Feel of the Ocean: Final Report

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ME Senior Capstone Project

Feel of the Ocean

by

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List of Nomenclature

T_{Rope}	tension of the raising rope,
q_{beam}	weight per unit length of the beam
q_{pvc}	weight per unit length of the PVC pipe
l	length of the beam
W	weight of a particular component
n_	number of that component present
T_{sway}	tension in the rope that is used to sway the kelp
d	diameter of the shaft
n	safety factor desired
S_e	effective strength of material
K_f	fatigue factor
M_a	alternating moment
K_{fs}	fatigue factor for torsion
T_a	alternating torque
S_{ut}	ultimate strength of material
M_m	mean moment
T_m	mean torque
δ	deflection in the center of the beam
q	distributed load in lbs/ft
L	length of the beam
E	stiffness of the material
I	second moment of area
f_{nat}	natural frequency of the system
g	acceleration due to gravity
l	vertical length of the ropes holding up the system

Executive Summary

The overall goal of this project is to create a system that will enhance the audience's sense that they are actually in the ocean, surrounded by whales, as they attend the Music Department's 2014 Spring RSVP show. We have designed something that, through the interaction of light and moving fabric, will augment the performance. Our project is aimed to please three main parties. First and foremost is the audience that attends the performances in June. If their experience is not enhanced, then the project has failed. The second party is Dr. Barata, the sponsor of the project and the producer and director of the RSVP show. Third and finally, we must also create something that is usable, safe, and helpful to the members of the MU 412 class and the other performers that will be putting on the show.

Team FOTO consists of three members: Kevin Dunlea, Ian Hoffman, and Ryan Palo. We are all Mechanical Engineering students, and this project is our Senior Capstone Experience. We are advised by Dr. Jim Widmann, a professor in the Mechanical Engineering department. A successful completion of this project will allow us to graduate from Cal Poly on time and move into the working world. We have expanded our "Learn by Doing" experience by interacting with multiple disciplines throughout this project, learning about how other individuals approach problems and the creative process. Through our combined efforts, we have created a product that is significantly better than it would have been without collaboration.

In order to complete our design and stay on schedule, our team followed the standard Mechanical Engineering design model. Steps within this model include researching background and current designs, defining the problem, and brainstorming as many ideas as possible to solve the problem, narrowing and improving our ideas using a "Christmas tree" approach (narrow down a lot, and then generate some more better ideas, and narrow down again, etc.). After the best design was selected, we pinpointed the parts that would require sizing or extra analysis to prevent failure. We then machined, assembled, and tested our design. Every step of the way was accompanied by constant iteration, finding ways that our design could be improved.

The final design is a 22'-tall swaying "kelp forest" made from theater fabric. It consists of three rows of multiple strands of fabric that are swayed back and forth by the user. The fabric is attached to nylon cylindrical shuttles which are attached to each other by either static or elastic line. The shuttles slide back and forth through a slotted PVC pipe, which is zip-tied to a steel pipe for structural support. One end of each row is attached via tie line to a driving mechanism on the ground. The driving mechanism on the ground is a shaft with three offset shaped cams. As the user turns the handle, the cams rotate, and the tie line connected to the shuttles is reeled in and out as it gets wrapped around the cams. Each row can be raised and lowered independently via ropes that are run through pulleys attached to the ceiling. This is so that the kelp can be hidden out of sight if needed. The project was budgeted at $1500, which we received from the CP Connect program. Our overall costs came to approximately $1077, and we completed the project nearly 30% under budget.

The "Swaying Kelp Forest" that we designed and built more than met the expectations of the MU 412 class, Dr. Barata, and, most importantly, the audience that attended RSVP. Each night there was a small malfunction where one of the knots in the line connecting the shuttles of the back row fell out, causing that row to be non-operational for part of a song. This was not a major problem and was easily fixed, and, due to our added safety measures, no one was in any danger because of this. Overall, It added ambiance to some scenes, was the main focus of other scenes, and was able to integrate seamlessly with the rest of the production. The end result was interesting, functional, and safe.

If this project was to be attempted again, there are some improvements that could be made. First, more care could be taken when machining the PVC slot (which is already a difficult process). This would ensure smooth motion, no unnecessary catching or noise, and easier operation. The other thing that could be improved is the shape of the cams. They were drawn and measured by hand instead of following a stencil, and this caused them to be not quite ideal. Using a stencil would allow for a uniform and aesthetically pleasing shape.

Chapter 1 - Introduction

Sponsor Needs

The Feel of the Ocean Project's intent is to create a desirable and interesting experience for both the performers and the audience in a concert based on the song of whales. In order to accomplish this, some customer requirements were presented to us. Above all else, the mechanism must safely interact with performers and audience. In order to satisfy this need, we will be using a hazard risk index (a scale developed by the U.S. Government to quantify risk) to appropriately analyze the risk and danger involved in each aspect of the product. Furthermore, the customer requires that the proposed mechanism integrate with the space provided. To address this concern, we formed several design requirements. The mechanism and its parts must not unintentionally block lights on the stage. The sizing of the mechanism must be such that it can fit through the pavilion doors and be moved onto the stage. Should the design require any parts to be hung from the ceiling, the weight must not exceed the tolerance set by the railings along the ceiling. Another important request from the customer is that the mechanism must have reliable functionality (it must work on the nights it is needed). Therefore, we have the design requirement that the mechanism must be able to operate over a period of 100 hours or more. This time of 100 hours was chosen because of the expected usage by the performers. After considering rehearsal times, testing, and performance time, the mechanism does not need to operate for a long period of life.

Objective Development

A method of identifying engineering requirements that satisfy customer requirements is to use a QFD, or Quality Function Deployment (Figure 1). It helps to identify customer requirements and to create a complete engineering specification. Along the left side is a list of customer requirements as stated by the sponsor. Across the top are the chart are some quantifiable engineering requirements our team came up with. The center region shows which engineering requirements relate to which customer requirements, with triangles indicating weak correlation, white dots indicating medium correlation, and black dots indicating high correlation. This proves that all customer requirements are met and all the engineering requirements are relevant. Along the bottom is an actual goal for each engineering requirement, complete with units. Also compared are currently available technologies for reference. The two benchmark technologies compared are a stationary piece of fabric with light being shined on it and a piece of fabric being moved by stage-hands.

Your Project Name Here Feel of the Ocean Customer: Audience, Performers, Dr. Barata		Weighting (Total 100)	Must fit through Pavilion door	Must operate within the space of the room	Weight must be able to be supported by ceiling rigging if hung	Cannot be simple harmonic motion	Cannot be completely random motion	sound intensity is low	Hazard risk index must be ≥ 16	Doesn't block light for other parts of the stage	Able to be lit using the available resources	Must work between May 29th and June 5th	Assembly Time	Does not interfere with actions of performers and other effects	Does not cost more than what's budgeted	Inputs controlling movement	Modes available		1) Still Fabric	2) Students wiggle
Customer Requirements (Step #2)	Safely interacts with performers and audience*	17		Δ	•			Δ	•	Δ		o		o					5	4
	Integrates with the space provided*	14	•	•	•			Δ		•	•	Δ	Δ	o					5	4
	Reliable Functionality*	13		Δ		Δ	Δ					•							5	3
	Embodies the ebb and flow feel of the ocean	12				•	•	o		Δ	•			o		•	•		2	4
	Aesthetically integrated with the concert	10				o	o	Δ		•				•		○	•		2	4
	Quiet or appropriate level of operation noise	9						•								Δ	Δ		5	4
	Affordable	8						o				o			•				5	5
	Variable	7				•	•									•	○		3	5
	Quasi-Periodic	5				•	•									○	•		2	4
	Sex Appeal	3				•	•	•		o	•	o		o	o	•	○		1	2
	Convenient assembly/disassembly	2	•	o	Δ							Δ	•						4	3
	Units		ft^2	ft^3	lbs	binary	binary	dB	index	lights blocked	binary	hours	hours	actions	dollars	inputs	modes			
	Targets		20	100	1000	1	1	≤50	16	3		100	24	2	1500	2	2			
	Benchmark #1		1	1	1	0	1	20	18	?	1	100+	10 to 15	?	150	0	1			
	Benchmark #2		1	1	1	1	1	40	18	?	1	100+	5 to 10	?	150	many	∞			

• = 9	Srong Correlation
○ = 3	Medium Correlation
Δ = 1	Small Correlation
Blank	No Correlation

Engineering Requirements (HOWS)

Figure 1 - QFD diagram

Specifications

The Formal Engineering Requirements Table (Table 1) displays the engineering requirements discussed in the QFD in a concise and simple form. For each requirement there is a tolerance, risk, and compliance. The tolerance is the acceptable range around a nominal value. For most measurements, it is impossible to truly be at the nominal value. The risk of each requirement shows how ambitious it is to complete each goal: H = High, M = Medium, L= Low. For example, having multiple inputs controlling movement can be an intensive task, so the risk of completing the goal would be high if we were trying to create a mechanism with 6 or more inputs. However, since the target was at a minimum of 2 inputs, we expected there to be a low risk associated with completing that goal. The compliance column delineates how we determined whether or not we have reached the target or goal for each engineering requirement: A= Analysis, T = Test, I = Inspection. Most requirements required testing during a rehearsal to determine if the target has been reached.

Table 1 - Table of Engineering Requirements

Spec. #	Parameter Description	Requirement or Target (units)	Tolerance	Risk	Compliance
1	Must fit through Pavilion door	20 ft^2	- 1 ft^2	L	T, I
2	Must operate within the space of the room -Height	20 ft	±5 ft^3	M	T, I
3	-Length	35 ft		M	T, I
4	-Width	20 ft		M	T, I
5	Weight must be adequately supported by ceiling rigging if hung	1000 lbs	max	L	A
6	simple harmonic motion	No	--	L	I
7	Completely random motion	No	--	L	I
8	Low sound intensity of operating system at audience ear level	Less than 50 dB	max	M	T
9	High Hazard risk index	18 hazard index	min	H	S, I
10	Interferes with lighting for different aspects of stage	No	--	L	T, I
11	Lit using available resources at Pavilion	Yes	--	L	T, I
12	Must function during rehearsal and performances between May 29th and June 5th	200 operational hours	min	M	A, T, I
13	Assembly Time	24 assembly hours	max	M	I
14	Interferes with actions of performers and other effects	No	--	M	T, I
15	Stays Within budget	$1500	±$250	M	A
16	Inputs controlling movement	2 inputs	min	L	A, T, I
17	Multiple Modes Available	2 modes	min	L	A, T, I
18	Flame-retardant fabric	CA Fire Code 13115, 13119-13128		L	I

Project Management

Project management responsibilities were assigned at the outset of the project to ensure project success. Ian was responsible for all scheduling concerns as well as the documentation of project progress. Scheduling tasks included setting deadlines, monitoring design and build flow, and providing recovery plans when necessary. In order to keep track of project progress, Ian created and maintained a Gantt chart (included in the appendix and separated by quarter) as well as an organized repository for all documented ideas, problems, solutions, and decisions on Google Drive. Kevin was responsible for monetary and testing needs. Budgeting and material acquisition were the main money-related tasks. Kevin was in charge of testing methodology and conduction. Ryan was responsible for information gathering, document review and finalization, and installation. Information gathering included researching and contacting outside resources. Document review and finalization ensured that all information that our team presented to outside sources was complete, correct, and cohesive. As the installation coordinator Ryan worked with technicians to organize a safe and swift installation.

Chapter 2 - Background

The RSVP show is a multimedia production created by students in the MU 412 class, Dr. Barata, and any other students that wish to perform. According to Dr. Barata, the show is based on the concepts of “electro-acoustic diversity and compositional risk.” “Electro-acoustic diversity” simply means that the show will focus equally on creating the music within music production software and creating the visual aspect through sets and performers. “Compositional risk” means that RSVP contains aspects that have never been tried before in theater. Things that are new technologies, unique ways of presenting theater, and interesting changes to current ideas are all considered. This show is the 19th installment in the RSVP series and celebrates the sheer size, power, and majesty of whales. It is a tribute to their lives, their struggles, and especially their songs.

The main objective of the project is to augment the experience of the audience as they enjoy the performance. The audience was made up mostly of professors, students, parents of performers (and of Team FOTO), as well as members from the San Luis Obispo community at large. Most of these people are casual theater-goers, with no extensive experience in theater arts or technologies.

RSVP takes place within the Pavilion Theater inside the Cal Poly Performing Arts Center bottom floor. It is a multipurpose space (see Figure 2,Figure 3 , and Figure 4) with a basically rectangular floor plan, high ceilings, and extensive railings for lighting, sound, and for hanging things. There are large loading doors along one wall, and two different locations for control booths as shown in Figure 2 and Figure 3.

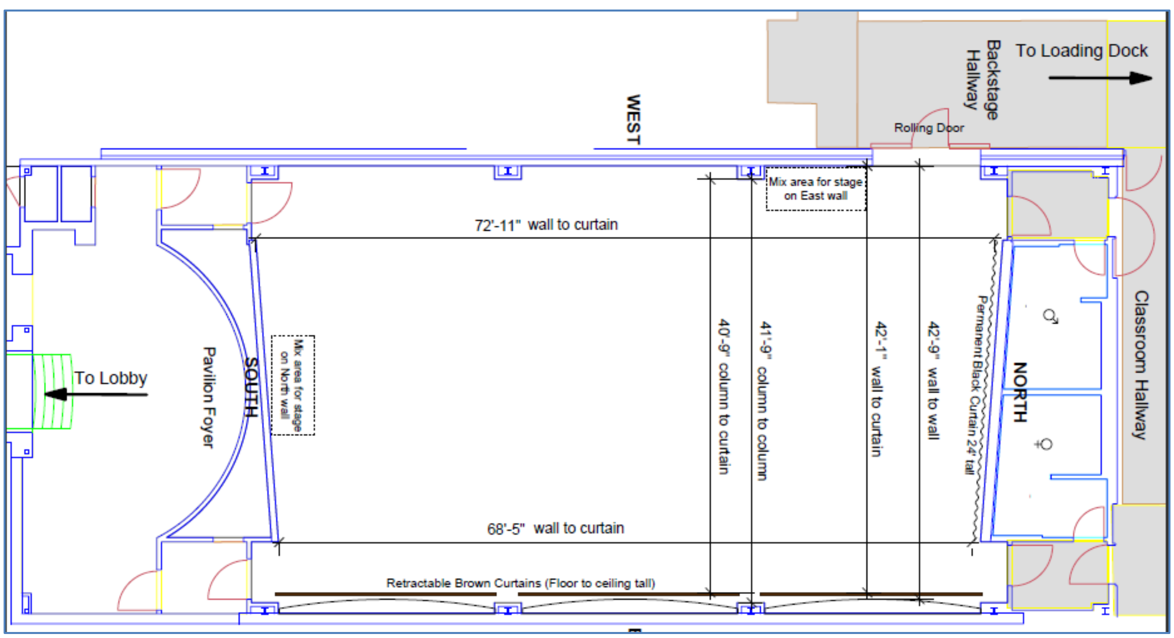


Figure 2 - Dimensions of the Pavilion

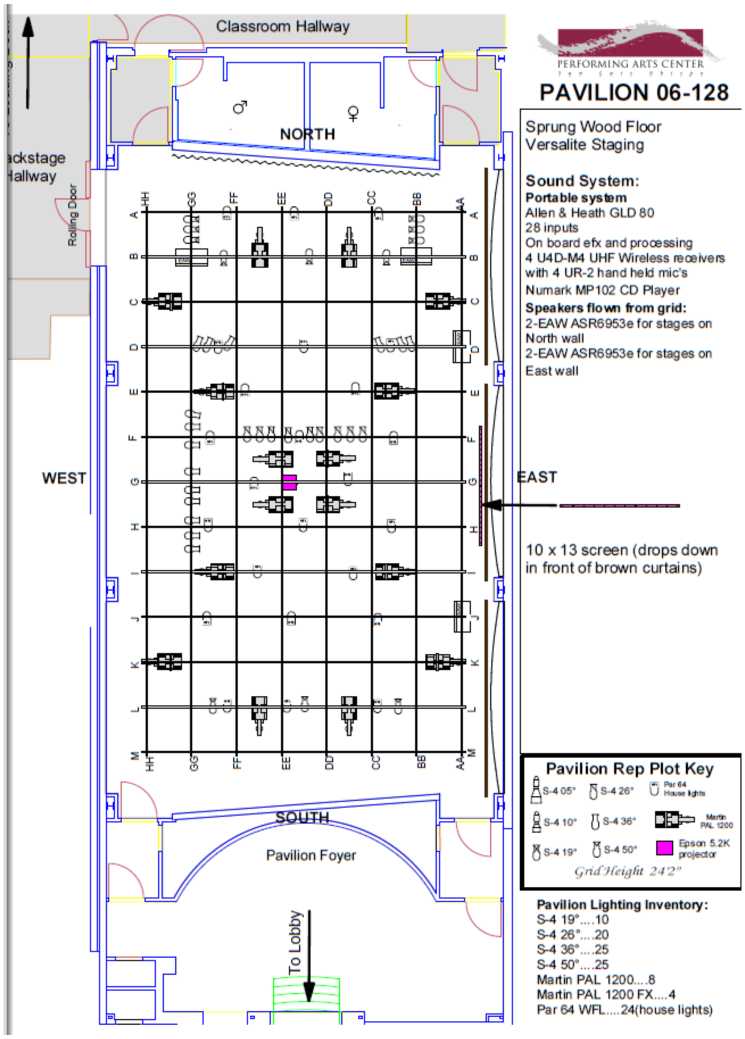


Figure 3 - Lighting and Sound Layout of the Pavilion

Figure 4 - A View of the Pavilion (looking from South to North)

Figure 4 shows the backdrop for the RSVP performance. The stage was set up approximately 10 feet from the back wall. The back wall was covered in a large projection screen. The stage consisted of a rectangle measuring 12 by 24 feet, and was made up of various heights.

