Final Report
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Abstract

This project constitutes the design, build, and test of a camera system that runs on a track along the length of a pier piling at the Cal Poly pier in Avila Beach. The goal of the camera system is to observe the abundant sea life active on the surface of the piling underwater and in the tidal zone. The camera system will stream live video to the internet, record HD video, and be controllable remotely. The track is mounted to the piling with brackets and extends from the sea floor to a few feet above the pier deck. The camera, all lighting systems, and motion control hardware is housed inside a clear acrylic tube. The tube is sealed on both ends and can be removed from the cart. The cart has rollers that connect to the I-beam. The rollers act as a guide for the cart and as suspension due to their flexible composition. A winch connected to the cable for the pod provides vertical movement along the track. The cable is passed over a sheave above the track before connecting to the cart. The camera and lighting system will move with three degrees of freedom inside the pod: pan, tilt, and focal length. The motion control will allow the user to view the entire vicinity around the camera pod and see the sea life on the piling from different angles and different heights.

Introduction

The goal of this project is to develop a system that will enable educators, scientists, and anyone else with an internet connection to explore sea life at the Cal Poly Avila Pier. We are designing a camera system that travels up and down alongside one of the pilings supporting the pier to observe the sea life present on it. The piling is near the end of the pier on the north east corner of the docking platform. It is 30 inches wide and composed of a steel tube filled with cement. There are many other pilings similar to this one that support the platform, but the north east one was chosen for a few specific reasons. Firstly, the north east side of the pier receives the least magnitude of wave forces. This is important because it is necessary to reduce as much vibration as possible that will come from the oscillation of the waves. Secondly, this piling receives less sunlight than others, which is important for maintaining the quality of the camera and its lens. The existence of abundant sea life around the pier is no different at the north east piling, as sea life completely covers the piling from the sea floor up to the tidal zone. Anemones, crustaceans, plankton, and a variety of other plant and animal life have found refuge on the pilings surface, which extends 40 feet underwater. The piling stretches an additional 20 feet above the water to the platform.

We aim to build a system that will stream live video to users, as well as archive content for later browsing. Additionally, the camera will have the ability to be controlled remotely; the viewers will be able to move the camera up and down along the piling to allow for viewing anywhere between the seafloor and the top of the piling. Existing designs exist that can film and be controlled remotely underwater, but they are unable to achieve a stable image. In addition to view quality, the system must self-clean, minimize maintenance required, reduce environmental impact, and survive in the harsh conditions of the ocean. Our design will focus on these challenges.

The team is made up of five engineering seniors, Aaron Hein, Aaron Poulos, Andy Crafts, Jeremy DePangher, and Michael Machado. For guidance the students contact two Cal

Poly professors, John Ridgely and Bridget Benson. For onsite questions and installation the team contacts Tom Moylan, the pier manager at the Cal Poly Avila Pier.

Background

Existing solutions

The type of system that best meets the needs of the project that currently exists is a remotely operated submersible with a camera system. This will provide a benchmark for the project and set standards for user control, maneuverability and positioning of the camera, image, video quality, and maintenance. Figure 1 represents an example of such a system.

Figure 1: "Sea Lion" ROV from JW

A shortcoming of this type of system for the desired application is image stabilization. Overcoming this challenge will be the focus of the project. It is also important to note that some functions of a remotely operated submersible such as depth rating may be unneeded and would only add cost and complexity to the project.

Another system that is currently in use that is similar to our project is the underwater dive camera utilized in the Olympics[4]. This system runs on the inside of a single track and views through a plastic sheet sealed to the track. A similar design would protect the camera from the seawater. An image of the system is provided in the following figure.

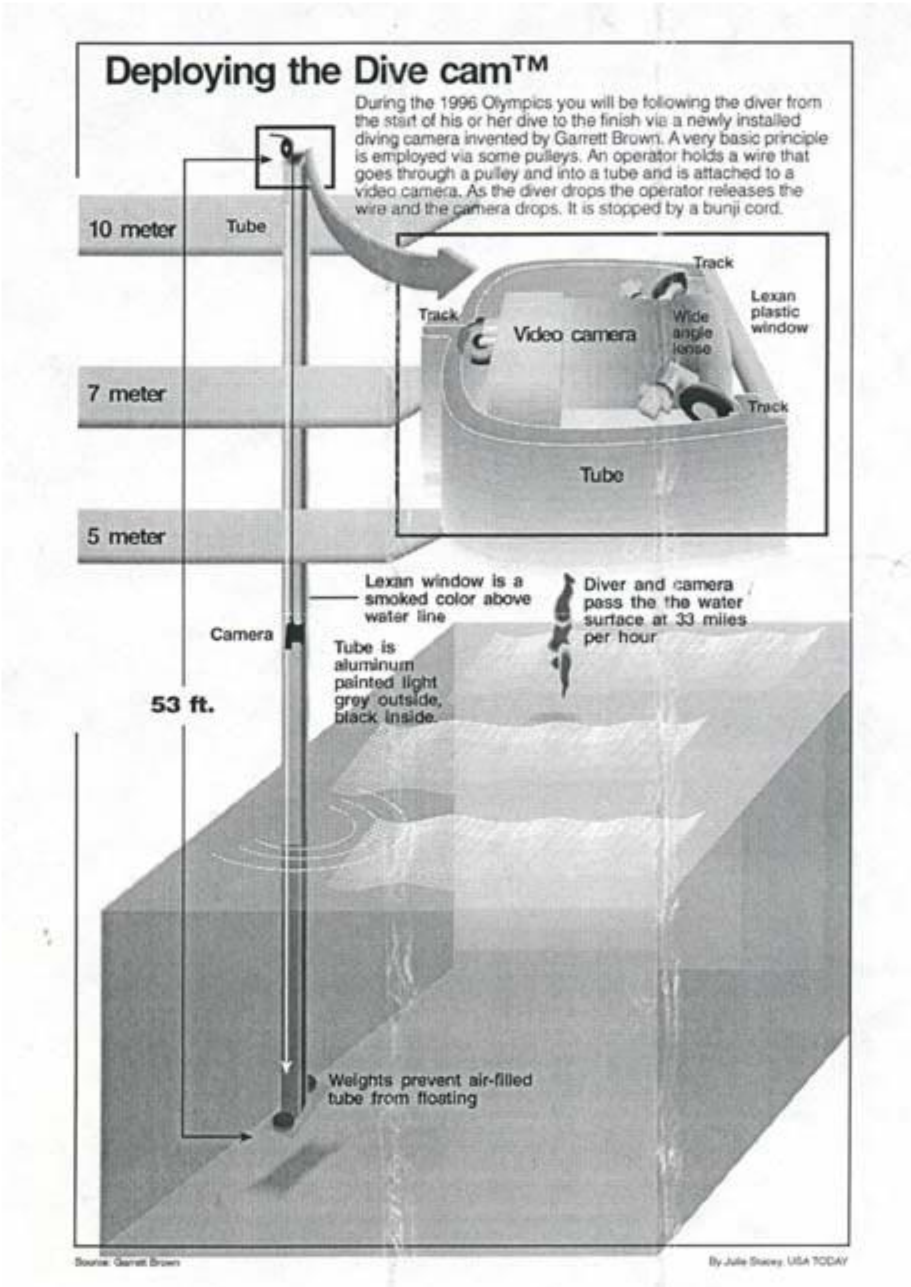


Figure 2: Dive Cam Used in the Olympics http://garrettcam.com/divecamDoc.htm

Lastly, there is the Center for Coastal Marine Sciences data profiler. This system is already installed at the pier and is also controlled automatically. Periodically the system is lowered into the water via a winch. Although this system does not utilize a camera, it does provide some insight into problems that can arise due to the marine environment and also the capabilities of the pier staff for maintenance. One aspect that was implanted in the data profiler was a fresh water rinse, and when this stopped working, a noticeable difference was seen in the corrosion resistance of the materials. Other noticeable features are safety shut-off switches to be used in an emergency. The most similar aspect from the data profiler is the winch, which is currently an aspect of both of our surviving designs.

Codes and Standards

The system we design will be maintained and assembled manually so an understanding of OSHA codes applies. We must ensure the system is safe to assemble, use, and maintain. Since the system will operate outdoors in a marine habitat, we must ensure the system does not violate EPA standards or any other applicable environmental regulations. This particularly applies to the release of fluids into the ocean which would be deemed as hazardous to the environment by the EPA. ASTM standards will also provide a guideline for generic testing of components and materials.

Research

Extensive research is being gathered on existing ways to solve the design problems associated with this project, as well as the various design considerations from external influences. Such considerations include protection against corrosion, cleaning off algae and encrusting organisms such as barnacles, and protecting from tidal and impact forces. Some considerations such as impact forces have been researched and can be incorporated into most foreseeable designs but other considerations such as corrosion will be dependent on the nature of the design.

Scope

Another important consideration, as with any design project, is the scope of problem solving through raw design. A camera system with separately designed degrees of freedom, housing, and electronics could be an inferior choice to simply using an existing camera system that provides some or all of these needs. Such a possibility is pictured below in Figure 2. This camera system is capable of panning, tilting, zooming and focusing.

Figure 3: Camera from Outland Technology with Multiple Degrees of Freedom

This type of research is vital because most of the sub-problems we will encounter in the design process have probably already been solved to a certain extent by other engineers.

Materials

Material selection is particularly important in regards to the marine environment in which the system will be operating in. One option found so far is to use molybdenum containing stainless steels such as AISI 316L/ASTM CF3M or 2205/2507 flavors of duplex stainless steels. “Marine Corrosion: causes and prevention”[8] gave different options on how to protect materials in marine environments. These include applying a current to the material, coating the material, or using sacrificial galvanic anodes such as zinc. Specific coatings mentioned were epoxy, vinyl rubber, and polyurethane. Sacrificial anodes such as zinc are commonly added to steel structures underwater. In the types of conditions present at the pier, we can expect a zinc depletion rate of 25-48 mm per year.

“Corrosion of Stainless Steels”[14] provides an expansive breath on the subject of stainless steels in which specific blends of 316 could be analyzed. 317 is actually more corrosion resistant than 316, but is very rare and expensive. 316N is stronger than the 316L version but also less common. “Stainless Steels for Design Engineers”[10] suggests that 316 stainless is only marginally successful in marine environments. It suggests that 316 is not commonly used anymore and that the only commercially viable form of stainless steel are the duplex grades. Most common forms of this steel are 2205 and 2507 alloys. A basic cost analysis yielded that duplex stainless flavors are twice as expensive as commonly found 316 flavors.

Other non-ferrous options include composites and plastics. Plastics are well known as to be non-degradable in the marine environment. This includes acrylic, ultra-high molecular weight polyethylene, and nylon, all of which have different strength materials. Composites such as Fiber Reinforced Plastic (FRP) tend to also work well in the marine environment as long as water is kept from the inner plies. This means that the entirety of the outer surface of the material must be coated in either a resin or acrylic coating because the fibers absorb up to 20% of their weight in water. Ted R. Morton author of “Fiber-Glass-Plastics for Corrosion Control”[19] suggests a 90% resin 10% glass outer layer.

Environmental Factors

Although material selection specifically relates to corrosion prevention, there are other environmental factors that will affect our system. One environmental factor that is specific to the tube concept design discussed later in this document is the change in temperature day to day and year to year. This can cause the tube to expand and contract which means that the brackets which hold it must be able to allow vertical movement.

Sea Life

Sea life is a major concern. Encrusting organisms such as barnacles will attach to surfaces, which can hinder motion in our system underwater and prevent the camera from getting a clear picture. The customer needs specify a self-cleaning system, so research is being done on what it will take to keep the system free of encrusting organisms. Information has been gathered on the suction surface pressure or “tenacity” of barnacles of different sizes. It has been found that a force of 6 N should be sufficient to remove encrusting sea life impeding the motion of the system. Average shear forces for barnacles range from 4.75 ± 0.387 to 6.0 ± 0.385 N. This data

will be needed if the system is designed to remove barnacles automatically. Information is also being gathered on barnacle growth rates so it is known how often the self-cleaning should take place. Any barnacles that form on any sort of view surface such as a camera lens cannot be fully removed by scraping. A thin residue is left behind from an adult barnacle that can only be removed by strong acids.

Larger organisms such as seals are also being considered. Impacts from such organisms will cause damage to a system not designed to take appropriate impact forces. Research and preliminary calculations have been done on the largest expected impact the system will encounter. Initial calculations use the largest local animal, a male northern elephant seal, to determine impact forces. A typical impact from this animal on our system will be between 3 and 4 kN. This number is based on average weight, swimming speed, and blubber consistency[12]. Wave forces are also analyzed to determine needed strengths.

Kelp can grow around or drift into the vicinity of the system so it is important the camera system is able to submerge and surface through kelp. The mean breaking stress of kelp has been found to be 3.64 MN/m^2. The average density of kelp can be used in a calculation with a given surface area to determine the amount of kelp the camera system will have to overcome.

Fresh water rinse

Whenever any components of the system surface out of the sea water, it will be necessary to apply a rinse of fresh water to rinse off any organisms and remove corrosive sea water as well as salt from any component housing. Such a system will also prevent the growth of algae. The camera needs a clear view path through the lens and any clear housing so all of these surfaces must be kept clean.

Camera system

In order to optimize camera feed for viewing, research into elements of underwater photography and into camera motion is being done. Effects particular to underwater video will be discussed first followed by research into camera motion.

Underwater Photography

Underwater photography presents two major issues not found on land: backscatter and color loss. These two topics and the means to reduce their effects are discussed below.

Backscatter

Backscatter is a loss of clarity in a photograph or video feed due to particulate matter between the camera and subject. This is common underwater, especially in areas with low underwater visibility such as ours. Visibility at our site ranges from inches to 30 feet but is typically around 5 feet. The necessity of strong lighting while taking pictures/video underwater amplifies backscatter much as high beams do while driving in a snowstorm or heavy fog.
The most common approaches to eliminating or reducing backscatter involve positioning of the lighting in accordance with conditions and subject. Typically, lights are fitted with diffusers and

aimed slightly away from a subject to allow an increase of ambient light without directly lighting up particles between the lens and the subject.

Color Loss

Color loss in underwater photography occurs even in the shallows. Light is absorbed by water according to its energy level. For example, red light has the lowest frequency and energy level of the visible light spectrum. In optimum water conditions with ideal equipment, red light is lost in approximately 15 feet of travel. Orange and yellow are the next two colors to be absorbed followed by green. Color loss is a function of distance and depth, so planning is relatively straightforward. To prevent color loss, there are four aspects to balance: Distance, Lighting temperature, Filtering effects, and Light intensity.

Distance from light to subject to lens

The farther the light must travel, the more color will be washed out for a given lighting system.

Lighting temperature

Temperature refers to lighting wavelength or energy. You want to supply more low energy light in an underwater environment.

Filtering effects

By applying red, orange, or yellow filters at the camera you can achieve a different perceived lighting temperature at the camera than what you have actually supplied.

