$
$$F_{total} = F_H + F_F + \Sigma F_{(internal)}$$

$$\Sigma F_{(internal)} = 0$$

The boat travels via the oar from the force applied at the blade, which is felt at the oarlock by the boat. The force applied at the oar handle moves the handle from its starting to finishing position, in addition to being the source of the oarlocks applied force. The seat moves to allow the rower a larger span for which to apply their force, and the oarlock rotates about the z-axis so as to allow the oar to reach this larger span.

2.3 Rowing Applications

The boat and its components allow the rower to perform to the best of their ability. They are similar to the football, shoes, jersey, and goalpost when it comes to integral need

within a sport. There are currently few other ways to train for rowing without actually being on the water, sitting in a boat. The two most common alternate training methods are ergometers and rowing tanks. Ergometers utilize resistance from a chain and flywheel design. Rowing tanks are stationary with a sweep oar placed in a small body of water.

2.3.1 Boats

A shell or boat contains many parts, mainly the hull, seats, foot stretchers, and riggers, as seen in Figure 10. Most of these features are adjustable, to provide the maximum output for each individual. The boat as a whole is called a shell; the hull refers to the outside surface, typically between an eighth and a quarter of an inch thick. The average length for a shell that holds eight rowers and one coxswain is approximately sixty feet.

Originally, shells were hand made from wood. As technology has increased, so has knowledge that contributes to the design of successful shells.   Shells are now made from composite materials such as fiberglass, carbon fiber, or Kevlar. This has been the pursued path due to the need for boats to be as light as possible which limits the extraneous weight each rower must overcome.
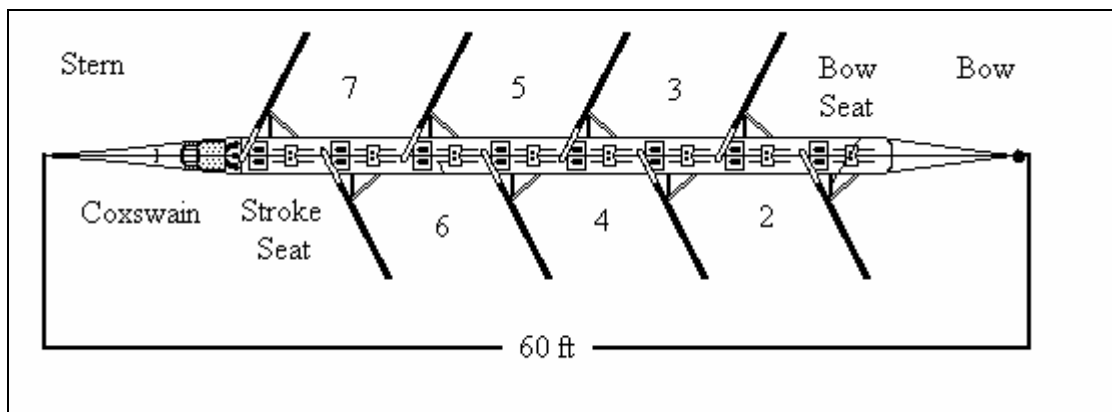
Figure 10: Boat Diagram [9]

Terminology for any shell is consistent, as shown in **Figure 10**. The bow is the front most part. 'An eight' has eight oars in sweep formation, (meaning one oar per person), with the coxswain in the stern of the boat dictating directions, and steering. Steering is achieved through use of a fin and a rudder on the underside of the hull. Some boats also have a small propeller about three inches in size, which gives an output reading to the coxswain indicating boat speed. The decking is the area on top of the boat in the bow and stern where no one is rowing where the boat tapers to a point. Underneath the decking are air pockets for the boat which keep the boat afloat if it is 'swamped' or filled with water. Most shells have at least two portholes, one in the stern and one in the bow, which create the air pockets.

The inside of the boat is more complicated. There are eight seats for rowers, and one for the coxswain. The sides of the boat are termed port and starboard, with four seats rigged for each side. The eight rower seats are identical, and include foot stretchers and a seat that slides along a track. **Figure 11** shows what a typical seat will include. Shown here are the shoes and foot stretchers with adjustable lengths, as well as the seat and sliding track.

Figure 11: Boat Components [7]

Foot stretchers are adjustable for angle and length to accommodate for individual flexibility and leg length. Shoes are attached to foot stretchers at the balls of the feet to ensure each rower is grounded in the boat, yet allowing mobility at the heel for optimal reach.

The track is a set length, also which can be translated forwards and backwards. The front and back stops on the track prevent the seat from falling off the end.

The rigger is the most complex part of the shell. The side that the stroke (lead) seat is rigged determines whether the boat is port or starboard rigged. Each seat has the ability to be rigged on either side. The rigger is mounted to the boat with nuts, bolts, washers, and guards that are fixed through four small holes near the top of the hull. The three main components of the rigger are the back stay, front stay, and main stay. The front and main stays are solid, and cannot be adjusted unlike the back stay. It is mounted furthest to the bow of all the stays. For a schematic see Figure 12.
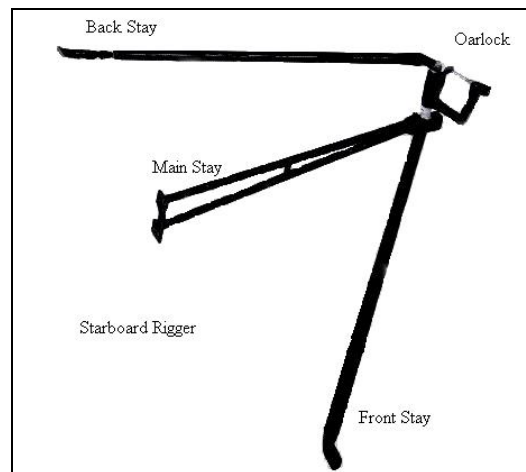
Figure 12: Rigger Diagram

The fulcrum of the oar rests at the oarlock (Figure 13), which is positioned at the outboard edge of the rigger. This is the leverage point. The pitch of the oarlock determines how deep in the water the blade will bury. If an oar buries too deep or two shallow, rowing becomes awkward optimization is not achieved [5].

Figure 13: Oarlock [8]

An oarlock consists of a pin, top nut, bottom nut, and spacers. Adjustments to each can make rowing feel more comfortable for different people. This includes making the outboard length longer or shorter by moving the pin depending upon whether you want the blade to be further out or not. The oarlock, like the back stay, is adjustable. It can be moved up and down by the spacers to accommodate different size rowers. The oarlock is also set at a certain pitch usually around five degrees. Pitch is what keeps the oar from digging deep into the water and getting caught while rowing at full speed [5]. It also allows for a boat to set up naturally in the water, and not flip over when all the oars are squared.

The coxswain's seat contains a rope that attaches to the steering column located directly behind her, and a place for her 'cox box.' The cox box is a microphone system that connects into the boat and powers the speakers. It also will provide the crew with the stroke rate, and the speed if a propeller is connected to the boat.

Different types of oars have developed over the years of rowing including Spoon, Hatchet (**Figure 16**), Macon (**Figure 17**), and Smoothie. They all have different surface dimensions. The shafts are concurrent, as are the collars. The only part of an oar that is adjustable is the collar, which can be moved back and forth to shorten or lengthen the oar. Coaches will use what are called clip-on load adjusting mechanisms (CLAMs) [4] so they do not have to physically unscrew the collars on each oar, but will shorten or lengthen the oar

with each addition or subtraction of the CLAM [4]. Oars used for tanks are the same except for the face of the blade will typically have sections taken out so as to reduce the resistance felt from the water. This will make the load, or the pressure one feels by moving stationary water, feel lighter than if the whole blade was still intact.

Figure 14: Hatchet Blade **Figure 15: Modified Macon Blade**

The blade has two different positions: squared, or feathered. Feathered constitutes the blade's face being parallel with the water. When one is not rowing, their blade will sit on the water in the feathered position, curve side up, and not obstruct the boat except for the minimal drag seen between the oar and water [6]. The squared position is when the blade is perpendicular and able to enter the water without obstructing the boat. The oar lock is set at a specific pitch to help the blades positioning in the water. To get between the squared and feathered position, a rower turns the handle with the hand closest to the rigger [5].

Contact between the oar and air medium creates less of a drag force than between the oar and water [6]. This makes balancing the oar off the water crucial to optimal speed. This is done by pushing the oar handle down with the hands, and balancing it at even levels with the fulcrum point in the oarlock. When everyone's blades are balanced at the same

height, the boat will stabilize and rowing is more effective. When even one person has their handle lower than others, it will offset the boat to either port or starboard side. Extremities can cause anywhere between one and everyone on the respective side to drag their oars on the water. This creates more drag, and will slow down the boat.

2.3.2 Ergometers

Ergometers are stationary devices that give an output of a rower's strength relative to the water speed of a boat. Seen in **Figure 16**, ergometers simulate rowing, but do not use water to accomplish the feel of pressure on the oar or allow for port or starboard differentiation. Ergometers consist of a handle, chain, gears and a fly wheel. Form is similar to on the water rowing, the differences being an erg gives an output of strength and distance, does not incorporate balance, or the respective port/starboard side rowing. It is used as a work out device typically in the winter months, or when the water is undesirable to row. It still helps strengthen the appropriate rowing muscles, mainly the legs, rather than attempting to accurately simulate on water rowing.

Figure 16: Ergometer

Ergometers provide the following readout information: meters or distance, average split or how long it takes one to row 500 meters, time, calories, and watts. Although useful to coaches, ergs unfortunately still do not take into account balance, or port and starboard rowing.

2.3.3 Rowing Tanks

Rowing tanks were originally designed to help coaches teach on water rowing technique more effectively. They have developed over the ages with new designs and ways to address different problems. They are typically stationary, and do not incorporate one of the most important rowing concepts: balance.

Most rowing tank designs have water circulating and oars extended into the water. The tanks at the Massachusetts Institute of Technology (MIT) (**Figure 17**) have everyone sitting in a line, with riggers fixed both to the port and starboard sides with two separate bodies of water for the port and starboard side. The water for the ports and starboards circulates independently of each other. The foot stretchers and rigger height are adjustable, just like in a boat.

Figure 17: Rowing Tank Facilities

Another design is the one seen at Holy Cross. These tanks have only one body of water. They also have ports on one side, and starboards on the other. This way the water will still circulate so that each side can row without interfering with the other, and everyone can row at once. Like MIT's tank, the foot stretchers and rigger height are adjustable.

Bates College, too owns tanks, but they are different from those seen at MIT or Holy Cross. Their tanks, shown in **Figure 18**, suspend over the side of a pool. This simulates rowing more closely due to the relative height from the water. It too is stationary, but there are more forces to account for in keeping their device stable. There are also more issues dealing with the fluid dynamics of a pool that is eight feet deep compared to a small waterway that is only two feet deep and two feet wide.