Although lighting and moving fabric are certainly not new technologies in the theater realm, only a very small number of these technologies have been patented. Some patents have been documented (and are referenced in the Appendix). One such patent is a design for a screen used to provide a rolling background (Figure 5). It is essentially a curtain hanging from a chain that runs around sprockets and is used to provide a background that constantly changes. A second potentially helpful technology is a stage curtain drawing system with rolling carriages and an endless drawing string between two rollers (Figure 6). This allows for a smooth draw and a more organic feel.

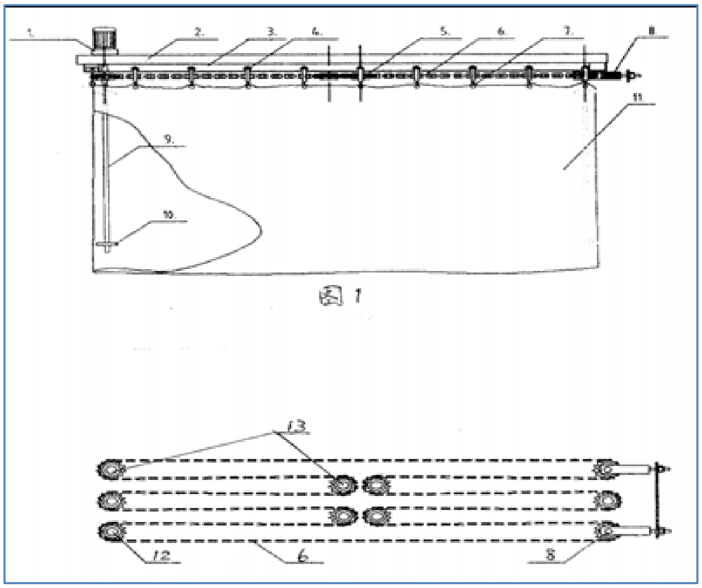


Figure 5 - Rolling Curtain Design

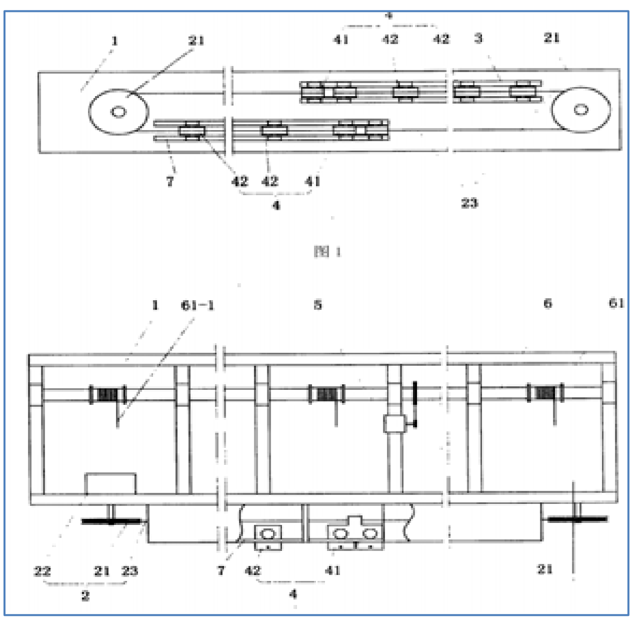


Figure 6 - Carriage Design

Another simple yet elegant way to achieve semi-random fabric motion is to blow air at it (Figure 7). This allows for a much larger number of degrees of freedom than with a simple fabric-pulling method because air moves in many directions all at the same time as opposed to one or two directions at a time. It creates random variations within a quasi-periodic motion, providing an organic feel.

Figure 7 - Fabric being blown by air to mimic water

Through background research into fabric materials, two types of fabric could provide interesting effects. "Scrim" is a type of fabric that is woven so that, when lit from the front, it becomes opaque, but when lit from the back becomes transparent (Figure 8). It is useful for making performers and objects appear and disappear very quickly. The second type of fabric is silk, which provides an extraordinarily organic feel under theater lighting. These two fabrics were good starting points that came in handy when we were coming up with our designs.

Figure 8 - Scrim under various lightings

A further requirement is that any and all fabric used must be fire-retardant per California State Fire Code requirements (CA Fire Code 13115, 13119-13128). Fabric can be made safe in two different ways. It can be made of fibers that are resistant to fire, such as Kevlar and Nomex. This is called "inherently fire retardant" fabric. It can also be treated with chemicals after it has been woven, which is known as simply "fire retardant" fabric. Fabric can be bought pre-treated, so it is already fire-retardant and ready to go. The one downside of treated fabric is that the treatment is usually water-soluble so the fabric cannot be cleaned. Also, dust is extremely flammable, so even if the fabric resists fire, if it is dusty, it will still burn readily.

A common theater fabric and set-up provider that is the best source for the materials for this production is the Rose Brand Company. One of our top ideas involved a stretchy fabric tube that could be lit from one end. These can actually be purchased from the Rose Brand Company, along with many other shapes, layouts, and all the supporting fabric and metal tubing required to make anything else we needed. Their website also details some safety tips, fabric maintenance, and other useful knowledge. Everything that the Rose Brand Company sells is marked if it is Fire Retardant, Inherently Fire Retardant, or otherwise.

Figure 9 - A Sample of Rose Brand's inventory

Our system hung from a “stage grid,” which is a system that is used to hang lighting, pulleys, speakers, and anything else that needs to be hung from the ceiling. This system makes it so that our design did not take nearly as long to set up since we used the grid to raise and lower objects.

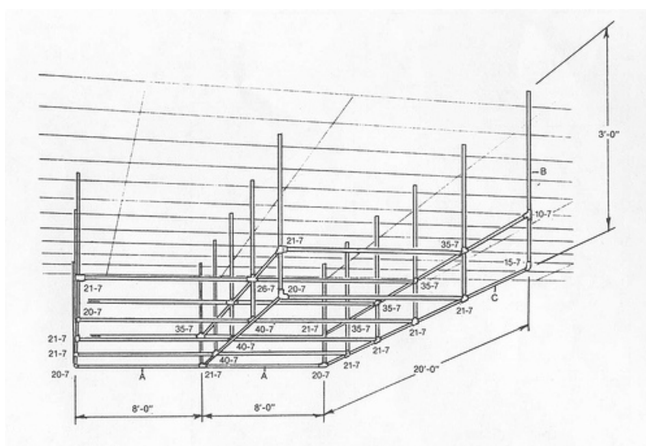


Figure 10 - 3D Layout of a sample grid (not in the Pavilion)

Chapter 3 – Design Development

Idea Generation

In order to select the best overall concept, we followed the method of controlled convergence, a method that involved expanding our idea base, contracting it, expanding some, contracting more, and repeating this process until we got to the best idea. We started by coming up with as many ideas as possible, throwing nothing out, and starting with a baseline of ideas. This stage included creating a morphological matrix and a model-building brainstorming session. Creating a morphological matrix involves identifying the primary functions and attributes required in the system and isolating them, brainstorming every possible way to achieve such a function or attribute. A sample of our morphological matrix is shown below in Table 2.

Table 2 - Morphological Matrix Sample

Function/Attribute	Ideas
Interact with Light	Create shadow, bend it, reflect it, silhouette, create it, diffuse it, focus it…
Change Speed	Brakes, push force, gears, increase resistance, impact, add weight, drop…
Create Awe	Confuse, illusion, use fire, be much bigger, surprise, unique sense input…
Move Fabric	Pull it, punch it, blow it, pull it, twist it, drag it, heat convection, sound…
Support the Show	Create a part of scenery/character, provide light, add to stage, backdrop…
Change Position	Motor drive, wave action, translate, roll up, pulley, springs…
Be Unobtrusive	Non-solid, slits in stage, quiet, below foot level, translucent, retractable…
Respond to Input	Direct touch, computer control, pulleys and motors, lever input…

Our model building session also yielded some fruitful results and allowed us to check the feasibility of some of our ideas. Using materials such as wire, string, and foam board, we created a number of ideas. The following figures show a few of our ideas. The offset cam idea actually factored into our final design (Figure 11). Ian experimented with an overhead design (Figure 12). Swaying fabric (Figure 13) also was incorporated into the final product.

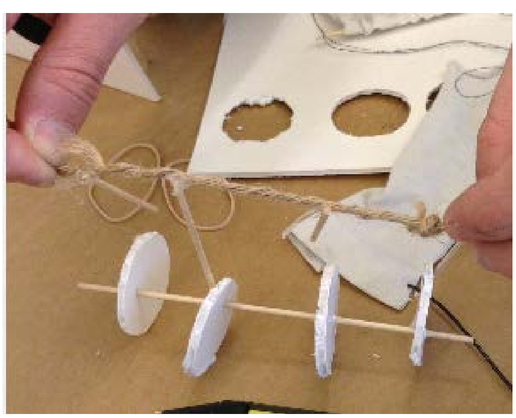


Figure 11 - A model simulating offset cams with followers

Figure 12 - A model simulating an overhanging effect with multiple points of motion

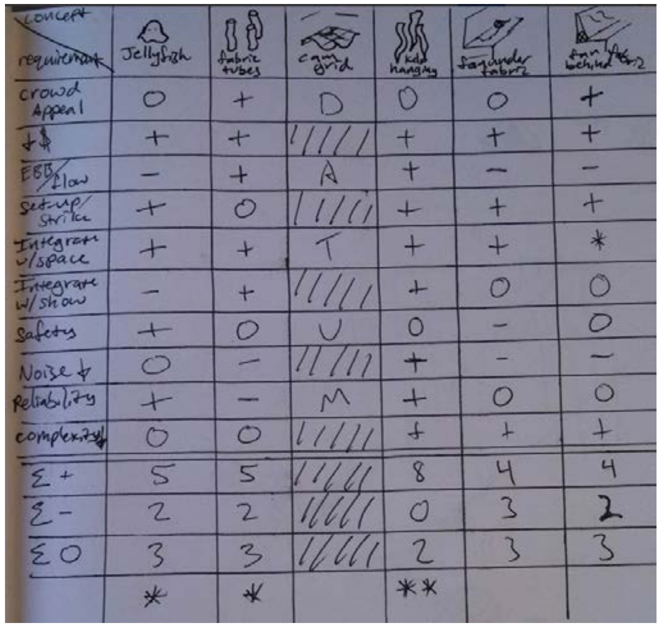
Figure 13 - Weighted fabric to simulate a swaying motion

Selection Process

Once we had a large selection of ideas, we could immediately throw out most of the ideas based on whether or not they met the requirements or not. After generating a large number of ideas, we used several Pugh matrices to narrow down our choices. We first examined, in general terms, the effects of the input method, the audience perception, and the location or orientation of the device. These three Pugh matrices resulted in the following key attributes:

- A mechanical system that is easily and quietly controlled, most likely driven by a cam system
- A surface that lends itself to being lit in an interesting way
- A device that can be positioned on or above the stage

We eliminated ideas that could not be accomplished within these criteria and focused on the remaining six ideas. Next we compared these based on previously developed customer requirements using a final Pugh matrix (Figure 14). This analysis showed us that we had three clear top ideas, an array of moving jellyfish, a series of fabric tubes, and a forest of kelp, with one shining above the rest.



concept / requirement	Jellyfish	fabric tubes	cam grid	kelp hanging	fan under fabric	fan behind fabric
crowd Appeal	O	+	D	O	O	+
-$	+	+	/////	+	+	+
EBB/flow	−	+	A	+	−	−
Set-up/Strike	+	O	////	+	+	+
Integrate w/space	+	+	T	+	+	*
Integrate w/show	−	+	/////	+	O	O
Safety	+	O	U	O	−	O
Noise +	O	−	////	+	−	−
Reliability	+	−	M	+	O	O
complexity	O	O	/////	+	+	+
Σ +	5	5	////	8	4	4
Σ −	2	2	////	0	3	2
Σ O	3	3	/////	2	3	3
	*	*		**		

Figure 14 - Final Pugh Matrix

Our design process led to the conclusion that a hanging kelp forest would be quieter, more reliable, more integrated with the show feel, and more feasible, and Dr. Barata agreed with this decision. We also reviewed our engineering requirements and confirmed that all goals are achievable with this idea.

Top Concepts

In developing our final design, three top concepts were created and compared. The three concepts were the swaying kelp design, the ploofing jellyfish design, and the billowing fabric tubes design. From these we selected the swaying kelp design as the best one. Below, the other two concepts are discussed as well as the process taken to arrive at the final design.

The Ploofing Jellyfish concept (Figure 15) is based around a dome-like frame covered with fabric. This frame would be lifted up and down and light from underneath/within to provide the image of a glowing gelatinous blob floating through the ocean. This idea was not selected as the top concept primarily because it is fairly simple. Dr. Barata felt that this concept could be built satisfactorily by music/theater students in the MU 412 class, and that our level of skill was not required.

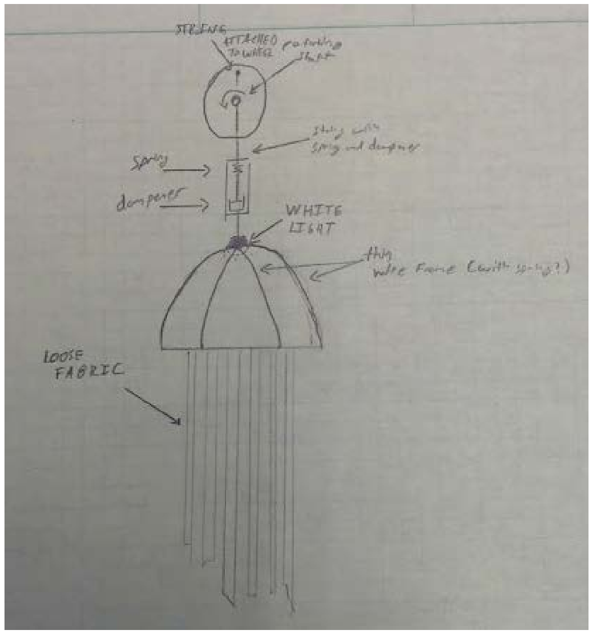


Figure 15 - Ploofing Jellyfish concept

The Billowing Cylinder Tubes (Figure 16) are a similar idea to the Hanging Kelp, except that, instead of groups of strips of fabric, the hanging units are cylinders attached at the ceiling and stage. These tubes could be lit longitudinally, and they would be coupled with an air delivery system that would send puffs of air down the tubes, causing them to billow, flow, and distort. This would have provided the feel of flowing water, waves, and an overall fluid motion. This idea was not selected for a number of reasons. The inclusion of flowing air would have required a compressor and would have been loud and complicated to set up within the Pavilion. The cylinder tubes could actually be bought from the RoseBrand Company, but they are fairly expensive, with the least expensive ones costing approximately $300 each. This would clearly not allow us to stay within our budget.

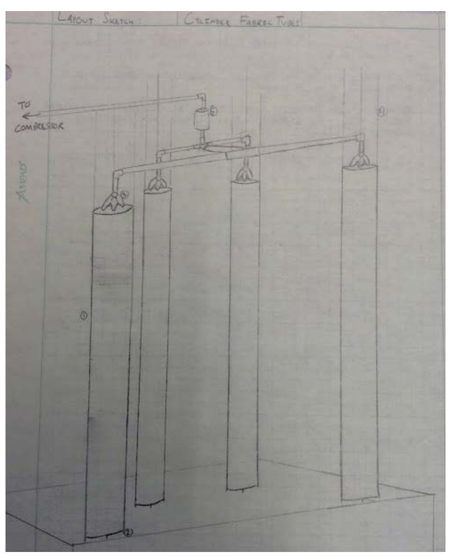


Figure 16 - Billowing Cylinder Tubes concept

Chapter 4 – The Final Design

Layout

Our simulated kelp forest is run by two separate but connected systems. There is the driving system and the hanging system. The driving system uses a set of cams to pull and release light-weight rope which connects to the hanging system. The cams are manipulated using a driving wheel which rotates the shaft to which the cams are connected. Tension in the light-weight ropes along with stops in the hanging assembly keeps the driving wheel from being turned too far. Assembly and part drawings of everything mentioned in this section can be found in the Appendix. Figure 17 shows the driving assembly.