Lighting intensity

Filtering dims the total amount of light allowed into the camera, so lighting intensity must be increased as filtering levels increase.

Camera Motion

With intent of optimizing a video feed from our system comes the hope that the feed will not make someone sick while viewing it. Simulated motion sickness is a documented ailment where subjects can feel “car-sick” while viewing a moving screen. Motion sickness is a condition in which the body’s sensory systems disagree with how the body is moving, i.e. the eyes *see* one thing while the body *feels* another. It is widely hypothesized that the body assumes that it has been poisoned when this happens and begins to induce vomiting.
Two major factors seem to play a role in simulated motion sickness: jerk and vibration.

Jerk

Jerk is the rate of change of acceleration. The army[17] suggests keeping jerk below 0.1 ft/s^3

Vibration

Vibration rates in the range of 1-2 Hz have been clinically proven to cause motion sickness, regardless of whether the subject is being moved or the subject is viewing a simulator. In a separate test, random oscillatory movements of 0.13 - 0.17 Hz have been deemed acceptable by 99.5% of test subjects[17].

Objectives

This project has many goals; first and foremost it is a project that will give many users the ability to view sea life along the Cal Poly Avila Pier. This will be accomplished by viewing a single piling of the pier and have the ability to be controlled by the user.

Lastly, we are hoping to leave Cal Poly with a system that will work for years to come and enable future projects and research at the pier.

We started our project by visiting with Tom Moylan to gather some of the requirements for our project. After refining the specifications we set out to make a list of technical specifications based on our initial customer specifications (Appendix A). These technical specifications must be quantifiable, measurable, implemented in a well-made system. After constructing the two lists, we verified the validity of the technical specs using a quality function deployment table (the QFD is viewable at Appendix B).

QFD Progression

The House of Quality (QFD) was developed in two main stages. The original rough copy with handwritten values and notes is included along with the final version. Components of the QFD are discussed below and then modifications for the final version are described.

Components of the QFD

- **Customer Specifications**
  Specifications that our main customer, Tom Moylan, wants in the final product. This list is in gray at the left of the QFD.
- **Customers**
  All prospective users of the product are listed here for the purpose of evaluating the interest level each would have for each of the customer specs. This section is in salmon at the top left. Customers are ranked against each customer spec according to interest level on a scale of 0-5 with 5 being very interested.
- **Benchmarking**
  Three products which are comparable to our project are listed in salmon on the upper right of the spreadsheet. These products are ranked on how well they fulfill each customer spec using the relationship symbols defined in Table 1 below.
- **Technical Specifications**
  These specifications are more advanced versions of the customer specs and are backed by research. The specifications are in gray along the top of the QFD. The units and ranges associated with each spec are located along the bottom in salmon. The center of the spreadsheet shows the relationships between each tech spec and customer spec. Relationships are denoted using the symbols shown in Table 1.

Table 1: Relationship Symbols used in QFD

Strong Relationship	●
Some Relationship	○
Weak Relationship	Δ
No Relationship	

- **Risk Assessment**
  A single red row at the bottom of the spreadsheet evaluates the risk assessment associated with each tech spec. Ranking is based on the repercussions of a failure to meet each spec. Rankings are low, medium, and high and are denoted by L,M, and H respectively.
- **Compliance**
  This table forecasts the steps we will take toward ensuring each tech spec is complied with. The symbols used are listed in Table 2.

Table 2: Tech spec compliance symbols

A	Analysis
T	Testing
S	Comparing to existing products
I	Inspection

QFD Revision

In revising the QFD, we found a number of issues. Two customer specs were found to be unaddressed by any tech specs. Limits on vibration of the camera feed and forces required to surface through kelp were not included in the original spreadsheet. Additionally, performing a risk assessment and forecasting our compliance methods were not included in the first draft. Lastly, the spreadsheet was cleaned up grammatically and colored to help compartmentalize the sections.

Design Development

The first step that we have taken is to collaborate with our sponsor to make sure that the customer specifications are agreed upon by both parties. From here we developed a list of engineering specifications to further detail the requirements of our design. This provided a foundation for brainstorming ideas, which was used to formulate into multiple designs. These were narrowed down to two ideas and compared via a weighted decision matrix. The design chosen will be well supported by analysis and feedback from our sponsor.

Utilizing our sub-groups, we will begin to hone the design of components and sub-systems, including CAD drawings and BOM. Some portions of the system can begin to be built concurrently in order alleviate pressure later on in the build phase.

An important part of ensuring all the requirements are met, is having constant communication with our sponsor. We will be taking time to meet with our sponsor about once a month. Once a final design has been selected, the construction of each sub-system can begin. Once each sub-group finishes their part, each component can be tested. Three major areas that must be tested are the camera's performance at depth (i.e. waterproofing, visibility, lighting), the movement of the camera along the track, and the ability to control the camera from a laptop computer. These tests will be performed with full-scale prototypes before assembly of the entire system at the pier. A detailed test plan shall be presented to Tom before testing begins. After the successful completion of component testing, the system shall be installed and more extensive complete system testing shall be completed. This should be completed so that, ideally, at the design expo, guests can operate our Pier Portal camera at the pier from the expo at Cal Poly.

Top Concepts

The top concepts for this project were developed from initial idea sketches. Each team member contributed to this process. These ideas were discussed in detail and aspects of certain designs were combined to develop the ideas further. The ideas everyone thought were feasible were developed through research on solution, analysis, cost estimation, and physical modeling. The top two ideas were narrowed down by this process and were compared using a decision matrix. The two ideas were a "roller coaster" track and pod and a clear tube and pod. Both ideas were determined to be feasible and good solutions and nearly tied for best design in the decision matrix.

"Roller Coaster" Track

This design is developed from the concept of a roller coaster track system. It consists of two rails connected to brackets on the piling upon which a waterproofed camera pod can roll up and down on. Rollers grip the rails and provide smooth travel. Sliding collars may also be used to ensure the track is kept free of algae and encrusting organisms. A winch at the top of the piling on the

pier pulls the pod up. The pod moves down by its own weight as guided by the winch. The following figure shows a concept sketch of such a camera pod and track.

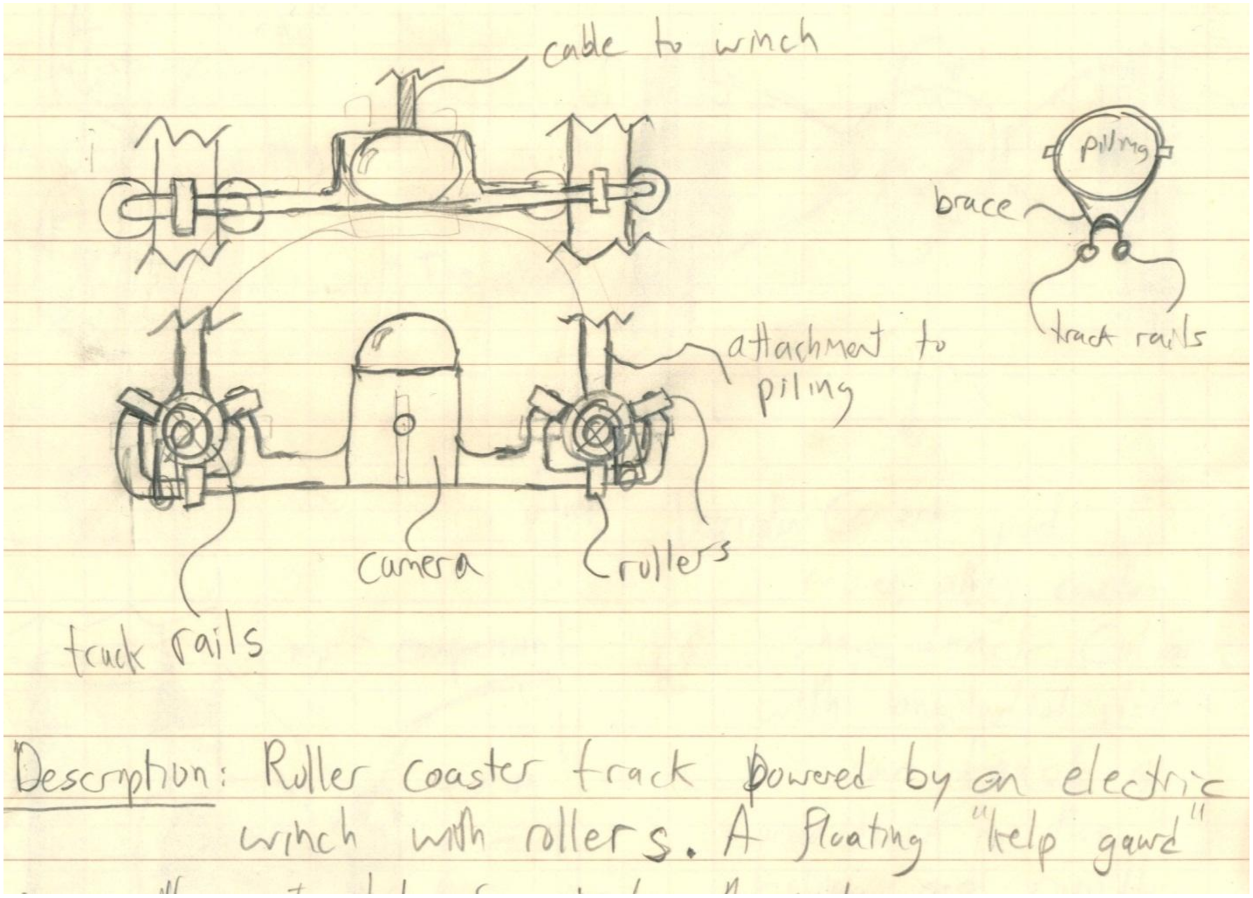


Figure 4: Concept Sketch of "Roller Coaster" Design

Analysis overview

The critical aspects of this design were analyzed. One of the most important considerations is the shape and material of the track. Various shapes were considered and sketched to visually understand how the camera pod would attach. The main considerations were corrosion and structural integrity. Various metals were researched, including types of aluminum, steel, stainless steel, and FRP. Selections were made based on yield strength and corrosion resistance.

Structural Integrity

The types of forces our system is being designed for are from sea life and ocean waves. Worst case scenario sea life impact was chosen as an average speed collision of a male northern elephant seal. Worst case wave forces were estimated from analysis done by UNOCAL on the pilings. Seal impacts were determined to be the most critical with an impact force of around 800 pounds. This value was used to select track sizes. An example of the analysis done to select track appears in the following figure. The failure mode analyzed was bending with a 15 foot span of

track. All calculations were done in MS-Excel™ to generate the data. At this point, the decision will be made based on cost. We are looking into sponsorship for the track material since 120 feet of track will be needed.

Track selection for dual rail design

elephant seal max M (lbf*in)	stainless steel max stress (psi)	aluminum 6063 max stress (psi)	aluminum (6061t6) max stress (psi)	price for 120' onlinemetalstore.com shipping $275
47794	40000	21000	40000	

square ~~channel~~ tube

outer (in)	thickness (in)	inner (in)	stress	s. f. (steel)	s. f. (6063)	s.f. (6061)	Price ($)
2	0.1875	1.625	63534	0.63	0.33	0.63	
2	0.25	1.5	52437	0.76	0.40	0.76	
2.5	0.1875	2.125	38396	1.04	0.55	1.04	2440.5 [1]
3	0.125	2.75	36134	1.11	0.58	1.11	**688.65 [2]** 555.6 U[5]
3	0.1875	2.625	25666	1.56	0.82	1.56	
3	0.25	2.5	20514	1.95	1.02	1.95	1523.84 [4]
4	0.125	3.75	19693	2.03	1.07	2.03	1047.28 [4]
4	0.1875	3.625	13766	2.91	1.53	2.91	

pipe

outer (in)	thickness (in)	stress	s. f. (6061)	Price ($)
2.375	0.154 (2" sche 40)	85251	0.47	
2.375	0.218 (2" sche 80)	65392	0.61	
2.875	0.203 (2.5" sche 40)	44918	0.89	
2.875	0.276 (2.5" sche 80)	35705	1.12	1586.64 [3]
2.875	0.276 (2.5" sche 80)	35705	1.12	1361.00 [2]
3.5	0.12 (3" sche 10)	45906	0.87	
3.5	0.216 (3" sche 40)	27721	1.44	1568.64 [3]
3	0.25	34825	1.15	

[1] (stainless steel)	[2] (6061 - t6)	[3] (6061 - t6)	[4] (6063-t52)
onlinemetalstore.com	onlinemetals.com	onlinemetalstore.com	onlinemetalstore.com

shipping =

[5] metalsdepot.com (A500 steel)

Figure 5: Analysis of Track Options

Corrosion

Sacrificial anodes will be needed to protect against corrosion in the tidal zone and underwater. Observations at the pier indicate this is the only area where corrosion will be an issue. Research was done to determine what kind of maintenance will be needed to implement sacrificial anodes

but enough information on this already exists at the pier. Other materials being considered for the track are stainless steel, which has high corrosion resistance and aluminum. Aluminum oxidizes immediately and that oxidation layer is supposed to protect it against further corrosion. There are many sources that cite aluminum[18] as performing well in seawater. Titanium performs exceptionally well in seawater because of the oxide layer that forms very quickly to prevent corrosion.

Satisfying Design Requirements

The track satisfies the goal of the project by self-cleaning, providing virtually un-impaired viewing of the piling, having the ability to move up and down, resisting environmental factors, and being cost effective. This system will also allow the camera to see the entire 40 feet of underwater piling. This track will have no problem surviving an impact from a Northern elephant seal nor will require more than four divers to install. The distance from the camera to the pier will be fixed by the track. Effects of jerk from variations in acceleration will be minimized by having the winch rotate at a constant speed other than stop and start points. For these points we will ramp up and the power slowly. Vibration concerns will be minimized because the rigidity of the track will cause all frequencies to be high enough that they are unnoticeable. This assumes that the amplitudes are very small. The camera pod will have a small sealed section with outboard lights so that the effects of pressure at depth will be minimized. The out of water part of the design will have both manual (push button) and automatic safe shut down features, to prevent injury or destruction of the apparatus. This would include having the ability of an onsite operator to take over control of the system. The track will be installed about a meter under the sand so that the camera pod can reach the sea floor regardless of the seasonal sand level. It will also have a sensor that will tell the system how far down it should go before stopping. The entire system will not need more than two people for maintenance because the design will be modular so that no one piece is heavier than what two people can carry.

Testing the Design

The mechanics of moving up and down on the track will be tested in full scale with a short section of track. Modifications will be made to the gripping/sliding mechanisms. During this time, the waterproof casing will be tested. This will be sent to the bottom of the sea floor, slightly deeper than the lowest depth expected at the pier, without a camera. Another test that must be performed is the susceptibility of support cable to vibrations from waves. Predictions can be made with vibration analysis but manually tuning the tension in the cable may be necessary. The scraping mechanism will also be tested out of water in order to make adjustments so that a compromise is made between cleanliness and friction. This system will also be tested extensively after installation. This means that the installation date must be around a month before the proposed finish date.