Figure 18: Bates Rower

Tanks currently are valuable to any crew program. If a team has access to tanks, then they no longer need to teach rowers proper technique via dock rowing. Tanks allow a coach to teach a new rower proper technique without being in a boat. Tanks also take the stability factor out of the picture, and allow for concentration on form. For a more advanced

rower, however, stability should be thought about and incorporated into other training techniques such as tanks. During the winter months when the team cannot row due to temperatures and conditions of the bodies of water including ice formation tanks are a preferred type of training device.

Ideal circumstances would allow a crew to practice in a boat year round to perfect the vital aspects of rowing, form and balance. Due to New England weather, and subsequent frozen lakes, this is impossible, requiring teams to use alternative practice methods. These training devices, the ergometer and rowing tank, though adequate in some respects, do not fully simulate on-water rowing.

2.4 Rowing at WPI

Crew has been a varsity sport here at WPI for the last seven years. The WPI team has won many prestigious competitions over the years including the New England Championships. This past year, twenty women and fifty men competed against teams all across the Northeast. Most of these teams have some sort of water simulation, technique training device, be it tanks or a device that hangs off the side of a pool. In order to be even more competitive, WPI must increase and vary its training.

2.4.1 Current Training

Currently, the focus of the WPI crew team is on ergometer and weight training. Some initial training is done at tanks at Holy Cross. Novice rowers in their first few weeks of training are bussed over to Holy Cross for one or two training sessions. They get to try out rowing on both sides to see which feels the most natural. Additionally they are instructed in the basics of holding the oar, how to balance it and pull it through the water. This is all that is taught at the tanks, and from here they proceed directly to on-water rowing.

Once the novice get on the water there is a steep learning curve from their initial time in the boat, until they become competent rowers able to balance the boat and row with power. It takes months, sometimes years, of training for the fine techniques to be mastered. Currently at WPI there is no feasible system for technique training other than on water experience.

When the novice get on the water for the first time they practice by having six people, in a boat of eight, sit out while pairs of people row. This gives a stable, muted feeling of rowing. The first month of practice or so is devoted to this baby step style training. There are many intricacies of rowing that are taught over this period. Firstly the

stroke is broken down so that the rowers can get a feel for their body positioning at each section. The body is oriented differently for different parts of the stroke, which alters the center of gravity. Pairs of rower take turns rowing, which is done so that you have to balance against only one other person's weight opposing you.

2.4.2 Team Statistics

The most recent season's statistics show that the WPI Crew Teams, both men and women, compete at a high level. The teams consistently place in the top ten for larger races. Improvements in training facilities can only help to increase this aggressive program. **Table 2** shows the results for WPI's Fall 2005 head races.

Table 2: Fall 2005 Race Results

Women's Results

Event	Placement
Textile River Regatta:	Novice Four: 3rd of 8 Club Eight: 4th of 30 Open Four: 4th 0f 28 Open Eight: 13th of 19
Head of the Housatonic:	Open 4 (non-DI) 3rd of 14 Open 8 (non-DI) 3rd and 8th of 9
Head of the Charles:	Collegiate eight: 16th of 46
Head of the Shukyll	Club Eight: 5th of 46

Men's Results

Event	Placement
Textile River Regatta	Open Four: 4th of 24 Club Eight: 5th and9th of 22 Open Eight: 3rd and 11th of 15
Head of the Housatonic	Open 4 (non IRA div) 1st of 12 Open 8 (non IRA div) 2nd, 4th and 7th of 9
Head of the Charles	Club eight: 25th of 51 Collegiate Eight: 25th of 41

Chapter 3. Rowing Mechanism Design and Manufacture

3. Introduction

To create the most optimized pool side rowing mechanism, a standard design cycle is followed: analysis, design, implementation, assessment. Through these stages a design is produced for the WPI Crew Team that fulfills their needs and our objectives. The analysis phase consists of taking an objective look at the problem. The WPI Crew Team currently lacks on campus facilities for training technique other than ergometers, which do not differentiate between port and starboard rowing. For specific sweep oar training the rowers are bussed to Holy Cross to practice technique on their rowing tanks.

While this has been adequate for many years, the coaches would like a facility on the WPI campus. While a new recreation center is being built in the next several years, the coach would like a mechanism for people to use in the very near future. His logical suggestion is to create a device that would work on or in Alumni pool. His idea streams from a device he had seen at Bates which hangs off the side of the pool. His hope is that it can be reproduced for a full set of eight stations.

The initial idea of the Bates Rower (**Figure 18**) is the inspiration for the project outlook. Looking at the limitations as well as the objectives of the project helps to determine the initial designs. Alumni pool, the only feasible place on campus where a device to replicate rowing could be placed, has one noted limitation: the swim team will also need the facility until the new center is built. This determines the first main objective: the mechanism must be removable, and subsequently portable. It is also desired for the device to be light enough for one person to take in and out of the pool. Other practical limitations

include budget and safety. An additional main objective is to replicate the feel of rowing on the water. Additional features for the mechanism centered on this.

To accurately represent rowing, it is desired to have the same layout as in a boat, including personal adjustments of all concerned parts. Taking our research and main objectives, an additional feature is considered. Current training devices on the market and patented, can not accurately represent the instability of a boat on the water. When rowing a rower's center of mass moves back and forth in the x direction but sometimes also in undesirable ways, or the y and z axes (see Figure 8: Buoyancy DiagramFigure 8).

Simulation of this boat movement or the rotation about the x-axis, such that a novice rower training can get a feel for rowing in a moving boat is one of the most important objectives of this project. With all the considerations and objectives six initial designs were created to solve these key problems.

3.1 Design Process

The first step in any design process is to ask questions, and formulate objectives. We compiled objectives on this project through discussion with the WPI Crew Team and our own desires for a comprehensive training device. These objectives, some described previously, allowed us to formulate several preliminary designs. We then weighed the designs against our objectives to determine the compilation of designs that would best satisfy the project needs. The preliminary designs and corresponding design matrix can be found in **Appendices A and B**, respectively. From there, we selected a material with which to fabricate our prototype design. This material would need to satisfy our objectives, just as the design had. The prototype manufacturing process introduced complications and ideas that

would otherwise be left unnoticed. The generation of a prototype was a step in the cyclical design process which led to improvements upon the final design. Plans for the final design were then presented to the crew team so that they may manufacture additional stations other than the prototype of the final design.

3.1.1 Final Design

The final design is corrosion resistant aluminum welded with a design focus of versatility and controllable instability. The entire device weighs less than 50 lbs, and takes up less than 5" of width space when disassembled. The mechanism breaks down to five separate pieces for easier handling by one person. The mechanism utilizes springs in a set of machined spring boxes to allow the rower to feel instability similar to what can be found in a boat. Assembled, the mechanism has a footprint of 6x4x3 feet. Symmetry allows the device to be rigged for either port or starboard rowing. The oar is a symmetric Macon blade with sections removed to decrease the still water resistance. The poolside needs small modifications to support the mechanism, consisting of two holes for each mechanism. Designs for protective hole caps are also included. The following sections will detail the iterative process and final attributes for each component.

3.1.2 Spring Box

The main feature that this design has, that any other dry land training device does not have is instability. In order to achieve controllable instability, several design iterations took place. The final design for this feature, as seen in **Figure 21** is the spring box. Though originally far larger, see **Appendix C**, the compact design offers the same outputs while using less material, being far lighter, and easier to manufacture. The boxes are positioned on either side of the mechanism frame. The central pole of the frame rests in the center cylinder of the box, while the wings extend into the spring area. The springs are described later in the report. The dimensions of the spring box are 5 x 2.5 x 3 inches, and are Computer Numeric Control (CNC) milled from solid aluminum block.
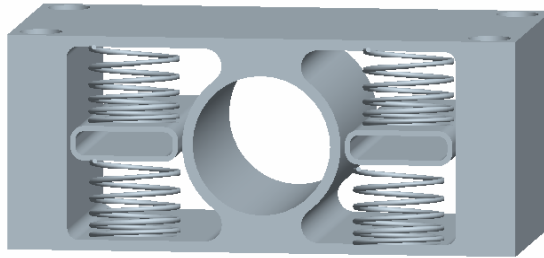
Figure 19: Spring Box

3.1.3 Support Arm

The support arm feature of the design allows for great strength and stability for the mechanism. Designed from 1.5 inch square tubing, the arm is lightweight, yet rigid. The mechanism, seen in **Figure 22,** uses two arms, positioned 72 inches apart that fit into the holes in the poolside, seen in **Appendix D**. In order to fully support a moving rower, and the weight of the mechanism itself, designs for support arms had to be evaluated for stress analysis. Those calculations can be found in **Appendix E**, as well as weight assessments for the mechanism found in **Appendix F**. From these assessments, the arms are modified from their prototype designs, found in **Appendix** C. The design is 40 x 36 inches, and uses an angle truss design. An additional angle iron piece welded to the frame allows for a platform for the spring box.
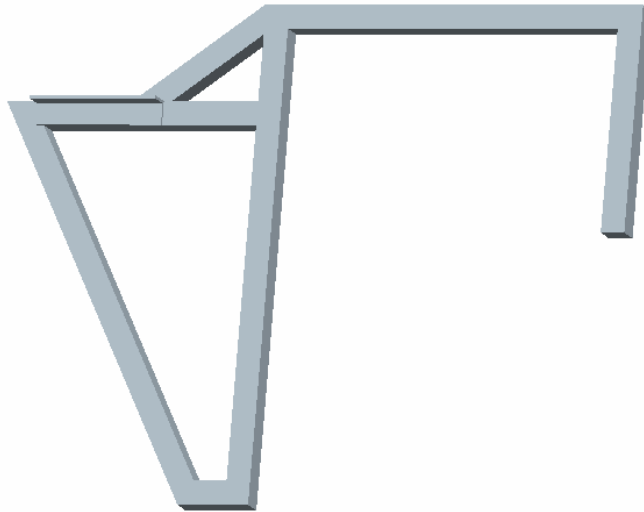
Figure 20: Support Arm