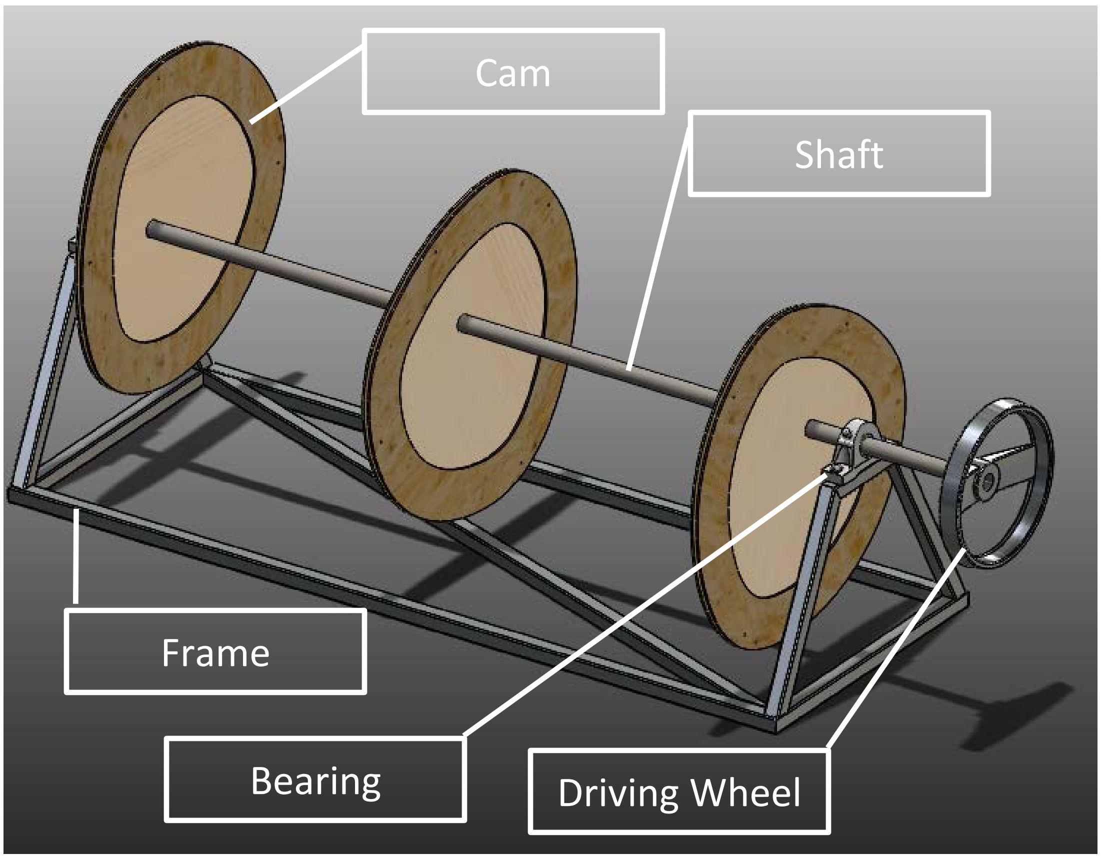


Figure 17 - Driving system 3D solid model

The hanging system consists of 3 rows 17' steel pipes, two 8' PVC pipes per row, nylon shuttles, pulleys, rope and chiffon fabric. The PVC pipe is attached to the steel pipe using plastic zip-ties. The nylon shuttles will be inside the PVC pipe and will have an eyelet attached to the bottom and two attached to the sides. The eyelet on the bottom will have the kelp-like fabric attached to it via a hole in the fabric slipped into the ring. The shuttles are all connected to one another with either bungee cord material or static line which attaches to the eyelets on the shuttles' sides. The shuttles will move back and forth within the PVC pipe to generate the desired flow effect. The number of shuttles is variable depending on the customer's wishes. For the current show, we created 50 shuttles and kelp strands and can add or remove shuttles easily. Figure 18 below shows a picture of the hanging assembly.

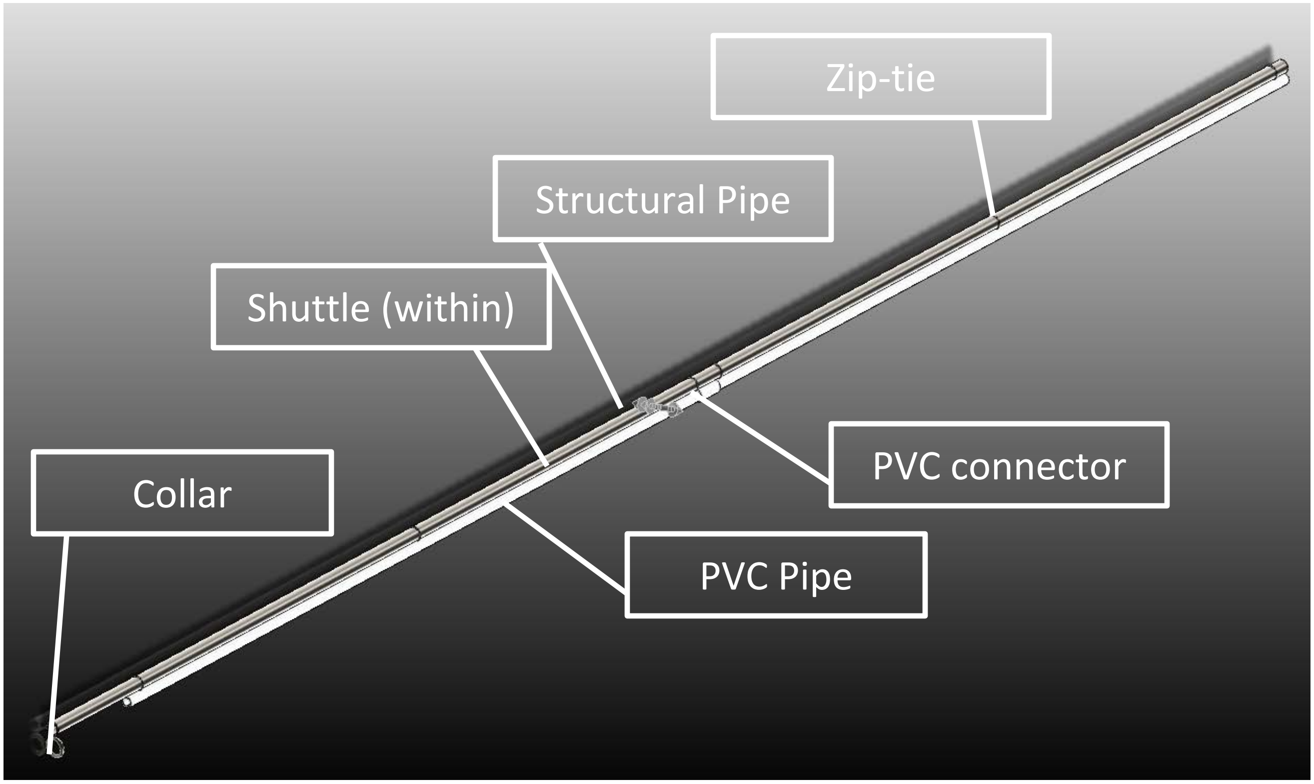


Figure 18 - The hanging assembly 3D solid model

The hanging system will be held up using rope, pulleys and cleats. The cleats are attached to weights provided by the PAC. The rope runs through the pulleys to the cleats. The pulleys will be attached to the grid using connectors and mountain gear carabineers, also provided by the PAC. On the far end, away from the driving system, the rope will be attached to the grid directly instead of to a pulley or cleat.

Design Justifications

Driving System

The driving system is composed of five distinct parts: the frame, a shaft, two bearings, three cams, and a driving wheel.

Frame

In order to create the frame for the driving system, 80/20 1”x1” T-slotted 1010 aluminum from 80/20 Industrial Erector is used. It is constructed to match the geometry shown above in Figure 17.

Shaft

The shaft is a 5’-long, 1”-diameter cylinder made out of 1018 carbon steel. It has two bearings and three cams along the length with a distance of 2’ between the cams to accommodate the distance between the rows of kelp. The shaft is held in the frame which sits the ground. The shaft’s input is a driving wheel which is a 1:1 ratio. The wheel directly turns the shaft which, in turn, moves the cams.

Bearings

The bearings selected are mounted pillow block cast iron ball bearings. They are located along the shaft at either end of the frame and bolted on. The bearings are rated at a dynamic load capacity of 825 lbs. The open steel ball bearings are easy to lubricate as needed to ensure a quiet performance. Since the speed of the shaft is less than 100 RPM, the maximum speed of 1200 RPM is more than sufficient for our purposes.

Cams

Cam profiles are designed to allow a variation of motion throughout the rotation of the shaft. The cams are made out of two outer layers of 1/4" thick plywood that extends past a center layer of 1/2"-thick plywood to provide a channel for the rope to wrap into. Holes for bolts are placed at multiple locations around the rim to allow for different cam functionality options.

Driving Wheel

The driving wheel is a 10" stock hand wheel with a hole for the shaft and a tapped hole for a #8x32 set screw to fix it in place.

Hanging System

The hanging system is the most complicated part of our system and is comprised of 3 almost identical rows with the same eight distinct parts: structural pipe, PVC track pipes, a PVC pipe connector, shuttles, eyelets, a collar to silently redirect tie-line, elastic rope, non-elastic rope, and kelp.

Structural Pipes

We use 3 Schedule 40 steel pipes with a 1.5" diameter that are 17' long. Each row has one of these steel pipes. The steel pipes serve as the main structural support of the hanging system, and greatly limit the amount of deflection due to bending because of steel's high modulus of elasticity.

PVC track pipes

The 1" PVC track pipes are 8' long, so that when they are attached to the bottom of the structural steel pipe there is enough room on the side closest to the driving mechanism to also attach a steel collar underneath the end of the structural pipe. The PVC has an inner diameter of 1.033 inches and was chosen to accept the slightly smaller shuttle. PVC was chosen because of its low cost, light weight, and its smooth surface. Because of this smooth surface, the shuttles slide easily and silently through the interior of the track pipe. We cut a channel down the entire length of the PVC pipe with a mill. Each structural pipe and track pipe is attached to each other with 6 8"-long zip-ties.

Shuttles

We have chosen to use ⅞"-diameter self-lubricating MDS filled Nylon. The material comes in 5'-long segments, so we cut the material down to 6" segments and drill holes for the eyelets to screw into. The shuttles slide easily in the PVC track pipes, and if extra clearance is needed, the shuttles can be machined down to a more effective diameter.

Eyebolts

A light-duty wood screw eyebolt was selected. The wire of the eyebolt is 3/16" thick, with a 3/4"-long screw. The eye diameter is 7/16" wide, which allows for enough space for rope to be pulled through. There is one eyebolt on the bottom of each shuttle and two eyebolts on the sides. The eyebolts on the side each have rope running through them. The eyebolt on the bottom of the shuttle is connected to a strand of fabric. The bottom eyebolts move through the slit on the bottom of the PCV pipe.

Rope

The shuttles connect together by a length of the elastic rope or tie line tied through each of their eyebolts. The last length of rope in each string of shuttles is tied off to a cap that will fit over the end of the PVC pipe. We chose a bungee nylon-coated rubber rope available on Amazon.com. It is low-cost, and can stretch to 100% of its original length.

Also, tie line with a diameter of ⅛” runs through the collar from the driving system and connects to the first shuttle in each row of kelp via the eyelet on the end. This tie line is more than adequate for the very limited forces that act on the rope.

Heavy-Duty Pulleys

The hanging system is held up by rope running through the heavy-duty pulleys. There are 9 heavy-duty pulleys holding up the system: 3 for each section of kelp. These pulleys are also manufacturer load-rated mountain gear from EMS. They were chosen because they have lubricated bearings -- which means they are quiet -- and because they have a high safety factor when it comes to working load. They have a working load of 2.5KN and a breaking load of 22KN. Since each pulley only takes about 30lb of force each, there is a high safety factor on each pulley.

Kelp

The fabric chosen is Earth-colored Party Knit Fabric from RoseBrand because the color scheme is oceanic, can be painted, doesn’t fray when cut or poked, and is lightweight (0.4lb per linear yard). The fabric will satisfy the aesthetic portion of our customer requirements, as the fabric will be manipulated to appear as swaying kelp. The fabric will be cut into 22’-long segments from a 50 yard roll of 58”-wide fabric. The kelps will each be 6” wide, with a tolerance of ± 2” to add a high variation in the geometry of the kelp. We want the high variation to make the kelp forest appear more organic and random. The kelp sides should be curved and nonlinear. Furthermore, one of the design requirements is that the fabric needs to be fire retardant. Because we are getting the fabric from Rosebrand, it is guaranteed certified as a fire retardant material.

On the next page, Table 3 shows how this design meets (and frequently exceeds) all requirements.

Table 3 - Customer requirements and how this design meets them

Customer Requirement	Solution
- Must fit through Pavilion door - Must operate within the space of the room	This solution is large, but most of the size is collapsible fabric, which can be sized to the requirements of the stage.
Weight must be adequately supported by ceiling rigging if hung	The weight hanging from the ceiling is almost all made up of the weight of pulleys, rope, and fabric. The available grid is being used to hold up stage lights and speakers, so this extra weight should be fairly negligible.
Must be an organic motion	The elastic separation, the periodic and smooth motion of the cams, and the continuously responsive input allows for an extremely organic motion.
Must have low sound intensity of operating system at audience ear level	This design involves no compressed air or motors. The wooshing sound of the shuttles is minimal.
Must be safe	There are no pinch points, sharp or dangerous mechanisms, or high-speed or high-acceleration motions. The biggest hazards are the slowly rotating shaft and the dangling fabric as a tripping hazard. No one is allowed underneath the hanging pipes.
Must not interfere with lighting for different aspects of stage	The groups of strips are basically free to be placed anywhere, so they can be placed out of the way of the lighting. Also, they are fairly narrow and will not impede the audience's line of sight.
Must function during rehearsal and performances between May 29th and June 5th	This design is actually the simplest of all of our designs. The reliability is extremely high since there are fewer parts, and the design has no problem functioning when it is needed.
Must be assembled within the allotted time	Again, the simplicity of this design allows for an off-site assembly which allows ample time for integration with the Pavilion.
Must not interfere with the actions of the performers	Similar to the reason that our concept does not interfere with the lighting, it also shouldn't interfere with the performers. In fact, the performers will not be allowed to be in the same area as the kelp.
Must stay within budget	See cost analysis below. We should be able to complete this project within a worst-case budget of $1500 (provided by CP Connect).
- Must have inputs controlling movement - Must have multiple modes available	The system is continuously controllable due to its human-controlled rotating camshaft.
Must use flame-retardant fabric	All fabric is purchased from the Rose Brand company, which specifically states which of their products are fire retardant.

Cost Analysis

For our project, we had a budget of $1500 provided by CP Connect. Of that $1500, we acquired materials amounting to $1076.80, staying within budget. We were able to stay within budget because we used much of the equipment available to use at the Pavilion. A big expense that we were able to avoid was the use of 3 steel 17' pipes which were in the backstage area of the Pavilion. Furthermore, we were able to utilize several of the pulleys available at the pavilion in addition to the rope. Since over 400' of rope was expected to be used, we had estimated that the rope was going to cost about $360. Since we did not have to purchase any rope, we had a lessened financial burden. The main cost was the Party Knit Fabric of $332.92 and the pulleys of $223.60. These two portions made up half of the total cost of materials purchased, which is what we expected in our initial estimations. See Table 4 for additional information on purchases and sources.

Table 4 - Cost Analysis Breakdown

	Items Purchased		
No.	Item	Cost	Vendor
1	20' pvc pipe, screw eyes, mini pack of bungees	15.49	homedepot
2	Cam plywood and connectors	54.71	homedepot
3	Pillow Block and bungie nylon	25.71	amazon
4	2' of MDS-Filled Nylon and shipping	13.93	Mcmaster
5	Party Knit Fabric	332.92	RoseBrand
6	1018 Carbon Steel Shaft and mds nylon	118.11	Mcmaster
7	cable ties	16.41	cabletiesandmore
8	Pulleys	223.60	ems
9	Pillow bearing and 80/20	91.43	Amazon
10	PVC Pipe and connections	17.05	Amazon
11	80/20 Connections	91.43	Amazon
12	PVC Pipe and connectors	17.05	homedepot
13	Screw eye and hex bolt	11.77	homedepot
14	Screw Eyes	5.63	homedepot
15	Bungie Nylon	14.00	amazon
16	Fabric Cutter	27.53	amazon
	Total Cost	1076.8	
	Final Account Balance	423.23	

Preliminary Analysis and Proof of Concept

There were four main areas that had to be analyzed to make sure the design would be safe to be around and operate: the tension in the raising rope, the diameter of the rotating shaft, the deflection of the overhead beam, and the natural frequency of the hanging system. Once these areas of concern were met, the rest of the design could be finished within those parameters. More in-depth calculations can be found in the Appendix.

First, we wanted to make sure that the tension in the raising rope was manageable for one person so that it could be operated safely and smoothly. A brief statics analysis was enough to prove that the weight was manageable even on the most complicated of the hanging assemblies. A basic sum of all forces in the vertical direction was all that was required:

$$T_{rope} = \frac{(q_{beam} + q_{pvc})l + W_{kelp}n_{kelp} + W_{bracket}n_{bracket} + W_{pulley}n_{pulley} + T_{sway}}{2}$$

Where:

T_{Rope} is the tension of the raising rope,
q_{beam} and q_{pvc} are the weight per unit length of the beam and PVC pipe, respectively,
l is the length of the beam,
W is the weight of a particular component,
n is the number of that component present, and
T_{sway} is the tension in the rope that is used to sway the kelp.

Total tension in the two ropes will be approximately 50 lbs, which is well within the comfortable lifting weight for our team, and is a conservative estimate.

Next, we needed to make sure the rotating shaft would not break under bending or torsion. Essentially, the DE Goodman criteria, which are very conservative criteria, were used to size a shaft according to the following equation. A safety factor of 5 was used.

$$d = \left(\frac{16n}{\pi}\left\{\frac{1}{S_e}\left[4\left(K_f M_a\right)^2 + 3\left(K_{fs} T_a\right)^2\right]^{\frac{1}{2}} + \frac{1}{S_{ut}}\left[4\left(K_f M_m\right)^2 + 3\left(K_{fs} T_m\right)^2\right]^{\frac{1}{2}}\right\}\right)^{\frac{1}{3}}$$

The specifics of this equation are not important, but the equation will yield the minimum shaft diameter under the specified loading at the desired safety factor. Our equation yielded .74 inches. Thus, we decided on a 1"-diameter shaft to be extra safe (especially about unplanned-for impacts). Although, due to the fact that the mechanism was only to be used for a limited number of cycles (only used for two weeks total), the loads are so small on this shaft that it was much less likely to break under a single failure. The extra factor of enlarging the diameter to 1" ensured that this shaft is much stronger than it ever needs to be.