Clear Tube

This design consists of a clear plastic tube that lies parallel to the piling and runs from the seabed to the pier deck. The tube will be mounted into the sea floor and attached to the piling with metal brackets available for use at the Cal Poly pier. The camera pod will run on the inside of the tube so it is protected from the seawater and other environmental factors. A winch pulls the pod up and the pod is lowered with its own weight. The main purpose of this design is to protect the camera from the corrosion issues inherent in marine environments. It will also allow for a versatile view because the camera pod can rotate inside the tube. The following image shows a concept sketch of the idea.

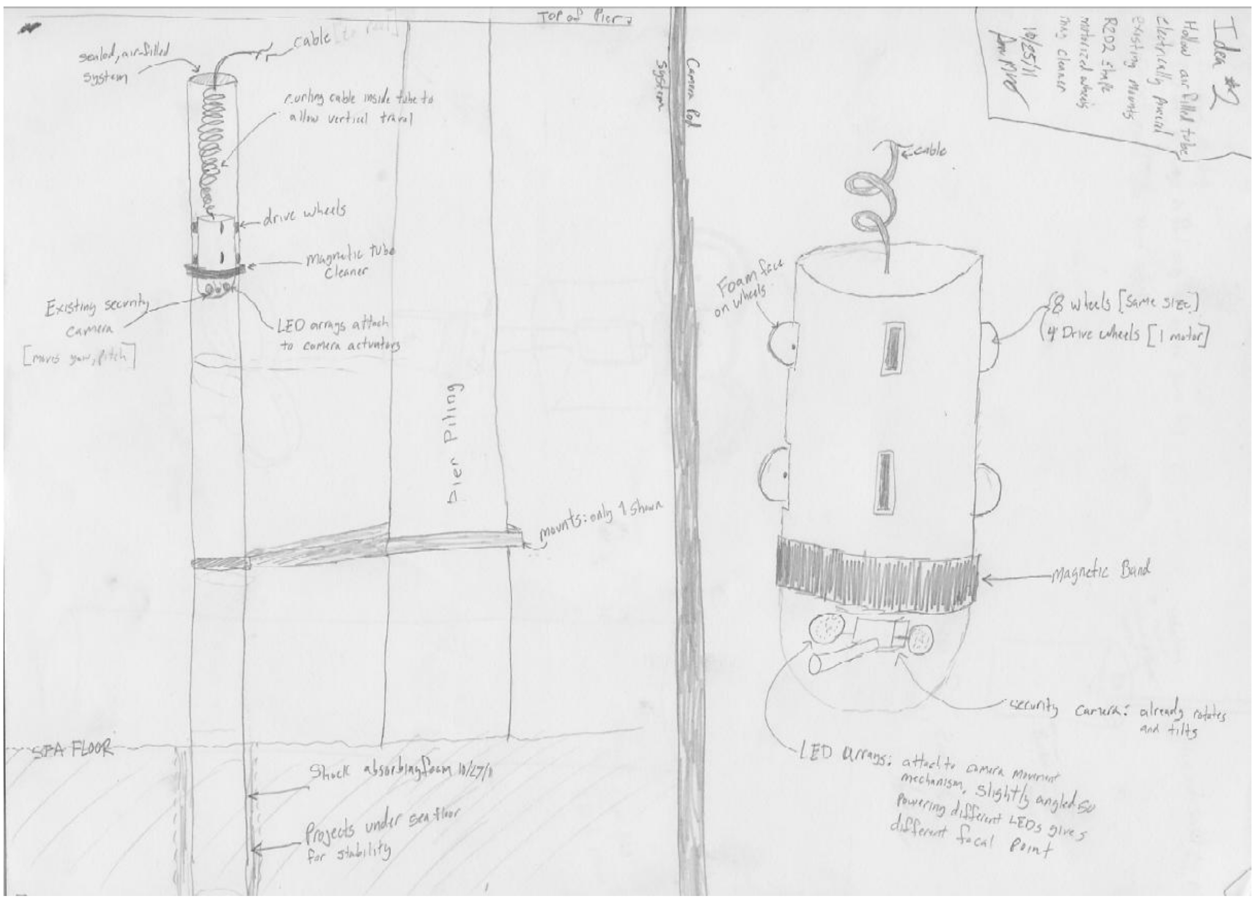


Figure 6: Conceptual Sketch of Camera Pod inside Clear Plastic Tube

Material Selection

Five families of plastics were considered for this design. Initially strength requirements guided the analysis towards acrylic and polycarbonate. When it was discovered that polycarbonate critically fails by losing all optical clarity and surface integrity when exposed to saltwater, analysis shifted to look at what was recommended in a marine environment. Acetal, PVDF, and Viton™ were all highly rated for resistance to seawater exposure. Acetal and PVFD were both eliminated because they aren't clear. Viton™ is much too flexible to be considered. This process leaves acrylic as the clear solution because it has good optical quality, performs well in seawater, is similarly priced to stainless steel, is strong, and has been proven effective in large scale aquariums.

Impact and Pressure Resistance

For this design, the tube acts as the structure and prevents seawater (or salt air) from contacting any moving parts. Because of this, analysis to the tube includes very conservative estimates of internal stresses with the goal of a high factor of safety. Stress analysis roots from three sources: pressure forces, buoyancy forces, and an 800 lb_f impact force. Although it is not possible for the impact force to occur in the middle of two supports and be at the highest pressure possible, that is the assumed worst case scenario.

In Appendix E, pressure stresses are calculated symbolically and calculated in spreadsheet form. Ocean density is assumed to be constant but is calculated based upon salinity and temperature values in our area. While pressure at the sea floor is only in 20 psi, the pressure stresses are the dominant stresses (until considering local stresses).

The analysis indicates that a 6 inch outer diameter tube that is ¼" thick would have maximum shear of 2365 psi and minimum stress of 6618 psi. This gives a safety factor of 2.6 in compression and 7.2 in shear.

Other considerations

Cleaning is going to be especially critical since any growth on the tube will impair viewing. A fish tank type magnetic cleaner is being considered to clean the outside of the tube automatically as the camera pod moves. If this design is selected, a magnetic ring which snugly presses a soft scrubber to the outside of the tube will be located between each set of brackets. The camera pod will also have a magnet and its movement will drag the cleaning ring on the outside of the tube. We also have permission from pier administrator Tom Moylan to mandate monthly cleaning on a small scale (not the entire tube). Optical quality is also an important consideration since the camera will be looking through a curved surface and the tube may be scratched during its life.

Fortunately, water and acrylic have nearly identical refractive indexes so any scratches on the outside will be filled with water and should be close to invisible. A Go-Pro© camera was used inside a scratched up piece of 6”acrylic tube with very optimistic results. Even with air outside the tube optical quality was very good.

Condensation inside the tube could also impair viewing so a pump and/or blower may be used. A pair of sponges above and below the camera which contact the inner walls of the tube are also being considered.

Satisfying Design Requirements

The tube satisfies the goal of the project by being cleanable, providing un-impaired viewing of the piling, allowing for extra viewing directions, having the ability to move up and down, resisting environmental factors, and being cost effective.

Testing the Design

Optical quality is one of the biggest concerns so a sample of acrylic tube with a camera inside will be submersed in water. Initial tests in air show great results but a submerged test has not been performed yet. The next hurdle is to test methods of joining tube lengths together for sealing ability and strength.

Management Plan

The responsibilities of the Pier Portal team can be broken down into five main categories. A person or group of persons will focus on each one of the categories to ensure balance and high productivity.

Team Member Roles

1. Documentation of project progress:

Andy Crafts will thoroughly document the progress of the project. This includes keeping detailed logs of team meetings, records of design ideas, and any data or information gathered from testing and analysis.

2. Team Administrator

Jeremy DePangher will maintain a role as team administrator. This will include sending out group emails, scheduling, planning group events, and creating deadlines. Any administrative paperwork, including reimbursement forms for travelling, are included in this role as well.

3. Manufacturing Coordinator:

Aaron Hein will be in charge of manufacturing considerations. These considerations will include contacting manufacturers for information about existing products, searching for necessary parts for the project, as well as purchasing those parts.

4. Prototype Fabrications:

Michael Machado will be in charge of fabricating the prototype. Michael uses the on campus shops regularly, so he will have the best insight on planning when our project can be built. While Michael will be coordinating these activities, each team member will be involved in helping to make models as well as fabricate the final design.

5. Testing:

Aaron Poulos will create the testing plans. After the entire team determines its top few initial designs, we will make a decision about which ones are to be fabricated for testing. Aaron will determine the steps involved in testing the design. He will also organize the test data so that Andy can log it.

6. Designing of subsystems

The pier camera project must be divided into three main categories. First, the mechanical system and choices about the materials must be made. Aaron Poulos and Michael Machado will be responsible for these considerations. Second, Aaron Hein and Jeremy DePangher will create the control systems that govern the entire structure. Andy Crafts will be helping in this role, as well as focus on creating the web interface, which will make the system capable of streaming to the public. (The completion of the web interface may be outside the scope of the project. See QFD.)

Timetable of Milestones

The following is a timetable of project milestones that will be relevant to our sponsor, Tom Moylan. This schedule includes monthly meetings with our sponsor. The tasks may vary, depending on the demands of the project. This table was used to set goals but does not necessarily reflect the actual progress of the project.

Table 3: Table of Milestones

Deliverable	Date Due
Conceptual Model/Meeting with Sponsor	11/1/2011
Conceptual Design Report	12/1/2011
Conceptual Design Review/Meeting with Sponsor	12/5/2011
Final Design decided	12/10/2011
Critical Design Review with Sponsor	1/5/2012
Design Report	1/31/2012
Scaled prototype built/Meeting with Sponsor	2/1/2012
Meeting with Sponsor	3/1/2012
Complete prototype built	3/16/2012
Project Update Memo to Sponsor	3/26/2012
Meeting with Sponsor	4/1/2012
Meeting with Sponsor	5/1/2012
Hardware demo	5/7/2012
Design Expo	5/28-6/1/2012

Final Design

<u>Overall Description</u>

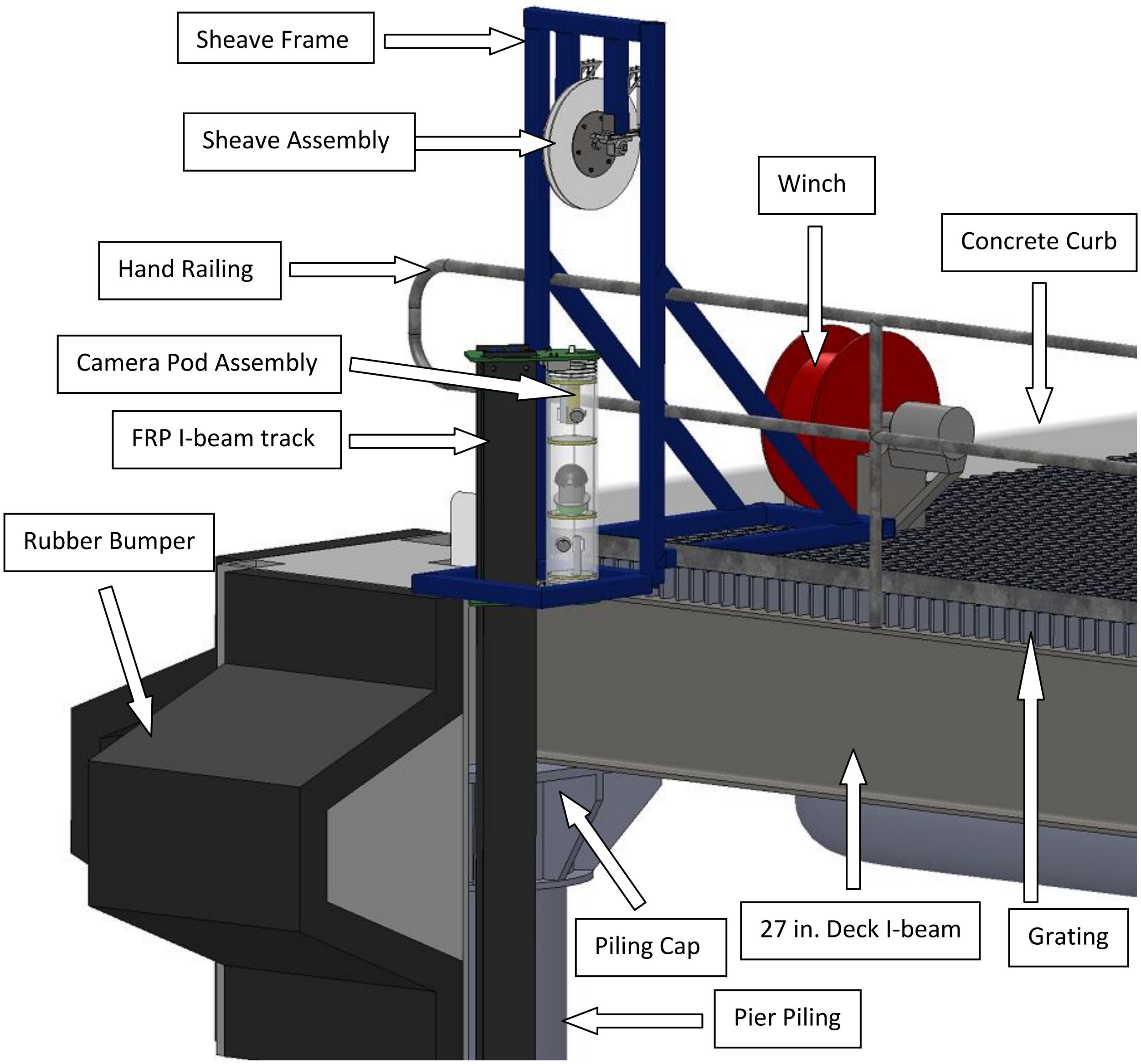


Figure 7. Pier Corner View

The final design utilizes a Fiberglass Reinforced Plastic (FRP) I-beam purchased from Seasafe®. A cart that holds the camera pod will be attached to a power and data cable by a cable grip. The cart will be moved up by a winch that spools the cable and a pulley (sheave) that keeps the cable above the center of mass of the cart. This winch will be attached to the pier deck and the pulley will be attached to a frame that also supports the open air housing (dog-house). The I-beam will be supported by 5 existing stainless steel brackets. In order to attach the I-beam to the mounting brackets we will have a mounting plate to mate the two.

Detailed Description

The following sections describe components of the design individually.