3.1.4 Frame

The frame of the mechanism is the main area of contact between the mechanism and the rower. To maintain the correct atmosphere of boat rowing, this component is designed to mimic the features of a boat as closely as possible. The designs have changed considerably throughout the iterations, (see **Appendix C**), and yet maintain many of their original characteristics. The frame (**Figure 23**) features a central pole, about which the entire frame rotates (x-axis), with help from the spring boxes. The riggers require front, middle, and back attachment points. To maintain reversibility, the attachment points are mirrored left and right, so that while only one set of points would be used at a time, an individual could quickly change to the other side rowing without major hindrance. The far ends of the frame are winged. These wings slide into the spring box, and allow the springs to compress with the motion of the frame, creating a smooth rocking motion, a main feature of our design. The frame is 6 x 2 feet, and made primarily from 1.5 inch aluminum angle iron, and 1.5 inch diameter tubing. The other components will be discussed later in the report.
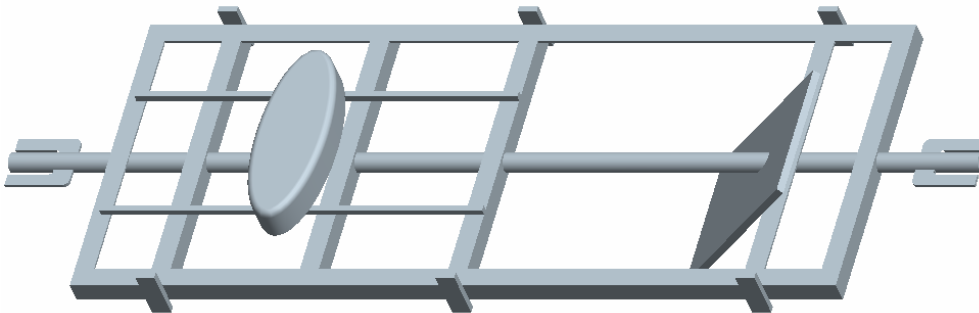
Figure 21: Mechanism Frame

3.1.5 Oar Blade

The oar is the primary contact with the water. Modifications to the oar blade (**Figure 24**) were necessary to counterbalance the high resistance of the pools stationary water. In order to decrease the resistance on the oar blade, sections had to be removed, decreasing the surface area of the blade. The type of oar used was a Macon blade, which has the attributes of symmetry top to bottom, allowing for simpler calculations of surface area, as well as making it useable for either side rowing. The oar is 15 feet long, and the modified blade is 18 inches long with 10 inch sections removed.
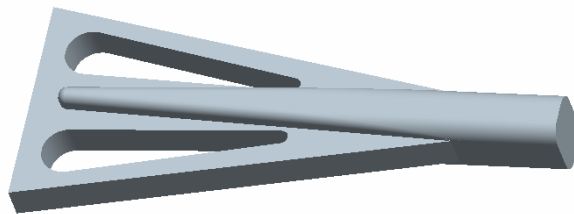
Figure 22: Modified Blade

3.1.6 Poolside Modifications

In order to accommodate the rowing mechanism, and ensure its stability, modifications to Alumni Pool are necessary. Seen in **Figure** 25, the holes will be on the pool deck spaced 72 inches apart, to offer better support to the rig. The holes will be drilled 5 inches in diameter, approx 8.25 inches deep, allowing .25 inches for tile. The holes will be filled in with concrete about the 2.5 inch square tubing, which is cut to 8 inches in length. In order to provide safety to pool users when the mechanism is not in use, it is necessary also to design caps for the holes, providing a flush surface for people to walk over. The caps will be 5 inch diameter, .25 inch thick Plexiglas disks, corrugated to decrease slip, affixed with epoxy to a 1.5 inch square tube at 2 inches in length, to ensure the cap stays in place. For more detains on the poolside modifications see **Appendix D**.
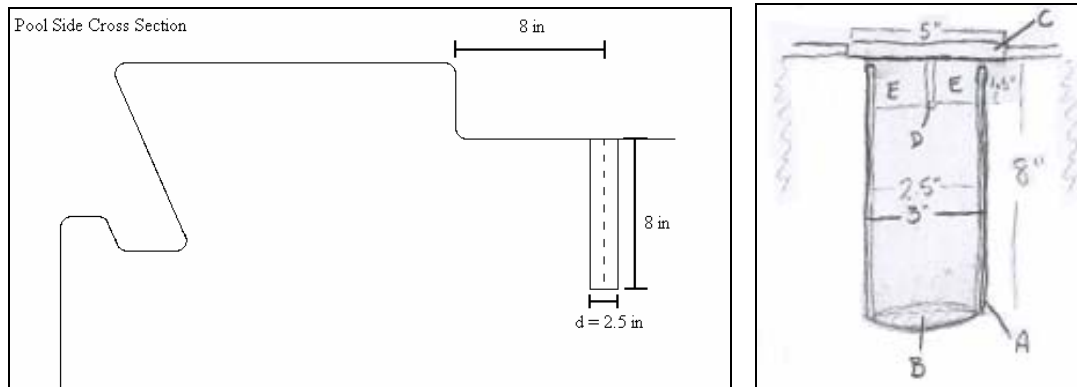
Figure 23: Poolside Modifications

3.1.7 Additional Components

Aluminum is a lightweight, inexpensive, yet durable substance that is used frequently for commercial products. With a density of .098 lb/in^3, Al 6061 T6 is one of very few heat treatable aluminums. The most common method of welding AL6061 is through tungsten arc welding, which is available on campus. Al 6061 is less expensive than Al 2024, which is typically used for aircraft applications. Al 6061 is used for marine applications, and thus it will be more corrosion resistant than typical aluminum alloys.

The springs used in the spring boxes were ordered from an online warehouse, doityourself.com. The specifications for these springs are closest to the desired length and compressive attributes. Each spring needs to handle approximately 15 pounds of compressive pressure. This figure originates from the idea that with eight springs reacting to rotation of the mechanism, 120 pounds could be exerted without the springs maxing out. The maximum amount that a 250 pound person can exert in tilting is one-third their total weight, or eighty-three. The springs, described in **Table 3** have a full compression of two-thirds inches, and an unloaded height of two inches.

Table 3: Design Features

Design Feature	Qty	Material	Weight	Dimensions
Springbox	2	Al brick	~5 lbs	3x5x8"
Springs	8	Al spring	< 1 lb	2/3" solid height
Support Arms	2	Al 6061	~4 lbs	40x36", 1.5" square tubing
Mechanism Frame	1	Al 6061	~15 lbs	24x76", 1.5" angle iron

The foot stretchers on the mechanism are purchased from concept2 [4], the main manufacturer of ergometers. The ergometer foot stretchers are designed so that a rower can wear their own shoes while practicing. They are made of plastic, which is a lightweight and water resistant material. They also allow for different sized feet, adding personal adjustability to the mechanism.

Additional components to the overall mechanism have been donated by the crew team. These include a set of mirror riggers, a macon blade oar which can be used by both a port and starboard rower, a seat, and a set of seat slides. These components are from an older boat that is no longer used. The riggers are approximately five pounds each, and span five feet by two feet. The macon blade oar has the special feature that it is symmetric top and bottom, thus it can be used interchangeably port and starboard. It weighs approximately fifteen pounds, and is fifteen feet long. The seat slides are thirty inches long and approximately half an inch wide. The seat is seven inches by twelve inches and positions the rower three inches off the frame.

3.2 Manufacturing

The manufacturing process of the prototype mechanism, seen in **Figure 26**, allows the group to reassess preliminary designs and create new designs that were more streamlined, easier to produce and reproduce without supervision from the designers, as well as using the smallest amount of material possible. The first step in fabrication is locating materials. Materials for the mechanism come from four main sources: Peterson Steel, WPI Machine Shop, WPI Crew Team, and online direct distributors. The primary source for stock material was Peterson Steel Company, where we purchased the aluminum angle iron (**Figure 24**), square tubing (**Figure 24**), and pipe, as detailed in **Table 4**.

Table 4: Materials
Material Order: Peterson Steel

Material	Cross Section	Length
AL6061 T6 Square Tubing	1.5 inch, 3/16 inch thick	24 feet
AL6061 T6 Angle Iron	1.5 inch, 3/16 inch thick	24 feet
AL6061 T6 Pipe	1.5 inch diameter, 1/8 inch thick	8 feet
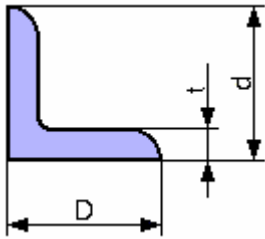
Figure 24: Angle Iron Cross Section
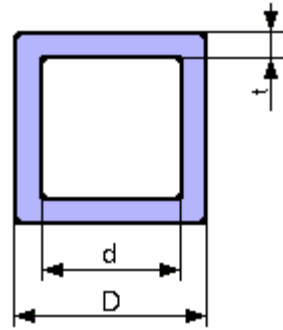
Figure 25: Square Tubing Cross Section

The aluminum for the spring boxes comes from the WPI Machine Shop stock room. It is more cost effective to recycle the large scrap material than to purchase expensive block aluminum from a vendor. Materials for foot stretcher plates, as well as pool hole caps, are recycled from scrap material as well. The springs are ordered based on specifications from doityourself.com. The foot stretchers are purchased from concept2.com [4]. The boat components (seat, seat slide, riggers) are all donated from older boats belonging to the WPI Crew Team.

Figure 26: Prototype at Alumni Pool

3.2.1 Equipment Utilized

In order to fully fabricate the mechanism, several pieces of equipment are utilized. The first of which, the horizontal band saw, quickly cuts the long stock material to the desired lengths. Two different horizontal band saws are utilized, one in Washburn Shops, and one in Higgins Shops. The Washburn horizontal band saw workes well for rough cuts, and thick materials, but lackes the precision and angle cutting found in the Higgins saw. Some angles, primarily the steep 60 degree angles on the support arm component, cannot be cut on either horizontal band saw. For these cuts, a vertical band saw and a t-square are used. These pieces of equipment are also used for detailed cuts on the frame's angle iron cross bars, which require cuts on each side to fit to the frame length, and circular cut-outs to fit over the central pipe.
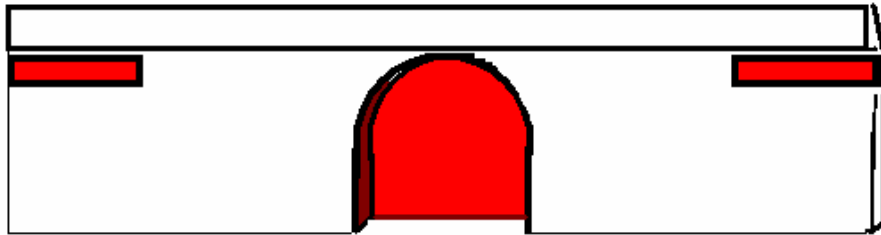
Figure 27: Cross Bar Section Cuts

A manual mill is used to produce the wings. The mill is used because it accommodated interior cuts and straight lines with small tolerances. The spring boxes, requiring even more narrow tolerances, are machined on the CNC mills. First the Pro-E files are imported into Gibbs CAM, from which a machining plan is developed, and then the parts and files are imported into the CNC where the milling occurred. After all the parts are cut and machined, they need to be filed and sanded to remove oxidation before welding can begin. Welding aluminum requires a clean welding surface to adhere properly. Aluminum is welded with tungsten welding tips, aluminum filler, and argon gas.