The overhead hanging beam is a long thin (relatively) beam, and therefore deflection under the weight it carries is a concern. Using superposition, we were able to calculate the total deflection at the center of the beam. The following equations were the fundamental equations:

$$For\ pin - pin\ supports\ under\ a\ distributed\ load:$$

$$\delta = \frac{5qL^3}{384EI}$$

Where:

δ is the deflection in the center of the beam,
q is the distributed load in lbs/ft,

L is the length of the beam,
E is the stiffness of the material, and
I is a measure of the cross-section of the material.

Under the most severe loading conditions, the pipe would only deflect 1.5", which is less than .5 degrees at the ends. These are both acceptable deflections and shouldn't cause the PVC pipe to pinch the shuttles or inhibit motion.

Lastly, the rope causing the kelp to sway provides a periodic input. If the frequency of this input is near the natural frequency of the hanging system (which is essentially a huge bulky pendulum), the hanging system will be driven to instability. The natural frequency of a pendulum can be given by the equation:

$$f_{nat} = \frac{1}{2\pi}\sqrt{\frac{g}{l}}$$

Where:

f_{nat} is the natural frequency of the system,
g is the acceleration due to gravity, and
l is the vertical length of the ropes holding up the system.

In the worst case, the natural frequency is about 1 cycle per second. While this is a fairly fast speed for this system, it is within the feasible range. As operators, we are able to stay away from this frequency if we notice it swaying to instability.

Special Safety Concerns

From the outset of this project we have held safety as a high priority. The areas of safety that we have focused on include the overhanging loads of the structural pipes, pinch points on the shaft, and fire safety. We use pulleys rated to 12 times the working load needed to raise and lower the pipes as well as counterweights to keep the pipe from crashing to the earth. By reducing the tension on the rope attached to the cams to 10 lbs, the risk of a painful pinch has been mitigated. By sourcing our fabric through RoseBrand, a reputable theater fabric supplier, we are confident that we have adhered to the fire code and eliminate the possibility of a fire disaster. Since the elastic will be under tension and have some amount of stored energy, we have placed stops on the outer limits of the PVC pipes so that, were a failure to occur, the shuttles would not come rocketing out and hurt someone.

Maintenance and Repair

This device is only required for this year's RSVP show. Our team was able to perform any maintenance or repairs it needed. If, for some reason, Dr. Barata chooses to make future use of the driving mechanism, the bearings may need lubricated or replaced. Since those are the only moving parts and the device is used in an inside, regulated environment, other maintenance is not expected.

Chapter 5 – Product Realization

Machining

Luckily, for this project, most of the parts were ordered and used stock, so there was not an unreasonable amount of machining to be done. The parts that are custom-made are the frame, shaft, driving wheel, cams, shuttles, PVC pipe and connectors, and kelp.

Frame

The frame was built from 80/20 aluminum 1" stock. The stock was cut to length and angle with a miter saw and touched up on a circular sander. The base rectangle and structural diagonal was assembled and attached with flat triangular plates that had holes drilled to provide a right-angle connection. For the diagonal, two of the triangular connectors had to have an extra hole drilled in them. The upright sections of the frame used flat rectangular two-hole plates on the outside to attach together. The angles these pieces were cut to (see Figure 19) eased assembly and distribute load in a favorable manner. Two extra nuts were placed within the top of the upright sections for the bearings to attach to.

Figure 19 - Cutting an angled piece of frame

Shaft

The shaft was mostly completed when it came out of the box. However, it needed three flat spots with drilled and tapped holes so that the cams could be attached with brackets (Figure 20). The flat spots were milled off using a manual mill in the Hanger. The particular mill that was open was stuck in low speed, which left a rough surface finish. This detail is unimportant due to the fact that the brackets were installed on top of the milled surface. The holes for the screws were drilled using a drill press and tapped by hand. The prototype had to be varied slightly from the design, because the tap broke off in the last hole. This mistake led to one of the cams being moved over to a new location where fresh holes were drilled and tapped successfully.

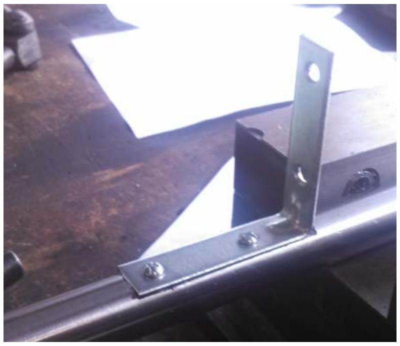


Figure 20 - The bracket for the cam attached to the newly flatted, drilled, and tapped shaft

Driving Wheel

The hole in the center of the driving wheel was drilled out to 1 inch diameter to fit on our shaft. A hole for a set screw was also drilled and tapped in the side of the hub.

Cams

The cams were created from three pieces. The first piece was the smaller, but thicker inner piece, and the other two were larger but thinner to serve as guides and sandwich the smaller piece. The profile of the cam pieces were hand-drawn on plywood and cut roughly to shape with a vertical band saw. They were then sanded down to a more precise shape using a belt sander. After the first small and large pieces were created, they were used as stencils for the rest of the pieces to ensure that, although they were very irregularly-shaped pieces, they would all be the same. Finally a 1"-diameter hole was drilled for the shaft (Figure 21). All three pieces were screwed together with framing screws. For any future large wooden cam manufacturing, we recommend printing and using a full-size stencil rather than hand-drawing everything. It would lead to smoother curves, easier cutting, and cut down on measurement time.

Figure 21 - Cam attached by bracket to the shaft

Shuttles

The shuttles were created using MDS-filled Nylon. For the final design, the shuttle length was changed to be 2"-long segments with only one eyelet along the surface of the cylinder so only one kelp is attached to a shuttle. The shuttles are connected in a line with alternating pieces of tie line and bungee nylon. This created a non-uniform movement of the shuttles along the length of the PVC track pipe.

The shuttles were manufactured by cutting out the same size shuttles using a vertical band saw. A stop was utilized to keep the pieces a consistent size while pushing the 5' length through. After the pieces were cut to size, the ends of the shuttles were sanded down to create a smoother edge. Then, the shuttles had holes drilled into the center of both of the flat ends of the cylinder with a depth of ¾". One hole was drilled into the shuttle on the round side in the center of the shuttle which had a depth of ½" (Figure 22).It was important to make sure the holes were within tolerance so that when we inserted the eyelets, there wouldn't be any interference from the threaded portion of the screws. All of the holes were drilled with a 9/64" drill bit. Three eyebolts were then screwed into the holes.

Figure 22 - Drilling a side-hole into a shuttle

The lines were made by cutting out varying sized lengths of bungee nylon. Most of the pieces varied in size from 10" to 20" long. The length was determined primarily at the main set-up, as the number of kelps in a kelp line was an artistic choice and not crucial to the mechanical operation of the device. The completed shuttles are shown below in Figure 23.

Figure 23 - A number of completed shuttles

PVC Pipe and Connectors

The PVC track pipes were slotted using a manual mill (Figure 24). The mill table was not long enough to accommodate the pipe, and, while cutting, the excessive length would create vibrations in the part if the chuck was more than 8 inches away from the vise. Due to both of these limitations, the pipe had to be tediously and repetitively fixed, slotted 8 inches, unclamped, moved, and re-fixed. This process led to several jagged or uneven spots in the slot. These uneven sections needed to be smoothed out later using a file. For future manufacturing of similar systems we recommend spending extra time aligning the slot to save time fixing errors later. Next the PVC had holes drilled on the opposite side of the pipe from the slot to accommodate the zip ties that held it to the structural pipe. Six holes were drilled per pipe --two for each of the three zip ties. We used a hand-held drill due to the unavailability of a drill press at the time of manufacturing. This worked well enough, but to ease alignment and mounting issues later down the line, we recommend using a drill press to ensure the zip ties are aligned properly. Finally, the pipes were glued together using a connector and rubber cement, and spray painted matte black to disguise it during the show.

Figure 24 - Milling the PVC pipe

Kelp

The fabric used for the kelp was purchased in an enormous brown roll approximately 60” wide. The fabric was rolled out and painted, section by section, with water-based acrylic green paint mixed with water. The idea was to add visual texture to the fabric so it could be seen to be moving, but not to color it too much or to make the fabric stiff with paint. The goal was a mottled green-brown color. Various techniques for painting were tried, but the speediest and most effective was soaking a sponge in paint and slowly squeeze-dripping paint onto the fabric (Figure 25). The job required approximately quadruple the estimated amount of paint, even with the severe 1:1 paint-to-water ratio. After the paint had dried, the kelp was measured for length (22’) and cut horizontally. Using a 6’ cutting board provided by the Cal Poly costume shop, and a rotary razor blade (which could cut through up to eight layers of fabric), the fabric was folded up into fourths to fit on the cutting board and strips were cut vertically. The razor blade cut the fabric quickly and easily. Ten strips of varying widths averaging 6” in width could be cut from each length. It was important to remember to keep the cut perpendicular to the edge when entering or leaving the fabric, because, since we had it folded, any angle would produce a kink in the kelp strand. It was also very important to smooth out all the wrinkles before cutting. Finally, only one razor blade was purchased and by the end of the work it was starting to dull. We recommend buying replacement blades to be safe and to keep cuts clean and sharp.

Figure 25 - Getting help from the MU 412 class for painting the fabric

Assembly

For the driving mechanism, it was very important to assemble the pieces in the correct order so as to not have to take everything apart and do it again. First, the middle bracket and middle cam of the shaft had to be attached. Then the outer two brackets and cams could be attached. The bearings then slid onto the end of the shaft, and were bolted to the frame. Once the bearings were attached to the frame, the built-in set screws could be screwed in to fix the shaft in position. Finally, the driving wheel could be slid on and attached via set screw.

For the hanging mechanism it was less strict of a procedure. The shuttles were laid out and attached together with either tie line or elastic line. Fewer shuttles were used for the front row, more in the middle row, and even more in the back row. The pulleys were hung from the grid, and rope run through them for raising and lowering. The beams were tied off and, once they were hanging a few feet off the ground, the PVC pipe was attached via zip-ties as mentioned above. The shuttles were fed in and settled and one end was fixed to the pipe. The other end was attached to a long tie line which was run through a shackle and down to the driving mechanism. Extra zip-ties were added at each end to ensure that the shuttles would not slip out the ends of the PVC pipe. After extra aesthetic tests during load-in day, it was determined that approximately ten more shuttles and strips of kelp were needed. This was not a problem, however, because we made a significant number of extra parts just in case.

In order to safely hang the ~50 lb hanging mechanism, the ropes were counterweighed with 25 lb sandbags. When they were raised to the proper height, there was a loop in the rope that attached to a carabineer tied to a weight plate. When they were lowered, the sandbag ran into the pulley, stopping the pipe safely a few feet above the floor.

Chapter 6 – Design Verification

To ensure the success of our product during the performances, we subjected the mechanism to several qualitative and quantitative tests. Most of these tests needed to be performed after the device was installed; however, some preliminary testing was possible. Before installation, we conducted a hang test, a sway test and a scale model aesthetics and functionality test.

As soon as the pulleys arrived, we were able to perform a hang test (Figure 26) for our hanging methods. This test proved that the system could be supported by the pavilion's hanging grid, and that the pulley system would function properly and safely. We set up the structural pipes as we initially designed, using only one rope and four pulleys per pipe. We found that because of inconsistencies in pulleys, the pipe would raise diagonally. We were able to rethink our design and raise the pipe straight, using one rope and two pulleys for each end of each pipe. We were also able to discover that hanging the system would be a quick process that would easily be accomplished in the allotted time for installation.

Figure 26 - Rigging pipe for hang test

While we had the pipes in the air we also performed a sway test. We applied forces to the end of the pipes to simulate operational forces while the pipes were hanging. These forces created swinging motion in the pipes, similar to pendulum motion. We estimated the operational frequency and amplitude of the forces and found that the pipes did not swing in an unsafe manner, or to a degree that would affect operation.

Once we had several pieces manufactured, we performed some scale model tests. Figure 27 shows Kevin and Ian performing aesthetic testing on a scale model of the hanging system. This scale model test set-up only included the hanging system with half of one kelp row length and excluding the structural pipe and the fabric. This scale model was used to make some preliminary estimation of noise level and fabric motion. From this test we determined that the slot needed to be sanded down to eliminate any jagged, rough movement of the shuttles. This adjustment would also end up quieting the device as well.

Figure 27 - Aesthetic testing on a small scale-model pipe

After installation, we were able to perform all other necessary tests to ensure the effectiveness of our final product and find areas that needed improvement. We conducted a spatial test, a full-scale aesthetics and functionality test, a sound intensity test, and fatigue testing.

Once the stage and lights were installed we were able to perform a spatial test to make sure that the system did not interfere with any other installations in the theater. After raising the kelp with the stage lighting on, as shown in the figure below, we found that our kelp forest was successful in this aspect. We also asked Dr. Barata to evaluate aesthetic and functional qualities of the kelp. After adding several strands of kelp and rehearsing harmonic motion that was also completely random, he was satisfied with the performance of the device, shown below (Figure 28).

Figure 28 - The final product, lit with theater lights

With the theater performance ready, the operational sound intensity could now be measured. We used a smartphone app to determine the sound intensity from the front row. We found that during slow and smooth operation the device only created 36 dB, and during fast and chaotic operation the device created 42 dB. Both of these values are well below our target of 50 dB.

To ensure the continued optimal performance of our device we performed 30 hours of operational fatigue testing on the device in the week and a half before the show. While the actors, dancers, and musicians were rehearsing their parts, we raised, lowered and swayed the kelp repetitively. We also operated it in ways that others using the system not properly trained might operate it. We found that the knots that we used to connect the hanging system and the driving system work well to prevent damage by slipping if too much force is applied after the kelp hit the stops at the end of the travel. This could be fixed simply by slipping the knots back into place. We did not find any fatigue issues with the device that could have lead to failure during a performance and deemed the kelp forest ready for use.

Table 5 below is a comprehensive Design Verification Plan and Report. It details the engineering requirements, how they were tested, and the results of those tests. The most important requirements that had to be passed were the sound intensity test, the lighting interference test, and the budget. These tests (as well as all other requirements) were passed. Many requirements, including budget, set-up time, and weight passed by a large margin.

Table 5 - Design Verification Plan and Report for the project

FOTO DVP&R														
Report Date: 6/5/2014		Sponsor: Antonio G. Barata	Component/Assembly: FOTO Kelp Forest			REPORTING ENGINEERS: Kevin Dunlea, Ian Hoffman, and Ryan Palo								
TEST PLAN										TEST REPORT				
Item No	Specification	Test Description	Acceptance Criteria	Test Responsibilit	Test Stage	SAMPLES		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Pass	Fail	
1	Must fit through Pavilion door	Inspection (Measurement)	20 ft^2	Ryan	DV	1	DV	1/1/2014	4/4/2014	pass			
2	Must operate within the space of the room	Inspection (Measurement)		Ryan	DV	1	DV	1/1/2014	4/4/2014	pass			
3	-Height	Inspection (Measurement)	20 ft	Ryan	DV	1	DV	1/1/2014	4/4/2014	20 ft			
4	-Length	Inspection (Measurement)	35 ft	Ryan	DV	1	DV	1/1/2014	4/4/2014	21 ft			
5	-Width	Inspection (Measurement)	20 ft	Ryan	DV	1	DV	1/1/2014	4/4/2014	5 ft			
6	Interferes with lighting for different aspects of stage	Inspection (confirm with Tim Douggan)	No	Ryan	PV	1	PV	05-25-14	05-29-14	No			
7	Lit using available resources at Pavilion	Inspection (confirm with Tim Douggan)	Yes	Ryan	PV	1	PV	05-25-14	05-29-14	Yes			
8	Interferes with actions of performers and other effects	Inspection (confirm with Dr.B)	No	Ryan	PV	1	PV	05-25-14	05-29-14	No			
9	Stays Within budget	Inspection	$1,500	Kevin	DV	1	DV	1/1/2014	5/6/2014	$1,077			
10	Inputs controlling movement	Analysis	2 inputs	Ian	CV	1	CV	1/1/2014	4/2/2014	4			
11	Multiple Modes Available	Analysis	2 modes	Ian	CV	1	CV	1/1/2014	4/2/2014	3+			sway mode is infinitely variable
12	Flame-retardant fabric	Analysis	*fire code compliant*	Kevin	CV	1	CV	1/1/2014	4/3/2014	compliant			rose brand
15	Weight must be adequately supported by ceiling rigging if hung	Analysis	1000 lbs	Ryan	DV	1	DV	1/1/2014	2/4/2014	150 lbs			
16	High Hazard risk index	Analysis, Hang test, Sway test	18 hazard index	Kevin	DV	1	DV	4/2/2014	4/3/2014	18			if operated incorrectly, the system tension will need to be re-adjusted
17	harmonic motion	Test (scale model)	No	Ian	CV	1	CV	2/4/2014	4/4/2014	No			
18	Completely random motion	Test (scale model)	No	Ian	CV	1	CV	2/4/2014	4/4/2014	No			
19	Low sound intensity of operating system at audience ear level	Test (decibel meter in pavilion)	Less than 50 dB	Kevin	DV	20	DV	05-25-14	05-29-14	36-42 dB			negligible sound compared to loud performance (80-100 dB)
20	Must function during rehearsal and performances between May 29th and June 5th	Test (Install and manipulate before May 29th - 5 raise/lower, 1.5 hours sway)	30 operational hours	Ian	PV	1	PV	05-25-14	5/6/2014	37 hours			
21	Assembly Time	Test (install before May 29th)	24 installation hrs	Ian	PV	1	PV	05-25-14	05-29-14	7 hrs			