Camera Cart

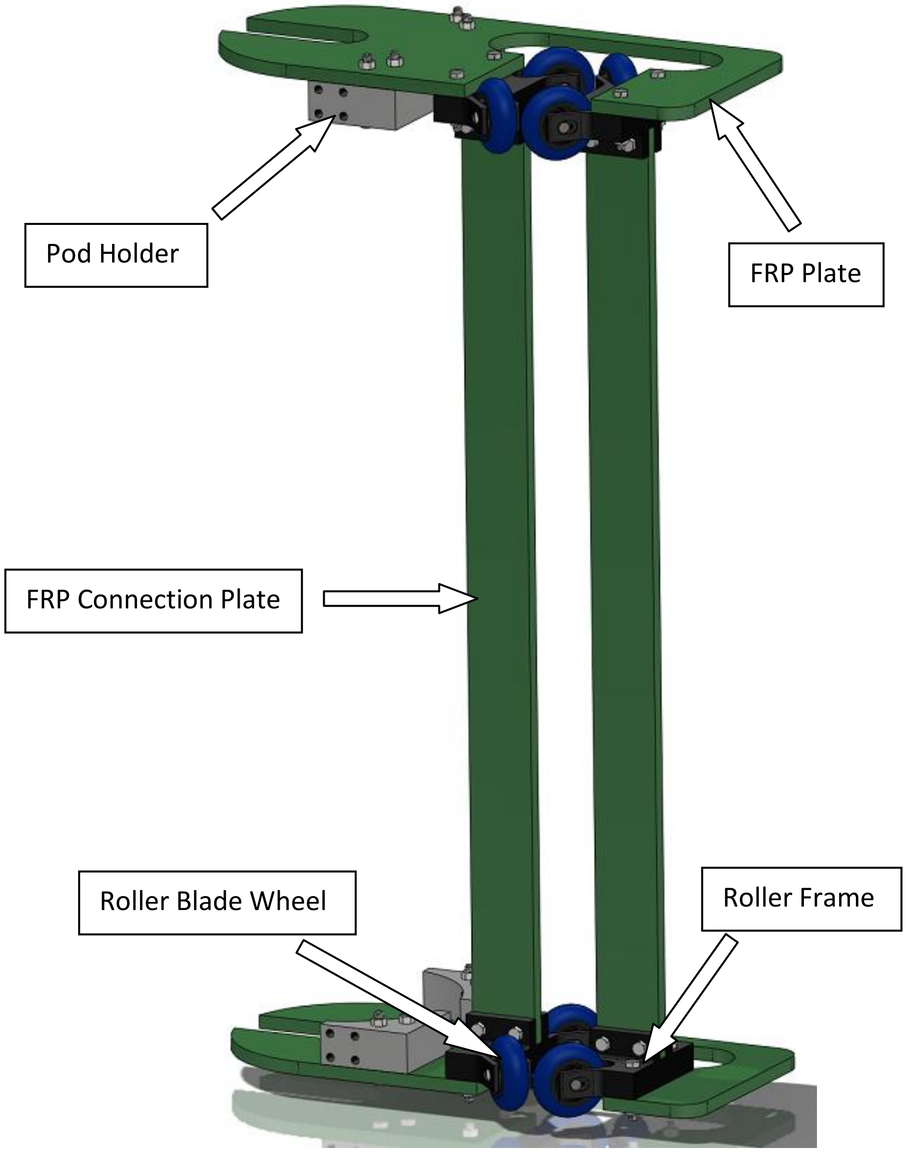


Figure 8. Cart layout

The camera cart holds the camera pod and allows for movement along the I-beam. Eight roller blade wheels will fit into the fillets on the inside of the I-beam to provide smooth rolling and secure attachment to the track. The cart will have an FRP plate on top and bottom that secures the camera pod, allows for the cable to enter the camera pod and provides a location for the cable grip to attach to the cart. This plate will allow the camera to look from the side of the I-beam because the I-beam will be in front of the pier. The FRP plate will be the same on top and bottom. Two long FRP connecting members will span the length of the cart and will ensure that

the camera pod will stay attached to the cart at all times by securing both sides of the cart. Straps also hold the pod into the cart. The roller frames hold the wheels in the proper location while also allowing for spring movement of the wheels so that they can negotiate any inconsistencies in the construction of the I-beam or sea life growth. Also to address sea life growth, there will be brushes to keep encrusting organism larvae off of the track.

Camera Pod

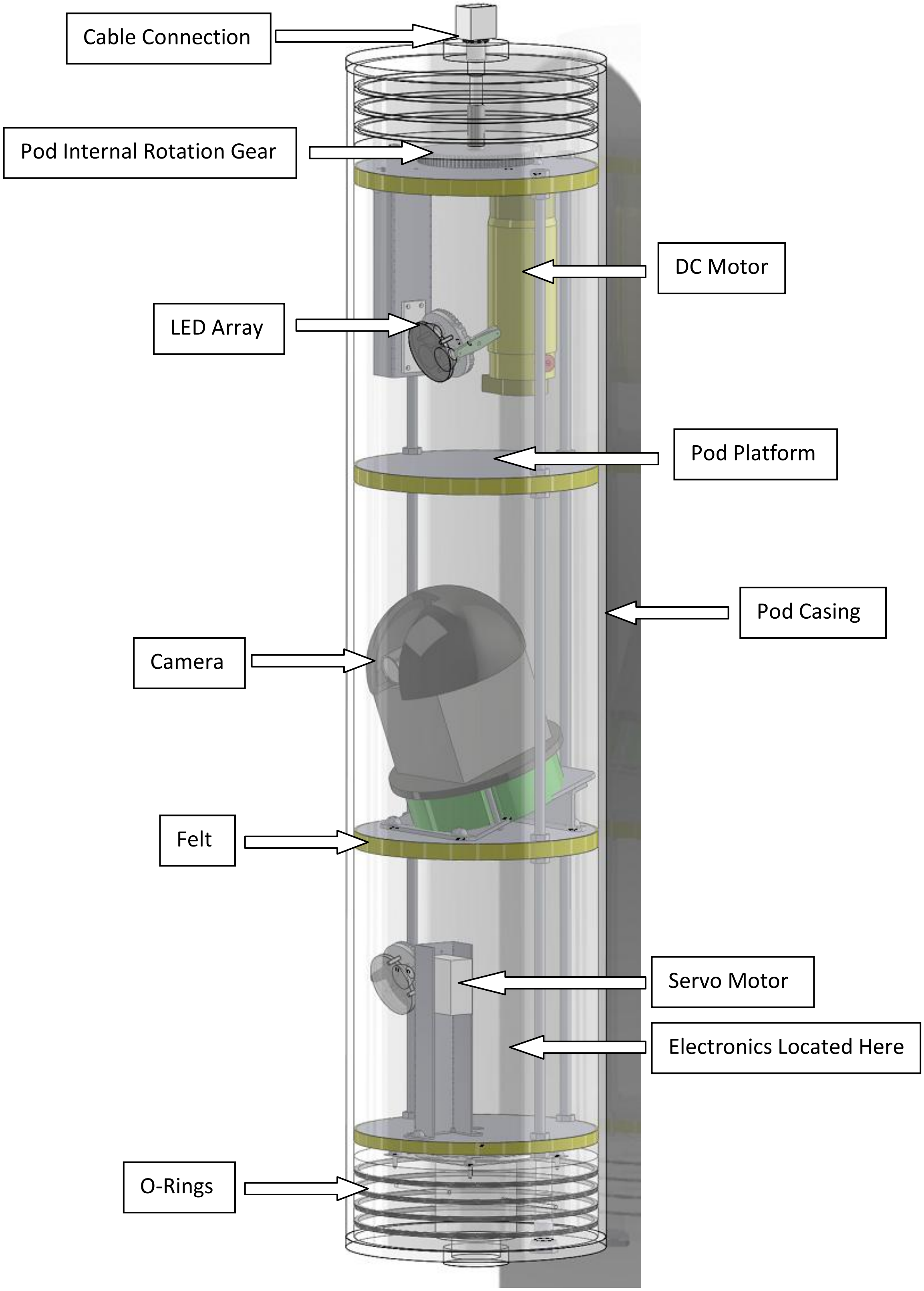


Figure 9. Camera Pod Layout

The camera pod is designed based around a piece of extruded 8" outer diameter acrylic tube. The material lends itself well to the project due to its corrosion resistance, UV resistance, and optical qualities. Additionally, initial analysis for the tube proved that it would be feasible for our loads at a 60' length, so the 3' length required for our pod is a shoo-in as a material choice. In the drawing below, the exterior tube is ommited for clarity.

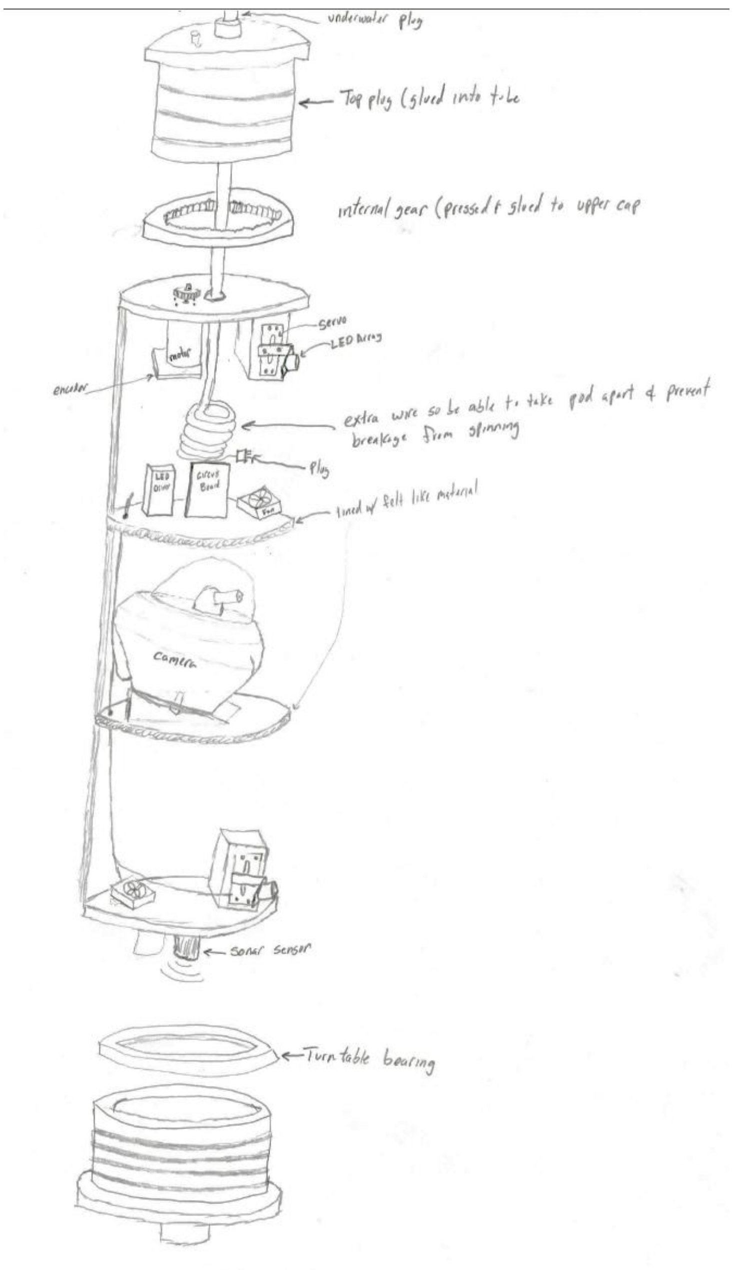


Figure 10. Camera Pod Assembly

The end-caps for the pod will also be made from acrylic. The caps will both be machined from 7.5" acrylic rod and will have only minor differences. The upper cap will be glued to the tube and will have an oceanographic wiring connector penetrating the cap immediately in the center. The upper cap will also have an internal spur gear pressed into it and glued which will allow the internal structure to rotate relative to the tube. This movement will be described in detail in the next paragraph. The lower cap is removeable and will offer four sealing surfaces via O-rings. A hollow in the center of the cap will allow room for periphary sensors which will be discussed shortly. The bottom cap will also support a turntable bearing which allows the support structure to rotate with minimal friction.

The inner support structure of the pod is to be made from Delrin® sheet and will have 4 platforms as shown above. The area in the center will house the camera. The upper and lower portions each contain a light array and a small fan. The lower section will contain the microcontroller board, LED driver, and a voltage step-down device. A motor will be housed in the upper section and its shaft will protrude through the upper platform to a spur gear which will mate with the internal gear described in the cap section above. This will rotate the entire structure so that lights and camera automatically pan together. There will be some friction between the structure and tube at the light-insulating interfaces, and at this point those forces, motor torque, and gear ratio are still to be determined.

The central compartment of the pod will be insulated from light reflections eminating from the other sections by a thin layer of felt-like material around the edge of the platforms above and below the camera. The camera will be installed at an angle as shown so that its tilt function has the capability to look downward (as opposed to if it was mounted flat). The pan function of the camera will not be used. The motorization of the entire structure wastes some of the camera's capabilities but saves much effort by making no separate pan action of the lighting necessary.

All necessary electronics for the pod will be housed in the lower section. Also, cable will run from the oceanographic connector in the upper cap to ordinary connectors for the electronics in the pod. 2.5' of extra wiring will coil in the upper section behind the lighting to allow the inner support structure to drop out of the tube far enough to unplug the interior connectors. This will also prevent the rotation of the inner structure from damaging any wires from twisting.

The lighting will consist of two LED arrays of 3 LEDs a piece. Each array will be mounted to the arm of an RC servo motor, which is in turn mounted to the inner support structure. Software on the MCU will drive the lighting to track the camera's tilt and zoom features. Selection of the servo motors is detailed in the following figure.