3.2.2 Methods Utilized

The procedure for fabricating the prototype requires several methods. After considering each initial design carefully, a final design is created using the software Pro Engineer. The final design is an incorporation of several desirable design elements from our initial six designs. The CAD file created in Pro Engineer have all the necessary dimensions to fabricate the prototype. Going from computer generated design to a working model involves tolerancing, specifying materials, stress analysis, and other practical concerns. After doing a stress analysis of the rig to ensure it can support a 250 pound man, we specify appropriate materials, as well as their sizes and shapes. Square tubing and angle iron of aluminum 6061, are strong and light for their size and are the best fit for our prototype.

Table 5: Lengths for Arm
Square Tubing

Number	Length	Angle
A1	14"	90, 45
A2	24"	45, -45
A3	31"	90, 45
A4	3"	90, 58.83
A5	28"	58.83, 31.17
A6	16"	90, 31.17
A7	10"	36.87, -53.13
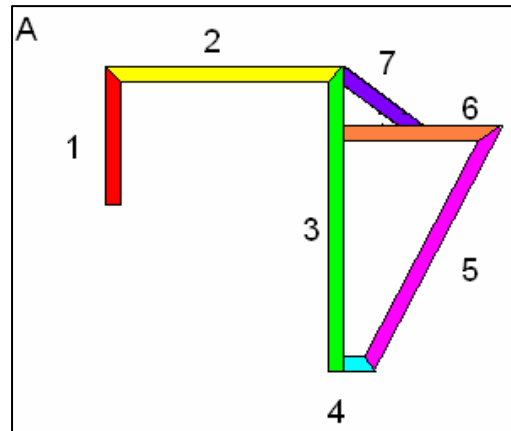
Figure 28: Support Arm Assembly Diagram

With the stock obtained from Peterson Steel, it is cut to appropriate sizes taking into account the specified tolerancing. Schematics for cutting can be found in Appendix G, Table 5, and **Figure 30**. WPI's machine shop helped facilitate the cutting, and did the welding for us, as aluminum is one of the most difficult materials to weld. As can be seen in Figure 29, it was difficult setting tolerances to account for the tungsten arc welding, so some of the pieces needed to be re-cut.

Figure 29: Aluminum Welds on Wings

3.3 Limitations

Assessing our design and prototype, we can make several conclusions about changes that should or could be made to better the design before it is mass produced. Depending on the final fabrication method, professional welding or otherwise, tolerances will need to be adjusted to insure everything will fit as designed.

3.3.1 Difficulties

Throughout any project, difficulties arise, and this project was no exception. Coordinating with companies and individuals outside the core group was often troublesome.

Though the project had a set schedule, it often changed to accommodate other schedules. Shortly after developing our final design, we knew we needed modifications to the pool. This required coordination with WPI Plant Services, Alumni Gym Staff, the Athletic Department, and the Risk Management Office. Modifications have yet to be completed, though the completion of the prototype encourages completion of this necessary step. Another area of difficulties lay in materials purchasing. Peterson Steel was very helpful in material selection; however several delays occurred at Peterson and the Mechanical Engineering Department from purchase orders, delaying material arrival by two weeks. The main source of delay, difficulty and frustration, however, came during fabrication. Each day, the understaffed machine shop had a myriad of problems. Often, at least one vital piece of machinery was out of order. The two machinists were often too overloaded with other projects to assist with our project. Both welding and CNC machining were initially scheduled for early February, but they were not completed until the middle of April. However, without the help of any of the aforementioned people, the project would not have happened at all.

3.3.2 Improvements for the Future

We think there are some good improvements for the future that can be made. These improvements would be beneficial. The benefits of these improvements would help the WPI Crew Team. The WPI Crew Team needs to create this product without the limitations we experienced. Limitations make fabrication difficult. Difficulties are expensive and should be avoided. We would like to avoid these difficulties by making improvements.

Our first improvement would be to design for a more streamlined fabrication method. In order to streamline the fabrication process, we recommend using an aluminum

fabrication contractor. This would slightly increase the amount of money spent on the project; however it would drastically decrease the amount of time for the project to be completed. Also it would increase the precision with which the devices are created.

The second improvement we would recommend, after contracting out the fabrication, would be to work with the contracted machinists. Those machinists would be able to alter the tolerances based on provisions the WPI Athletic Department stipulated. The Athletic Department might decide to tighten the tolerances for precision, or loosen the tolerances for speed of production. Speed of production may be an important factor for the Athletic Department, so the machinists would be able to alter the tolerances to give them that option.

Other future work to be done, as explained in Chapter 4, do not directly relate to an improvement in the MQP process. There is much work that can be done, and should be in order to produce a superb product.

3.4 Overall Discussion

The project is a complete process from initial design stages through to prototype fabrication and plans for full production. By incorporating design and manufacturing, the project presents several learning experiences, from needs assessment, to design iteration, materials sourcing, and finally to fabrication optimization. The project brings together two seemingly isolated departments, Mechanical Engineering and Athletics, creating a device that is optimal for both groups. This project, which was initiated, planned, and executed by students, brings new versatility to the antiquated Alumni Pool, which will soon be redundant

due to the larger recreation center. Finally, this project enhances the overall WPI Crew program, allowing rowers to use a dynamic on-campus training facility to learn technique and balance.

This device trains rowers in a new, innovative way. The most innovative aspect of this mechanism design is the spring box. An ergometer may be purchased for $850. An indoor rowing tank facility may be purchased for $50,000. Neither mechanism gives the balance training necessary to row successfully in a boat. This mechanism, with its spring boxes provides that training. The spring boxes allow for a 15 degree rotation, enough to make the rower aware of being off balance.

Chapter 4 – Conclusions

On water rowing and rowing tanks are closely interrelated, as they are essential for learning basic technique. To build tanks, one must have a complete knowledge of the physics of rowing and rowing tanks. Based on this knowledge, designs of pool side rowing devices can be maximized to help one learn the rowing process comprehensively. This knowledge enables us to design a rowing device that will simulate on water rowing effectively.

After successfully designing the mechanism, it was manufactured with the help of WPI's two machine shops. The frame was welded together, and the spring box was machined with the CNC machines in the machine shop. The oar was modified so the pressure felt from the oar in the pool is similar to on the water rowing pressure. From the fabrication stage it will be utilized as a supplementary training and form device for the crew team. Recommendations for mainstreaming the device include a quicker and easier way to create a spring box, as well as having professional aluminum welders take over that part.

Our poolside rowing mechanism is innovative and directly fulfills a need for the WPI campus. It has been designed, analyzed and fabricated per objectives discussed with both the crew coach as well as the rowers. Rowers and coaches no longer have to rely on Holy Cross facilities to work on technique. The team will now be more competitive in recruiting rowers as well as keeping up with other teams in the areas solely based on the effects of our project. It is said that nothing can completely simulate on water rowing, but we believe we have come the closest thus far.

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Contributions from Amanda Gray, Sarah Pavis and Corinne Linderman based on their knowledge obtained by rowing for WPI Crew.
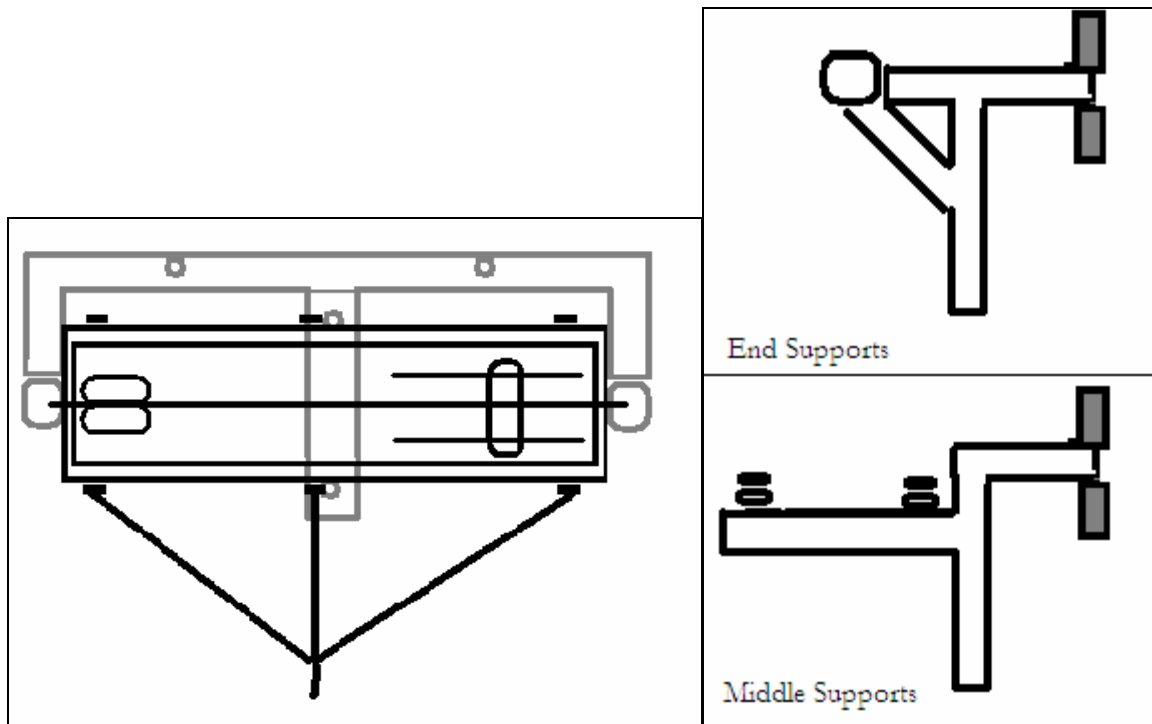
Appendix A- Preliminary Designs

Design 1: Symmetry

Figure 30: Design 1 Schematics

The main idea for this design is to accommodate port and starboard rowing on one device. The design utilizes symmetry throughout, which increases balance, and quick changes in rigging. Additionally, the device is supported at each end, but is allowed to freely rotate about a center axis with cylindrical ball bearings, while being dampened by springs. This allows for controllable instability, which will aid a new rower to understand the fundamental instability of on water rowing.