Chapter 7 – Conclusion and Recommendations

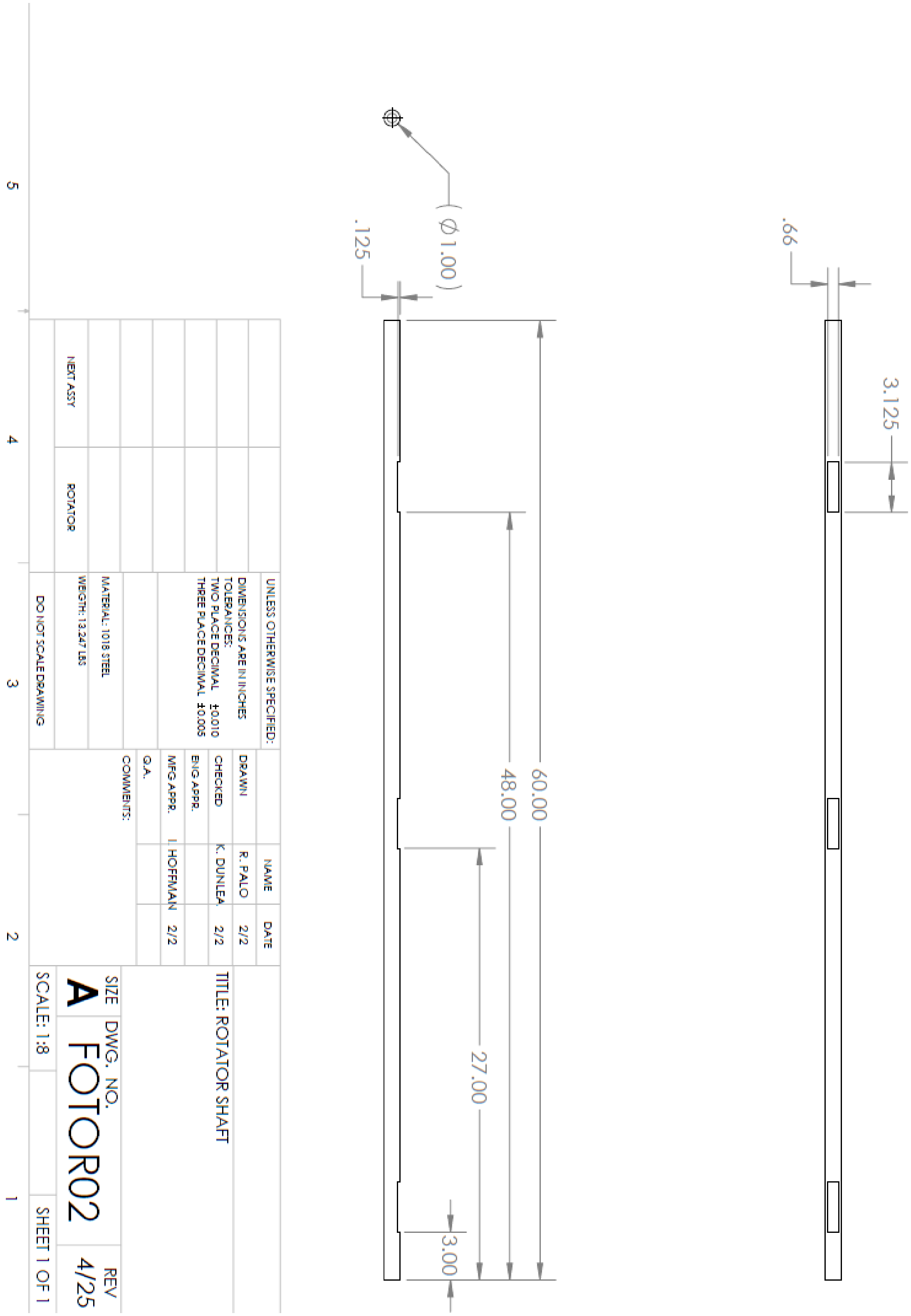
After the manufacturing, assembly, installation, and testing was done, all that remained was the show. The show was a great success, and the kelp forest received many compliments. The lighting enhanced the look and feel immensely, and the kelp aesthetically fit with the performance. There were two minor failures, one during each performance. These were due to faulty knots and could have been prevented if we had double checked all the knots. This also tested our safety precautions. We included stops at either end of each row in order to prevent stray shuttles from escaping the PVC track. These stops kept the shuttles from falling from 20 ft in the air, which not only prevented injury, but also kept the kelp in relatively the same place so that the failure went mostly unnoticed by the audience.
Even with these minor failures, this project was a success validated by both testing and the approval of the audience and fellow cast and crew.

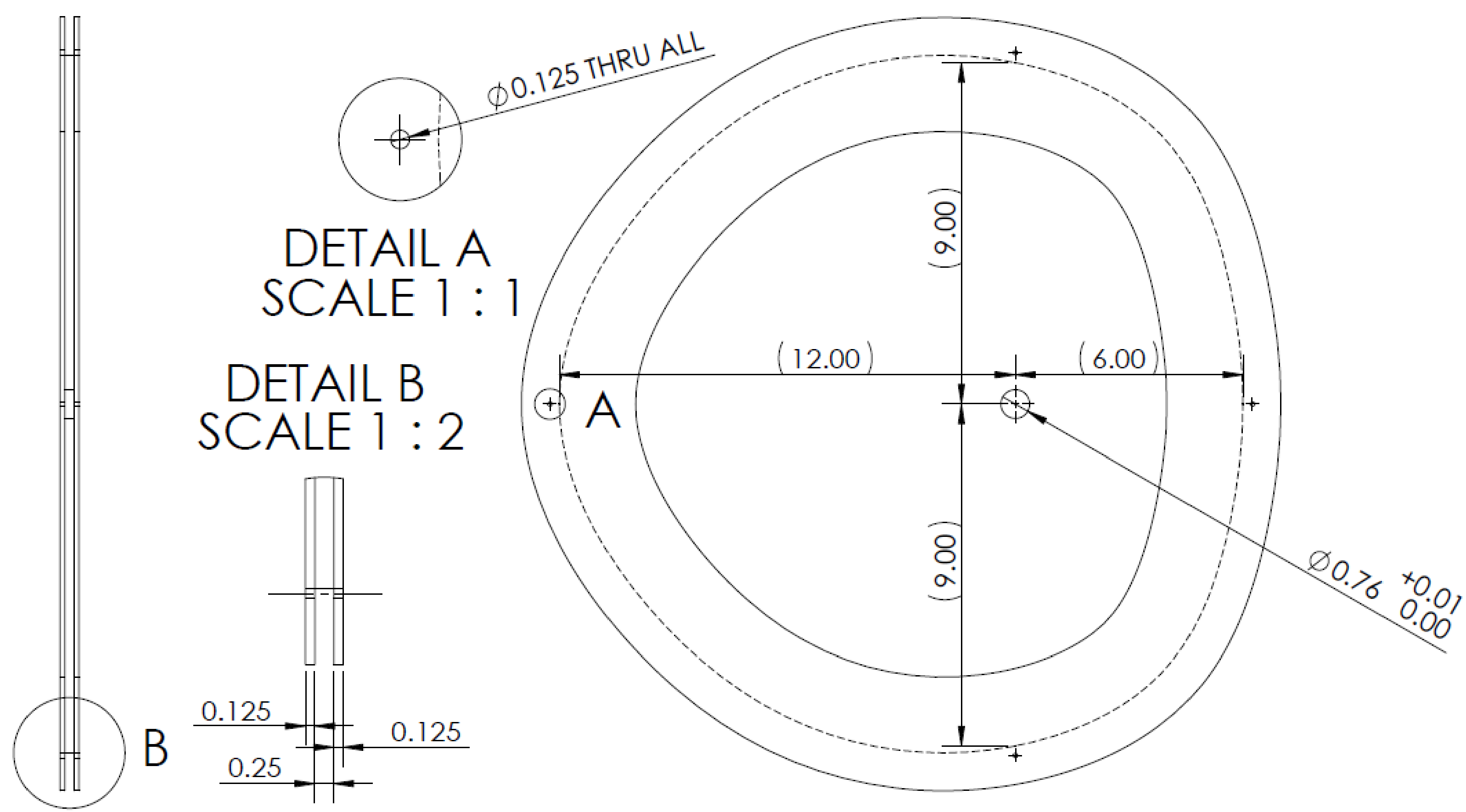
Some things that we would improve have been mentioned above. If this project was to be attempted again, more care could be taken when machining the PVC slot (which is already a difficult process). This would ensure smooth motion, no unnecessary catching or noise, and easier operation. The other thing that could be improved is the shape of the cams. They were drawn and measured by hand instead of following a stencil, and this caused them to be not quite ideal. Using a stencil would allow for a uniform and aesthetically pleasing shape. Other, administrative things to make the project run smoother could be done as well. Due to the nature of the project, as well as the working style of the sponsor, changes to the design requirements can often come up unexpectedly. Throughout the course of this project, the kelp changed from being on the stage to off the stage, it flipped orientations from stage right to stage left, and kelps were added, among other things. None of these changes were problems, but it suggests that the more closely the team can keep in contact with the sponsor, the more efficiently and smoothly these changes can be incorporated. This falls to the team to make sure the sponsor is on board at all times with their design decisions to avoid a communication breakdown. The last improvement is merely for the sanity of the person going to the hardware store. Making sure to plan and double check the items before heading to the store, and then buying extra hardware just in case, is a good way to save time, money, and gas.

Some things, however, went very well for the management of the project, and these should not be changed. The time table was managed extremely well so that our team was never stressed or behind at any point. When it came time to finish this report, it seemed surprisingly stress-less to put everything together to finish it. The breakdown of duties worked well too. Each member handled his administrative duties efficiently and could always be depended on to know the answer to a question about something he was working on. The machining/assembly duties were also split up well, and each member got his assignments done on time and completely. The final thing that was done well was the acquisition of materials. Between finding contacts at the Performing Arts Center that could provide a large portion of our big ticket items and a tight control on budget and spending, we were able to keep under budget and complete our project without having to purchase any extra supplies due to mistakes made.

We highly recommend RSVP as a source for future senior projects, as the artistic and musical aspects made for an interesting and satisfying experience. The interdisciplinary nature of the project allowed us to interact and collaborate with a number of different majors and has greatly enhanced our Learn by Doing Senior Capstone Experience.

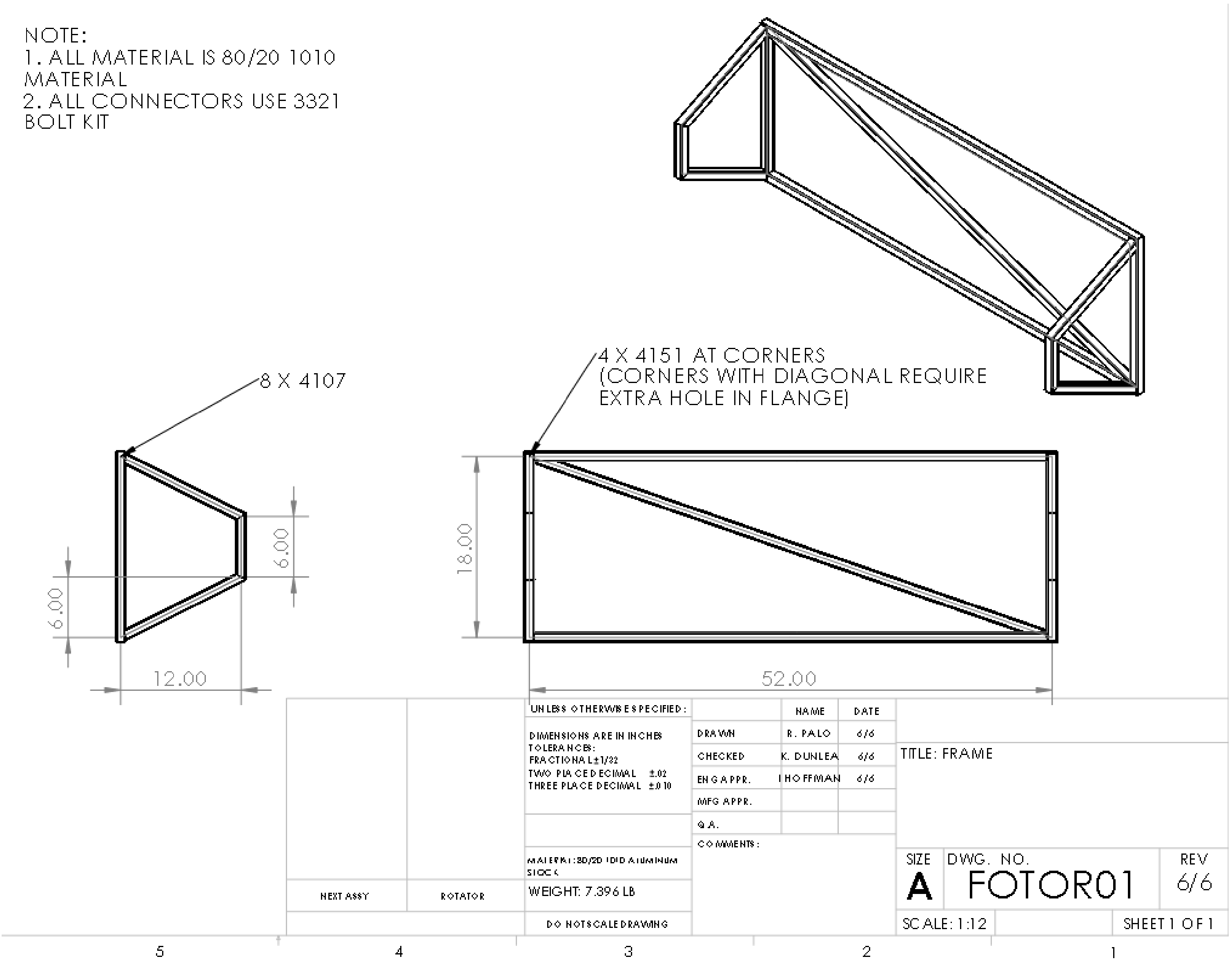
Appendix A – Drawings for Custom Parts and Assemblies

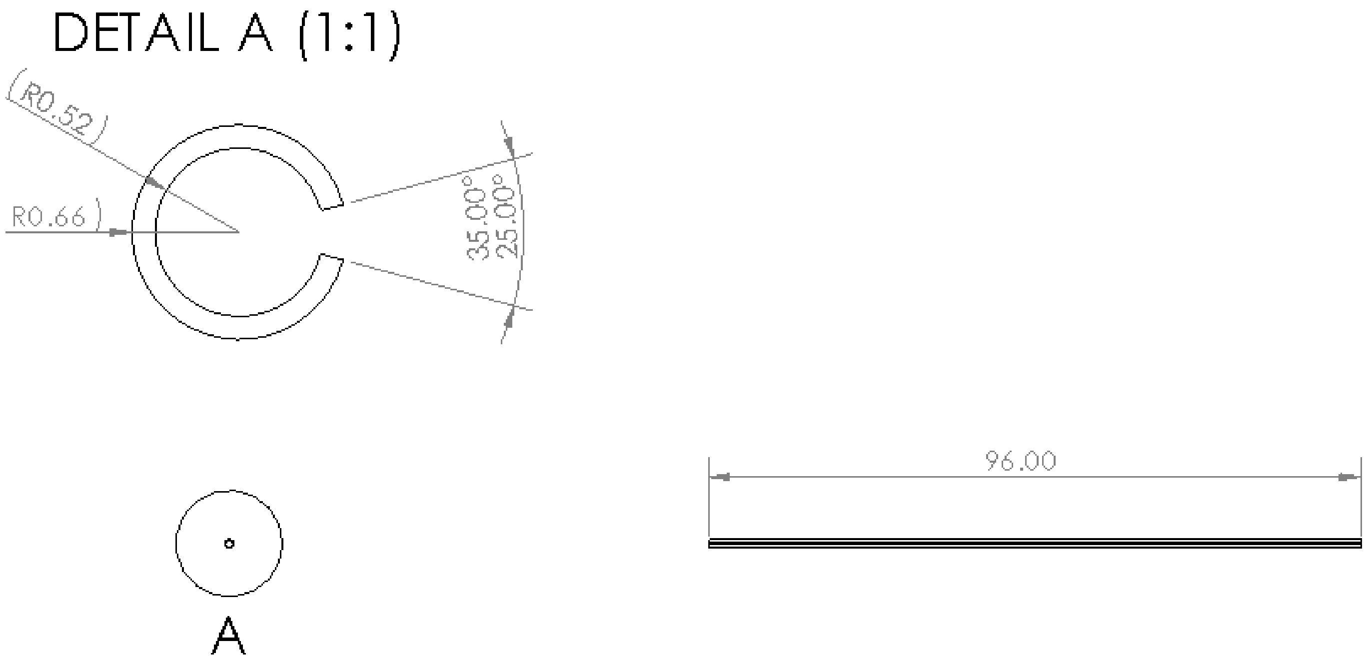




NOTES:
1. OUTER PLIES FOLLOW PROFILE OF INNER PLY, BUT ARE AN EXTRA INCH OUT FROM THE CENTER.
2. OUTER HOLES ARE .25 IN FROM THE EDGE OF THE INNER PLY.
3. OUTER HOLES SET AT 0, 90, 180, AND 270°