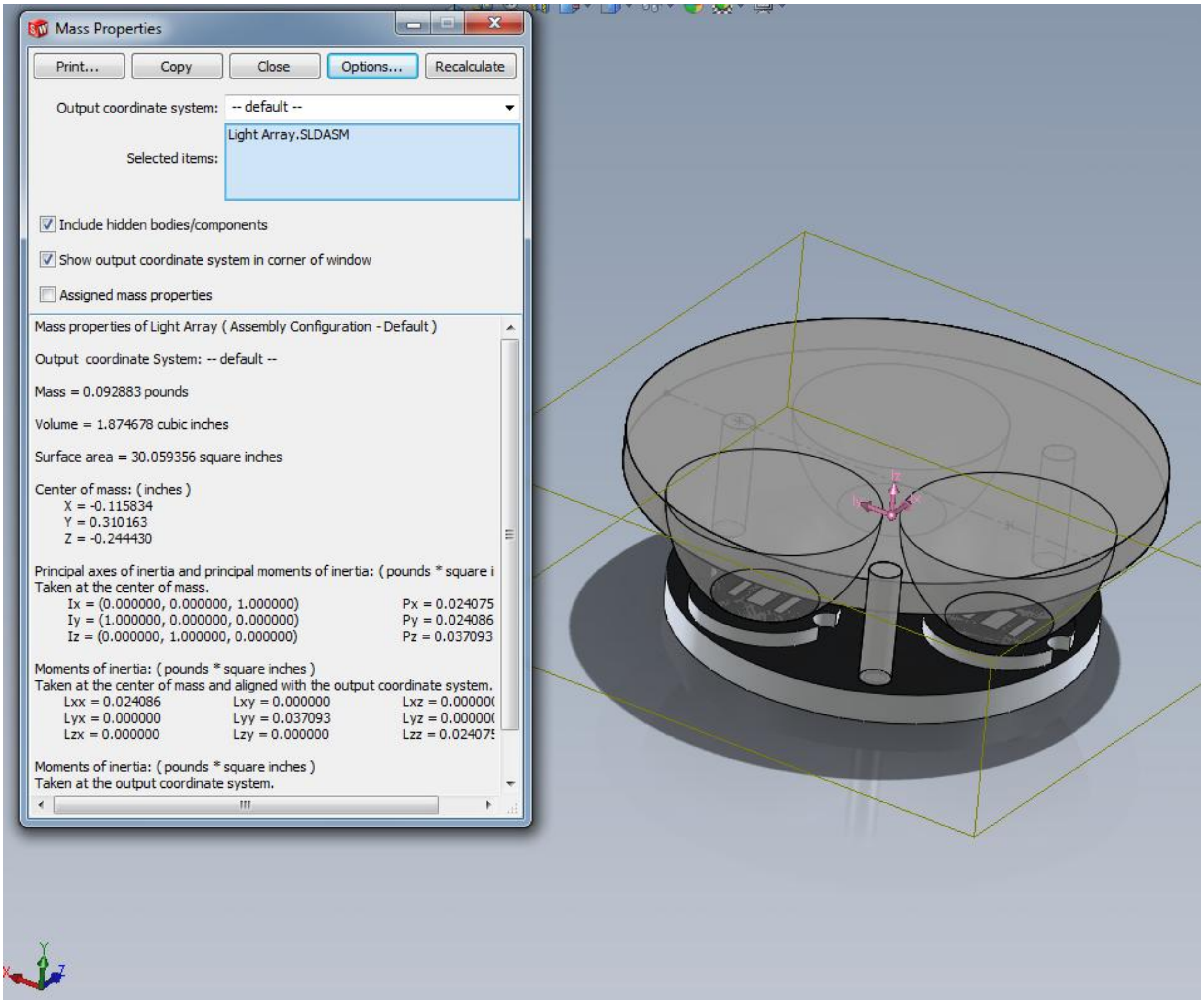


Figure 11. light array properties

This light array includes 3 Cree XML warm white LEDs, 3 aluminum heat sink boards, a spot light lens, and an additional aluminum mounting plate which will further dissipate heat from the LEDs. Using SolidWorks mass properties as a guide, an appropriate servo motor has been selected to control the array's tilt function. As shown in the attached spec sheet, this motor offers 43.1 oz-in of torque while the light array weighs approximately 1.5 oz and will have a moment arm of less than one inch.

The camera allows for pan, tilt and zoom control via Ethernet commands. This Ethernet cable also allows for video streaming, and remote control of the camera. The camera fits our image quality specifications as well. It allows for 1920x1080 video streaming with up to 10x optical zoom. We selected this camera due to the ease of using Ethernet communications, the fact that it matches our specifications well, in addition to the steep educational discount we were offered.

Above-Water Computer

The above-water computer will provide the automation for motion control, as well data storage for a high-definition copy of the video feed. Due to bandwidth limitations the live view that will be streamed to the website must be highly compressed. In addition to streaming the compressed copy, the computer must store an uncompressed copy for later viewing and transfer.

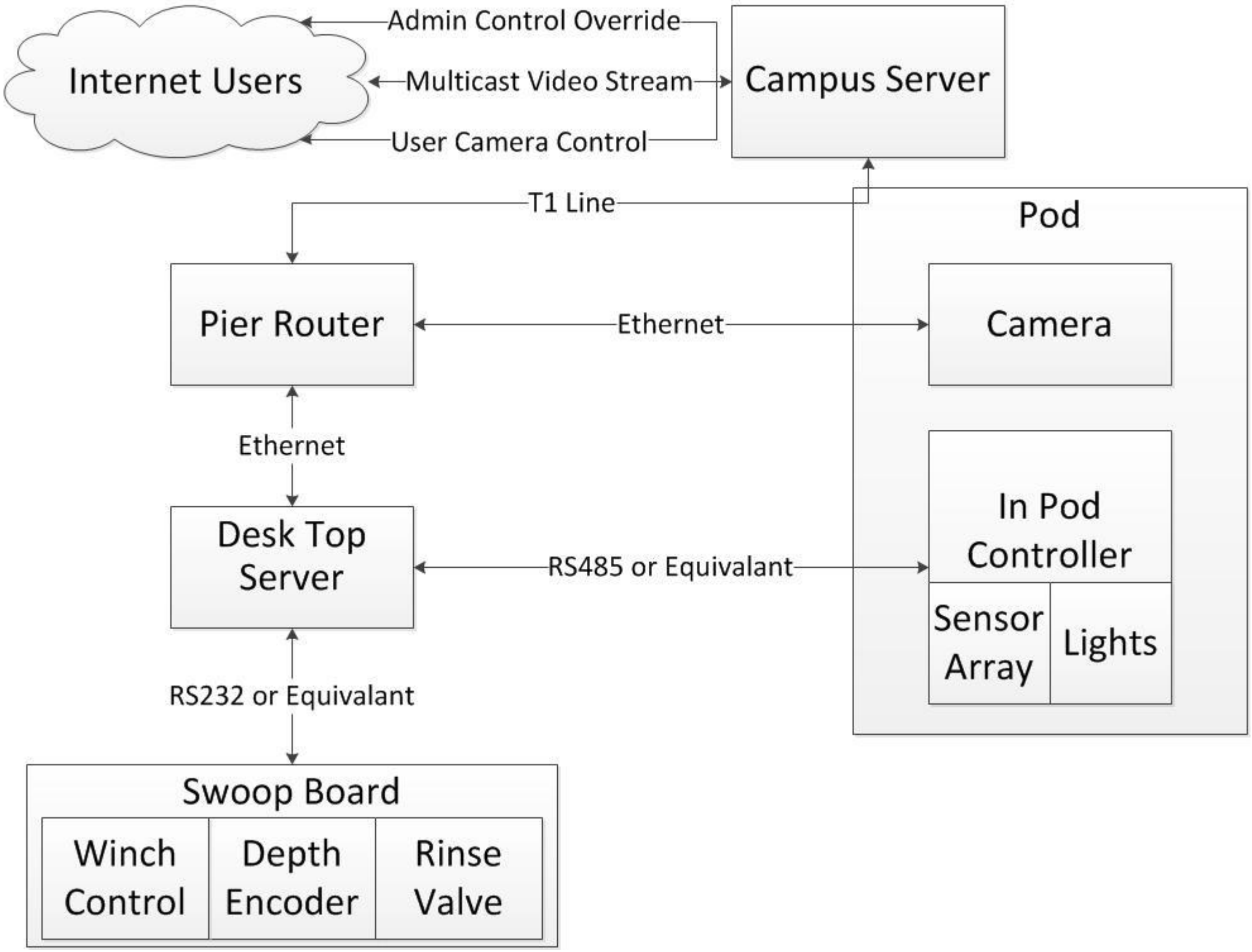


Figure 12. Computer flow chart

The computer must also respond to both local and remote commands with the proper administrative over-rides as well. The commands will be able to control the depth of the camera through the winch, the rinse valve, the viewing angle of the camera, as well as communicate with the microcontroller inside the underwater pod.

Assembly and Fabrication of Track and Pod System

FRP Connection Brackets

The Connection brackets made of FRP should be cut using a water jet from stock plate. The connection bracket is bolted to the piling brackets and to the I-beam. The bolts connecting to the I-beam should be button head or low head with the head on the inside of the I-beam. This is so the pod cart will clear the bolts when passing the connection brackets.

Pod Cart

The Pod Plates for the Pod Cart should be cut using a water jet from stock plate. Each of the pod mounting pieces that connect to the wheels are to be machined from blocks of plastic. These are bolted to the pod plate and to the connecting arms that join the two sets of roller assemblies. The connecting arms should be made from stainless steel bar bent and machined. The camera pod itself is slipped inside the stainless steel frame and the frame is bolted to the pod plates on the top and bottom.

Analysis Results

Although most of the analysis has been completed, some of the analysis still has to be completed once some components become finalized. The general overview of the analysis performed is shown her and the details are placed in the appendix.

I-beam Track:

Seasafe® has provided us with a design catalog that shows all allowable loads on the I-beams that we are analyzing. For a span of 15ft, the maximum allowable uniform load if the beam is not laterally supported is 251 lbs/ft, which corresponds to a total load of 3,765lbs (see appendix E). This is 4.7 times higher than any force we expect to see. These results correspond with hand calculations performed. $\sigma = \frac{Mc}{I}$, M=72000in-lbs, I=42.7in^4, c=1.93in, σ_{all}=ksi transverse, S.F=3.7. These calculations were coded so that a variety of shapes could be quickly analyzed (see appendix E). Further analysis and research needs to be done to fully understand the effects of fatigue from constant wave loading on the beam.

Track Mounting Bracket:

This mounting bracket connects the stainless steel brackets from the pilling to the I-beam. Since these brackets will take be located every 15ft, they will take most of the weight of the I-beam and all the forces will be transmitted through them. Assuming an 72000in-lb moment the a safety factor of 4.7 was calculated using COSMOworks. From these results we believe that at least a 1inch plate should be specified, due to the high risk failure modes and the possible inaccuracies of our FEA software. Results of this Analysis can be found in appendix E.

<u>Winch Drum:</u>

Based on the minimum bend radius of our cable, we were able to design and analyze the drum for our winch. The calculations can be seen below.

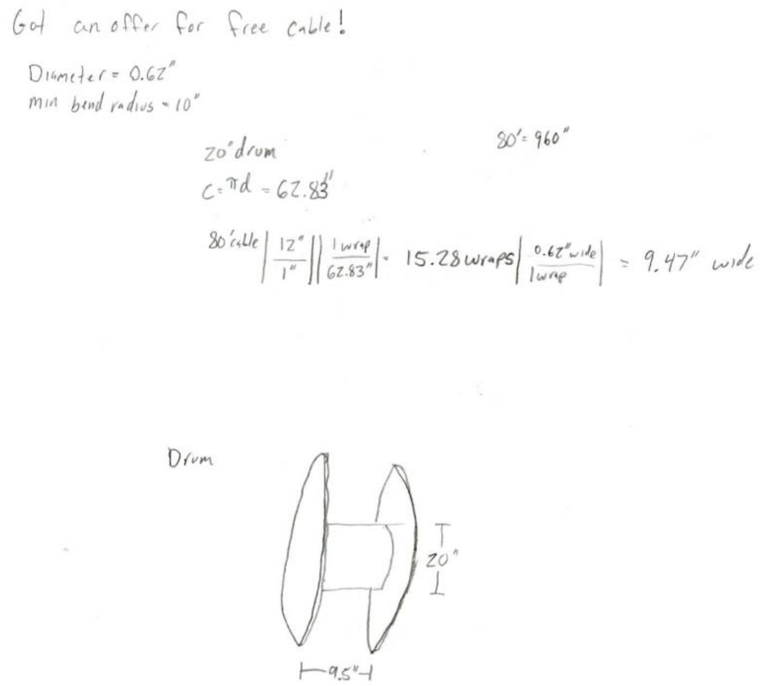


Figure 13. Drum Analysis

Cost Analysis

The first table lists all of the project expenditures based on actual and estimated costs of components. The list is divided into the major components of the project: Track, lighting, electronics, cart, camera housing, and deck components. The track portion consists of the Fiber Glass Reinforced Plastic (FRP) I-beams and plates. The lighting contains all of the LEDs in addition to the array components that will make them function inside the housing. The electronics includes everything inside the pod that is powered from the power source on the pier deck. The cart is the unit that carries the camera housing. The camera housing consists of the acrylic tubing, end caps, and everything required to keep the electronic components water proof. Lastly, the deck components are of the devices controlling the motion of the camera housing up and down the track. The winch will be mounted to the deck directly, and the cable will run through a pulley mounted directly above the track. The other end of the cable will be connected to the computer which will be stored inside the pier office.

At the end of the design stage, most of the components had either been purchased or had decent cost estimates. But there were a few parts whose prices were unknown because there were still some design decisions yet to be made. For example, the price of the bolts was unknown because a more thorough analysis of the stresses in the FRP plates mounted to the brackets had to be done before the bolts could be chosen. The total cost of this project is listed as $8,608. A more detailed breakdown of final costs is included in Appendix I.

Table 4: Cost Analysis of Expenditures

Component	Quantity	Estimated Cost ($)
Track		
FRP I-beam (20' section)	3	3500
FRP plate	4	0
Bolts	40	TBD
Lighting		
LED	6	49.74
LED lens	2	7.60
LED driver	1	19.70
Heat sync LED board	6	12.80
LED base	2	10.00
Electronics		
Microcontroller board	1	TBD
Gear for DC motor	2	TBD
Servo motor	2	24.98
Temperature/Pressure Sensor	1	25
Sonar	1	32
Humidity sensor	1	21
Camera	1	2150
DC motor	1	0
Cart		
FRP cage plating	2	0
Plastic wheel assembly	2	TBD
Wheels	8	TBD
Stainless housing cage	1	280
Springs	8	TBD
Camera Housing		
Acrylic tubing	1	250
Housing cage	1	80
Acrylic end caps	2	100
O-rings	3	5
Deck Components		
Winch	1	2000
Covering unit	1	40
Cable	1	0
Pulley	1	TBD
Pulley support	1	TBD
Computer	1	0
Total		$8,608

Table 5: Funds for Project Provided by Sponsors

Sponsor	Funds ($)
Marine Sciences Dept.	3500
Chevron	2000
Mike Adams	2000
John Nielson	1500
ME Dept.	1000
EE Dept.	150
Total	$10,150

Various discounts, donations, and grants have been received for this project, and these are listed in the table below. While there may be more discounts to certain components down the road, this is a complete list of all the money received up to this point in time. Due to the $10,150 in funds for this project, we are expecting the project to be sufficiently funded.

Material Selection

Initially most materials were selected in order to minimize cost; after more research and testing we realized that the most important factor in our material selection had to be corrosion resistance, even if cost had to be neglected.

Track:

Multiple material selection iterations had to be run through before finally selecting Fiberglass Reinforced Plastic (FRP) as our material for the track. At first we had selected to use type 316 stainless steel tubing for our track however, the price was above $5000 for the length needed and after analyzing a type 316 chain link that was under the sea for 5 years we realized that stainless steels have severe pitting issues. The inside of the link was completely corroded. After being advised that the steel can survive underwater with the proper galvanic protection we attempted to use steel as our track material. This led to a donation of 200ft. of 3x3x.120 square tubing. Samples of this mild steel were placed at the tidal zone for a period of 2weeks. After this time the steel was not only completely covered in rust but also had scaling over a millimeter thick. These negative results led to the decision to pursue composite materials. Tom Moylan led us to Seasafe®, a corporation he had worked with before, which constructs FRP structural elements for a variety of uses in corrosive environments. This material is ideal because it will not be corroded by the sea, even at the air-sea interface, will approximately cost $3500, and has a high strength to weight ratio.