Design 2: Stationary
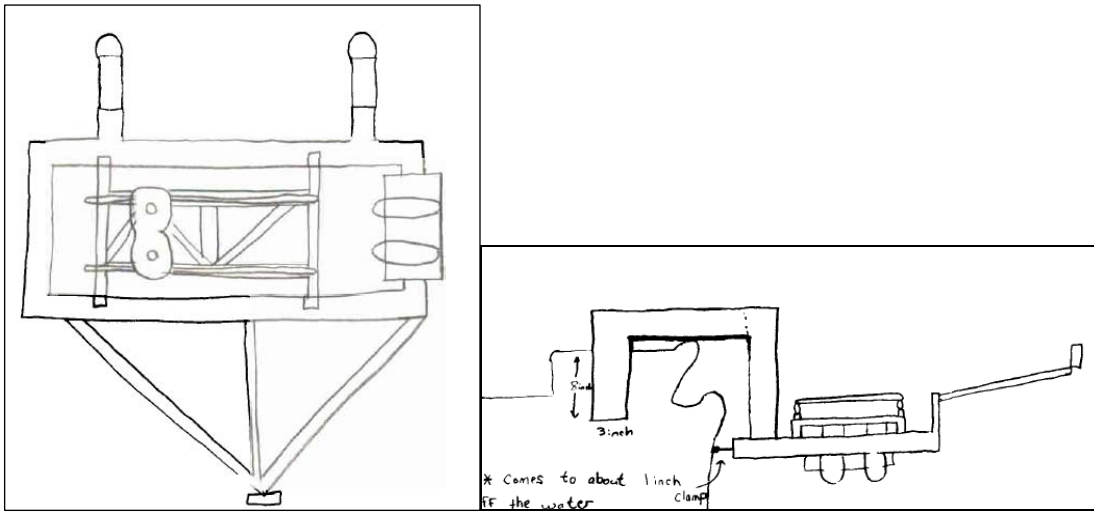
Figure 31: Design 2 Schematics

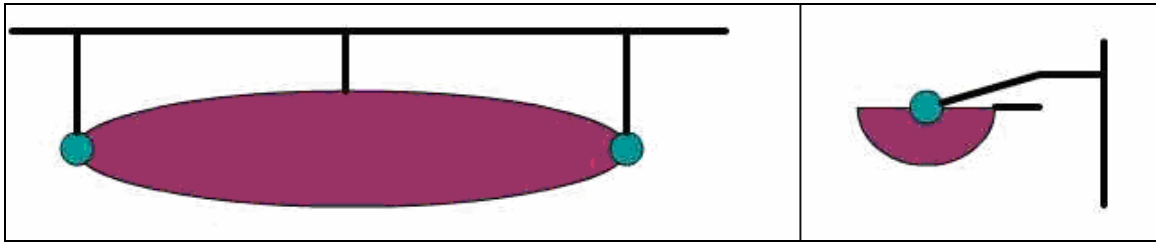This design is most basic in its principles. The main feature of the design is support and stability. The device is anchored by drilled holes in the pool lip, and stopped at the water line to prevent rotation. Though not including the desired controllable instability, or easy port to starboard switch, its design is simple and functional.

Design 3: Swinging Arm

Figure 32: Design 3 Schematics

This conceptual design relies heavily on free swinging arms to act as both support,

and controllable instability. The rounded section allows for the device to sit closer to the

water line. The circles at either end of the device represent points of rotation. The design

focuses on the positioning of the various mechanism components (frame, arms, rotator, etc),

without rigidly controlling what specific mechanism is used in each area.

Design 4: Suspended Linkage
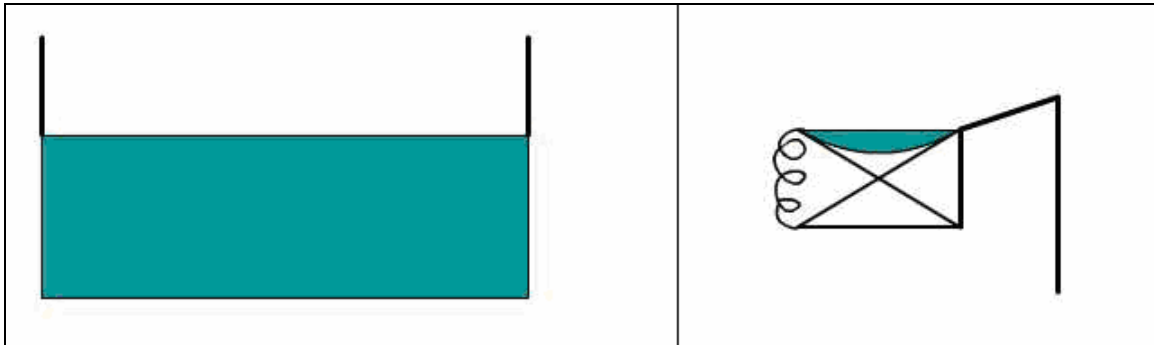
Figure 33: Design 4 Schematics

The main focus of this design is linkage motion. At either end, kinematic linkage allows the device to rock back and forth just as a boat on the water would. The center spring restricts the motion to a smaller defined path. The device is supported by drillind poolside holes either on the lip or the decking of the pool.

Design 5: Strapped, Free-Floating
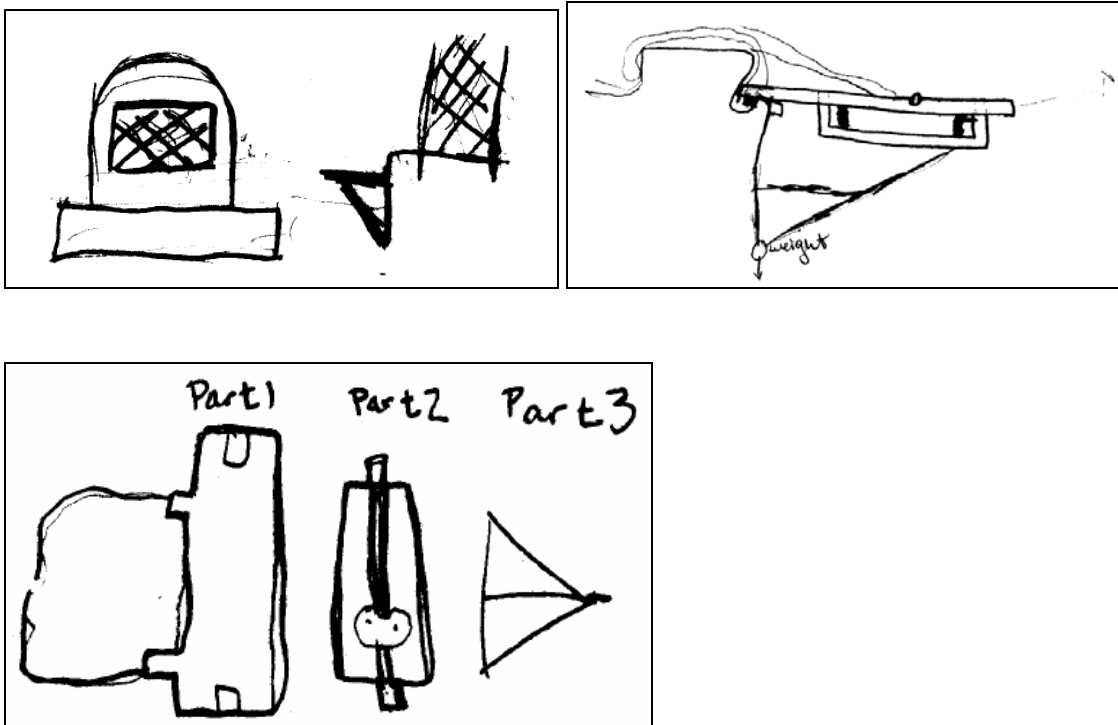
Figure 34: Design 5 Schematics

The strapped design came from a need to potentially support the device without drilling into the lip or decking of the pool. The first design idea was to strap the device around the support post. This is very similar in concept to how a boat is strapped to a trailer. Additionally, the design incorporates segments, to make the process of putting the device into the pool easier, and cutting down on the total weight carried at any time.

Design 6: Buoy
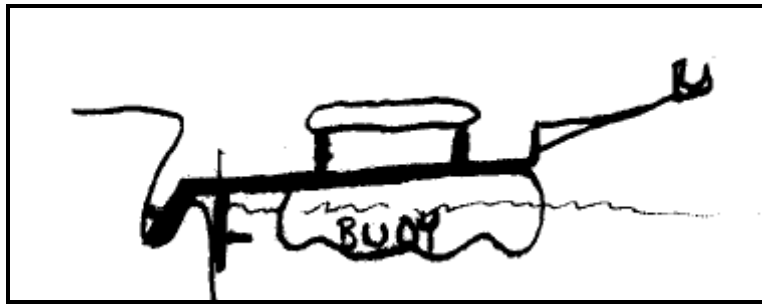
Figure 35: Design 6 Schematics
As a secondary design that would not change the pool façade involves the use of

clamps, and a buoy to support the majority of the device weight. The instability of this

design is less controllable than the alternative options.

Appendix B- Design Matrix

For the Prototype		Design #					
	Importance of aspect	1	2	3	4	5	6
transportable	0.9	6	2	8	4	4	9
light	0.6	4	5	5	3	8	8
reversibility	0.6	7	6	7	5	5.5	4
controllable instability	0.7	9	0	9	7	8	3
economics	0.8	5	8	3	7	7	6
dynamics	1	8	6	5	5.5	3.5	3
personal adjustments	0.5	3	3	5	3	5	3
accuracy representing rowing	0.7	7	4	5.5	5.5	6.5	5
Safety	0.8	6	9	4	5	4	4
Sum	66	41.5	32.3	37.65	33.75	36.65	33.4
		5	3	4	1	4	2

Design 1 — Amanda Gray
Pros: Simply supported; reversibility and instability
Cons: not lightweight; potential safety issues

Design 2 — Corinne Linderman
Pros: foot stretchers at both ends, simple, cheap
Cons: not transportable, personal adjustments minimal, one sided.