		UNLESS OTHERWISE SPECIFIED:		NAME	DATE	
		DIMENSIONS ARE IN INCHES TOLERANCES: ANGULAR: ± 5° TWO PLACE DECIMAL: ±0.02 THREE PLACE DECIMAL: ±0.01	DRAWN	R. PALO	2/2	TITLE: ROTATOR CAM
			CHECKED	K. DUNLEA	2/2	
			ENG APPR.			
			MFG APPR.	I. HOFFMAN	2/2	
		WEIGHT: 1.23 LBS	Q.A.			
		MATERIAL: PLYWOOD	COMMENTS: THIS SHEET IS A STENCIL WHICH WILL BE USED TO CUT THE CAMS VIA LASER. DIMENSIONS SHOWN ON PROFILE ARE JUST FOR REFERENCE.			SIZE A / DWG. NO. FOTOR03 / REV 2/2
NEXT ASSY	ROTATOR					
		DO NOT SCALE DRAWING				SCALE: 1:4 / SHEET 1 OF 1


NOTE:
1. ALL MATERIAL IS 80/20 1010 MATERIAL
2. ALL CONNECTORS USE 3321 BOLT KIT
8 X 4107
4 X 4151 AT CORNERS (CORNERS WITH DIAGONAL REQUIRE EXTRA HOLE IN FLANGE)
6.00
6.00
12.00
18.00
52.00
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL±1/32
TWO PLACE DECIMAL ±.02
THREE PLACE DECIMAL ±.010
MATERIAL: 80/20 1010 ALUMINUM STOCK
WEIGHT: 7.396 LB
DO NOT SCALE DRAWING
NEXT ASSY
ROTATOR
NAME
DATE
DRAWN
R. PALO
6/6
CHECKED
K. DUNLEA
6/6
ENG APPR.
I HOFFMAN
6/6
MFG APPR.
Q.A.
COMMENTS:
TITLE: FRAME
SIZE
A
DWG. NO.
FOTOR01
REV
6/6
SCALE: 1:12
SHEET 1 OF 1
5
4
3
2
1



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±0.02
THREE PLACE DECIMAL ±0.010

WEIGHT: 4.13 LBS

MATERIAL: PVC

DO NOT SCALE DRAWING

NEXT ASSY: HANGER

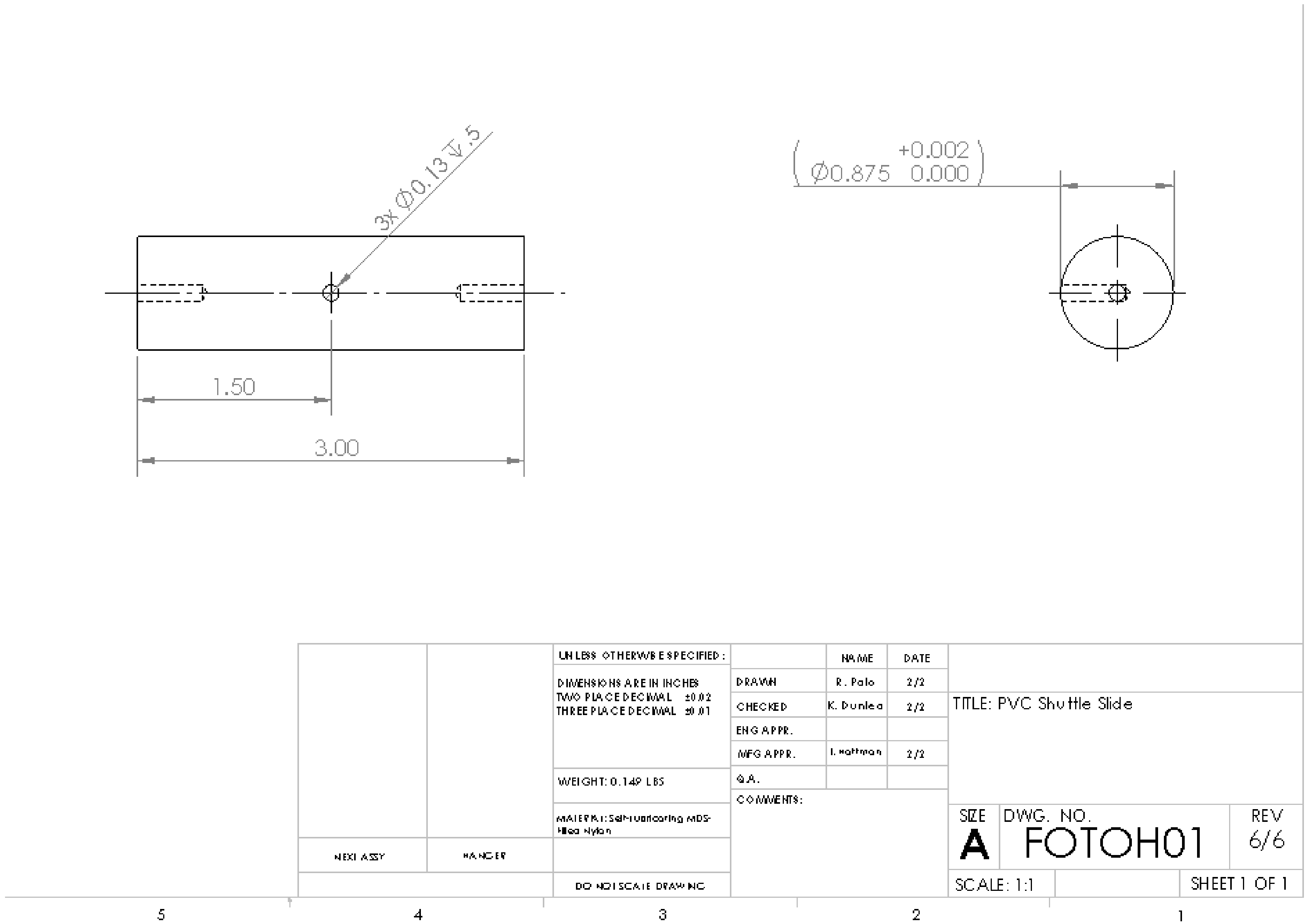
	NAME	DATE
DRAWN	R. Palo	2/2
CHECKED	K. Dunlea	2/2
ENG APPR.	R. Palo	2/2
MFG APPR.	I. Hoffman	2/2
Q.A.		

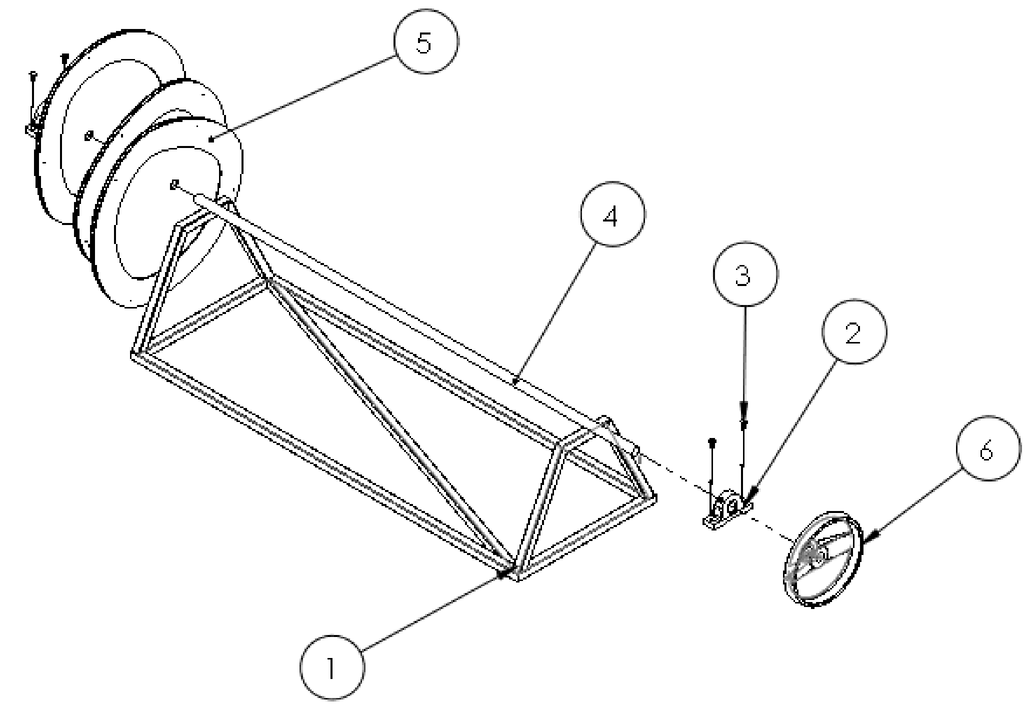
COMMENTS:

TITLE: PVC Shuttle Housing

SIZE: A
DWG. NO. FOTOH02
REV 6/6
SCALE: 1:24
SHEET 1 OF 1

5 4 3 2 1


3x Ø0.13 ↧.5
1.50
3.00
Ø0.875 +0.002 0.000
UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TWO PLACE DECIMAL ±0.02
THREE PLACE DECIMAL ±0.01
WEIGHT: 0.149 LBS
MATERIAL: Self-Lubricating MDS-Filled Nylon
NEXT ASSY
USED ON
DO NOT SCALE DRAWING
NAME
DATE
DRAWN R. Palo 2/2
CHECKED K. Dunlea 2/2
ENG APPR.
MFG APPR. I. Hoffman 2/2
Q.A.
COMMENTS:
TITLE: PVC Shuttle Slide
SIZE A
DWG. NO. FOTOH01
REV 6/6
SCALE: 1:1
SHEET 1 OF 1
5
4
3
2
1



	NAME	DATE
DRAWN	R. PALO	6/6
CHECKED	K. DUNLEA	6/6
ENG APPR.	I. HOFFMAN	6/6
MFG APPR.		
Q.A.		
COMMENTS:		

TITLE: ROTATOR ASSEMBLY

SIZE	DWG. NO.	REV
A	ROTATOR	6/6
SCALE: 1:16		SHEET 1 OF 2

DO NOT SCALE DRAWING

5 4 3 2 1

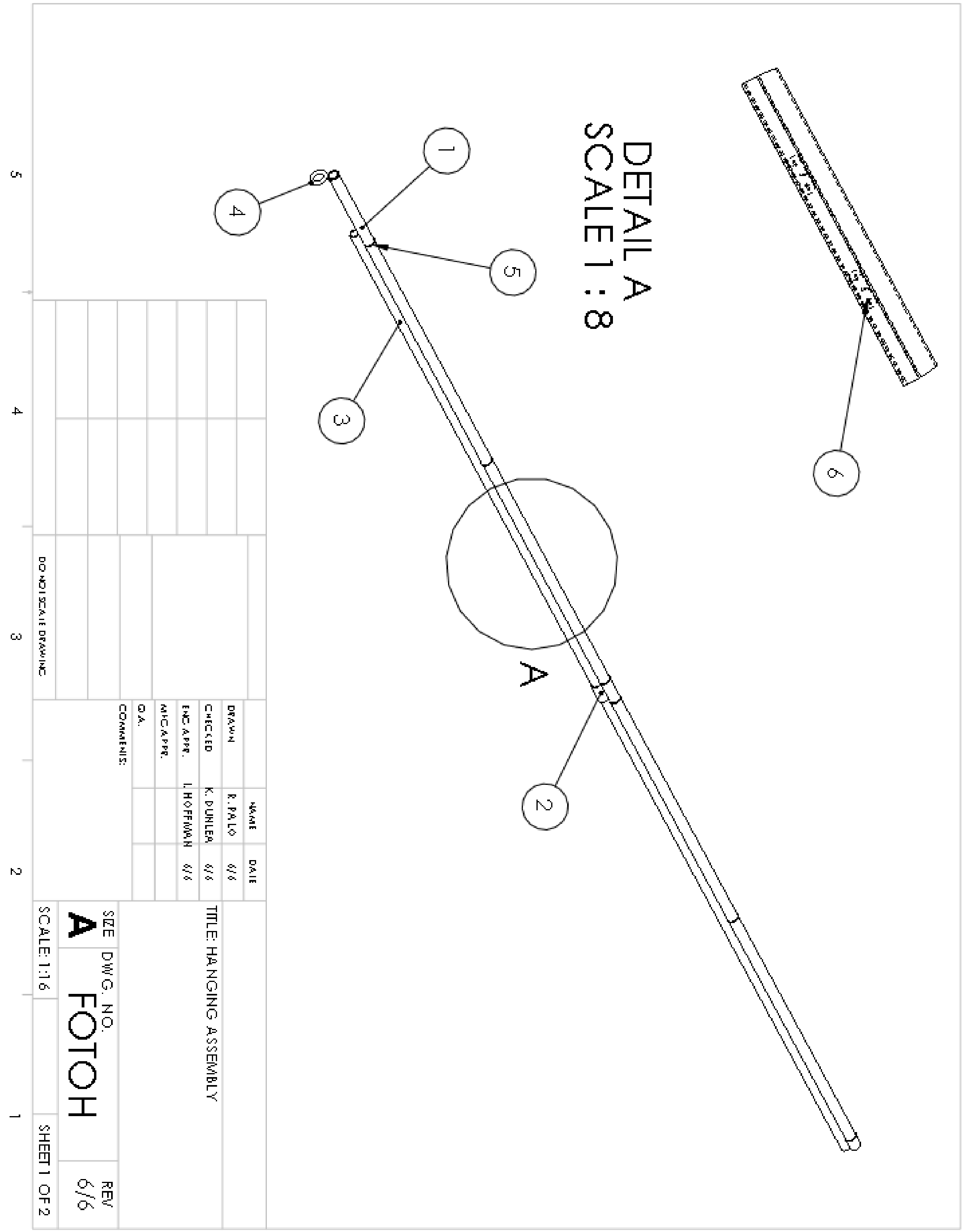
ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	FOTOR01	FRAME MADE OF 80/20 ERECTOR SET	1
2	FOTOS01	1" PILLOW-BLOCK BEARING SUPPORTING SHAFT	2
3	FOTOS02	1/4-20X1" BOLT TO HOLD BEARING ON FRAME	4
4	FOTOR02	SHAFT	1
5	FOTOR03	CAM	3
6	FOTOS03	10" ALUMINUM DRIVING WHEEL	1

DO NOT SCALE DRAWING

SIZE A DWG. NO. ROTATOR REV 6/6

SHEET 2 OF 2

5 4 3 2 1


DETAIL A
SCALE 1 : 8
A
1
2
3
4
5
6
DO NOT SCALE DRAWING
DRAWN R. PALO 6/6
CHECKED K. DUNLEA 6/6
ENG APPR. I. HOFFMAN 6/6
MFG APPR.
Q.A.
COMMENTS:
NAME
DATE
TITLE: HANGING ASSEMBLY
SIZE A
DWG. NO. FOTOH
REV 6/6
SCALE: 1:16
SHEET 1 OF 2

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	FOTOS04	SUPPORT PIPE	1
2	FOTOS05	PVC PIPE CONNECTOR	1
3	FOTOH02	PVC PIPE FOR SHUTTLES	2
4	FOTOS06	COLLAR TO REDIRECT TIE LINE	1
5	FOTOS07	ZIP-TIE	7
6	FOTOH01	SHUTTLE FOR SWAYING KELP	15

DO NOT SCALE DRAWING

SIZE	DWG. NO.	REV
A	FOTOH	6/6

SHEET 2 OF 2

5 4 3 2 1

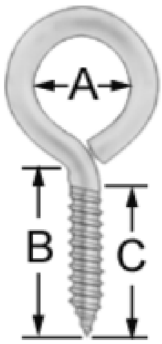
Appendix B – List of Vendors, Contact Info, and Pricing

No.	Item	Cost	Vendor	Contact Information
1	PETZL Fixe Pulley	223.60	ems	http://www.ems.com/product/index.jsp?productId=4055118
2	8" Type 304 Self-Lock Stainless Steel Cable Ties	16.41	cabletiesandmore	http://www.cabletiesandmore.com/american/catalog/type-self-lock-stainless-steel-cable-ties-pcspack-p-3895.php
3	PVC Pipe	17.05	homedepot	http://www.homedepot.com/p/JM-eagle-1-in-x-20-ft-PVC-Schedule-40-Pipe-530113/202353721?N=5yc1vZbueo
4	Steel Shaft and MDS Nylon	118.11	mcmaster	http://www.mcmaster.com/#rotary-shafts/=qkxj42
5	80/20 aluminum 1010	97.04	amazon	http://www.amazon.com/80-20-SERIES-T-SLOTTED-EXTRUSION/dp/B001F0F112/ref=sr_1_18/182-0487787-8968016?m=A1H481IPHNMK5K&s=merchant-items&ie=UTF8
6	Carabiner-Style connectors	21.42	mcmaster	http://www.mcmaster.com/#carabiners/=qf9bw0
7	Screw-in Hook	11.79	mcmaster	http://www.mcmaster.com/#hook-screws/=qfa4am
8	Pillow Block Mounted Bearing	23.64	amazon	http://www.amazon.com/Hub-City-PB251URX1-Mounted-Setscrew/dp/B00ECZZG7G/ref=sr_1_3?ie=UTF8&qid=1394819455&sr=8-3&keywords=pillow+block+bearing
9	Hardwood Plywood	13.97	homedepot	http://www.homedepot.com/p/Unbranded-1-4-in-x-4-ft-x-8-ft-Moisture-Resistant-Plywood-Underlayment-431178/203183010
10	Party Knit Fabric	332.92	rosebrand	http://www.rosebrand.com/product187/60-Chiffon-FR.aspx?tid=2&info=chiffon
11	Eyebolt, Light Duty Wood Screw	17.04	mcmaster	http://www.mcmaster.com/#general-purpose-eyebolts/=qgvacs
12	Bungie Nylon	14.00	amazon	http://www.amazon.com/Bungie-Nylon-coated-rubber-shock/dp/B0042YWZWG/ref=sr_1_3?ie=UTF8&qid=1390943319&sr=8-3&keywords=rubber+rope
	Miscellaneous costs (shipping/tax)	148.95		
	Total Cost	**1055.94**		

Appendix C – Vendor Supplied Component Specifications and Data Sheets

Zinc-Plated Steel Routing Eyebolt for Wood

9/64" Wire Diameter, 7/16" Eye ID, 3/4" Shank Length



In stock
$8.52 per pack of 50
9496T17

Also known as screw eyes, these bent-wire eyebolts have a sharp cutting point for mounting directly into wood.