Camera Cart:

The top plate of the cart will be made of FRP. The main driving decision in this was that the cart needs to be extremely stiff in order to not deflect under load and cause binding on the track.

Composites are generally known to be stiff and will also provide the corrosion resistance that will be need from every component that is in contact with the ocean.

The wheel mounts will be made of UHMW (Ultra High Molecular Weight Polyethylene). This decision is based on the rational that FRP is extremely difficult to machine without diamond tipped tooling whereas polyethylene based materials generally do not have a problem being machined. Since this part does not experience high loads then we can also have the thickness desired without being concerned with added weight.

Both the connection supports and pod cage will be made of type 316 stainless steel. These will be made of stainless because it would be very hard to manufacture a similar shape with another material. The pod and cart will also be receiving a fresh water rinse every day, which will significantly decrease the corrosion.

Camera Pod:

The outer casing of the camera pod will be made of cast acrylic. Although cast acrylic is much more expensive than extruded acrylic, the optical properties are far superior and the ability to attain the correct roundness tolerances will be much easier. The caps will also be made of acrylic because of the necessity of having a material with similar thermal expansion coefficients. If the walls of the pod expand faster than the caps, then there will be leakage through the o-rings.

The inner support structure will be made of a low grade stainless steel and lined with a felt like material. The reason for using a low corrosion resistant material is because this material will always be sealed from the water. Some type of stainless should still be used because when being maintained, the material might be exposed to the highly corrosive environment on the pier deck.

Sheave Frame:

This structure will be made of the plain carbon steel 3x3x.120 tubing that was donated to our project. This material was chosen because of the availability and absence of cost. This steel will be coated with Amer-Sheild, an industrial grade marine coating to prevent any significant corrosion. This product was recommended by Rob Brewster.

The sheave itself must be made of UHMW and a stainless steel hub because of all the sea water being shed off the cable as it winds back onto the spool. This corrosive water along with highly oxygenated air will cause accelerated corrosion to appear.

Safety Considerations

-The camera track will consist of 3, 20' I-beams connected together with flat FRP plates connected by brackets to the pier piling. This design will use bolts, which eliminates any need for underwater welding. Even without underwater welding safety concerns still exist. The 60ft section of I-beam must be lifted by a crane and then put into the water, and then released by divers, then raised vertically by the crane. If the crane, or any of the attachments to the beam should fail then there could be a safety problem. If the weather is less than ideal, wave energy could cause the beam to dislocate and put the divers in danger once again.

-There will be both manual and automatic fail-safes to ensure the safety of our design. Ensuring that no one is injured during operation or maintenance is our first priority. A lever within 3' of the winch will shut off power to the winch if pressed, which will directly stop the motion of the cable and camera pod. This is the most direct and efficient method of safeguarding anyone from getting injured on the job. Protection of the electronic components is our second priority, and several automatic features will be included to guard any components from overloading or breaking. While a large safety factor is already included in the cable itself, measures need to be taken to ensure that any point where the cable touches a potential failure point will not overload. This issue is resolved by placing a circuit breaker with the winch that will shut off the power if the maximum allowable load is exceeded. There will also be a surge protector on the pier deck to protect all electronic components in the pod.

Maintenance Considerations

Because this design is intended for use in a marine environment, maintenance plans for each subsystem will play a crucial role in keeping the Pier Portal up and running. Each subsystem and its plan is discussed below.

Track

The camera cart is designed with brushing capabilities to keep growth clear of all moving parts. However, an annual inspection and manual cleaning by a scuba diver is specified. Additionally, all submerged bolts will need to be replaced at intervals, which are still to be determined.

Cart

The cart is designed with its suspension being a function of the roller blade wheels used. These wheels will need to be inspected on a monthly basis and will likely need annual replacement. Additionally, the pins used to hold the wheels and the bolts holding the cart together will need periodic replacement; this period is to be determined.

Winch/Sheave

The winch will need lubrication at the drum bearings and both chains on a monthly basis. The spooling mechanism should also be observed for proper operation and lubricated monthly.

Camera Pod

The camera pod will receive a fresh-water rinse at least once per day, but will need to be wiped

down on a regular basis to ensure against any plant or animal growth. A manual wipe-down once per week will keep the acrylic surface clear much longer than rinsing alone. Additionally, the pod will need to be examined for O-ring breakdown by checking the color-changing paper inserted between O-ring sealed areas. Until O-ring life is determined, this should be a weekly check as well. If water has breached any of the seals, they should be replaced immediately. Lastly, proper operation of LEDs and sensors should be verified by pier personnel on a monthly basis.

Computer

The above water computer will be running on Linux and the communication ports will be monitored by Cal Poly's Net Admin team. This will ensure minimal user maintenance and upkeep for the computer. The machine will be housed inside of the office on the pier to ensure minimal complications with the marine environment.

Final Design Implementation

The final design has been broken up into subsystems and is detailed in the following sections.

I-Beam Track

The following sections discuss implementing the I-beam track.

Manufacturing

Manufacturing of the I-beam was mostly done by Seasafe but all details are discussed in the following sections.

Seasafe parts and stainless steel brackets

All stainless steel pile brackets were provided by the Cal Poly pier. Five brackets were available with one of them having slightly larger spacing of the holes that were used to bolt on the connection plates. Seasafe manufactured each of the 3 sections of the I-beam, the bracket connection plates, and joint connection plates to our specifications. One of the bracket connection plates was specified to be larger to accommodate the larger pile bracket that was available to use. A mistake was made in specifying the hole spacing for the larger connection plate to match the larger bracket so these holes were re-drilled using a drill press.

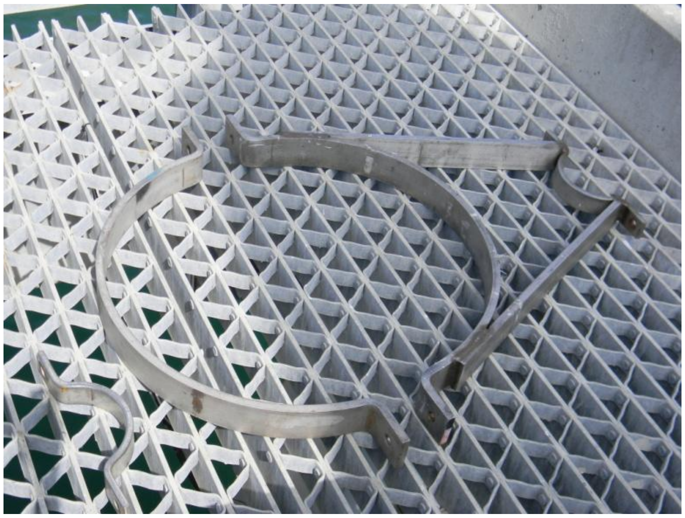


Figure 14: Stainless steel brackets available for use at the pier

Beam installation clips

The clips, shown in Figure 15 are designed so that the I-beam could be easily installed by divers under water as suggested by Greg Bryant, engineer and diving instructor at Santa Barbara City College. The base portion was made from type 304 3/8'' thick 2'' wide stainless steel flat bar. This flat bar was cut into 4'' lengths using an abrasive chop saw. The round portion was created from ½'' type 304 round bar cut to 2'' lengths, also on the chop saw. These round sections were then TIG welded to the end of the flat bar as shown. This process took about 4 hours to weld all 22 clips (2 extra),

Figure 15: Image of clip used in the track installation

and resulted in a sun burn of the right bicep. After the welding was completed, a 5/8’’ hole was drilled into the center of all 22 clips and the burrs removed.

Testing

Different tests were conducted to address concerns with implementing the track.

FRP drilling

One of the biggest concerns with the track was that trying to drill holes in the FRP material would wear down the drill bit quickly. An opportunity to test this occurred when one of the FRP connection plates had its holes re-drilled. The bit was observed before and after drilling to try and detect any changes. There were no noticeable wear issues after drilling. This test justified the purchase of cheap drill bits for the divers to use during installation. This was proven on installation day as the drill bits kept their edge.

Corrosion

Corrosion testing on both the track material and the brackets has been tested at the pier through use in other projects that use the brackets or Seasafe products. The track and brackets will outlast the fasteners in the track so pieces of fastener of the same size are mounted to each bracket and can be inspected by the camera. This ongoing test will keep track of corrosion at various depths with regards to the fasteners.

Component list

The components listed below make up the assembly of the track. Quantity is in parenthesis.

- 20 ft FRP track section (3)
- FRP joint connection plates ½” (2)
- FRP joint connection plates ¾” (2)
- FRP bracket connection plate (4)
- FRP bracket connection plate wide (1)
- Stainless steel piling bracket (4)
- Stainless steel piling bracket wide (1)
- 316 stainless steel 5/8” -11 2 ¼” partially threaded bolt (46)
- 316 stainless steel 5/8” -11 2 ¾” partially threaded bolt (20)
- 316 stainless steel 5/8” -11 1 ¾” partially threaded bolt (16)
- 316 stainless steel 5/8” -11 15/16” nut (42)
- 316 stainless steel 5/8” -11 15/16” locknut (40)
- Stainless steel installation clip (20)
- Stainless steel 5/8” washers (134)

Assembly

Assembly of the track was a very long and complicated process requiring the participation of a large group of people including pier staff, diving students, diving instructors, engineers, and crane operators. Greg Bryant especially was very helpful in working out the details of the track assembly. The assembly took place in three stages: Assembling the I-beam on deck, installing the topmost piling bracket, and installing the track. These processes are subsequently discussed.

Assembling the I-beam

After the 3 sections of 20 ft I-beam were delivered to the pier, a location for assembling the track was chosen. This location was critical since the crane would have to be able to pick it up and place it in the water. Once assembled, the track would be too large to move. Another advantage of using the FRP track is that it is relatively light compared to other structural materials so it was easy to assemble and for the crane to lift. With the I-beam in place on top of wood blocks, the joint connection brackets were placed over the holes in the I-beam. There were two thicknesses of these connection plates. The thin plates are on the outside of the track to give the cart more clearance as it passes the joints. All the fasteners were carefully gathered and placed on boards laid over the pier deck grating to keep them from being lost to the sea below. High strength Loctite and a Loctite primer were used on each bolt prior to inserting them in the holes. Washers were placed between each nut and each bolt head to prevent either from digging into the I-beam when the bolts are tightened. The shorter bolts (1 ¾” length) were used to fasten the thin connection plates on one side and the medium bolts were used to fasten the thicker connection plates to the other side. Before the bolts were tightened, the I-beam pieces were visually lined up to be straight and to keep the seams lined up. This was only possible because the holes in the FRP beam were specified to be ¾” and the bolts were 5/8” in diameter. All the bolts were carefully tightened using a long handled wrench and a torque wrench. Each bolt at a joint was tightened repeatedly as others were tightened at the joint since tightening one bolt pulls the connection plate closer to the I-beam surface. Figure 16 shows the track assembly in progress.

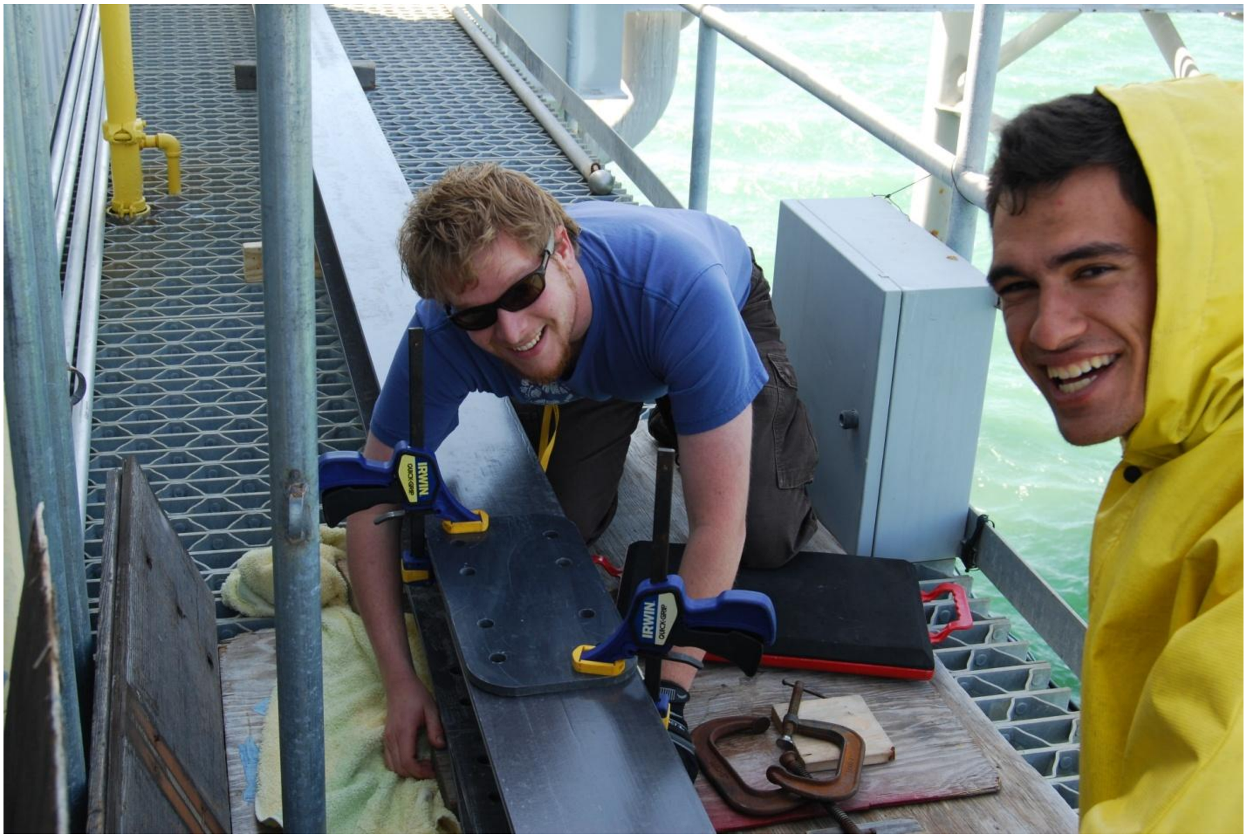


Figure 16: Engineers Michael Machado and Aaron Poulos assembling the I-beam track

Installing the top bracket

The track must be placed so the pod cart does not hit parts of the pier deck. These tolerances are very tight. It was decided to carefully install the top bracket so it would act as a guide to place the I-beam and the rest of the piling brackets. The top bracket was first assembled to the FRP connection plate on deck and tightened using a torque wrench to 60in-lbs. Four installation clips were assembled loosely onto the connection plate with nylock nuts. Thin rubber strips were glued to the inside surface of the piling bracket and the matching C-shaped bracket piece so it could grip the piling better. The bracket assembly was then ready to be installed onto the piling. It was decided that the bracket should be installed above the piling wrap and growth of muscles on the piling. Cleaning off the muscles would have been an arduous task in order to attach the bracket. First, a variety of methods were developed to determine the correct orientation of the bracket so the track would be correctly placed. The first method used was to make a 16 ft long wood frame that attaches to the piling bracket (see Figure 17). This was accomplished by connecting two 8 ft pieces of wood plank with two pieces of plywood and some wood screws. Holes were drilled into one end of the plank that matched up with the holes on the connection plate. At the other end, a piece of wood was placed perpendicular to the plank and secured to the plank with wood screws so it extended to the side a certain distance. The idea was that with this assembled onto the bracket, rotating the bracket would bump the wooden piece on the plank on the pier deck, indicating that is where the piling bracket should be placed. The numbers

necessary for this were pulled from the Solidworks model in which the pier deck was carefully modeled. The other method used to determine the correct orientation of the bracket was to sight it with lasers from the pier deck. Distances were again pulled from the Solidworks model and used to measure from the edges of the pier deck. A plumb-bob was also used in order to take measurements from the piling bracket to the edges of the pier deck. The laser beam was found with a sheet of paper at deck height. A layout drawing of the top bracket's final installed position can be found in Appendix G. All of these methods were used over the course of two days in order to accurately place the bracket at the correct orientation. The installation was accomplished by lowering a worker in a harness down the piling. A bucket of tools was also lowered, along with the piling bracket assembly and the C-shaped bracket piece that wraps around the piling. Both bracket pieces were on separate lines so they could be adjusted individually. The worker loosely secured the bracket to the piling and oriented it with help from engineers on the pier deck using the methods previously described. Once it was finally determined the placement was perfect, the bracket was tightened onto the piling using an all-thread bolt and nuts. Figure 18 shows the bracket being installed on the piling.