Design 3 — Sarah Pavis
Pros: dampening system, swing out arms, separate rigger
Cons: machining?, attachment secure, pricey

Design 4 — Sarah Pavis
Pros: instability, simple supported
Cons: toggle with underwater linkage, springs

Design 5 — Corinne/Shared
Pros: straps, no pool modification, springs, segmented
cons: dynamics, safety

Design 6 — Shared
pros: buoy, no pool modification
cons: permanent instable

Appendix C- Prototype Design:

Figure 36: Prototype Designs
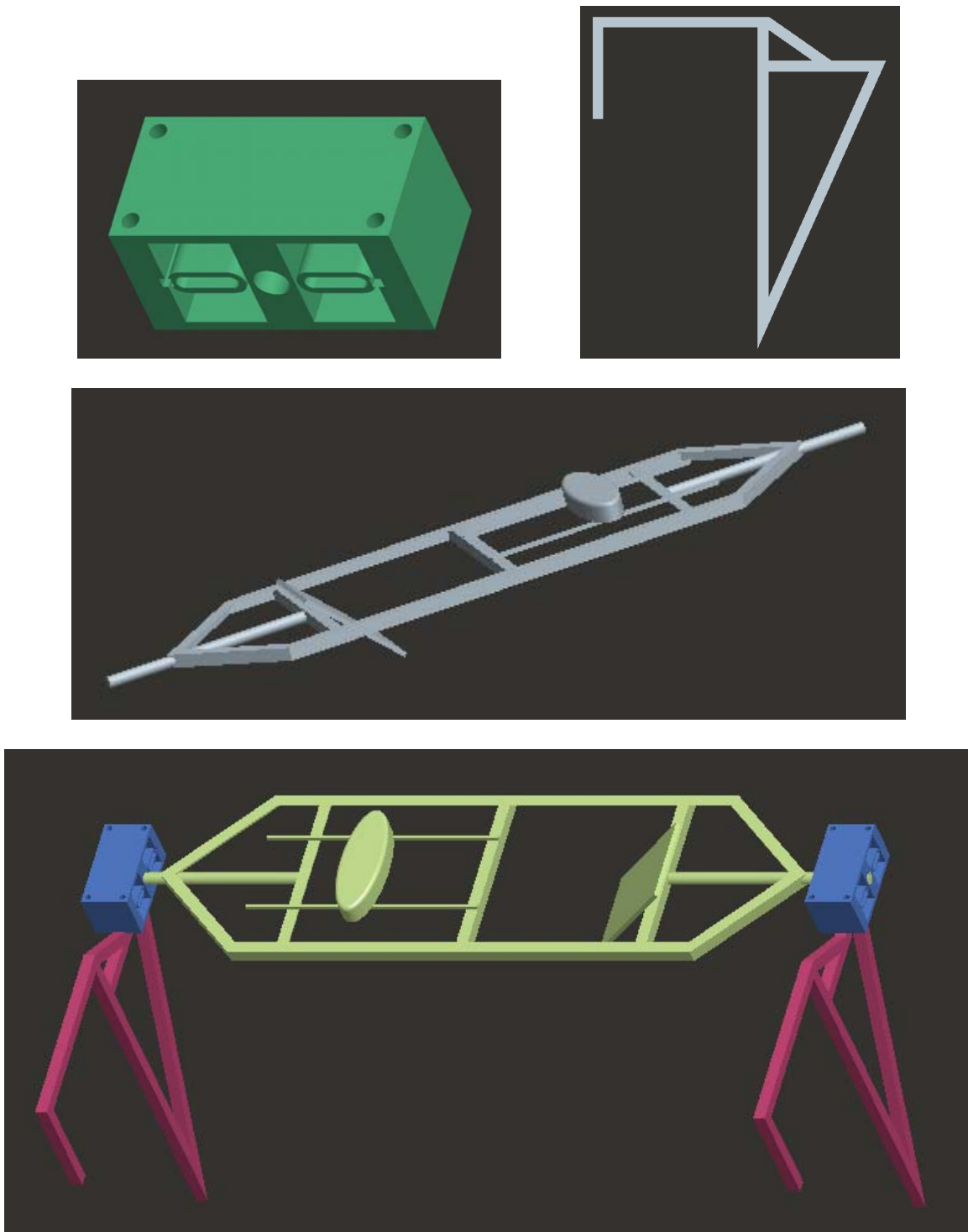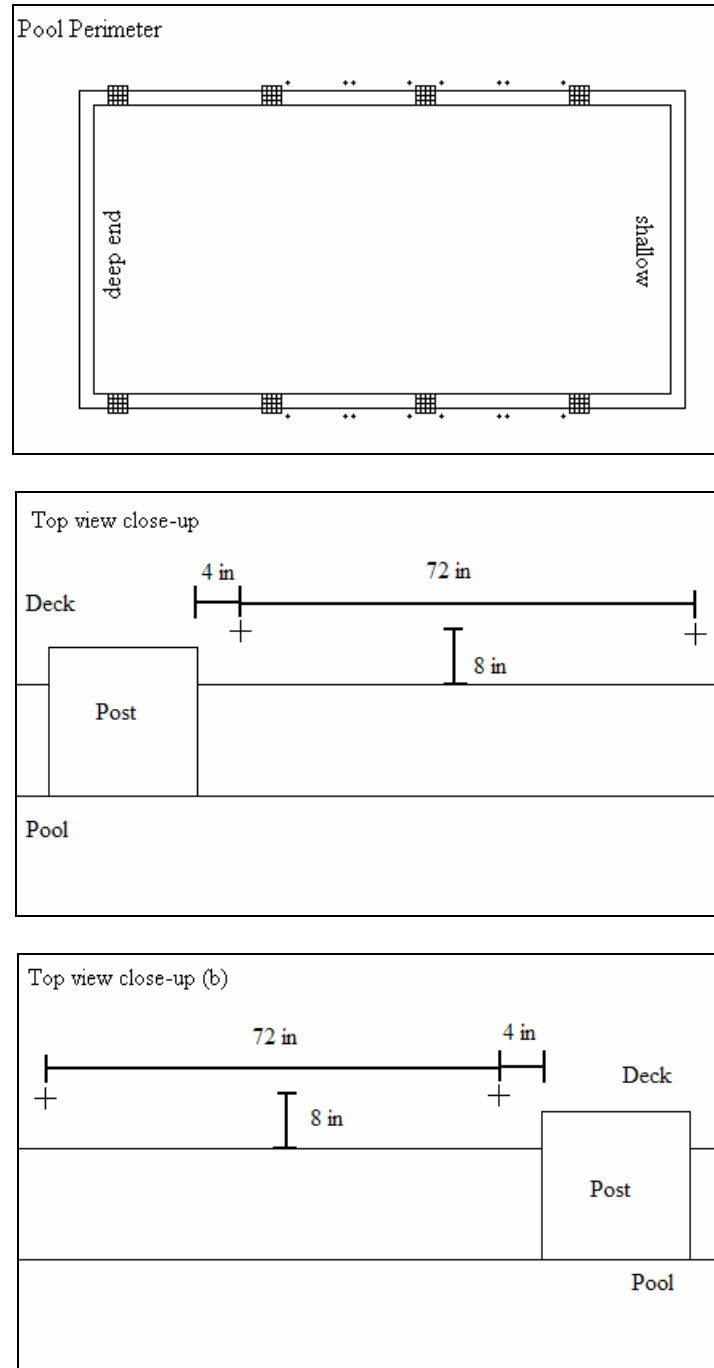
Appendix D- Poolside Modification Plans

Pool Perimeter

deep end

shallow

Top view close-up

Deck

4 in

72 in

Post

8 in

Pool

Top view close-up (b)

72 in

4 in

Deck

8 in

Post

Pool

Figure 37: Pool Modification Schematics

Appendix E- Stress Analysis
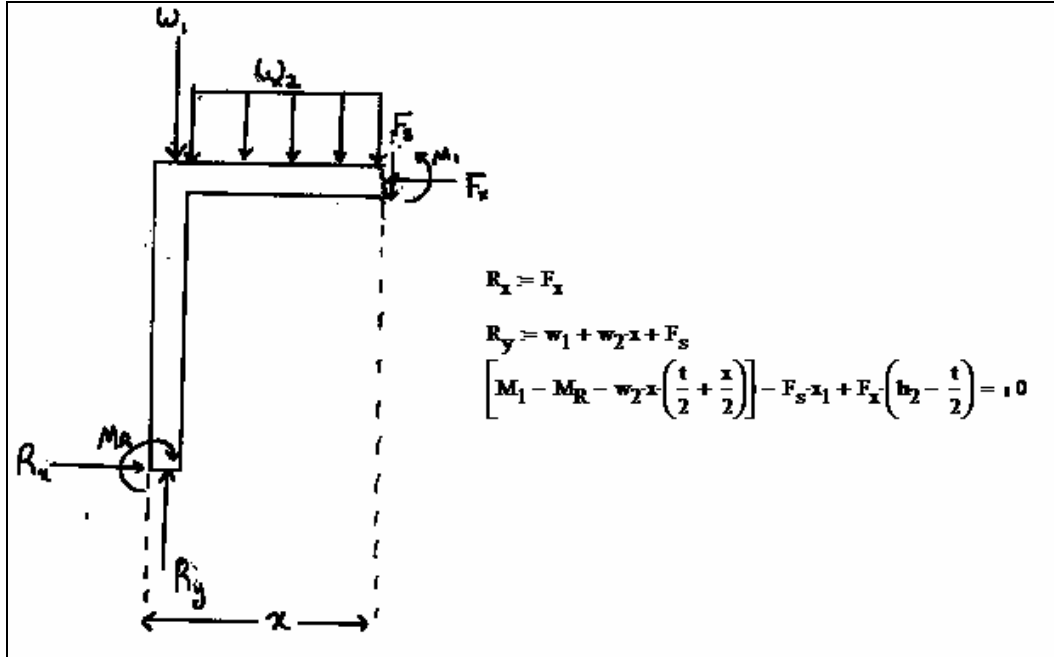
Figure 38: Free Body Diagram 1

$$R_x = F_x$$

$$R_y = w_1 + w_2 x + F_s$$

$$\left[M_1 - M_R - w_2 x \left(\frac{t}{2} + \frac{x}{2}\right)\right] - F_s x_1 + F_x \left(h_2 - \frac{t}{2}\right) = 0$$
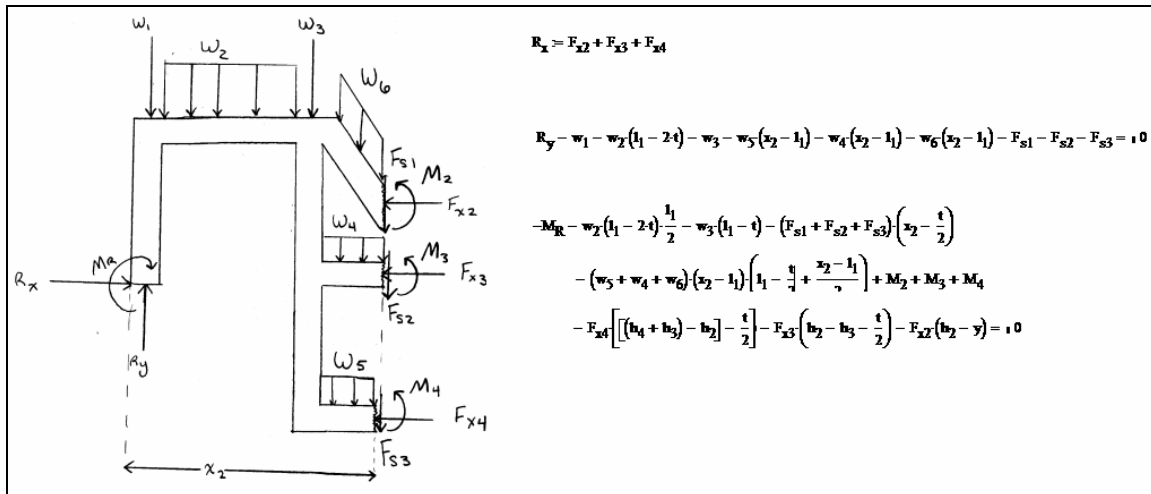
Figure 39: Free Body Diagram 2