Zinc-plated steel and brass have good corrosion resistance.

Warning! Never use for lifting applications.

Trade Size	9
Wire Diameter	9/64"
(A)	7/16"
(B)	3/4"
(C)	5/8"
Additional Specifications	Zinc-Plated Steel

Figure 29 - McMaster Carr Data Sheet for Eyebolt

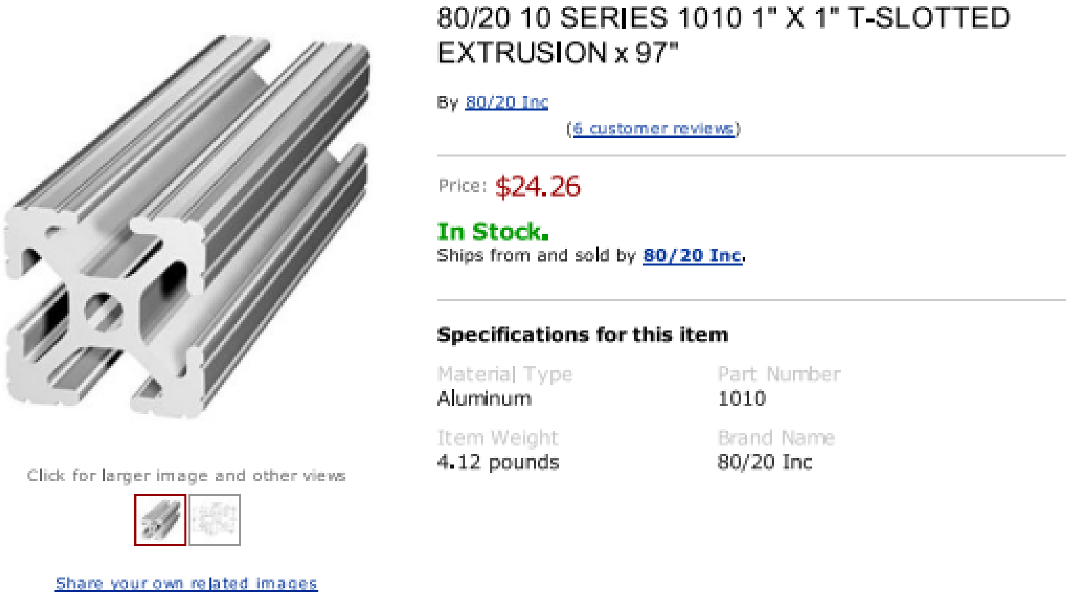
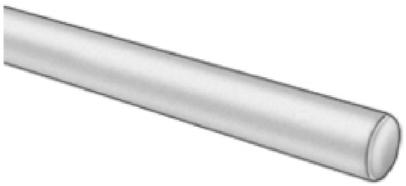


Figure 30 - Vendor data for 80/20 stock

Figure 31 - Vendor data for elastic rope

Steel Drive Shaft

3/4" OD, 36" Length



In stock
$36.90 Each
1346K33

Steel Shafts—Made of 1566 steel, these shafts are stronger than stainless steel shafts but are less corrosion resistant. They are unhardened for easier machining. Rockwell hardness is C25. Ends are beveled.

Shaft Dia.	Dia. Tolerance	Straightness Tolerance
⅜"-1"	0.0" to –0.003"	0.012" per ft.
1¼"	0.0" to –0.004"	0.012" per ft.

Length	36"
Additional Specifications	Steel Shafts—Inch Sizes 3/4" Dia.

Figure 32 - Vendor data for shaft

SPECIFICATIONS

Actual inside diameter (in.)	1.033	Actual outside diameter (in.)	1.315
Assembled Depth (in.)	240 in	Assembled Height (in.)	1.315 in
Assembled Width (in.)	1.315 in	Certifications and Listings	IAPMO Certified,NSF Listed
Coiled	No	Manufacturer Warranty	1 year
Material	PVC	Maximum working pressure (psi)	450
Maximum working temperature (F)	140	Minimum working temperature (F)	0
Pipe & Tubing Product Type	PVC Schedule 40	Pipe Size	1"
Pipe or Fitting Product Type	Pipe & Tubing	Product Length (ft.)	20 ft
Product Weight (lb.)	6.482	Rating	Schedule 40
Recommended function	Water Supply	Wrapped	No

Figure 33 - Data sheet for PVC pipe

Click for larger image and other views

UCP204-12 Pillow Block Mounted Bearing, 2 Bolt, 3/4" Inside Diameter, Set screw Lock, Cast Iron, Inch

By VXB

(4 customer reviews)

Price: $11.82 & **FREE Shipping** on orders over $35. Details

Only 3 left in stock (more on the way).
Ships from and sold by **Amazon.com.**

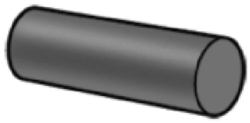
Want it Monday, Feb. 10? Order within **43 hrs 18 mins** and choose **One-Day Shipping** at checkout. Details

2 new from $7.88

Figure 34 - Vendor data for bearings

Self-Lubricating MDS-FILLED Nylon Rod

7/8" Diameter, Black



Length, ft.

1	4
2	5
3	

$3.86 per ft.
8554K28

This material is modified with MDS for a more slippery surface than standard nylon. It reduces the need for lubricating products in high-friction applications, such as gears and bearings. Meets ASTM D6779.

View detailed performance properties for plastics.

Rods meet UL 94HB for flame retardance and ASTM D5989.

Diameter	7/8"
Diameter Tolerance	+0.002"
Color	Black
Temperature Range	-40° to 230° F
Tensile Strength	Excellent
Impact Strength	Good
Additional Specifications	Rods

Figure 35 - Vendor data for shuttle nylon

by Monroe Engineering

2 Spoked Black Powder Coated Aluminum Dished Hand Wheel without Hand
Diameter, 3/4" Hole Diameter (Pack of 1

Be the first to review this item

Price: $64.13 & **FREE Shipping**. Details

Only 3 left in stock (more on the way).
Ships from and sold by Amazon.com. Gift-wrap available.

Want it Monday, June 9? Order within **22 hrs 35 mins** and choose **One-Day Shipping** at checkout. Details

Specifications for this item

Brand Name	Monroe Engineering	Hub Diameter	1-15/16 inches
Part Number	30740	Hub Length	1-3/8 inches
Number of Items	1	Overall Height	2 51/64 inches
Material Type	Aluminum	Thread Size	3/4 inches
Color Name	Black	UNSPSC Code	31171800
Exterior Finish	Matte		

Number of spokes: 2. Material: gravity cast aluminum. Black color. Black Powder Coated Matte Fini... Read full product de

Figure 36 - Vendor Data for driver wheel

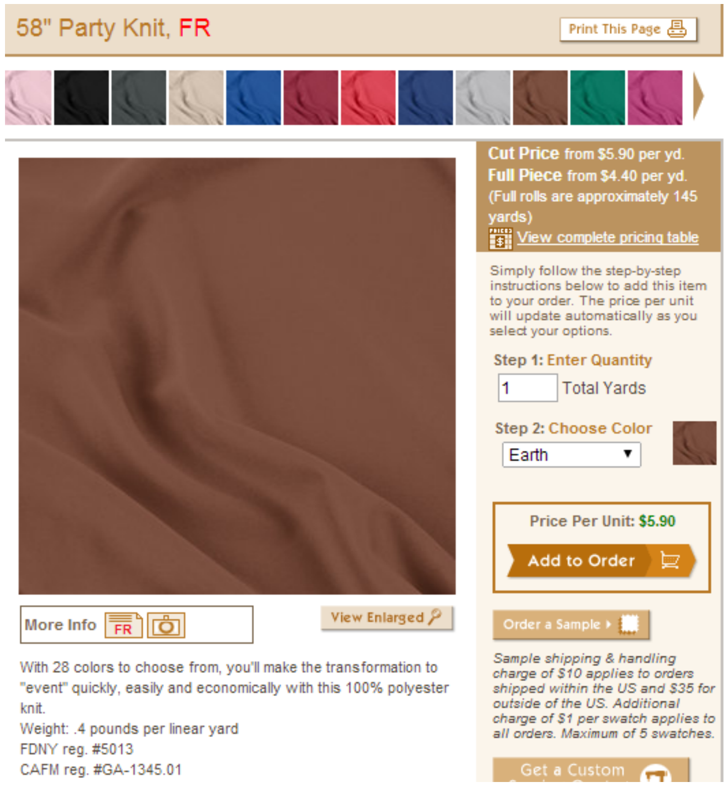


Figure 37 - Vendor data for fabric

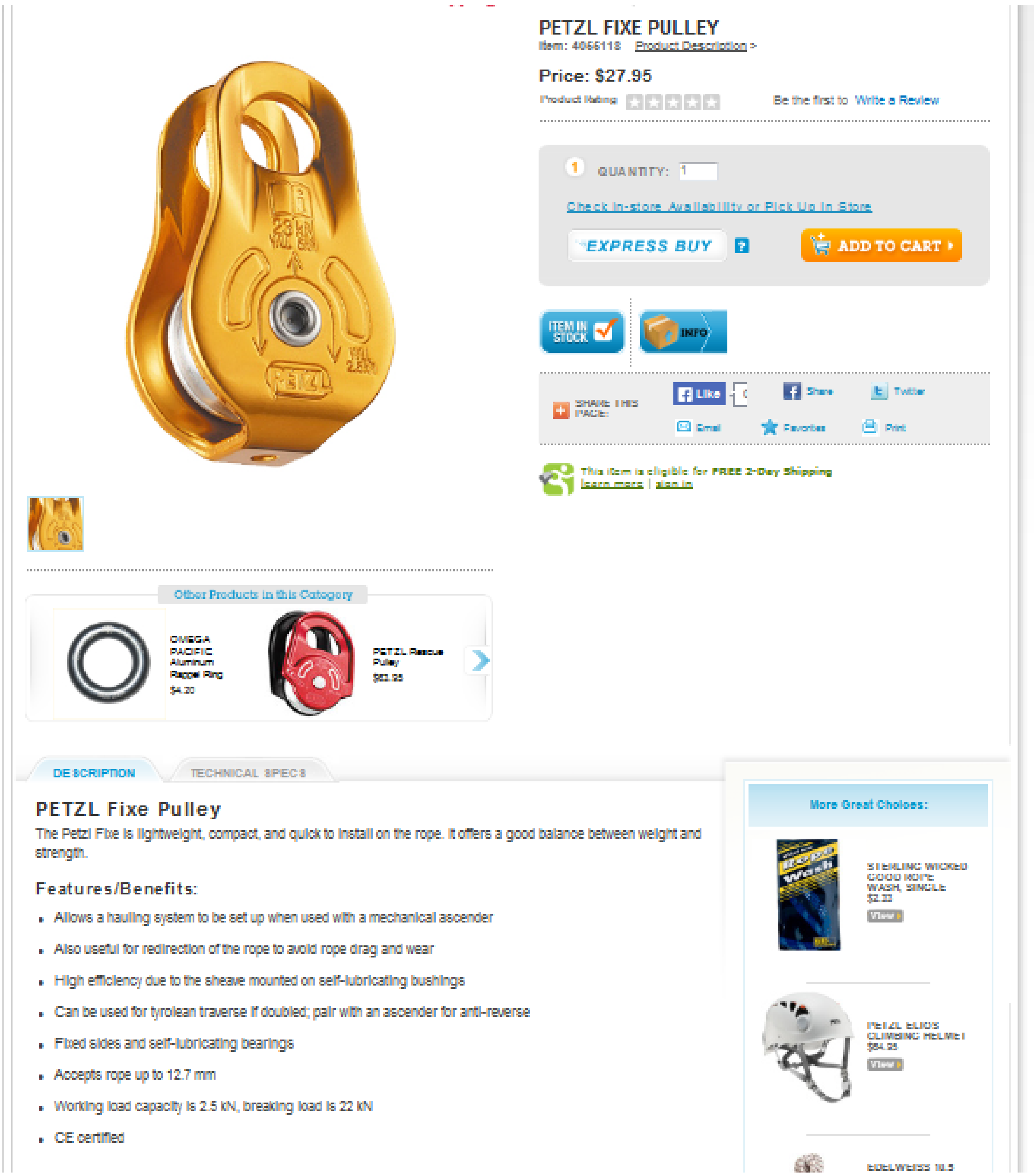


Figure 38 - Vendor data sheet for pulleys

Appendix D – Detailed Supporting Analysis

Table 6 - Pipe bending calculations

				Pipe Deflection				
	Rear	Middle	Front		**Delta From Weight**			
Shaft OD (in)	1.5	1.5	1.5			Rear	Middle	Front
Thickness (in)	0.253	0.253	0.253		r out (in)	0.75	0.75	0.75
Weight/Length (lbs/ft)	1.175				r in (in)	0.497	0.497	0.497
Number of Kelps (kelps)	6	5	4		I (in^4)	0.200585	0.200585	0.200585
Weight/Kelp (lbs/kelp)	1.771875				delta (in)	0.863777	0.863777	0.863777
Distance between Kelps (ft)	2.666667	3.2	4		**Delta from Kelps**			
Shaft Length (ft)	16	16	16		weight/ft (lbs/ft)	0.664453	0.553711	0.442969
Young's Modulus (ksi)	10000				delta (in)	0.488459	0.407049	0.325639
PVC weight (lbs)	5.12	5.12	5.12					
						Rear	Middle	Front
					Total Deflection (in)	1.352236	1.270827	1.189417
					Angle of deflection (deg)	0.403522	0.379229	0.354936

Table 7 - Tension calculations

	Rear	Middle	Front		**Tension In Rope/Required Weight on Plates**			
Shaft Weight (lbs)	18.8	18.8	18.8			Rear	Middle	Front
Total Pulley Weight (lbs)	1.782	1.782	1.782		T_{rope} (lbs)	14.85694	14.70928	14.56163
Weight of Kelp (lbs/kelp)	0.295313	0.295313	0.295313					
Number of Kelps (kelps)	6	5	4					
Weight of Spring (lbs)	2.24	2.24	2.24					
Weight of PVC (lbs)	5.12	5.12	5.12					

Table 8 - Shaft sizing calculations

Average Diameter of Cam (in)	18	12	12		Average Radius of Cam (in)	9	6	6				
Weight of hardware (lb)	1	1	1									
Max Tension in T_{sway} (lb)	10	10	10		Moment to be pulled (lb in)	90	60	60				
Diameter of captain's wheel (in)	24				Max Tangential Input req'd	8.75						
Distances from rear (in)	20.5	11.5	2.5									
Weight of Cam (lb)	5.305256	2.424153	2.424153		**For Max tension**						Fay	Fby
Net Force At Cam (lb)	3.694744	6.575847	6.575847		Bending Moment (lb in)	-50.0964	-68.5203	-27.7615		Reaction Forces (lb)	-11.1046	-0.74184
Weight of Captain's wheel (lb)	5				-30							
Total Length from rear (in)	30				Torsion (lb in)	210	120	60				
Length from rear to front wall (in)	24				**For Min Tension**							
					Bending Moment (lb in)	0.216066	21.16722	11.301		Reaction Forces (lb)	4.5204	13.63316
					-30							
					Torsion (lb in)	0	0	0				
M m (lb in)	-24.9402	-23.6765										
M a (lb in)	25.15625	44.84375			Se' (ksi)	32						
T m (lb in)	105	60			ka	0.896863	a	2.7				
T a (lb in)	105	60			kb	0.907913	b	-0.265				
Safety Factor	5				kc	1						
Kt Estimated	1.5				kd	1						
Kts Estimated	1.35				ke	0.814						
					kf	1						
Material Properties					Se (psi)	21.21019						
Yield Strength (ksi)	54											
Ultimate Strength (ksi)	64				Diameter	0.743199	0.666395					