Figure 17: Plank used to orient the top bracket

Figure 18: Worker in a harness installing the top bracket

<u>Installing the track</u>

Installing the assembled track onto the piling was a multi-day event that required the participation of many people. As part of their class, the Santa Barbara City College Marine Diving Technology students set about the task of installing the track. Prior to the first dive day, a beam installation plan was developed and documented for the divers. This plan can be seen in Appendix G. All of the piling brackets were assembled with clips just as the top bracket was. Each assembly was labeled with a direction to identify up and down. This can be seen in Figure 19. The letters on the installation plan matched with markings on the track where approximately the brackets should go. Float bags were attached at three points on the I-beam track so it would float in the water. Bolts were passed through the holes on the top end of the track so the

Figure 19: Orientation of piling bracket assembly specified using waterproof markings

crane would have a place to grab the end of the track as it was being installed onto the piling. bubble levels were also secured to the track so the divers could ensure the track was straight up and down. Once all of this was prepared, the divers went into the water. They were equipped with hard hat helmets, 2 way radio communication, and helmet-mounted cameras sending live video to the pier deck crew. The deck crew was broken into a group that manned the communications and monitored the video feed as well as air for the divers and other critical operational concerns (see Figure 20) and a group that watched the dive from the deck and communicated commands between the boat crew and the deck crew. The second deck crew group was also responsible for sending down tools and parts and feeding the power, data, and air lines to the boat. The boat crew monitored the divers, keeping them safe, and took care of launching and retrieving the divers (see Figure 21).

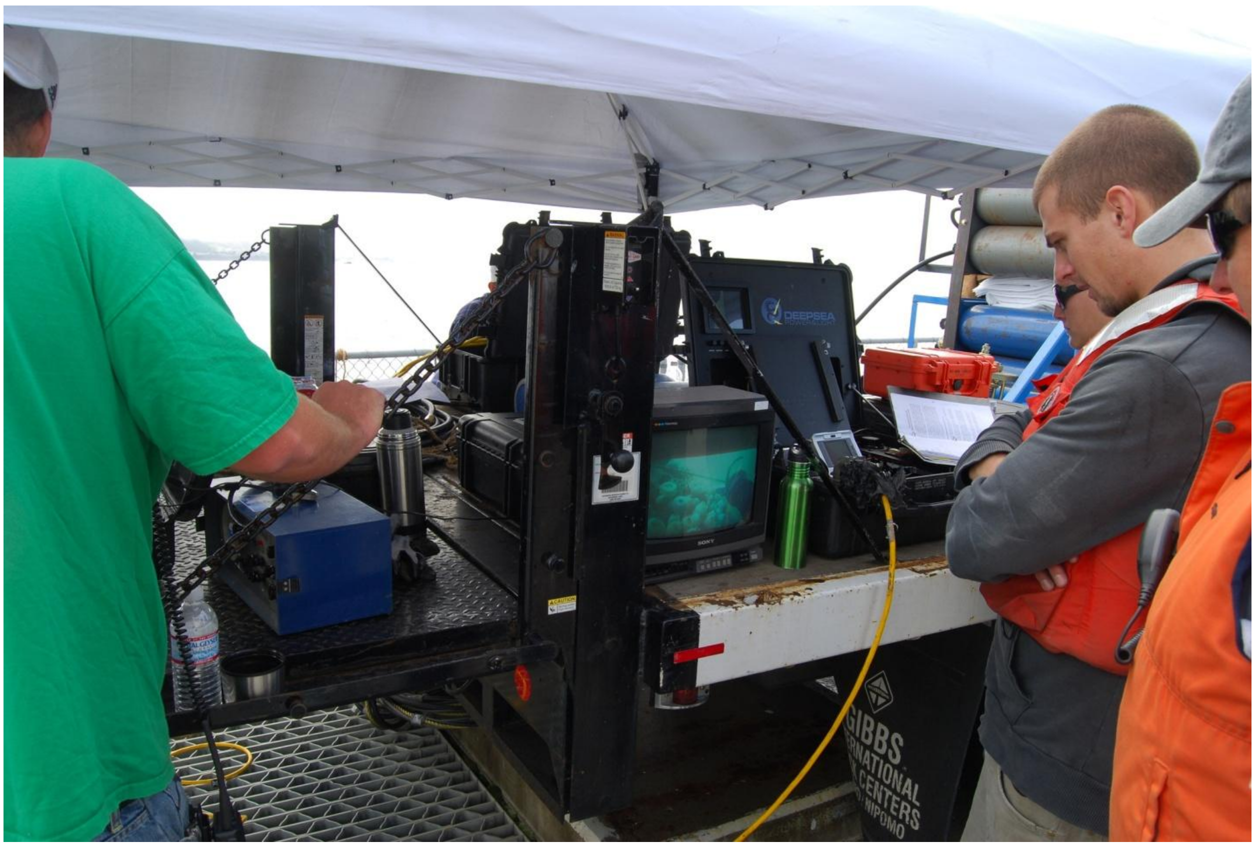


Figure 20: Command center for the dive team

Figure 21: Diver support crew above the dive site

A small crane was brought out from Port San Luis. This crane lifted the track up from the pier deck and into the water using slings (see Figure 22). Once the track was in the water, the divers detached the crane from the slings and attached it to the top end of the track. They then cut away the float bags. The crane lifted the track up and moved it into position against the pre-installed top piling bracket. It was then noticed that the track had bent at one of the joints. This was due to the float bags being removed improperly, temporarily exerting a huge moment at the joint (see Figure 23). The bending was due to the bolts moving in the larger holes in the track so it was readjusted and tightened.

Figure 22: The crane lowering the track into the water

Figure 23: The bent joint after a mishap with the float bags. This was fixed without issue.

The dive team then began securing the track to the piling brackets by swinging the clips into place and tightening them down, thus holding the track in place. The first one installed was the lowest bracket at the bottom. Once the track was secure in place, the crane could let go of it. The rest of the piling brackets were installed with the track, some having to be separated from the connection plates in order to fit it between the track and the piling. The track was flexible enough to easily slip in the plates and bolt everything together. The track was inspected to make sure everything was aligned correctly. It was discovered that the lower bracket was off by a significant amount so this was readjusted.

The last task involved adding a more permanent way to secure the track to the piling brackets. This involved drilling holes in the track underwater and putting a bolt through them. This had to be done since there was no way of knowing where the divers would be able to place the brackets and the kind of precision necessary to align holes underwater was nearly impossible to obtain. The FRP connection plates were manufactured by Seasafe with holes so the divers could use the hole as a guide to drill into the track. A pneumatic drill with a ¾" bit was used to make the holes. Bolts were put through these holes and tightened down. This concluded the main diving operations.

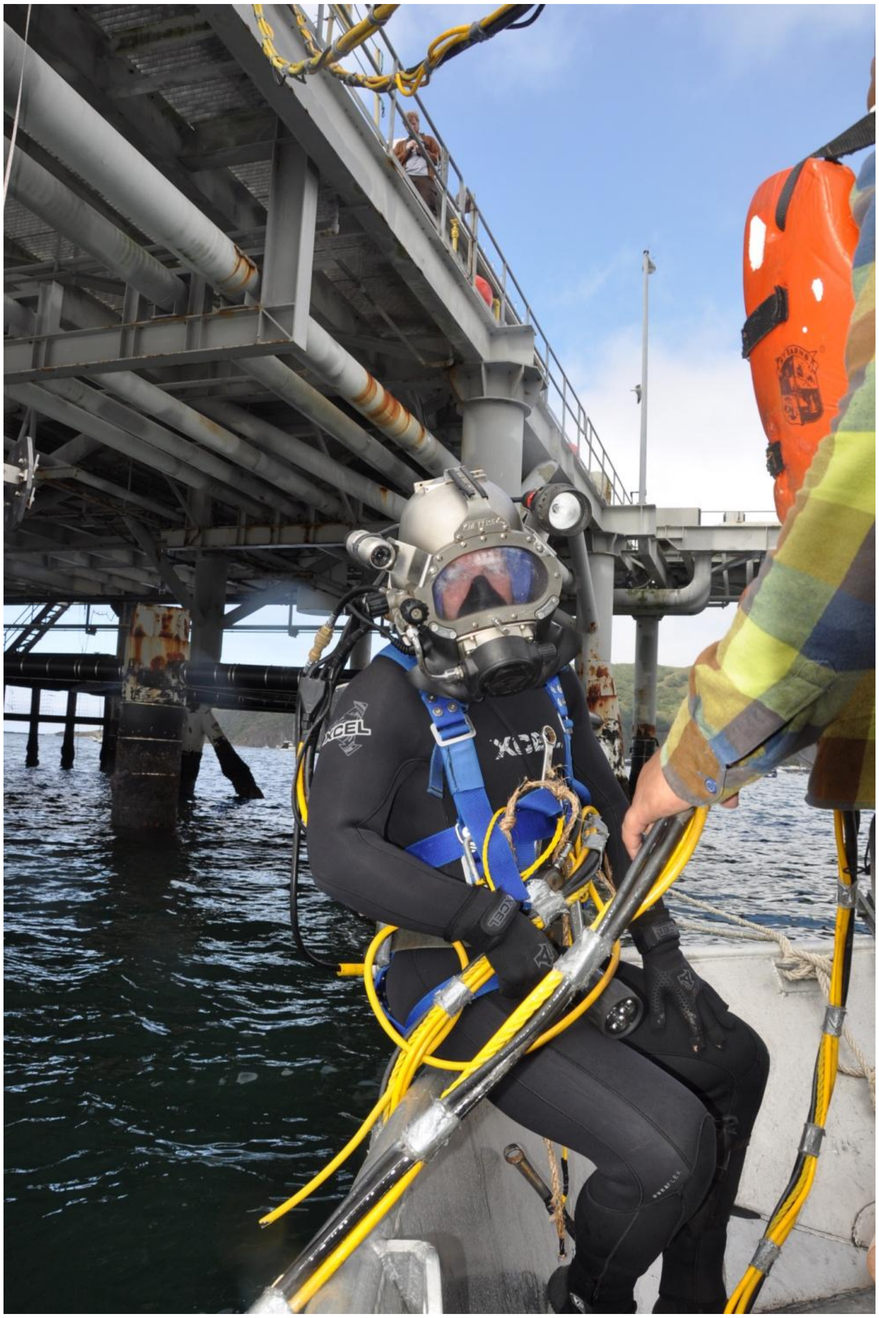


Figure 24: Diver in full gear preparing to enter the water.

Maintenance

The biggest maintenance concern with the track will be keeping it free of sea life. The cart will be set up to brush away encrusting organism larvae and these brushes will need to be replaced when they wear out. Sea stars have already proven themselves to be a nuisance for the track, finding their way from the piling to the track via the piling brackets. Sea stars are strong enough to impede the cart from moving along the track. A spiked barrier was installed to prevent this from happening but periodic cleaning maintenance will need to be performed to keep off the persistent and masochistic sea stars.

Fasteners may also have to be replaced at some point. Since corrosion varies with depth, bolts were welded to the brackets to attach zinc discs, allowing a visual inspection by the camera pod of the progress of corrosion.

Future improvements/iterations

Although it is not expected the track will ever have to be replaced, in retrospect there are some things that could have been done better. The holes in the I-beam pieces were specified as ¾" diameter when the diameter of the bolts used in these holes were 5/8" in diameter. This was done to allow for corrections due to any discrepancies in the I-beam hole size or placement. For example, if they were too far in or out, they could not be connected together by the joint connection plates. Upon assembly, it was discovered that this was unnecessary since the tolerances on the I-beams were very tight. Specifying 5/8" holes on the I-beam would have made for a stronger connection.

The I-beam itself could also have been smaller. The connection plates were the limiting factor in our design, the track itself can resist much more stress than the connection plates. A smaller size track of the same shape and length would have sufficed.

Pod Cart

The following sections describe the implementation of the final design of the pod cart.

Manufacturing the Pod Cart

Manufacturing the cart was done with a variety of different processes based on which part was being made, time and budget constraints, and material. The components of the cart have been broken down as follows: Cart Plates, Roller Frames, Rollers, Pod Stops, Fasteners, Strapping, Cable, and Weights.

Cart Plates

The plates are the main load bearing potions of the cart that hold the pod in place. They were designed as plates for ease of manufacturing. Rob Brewster was kind enough to donate FRP plates of approximately ½" thickness to make the pod plates. He suggested using an automated water jet system to cut the plates into the shape desired. This freed up creativity in design since it would not be any harder for the water jet to cut curves than straight lines. A test of the water jet cut of a scaled down plate design proved the water jet would cut curves within tolerance. However, it was noted that the water jet is only capable of cutting from a side of the plate material and not straight through. Doing so causes the water to explode into the plate as it finds the path of least resistance. This is due to the anisotropic nature of the FRP plate. Upon Mr. Brewster's suggestion, holes were pre drilled with smaller holes to allow the water jet to approach from a side. These holes still needed to be reamed to a clean 5/16" diameter so the chosen fasteners could be inserted. The pod plates were modified as the track design was finalized since it needed clearance to pass the fasteners holding the track together and to the piling. The 4 plates cut out of the FRP are 2 sets of identical shapes. 2 pod plates and 2 support members connecting the top and bottom sections.