$$R_x = F_{x2} + F_{x3} + F_{x4}$$

$$R_y - w_1 - w_2(l_1 - 2t) - w_3 - w_5(x_2 - l_1) - w_4(x_2 - l_1) - w_6(x_2 - l_1) - F_{s1} - F_{s2} - F_{s3} = 0$$

$$-M_R - w_2(l_1 - 2t)\cdot\frac{l_1}{2} - w_3 \cdot (l_1 - t) - (F_{s1} + F_{s2} + F_{s3})\cdot\left(x_2 - \frac{t}{2}\right)$$
$$- (w_5 + w_4 + w_6)\cdot(x_2 - l_1)\left(l_1 - \frac{t}{2} + \frac{x_2 - l_1}{2}\right) + M_2 + M_3 + M_4$$
$$- F_{x4}\left[\left[(h_4 + h_3) - h_2\right] - \frac{t}{2}\right] - F_{x3}\left(h_2 - h_3 - \frac{t}{2}\right) - F_{x2}(h_2 - y) = 0$$

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$$R_x = F_{x5} + F_{x6} + F_{x7}$$

$$R_y - w_1 - w_2(l_1 - 2t) - w_3 - w_4(x_3 - l_1) - w_6(x_3 - l_1)$$
$$- w_7(x_3 - l_1 - l_7) - w_5(l_7 - t) - F_{s4} - F_{s5} - F_{s6} = 0$$

$$-M_R - w_2(l_1 - 2t)\left(\frac{l_1}{2} - \frac{t}{2}\right) - w_3(l_1 - t) - (F_{s4} + F_{s5} + F_{s6})\left(x_3 - \frac{t}{2}\right)$$
$$+ M_5 + M_6 + M_7 - (w_4 + w_6)(x_3 - l_1)\left(\frac{-t}{2} + x_3 - \frac{x_3 - l_1}{2}\right)$$
$$- w_5(l_7 - t)\left(l_1 - \frac{t}{2} + \frac{l_7}{2}\right) - w_7(x_3 - l_1 - l_7)\left(l_1 - \frac{t}{2} + l_7 + \frac{x_3 - l_1 - l_7}{2}\right)$$
$$+ F_{x5}(h_2 - y_1) + F_{x6}(h_2 - h_3) + F_{x7}\left[h_3 + h_1 - h_2 - (x_3 - l_1 - l_7)\cdot\sin(\alpha)\right] = 0$$

Figure 40: Free Body Diagram 3

$$R_x = F_{x8} + F_{x9}$$

$$R_y - w_1 - w_3 - w_2(l_1 - 2t) - w_4(x_4 - l_1)$$
$$- w_5(l_7 - t) - w_2(x_4 - l_7 - l_1) - w_6 l_6 - F_{s7} - F_{s8} = 0$$

$$-M_R - w_2(l_1 - 2t)\left(\frac{l_1}{2} - \frac{t}{2}\right) - w_3(l_1 - t)$$
$$- w_6 l_6\left(l_6 + l_1 - \frac{t}{2}\right) - w_5(l_7 - t)\left(l_7 + l_1 - \frac{t}{2}\right) - w_4(x_4 - l_1)\left(\frac{x_4 - l_1}{2} + l_1 - \frac{t}{2}\right)$$
$$- w_7(x_4 - l_1 - l_7)\left(\frac{x_4 - l_1 - l_7}{2} + l_1 + l_7 - \frac{t}{2}\right) - F_{s7}\left(x_4 - \frac{t}{2}\right) - F_{s8}\left(x_4 - \frac{t}{2}\right)$$
$$- F_{x9}\left[h_1 + h_3 + t - h_2 - \tan(\alpha)\cdot(x_4 - l_1 - l_7)\right] + F_{x8}\left[h_1 - \left(h_3 + 3\cdot\frac{t}{2}\right)\right] + M_8 + M_9 = 0$$

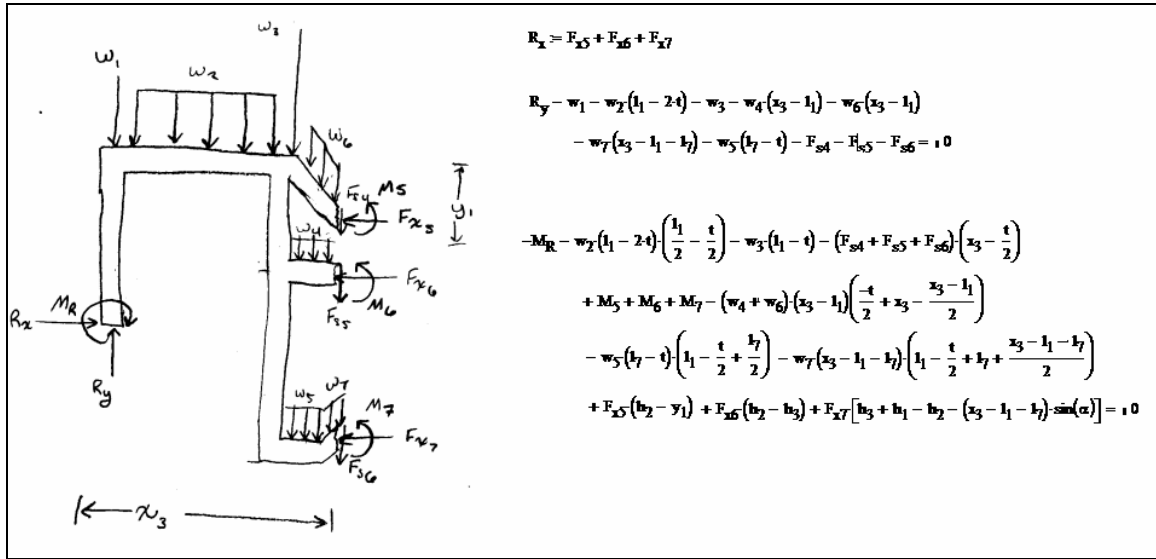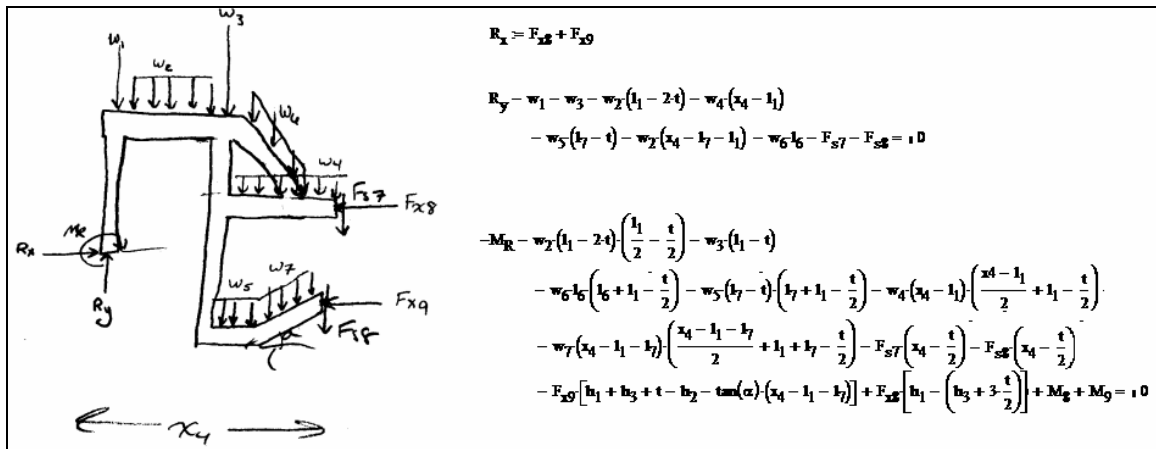**Figure 41: Free Body Diagram 4**

Appendix F- Weight Assessment

6061 t6: easiest to get a hold of, cheapest

$$\text{density} := .098\frac{\text{lb}}{\text{in}^3}$$

Spring Box

$$\text{Volume}_{sb} := 2\left[(5 \cdot 3.75 \cdot 3.75) - \left[4 \cdot \left[2 \cdot \left(\frac{.75}{2}\right)^2 \cdot \pi\right]\right] - \left[\left(\frac{1.5}{2}\right)^2 \cdot \pi\right] - (3.75 \cdot .2 \cdot .125) - \left[3.75 \cdot \left(\frac{.125}{2}\right)^2 \cdot \pi\right]\right] \text{in}^3$$

$$\text{Volume}_{sb} = 129.743 \text{in}^3$$

$$\text{weight}_{sb} := \text{density} \cdot \text{Volume}_{sb}$$

$$\text{weight}_{sb} = 12.715\text{lb} \qquad \text{for two spring boxes}$$

Arm dimensions 1/8th inch square tubing

$$\text{Volume}_{arms} := 2\left[\left(1.5^2 - 1.25^2\right) \cdot \left(14 + 24 + 30 + 3 + 28 + 16 + \sqrt{6^2 \times 9^2}\right)\right] \cdot \text{in}^3$$

$$\text{length}_a := \left(14 + 24 + 30 + 3 + 28 + 16 + \sqrt{6^2 \cdot 9^2}\right) \cdot \text{in} \qquad \text{length}_a = 14.083\text{ft}$$

$$\text{Volume}_{arms} = 232.375 \text{in}^3$$

$$\text{weight}_{arms} := \text{density} \cdot \text{Volume}_{arms}$$

$$\text{weight}_{arms} = 22.773\text{lb} \qquad \text{for two arms}$$

Rig 3/16th inch angle iron, 1.5 inch OD .125 inch thick tube

$$\text{Volume}_{rig} := \left[\left[76 \cdot \left(\frac{1.5}{2}\right)^2 \cdot \pi\right] - \left[76 \cdot \left(\frac{1.375}{2}\right)^2 \cdot \pi\right] + [6 \cdot (24 \cdot 1.5 \cdot .1875 \cdot 2) + 2 \cdot (60 \cdot 1.5 \cdot .1875 \cdot 2)] + 4(.5 \cdot 3 \cdot 2.75) + 8.13^2 - (8.13 - 1.94)^2\right] \text{in}^3$$