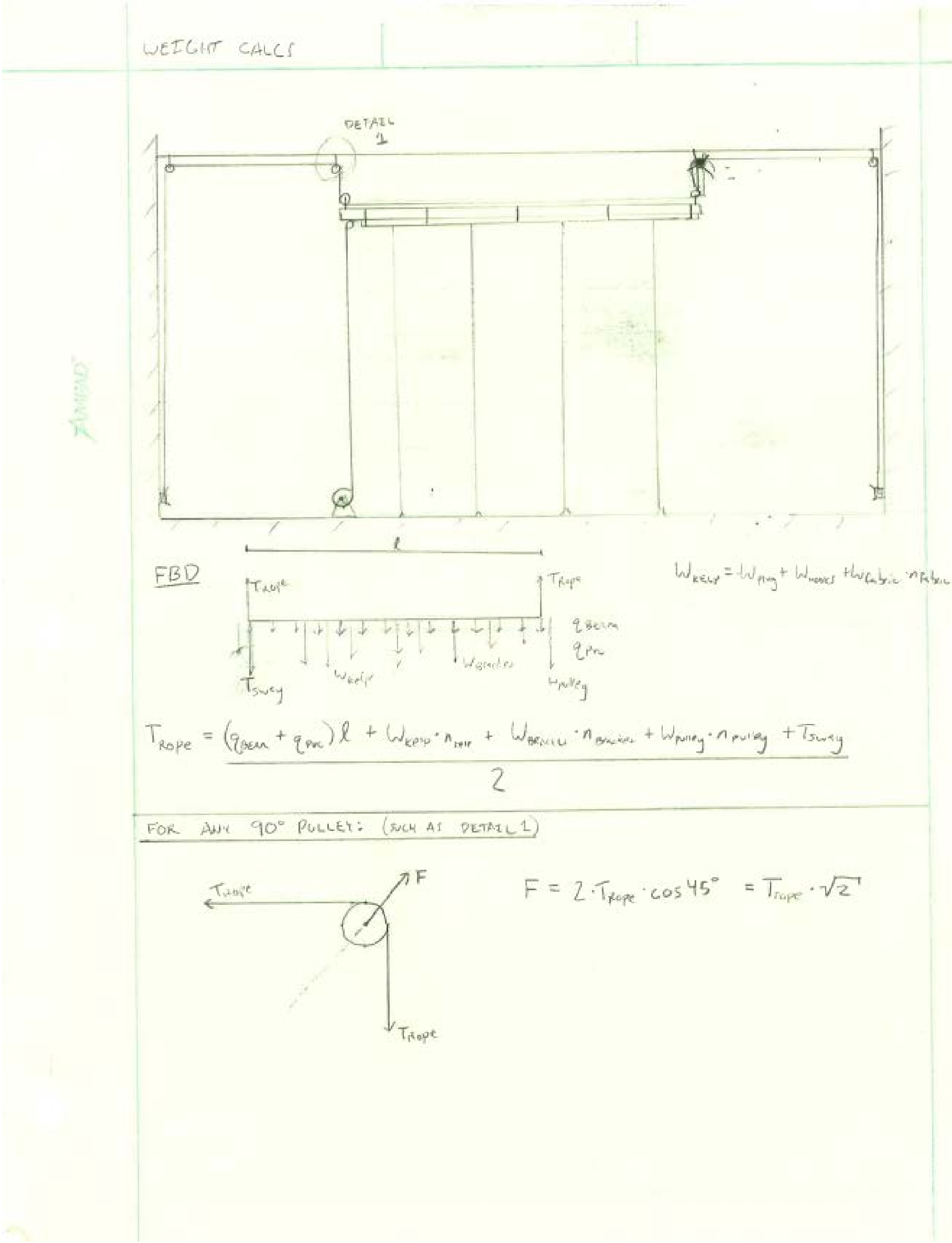


Figure 39 - Hand calculations

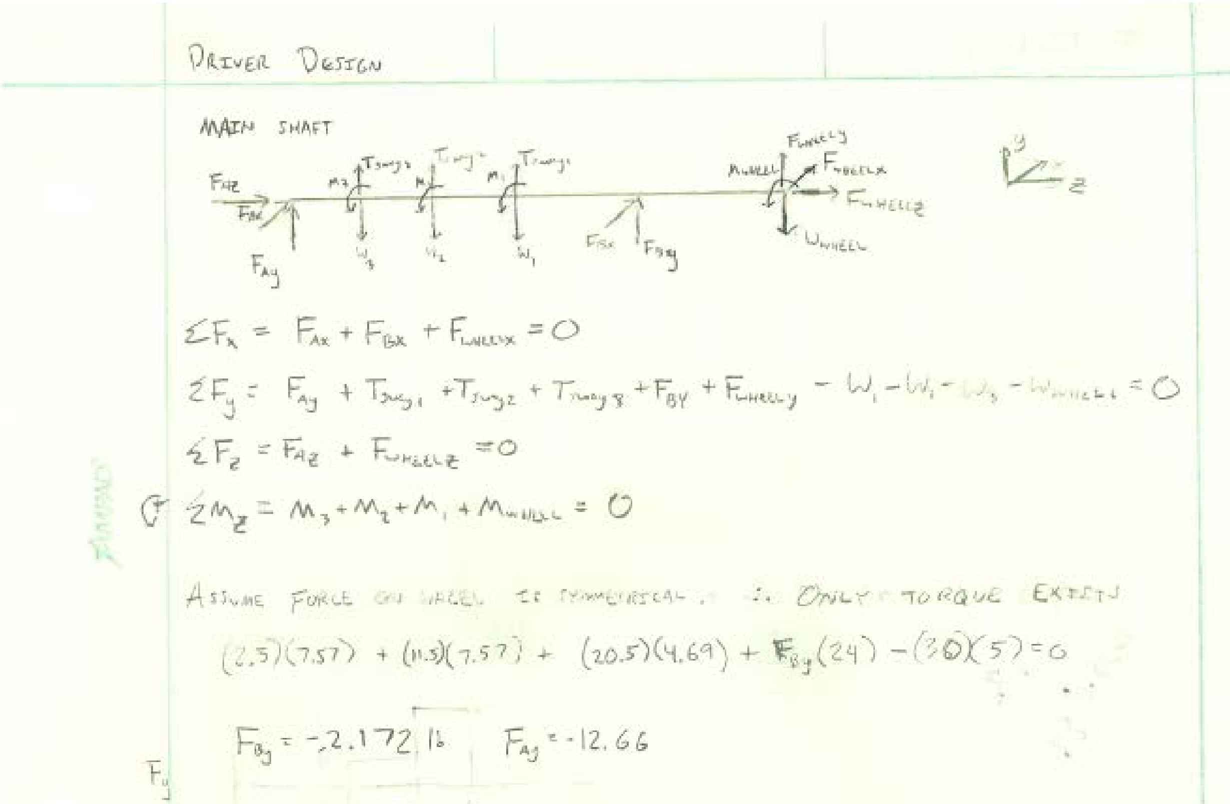


Figure 40 - More Hand calculations

Appendix E – Gantt Chart

Task Name	Start	Finish
Project Selection	**Mon 9/23/13**	**Mon 9/30/13**
Listen to Presentations	Mon 9/23/13	Thu 9/26/13
Complete Project preference form	Fri 9/27/13	Mon 9/30/13
Intro Email	Tue 10/1/13	Tue 10/1/13
Team Building	Tue 10/1/13	Mon 10/7/13
Writing Team contract	Tue 10/8/13	Thu 10/10/13
Team contract	Thu 10/10/13	Thu 10/10/13
Proposal	**Thu 10/10/13**	**Thu 10/24/13**
Background Research	Thu 10/10/13	Thu 10/24/13
Customer Requirements	Thu 10/10/13	Mon 10/14/13
Engineering Reqs.	Tue 10/15/13	Tue 10/15/13
QFD	Tue 10/15/13	Thu 10/17/13
Writing Proposal	Fri 10/18/13	Thu 10/24/13
Proposal Document Deadline	Thu 10/24/13	Thu 10/24/13
Yellow tag	Mon 11/25/13	Mon 11/25/13
Preliminary design Report	**Thu 10/24/13**	**Thu 12/5/13**
Concept Development	**Thu 10/24/13**	**Tue 11/19/13**
Ideation	Thu 10/24/13	Mon 11/11/13
Modeling	Wed 10/30/13	Tue 11/19/13
presentation	Thu 11/7/13	Thu 11/7/13
Top concept selection	**Wed 11/20/13**	**Wed 11/27/13**
analysis	Wed 11/20/13	Wed 11/27/13
Layout drawings (top concepts)	Wed 11/20/13	Fri 11/22/13
solid modeling	Thu 11/28/13	Thu 12/5/13
construction plan	Thu 11/28/13	Thu 12/5/13
testing plan	Thu 11/28/13	Thu 12/5/13
writing report	Wed 11/20/13	Thu 12/5/13
Design Report Deadline	Thu 12/5/13	Thu 12/5/13
Preliminary design review	Mon 12/9/13	Mon 12/9/13

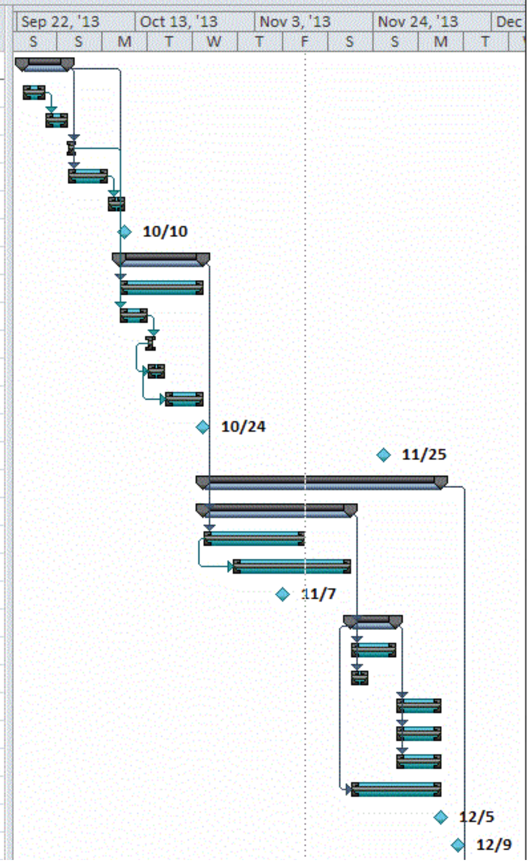


Figure 41 - Fall Quarter Gantt Chart

Task Name	Start	Finish
Preliminary design review	Mon 12/9/13	Mon 12/9/13
Critical Design Report	**Tue 12/10/13**	**Tue 2/4/14**
detail component design	Tue 12/10/13	Fri 1/24/14
Analysis	Fri 12/13/13	Thu 1/23/14
drafting	Thu 12/19/13	Mon 2/3/14
Bill of materials	Fri 1/24/14	Fri 1/24/14
cost report	Mon 1/27/14	Tue 1/28/14
test plan	Tue 1/28/14	Mon 2/3/14
Writing report	Wed 1/29/14	Mon 2/3/14
Critical Design Report Deadline	Tue 2/4/14	Tue 2/4/14
Critical Design Review	Thu 2/6/14	Thu 2/6/14
Manufacturing and testing review presentation preparation	**Thu 2/20/14**	**Mon 3/3/14**
Safety checklist	Thu 2/20/14	Mon 3/3/14
status update	Thu 2/20/14	Mon 3/3/14
update test plan	Thu 2/20/14	Mon 3/3/14
update manufacturing plan	Thu 2/20/14	Mon 3/3/14
Manufacturing and testing review presentation	Tue 3/4/14	Tue 3/4/14
Project update memo	Tue 3/11/14	Tue 3/11/14

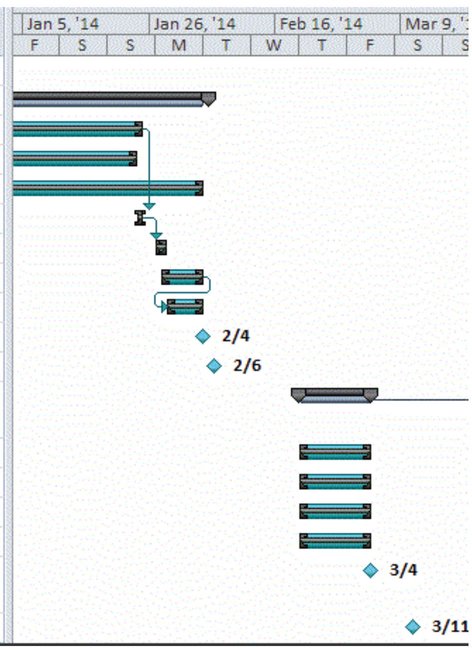
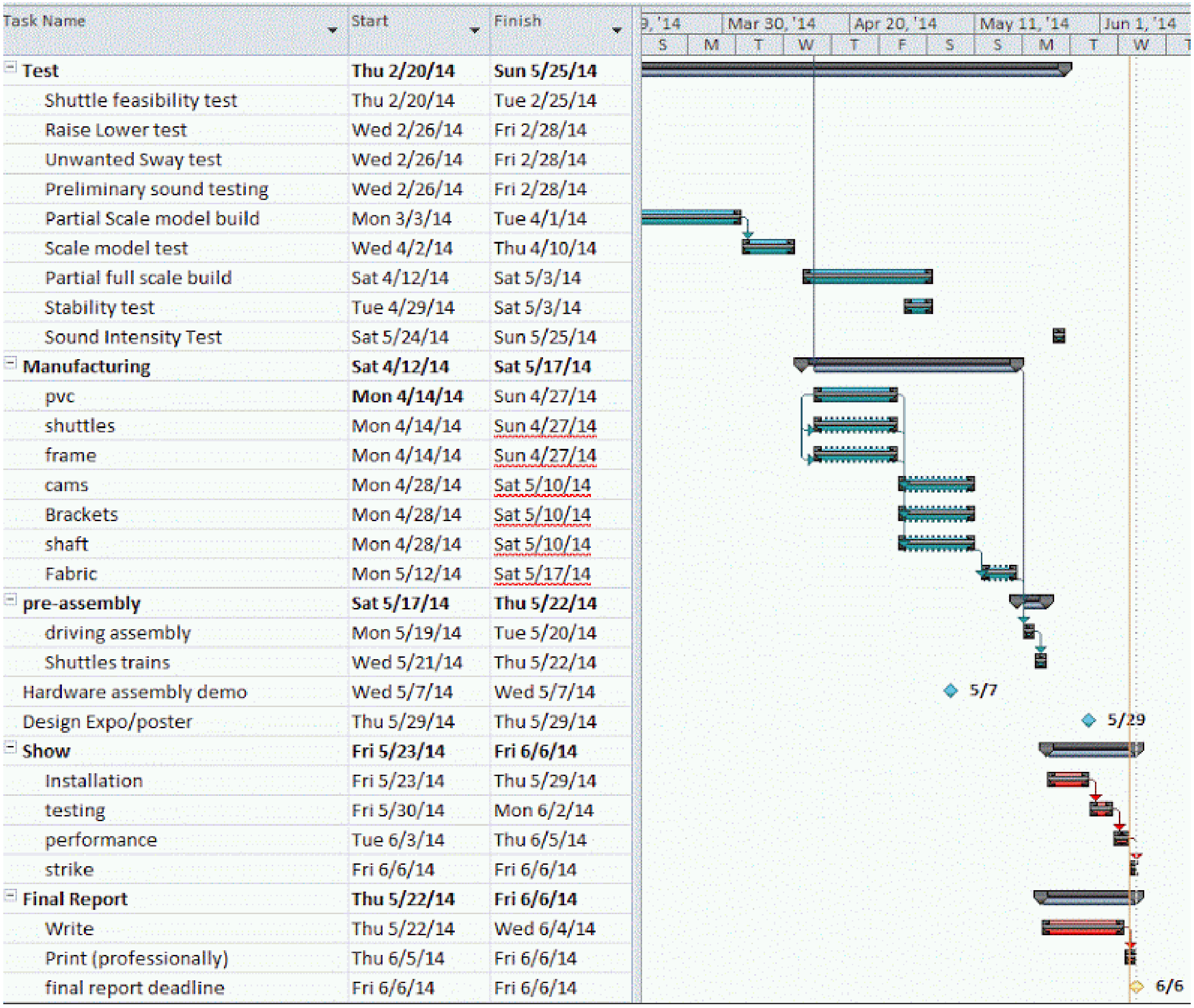


Figure 42 - Winter Quarter Gantt Chart



Task Name	Start	Finish
Test	**Thu 2/20/14**	**Sun 5/25/14**
Shuttle feasibility test	Thu 2/20/14	Tue 2/25/14
Raise Lower test	Wed 2/26/14	Fri 2/28/14
Unwanted Sway test	Wed 2/26/14	Fri 2/28/14
Preliminary sound testing	Wed 2/26/14	Fri 2/28/14
Partial Scale model build	Mon 3/3/14	Tue 4/1/14
Scale model test	Wed 4/2/14	Thu 4/10/14
Partial full scale build	Sat 4/12/14	Sat 5/3/14
Stability test	Tue 4/29/14	Sat 5/3/14
Sound Intensity Test	Sat 5/24/14	Sun 5/25/14
Manufacturing	**Sat 4/12/14**	**Sat 5/17/14**
pvc	**Mon 4/14/14**	Sun 4/27/14
shuttles	Mon 4/14/14	Sun 4/27/14
frame	Mon 4/14/14	Sun 4/27/14
cams	Mon 4/28/14	Sat 5/10/14
Brackets	Mon 4/28/14	Sat 5/10/14
shaft	Mon 4/28/14	Sat 5/10/14
Fabric	Mon 5/12/14	Sat 5/17/14
pre-assembly	**Sat 5/17/14**	**Thu 5/22/14**
driving assembly	Mon 5/19/14	Tue 5/20/14
Shuttles trains	Wed 5/21/14	Thu 5/22/14
Hardware assembly demo	Wed 5/7/14	Wed 5/7/14
Design Expo/poster	Thu 5/29/14	Thu 5/29/14
Show	**Fri 5/23/14**	**Fri 6/6/14**
Installation	Fri 5/23/14	Thu 5/29/14
testing	Fri 5/30/14	Mon 6/2/14
performance	Tue 6/3/14	Thu 6/5/14
strike	Fri 6/6/14	Fri 6/6/14
Final Report	**Thu 5/22/14**	**Fri 6/6/14**
Write	Thu 5/22/14	Wed 6/4/14
Print (professionally)	Thu 6/5/14	Fri 6/6/14
final report deadline	Fri 6/6/14	Fri 6/6/14

Figure 43 - Spring Quarter Gantt Chart (Note: Red signifies a high-stakes deadline, not a missed one)