$$\text{length}_{rig} := (6 \cdot 24 + 2 \cdot 60) \text{in} \qquad \text{length}_{rig} = 22\text{ft}$$

$$\text{length}_{rod} := 92\text{in} \qquad \text{length}_{rod} = 7.667\text{ft}$$

$$\text{Volume}_{rig} = 214.232 \text{in}^3$$

$$\text{weight}_{rig} := \text{density} \cdot \text{Volume}_{rig}$$

$$\text{weight}_{rig} = 20.995\text{lb} \qquad \text{for one rig}$$
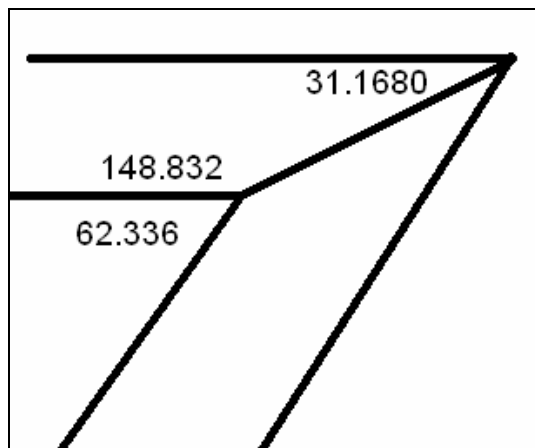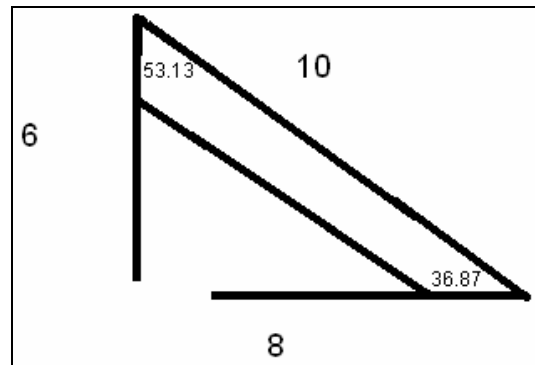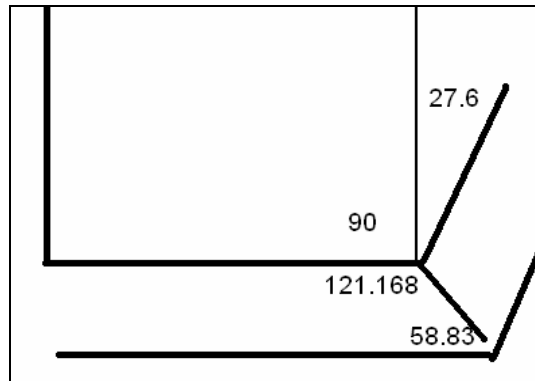
Appendix G- Support Arm Angle Cuts

Figure 42: Angle Cuts for Support Arms
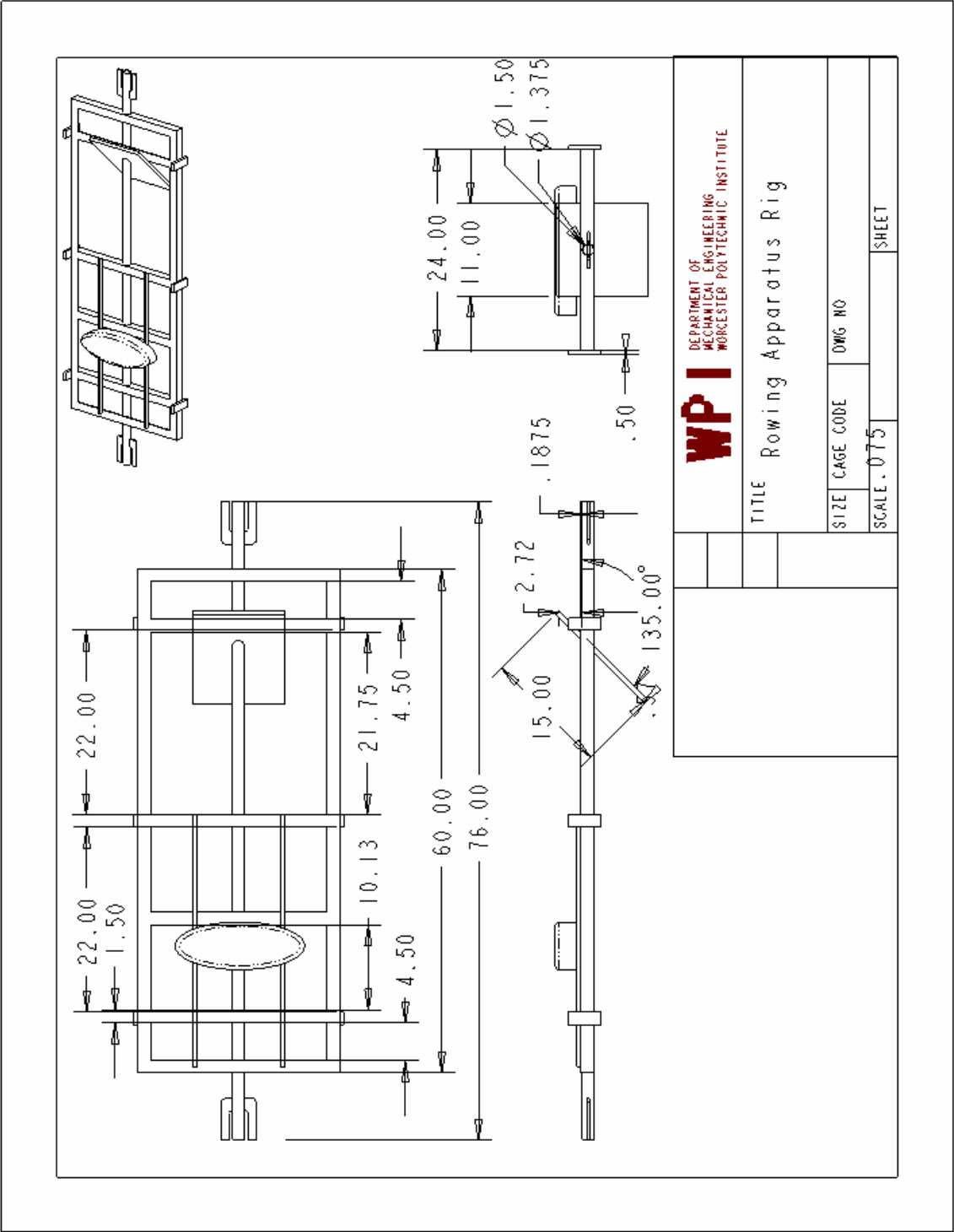
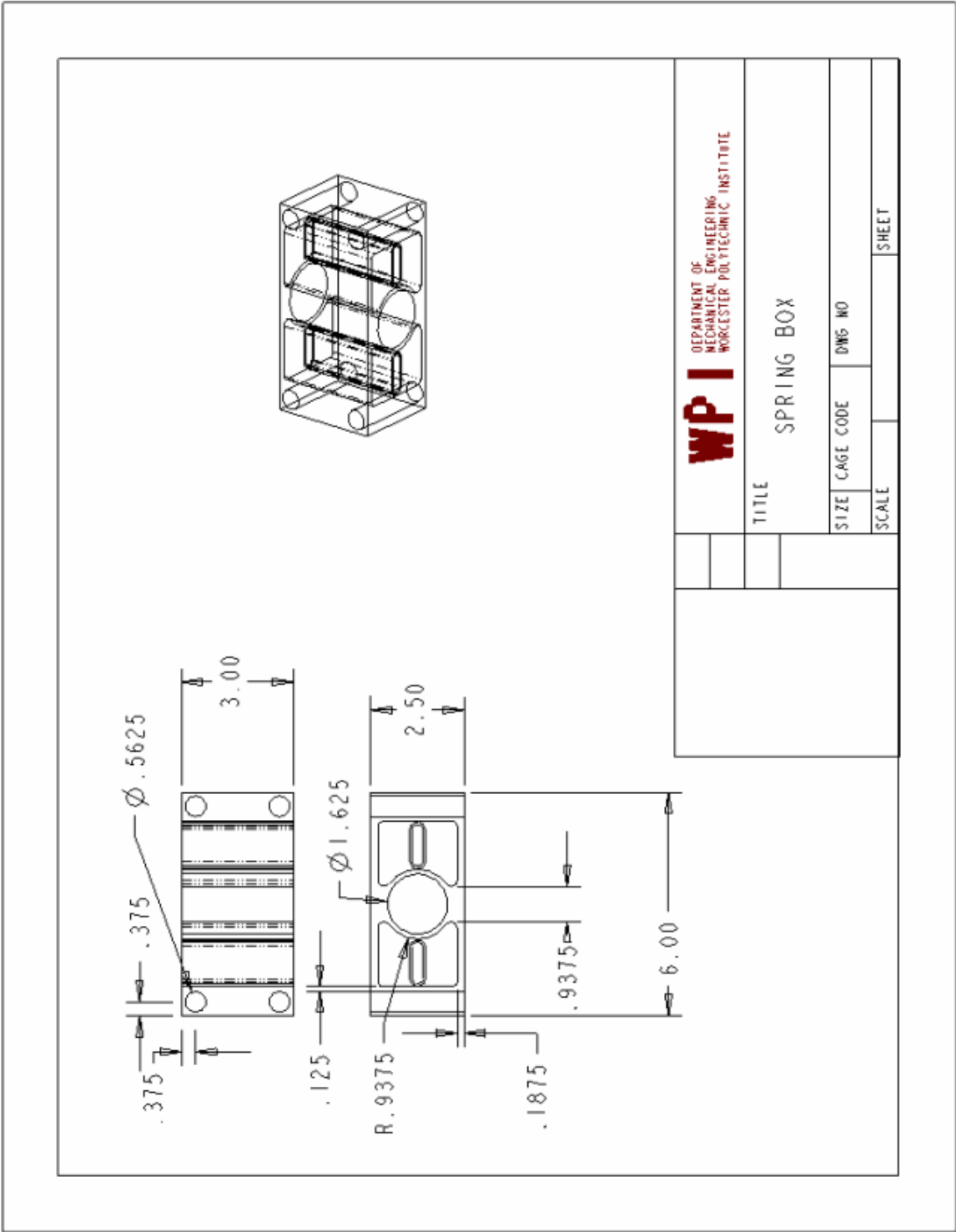# Appendix H: Detailed Dimensioned Drawings

Figure 43: Frame Drawing

Figure 44: Arm Drawing

Figure 45: Spring box Drawing