Roller Frames

The roller frames are the most complex part machined in this project. In addition to connecting the FRP plates together, they hold the rollers at right angles to each other but at a 45 degree angle to the other faces (and therefore the reference planes). The material chosen for this part was Delrin, an acetal resin, because of its excellence performance in saltwater environments and machinability. Four 7" x 2" x 3.5" blocks were cut out from a 2" sheet stock using a vertical band saw and machined flat. A process was developed to make these roller frames using a manual mill with a rotary table. Three attempts were made to create these parts and all failed to meet tolerance specs due to slight human errors during machining. Since 4 of these parts needed to be made and all were identical, an investment of time was made in a CNC process using a HAAS VF2 CNC mill. It is important to note that even though 4 of the same part needed to be made, using the CNC mill gives little to no advantage in terms of total time because of the time to generate the G-code. This G-code was loaded into the CNC mill. The total programming time was about 8 hours, and the full-speed cycle time was about 30 minutes per part (2 hours total), although the actual machining time including set up was about 4.5 hours. It was decided that

each part would be machined in two steps. The bottom side would be machined first then the top side. The part was saved as a step file in Solidworks® and then imported into Pro-Engineer® for the process code generation. The bottom section involved only one process where a flat end mill machined the webs for the rollers. The top section involved three different processes with flat end mills and one with a drill bit. Three different sections were machined flat and then two holes were subsequently drilled. Even on the CNC machine, the parts did not come out exactly expected, due to operator error. The machine coordinate system was originally defined as the back left corner of the stock for both the top and bottom section. The problem came when flipping the part because the work coordinate system is actually at a different location. This caused some of the features to be placed almost .25'' from their intended location. Deflection of the material while machining also caused a small layer of material to be left behind even after the offsets were adjust the remove this material. A small deburring tool was used to remove the remaining material and chamfer the edges. Additional holes were added using a manual mill that were not coded to be cut using the CNC mill. Figure 25 shows the CNC mill cutting the part. Figure 26 shows the solid model of the roller frame.

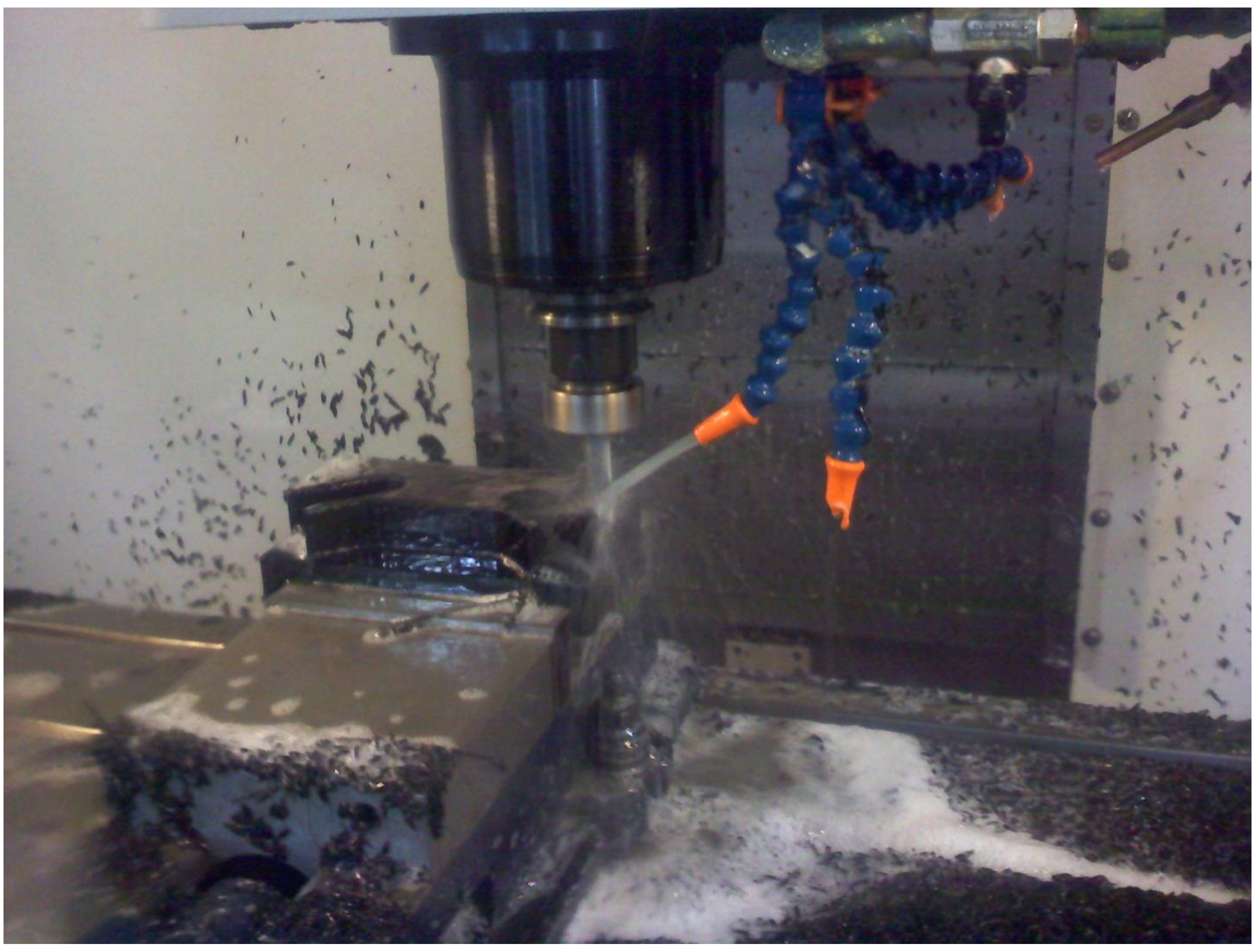


Figure 25: Machining the Delrin roller frames using the Haas VF2 CNC mill

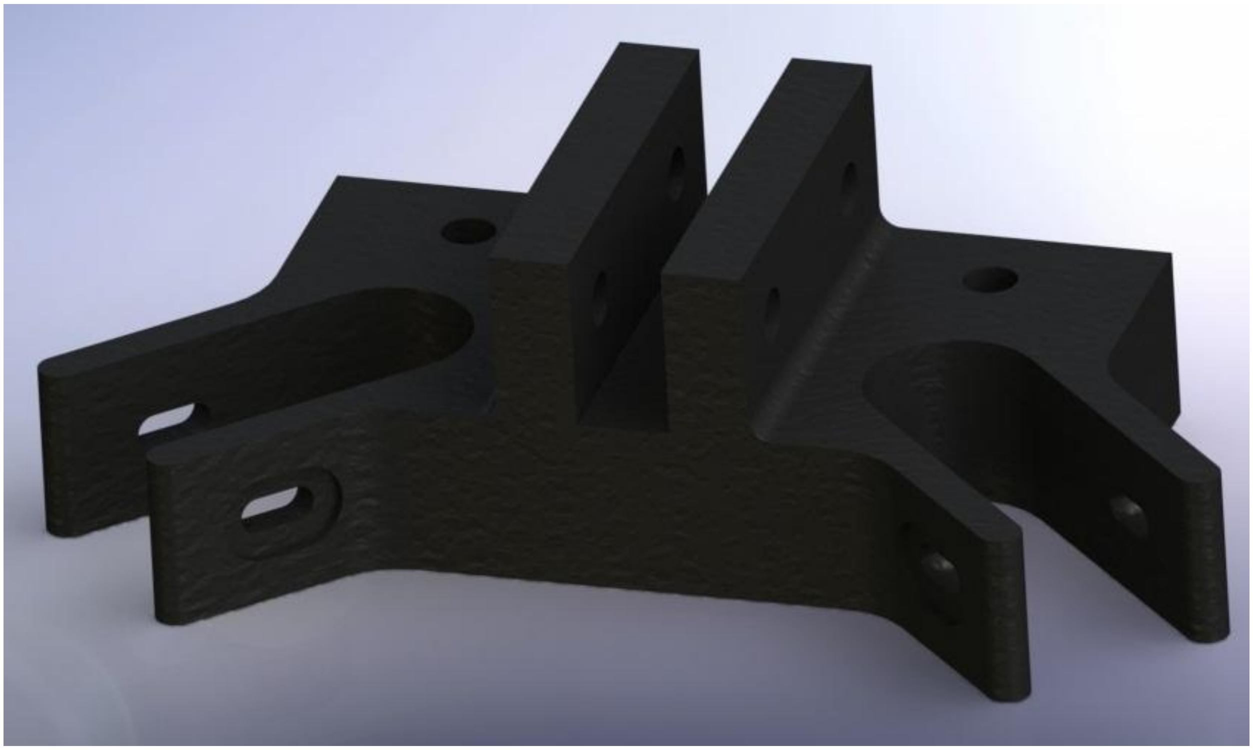


Figure 26: Rendered solid model of roller frame. The oval holes in the flanges were done on a manual mill

Rollers

The rollers chosen for the cart are roller blade wheels because they were cheap, already the correct size, and the material, polyurethane, was good for corrosion resistance. Since saltwater corrosion would destroy any metal bearings in the wheels, they were purchased without bearings. Delrin rod was turned down on a lathe to make bushings that pressed into the roller blade wheels. These bushings were fit to be rotated on stainless steel binding posts which fit into the roller frames.

Pod Stops

The pod stops cradle the pod while also providing attachment points for the strapping to hold the pod in. The pod stops were originally going to be made from Delrin, but UHMWPE material left over from manufacturing the sheave was used in order to reduce cost. This material was easy enough to machine and offers good corrosion resistance. These parts were all identical and were machined on a manual mill with a turntable to produce the rounded surface. 5/16” tapped holes were made into the side of these parts for the strapping attachment.

Fasteners

The fasteners chosen for the cart were sized based on maximum stresses expected in the cart (with a large safety factor), corrosion resistance, and cost. Type 316 stainless steel 5/16” bolts and nuts were chosen for the cart. All fasteners in the cart are 5/16” for simplicity. Fastener length was chosen as the minimum length permissible in order to reduce costs, keep components tight, and limit tolerance issues with the track upon which the cart rolls on. Final assembly was

done with medium strength Loctite to keep the nuts from unscrewing themselves. Hand tightening the nuts was allowed to the point of the fasteners barely digging into the cart material.

<u>Strapping</u>

Strapping is critical to holding the pod inside the cart. Although the pod plugs fit into the FRP plates, it can still come out in one direction. Neoprene straps were chosen to hold the pod in place due to neoprene's flexibility, strength, and corrosion resistance. A worst case scenario stress on the straps was analyzed with a safety factor of about 3 for ¼" neoprene straps. The straps are held by a clamping force produced by tightening down small Delrin plates. The two ends of each neoprene strap are held between the Delrin plate and the pod stops' outer surface with 4 fiberglass reinforced polyurethane bolts tightened with acetal spring washers. These bolts were used because it is critical that the threaded holes in the plastic pod stops do not get stripped from taking out the bolts in order to take out the pod. Metal bolts would strip the plastic threaded holes. The threaded holes are designed for fastener tensioning by hand with a 2" lever arm.

<u>Cable</u>

The cable used was chosen as a steel cable coated in vinyl. The coating prevents seawater from corroding the cable. The ends of the cable are sealed with epoxy. Cable thickness was chosen to be well outside any stress it well ever experience. Using a thicker cable did not incur any significant cost increase. Two holes were drilled into the top FRP plate of the cart for two stainless steel eyebolts which the cable runs through. The cable is run through the eyebolt of the cable grip of the main cable and clamped with two stainless steel cable clamps.

<u>Weights</u>

Weights were determined based on the final weight of the cart and pod and the total volume calculated with the Solidworks model. The weight added to the cart needs to be able to pull the entire pod underwater at a reasonable speed while also overcoming minor sea life obstacles and ocean swells. Lead plate was chosen since it is dense, does not corrode much underwater, and can easily be cut and attached to the cart. A 20" x 48" portion of 1/8" lead sheet was chosen after completing density calculations. It was cut into eight 32" long by 2.5" wide strips with a shear. 3/8" holes were punched out of each strip at both ends to match up with 5/16" holes drilled into the FRP support plates running the length of the pod. Four 5/16" type 316 stainless steel bolts were used to hold the lead sheets to the FRP plates.

Testing

Various tests were performed on parts of the pod cart before a final test was made to determine the effectiveness of its main task: to provide a smooth, stable guide for the camera pod.

Wave forces

Although transverse wave forces were taken into account in track design, there are also forces in a vertical direction from swells. This is important to consider for the cart since that wave force will change the apparent weight of the cart momentarily. If the cart is not heavy enough, it could trip the load sensor on the sheave whenever a swell goes by. In order to quantify the upward force caused by ocean swells, a rope with weights at the end was hung over the pier through a pulley into the water as deep as possible while still freely swinging. A scale was attached in line with the rope. The test day was stormy enough to still be acceptable for use of the system. Any stormier and the administrator would call the pod back to its home on deck. The force data from passing swells was used to help determine the needed weight to be attached to the cart.

Pod Fitting

A test was performed for fitting the pod into the cart. This was as simple as seeing if the pod easily fit into the FRP plates. It was determined that one of the pod plugs fit too tightly into the FRP plates. This was corrected by using a file to widen the slot in one of the FRP plates. The pod was held by the cart as desired after this correction as made.

Plastic Fasteners

The plastic fasteners and threads to hold the neoprene strap had to be tested to ensure it would perform under predicted environmental conditions and not fail in assembly. A sample treaded hole was made in a piece of UHMWPE, the same material as the pod stops, and a steel bolt was inserted into the threads. It was assumed the threaded hole would fail instead of the plastic bolts in the actual assembly so using a steel bolt ensured a single component failure of the threaded hole. The first test was loading the bolt axially. A static load of 55 pounds was tested as well as a dynamic load of over 100 pounds. The threads did not fail after the tests. This was well within our desired axial strength. The other test performed was tightening the bolt into the threaded hole with a wrench until the threads stripped. This was done by adjusting the lever arm on the wrench while tightening with average human strength. The threads failed at about a 4 inch lever arm so it is recommended not to use more than a 2 inch lever arm to tighten the plastic bolts.

Wheel Fitting

Fitting the wheels onto the I-beam track was tested using the sample 2 foot section of I-beam provided by Seasafe. The cart was fully assembled and placed onto the I-beam. The rollers were pushed against the inner corners of the I-beam by moving the pins inside the oval hole in the roller frames. The spacing was noted and small bits of neoprene were inserted into the roller frame to hold the pin in the correct spot in the oval hole while also providing cushioning to provide the rollers with some give.

Assembly

Assembly of the cart is meant to be permanent for the most part. There should be no need to disassemble the cart except for the rollers. Assembly was done using medium grade Loctite on the bolts and nuts so it can be taken apart if necessary. A wrench was used to tighten down the bolts and nuts. The sequence the cart was assembled with starts with the roller frames being secured to the FRP plates that hold the pod followed by attaching the FRP support pieces that connect the roller frames together. The strapping is assembled by placing the plastic bolts through an acetal spring washer and through the Delrin block and neoprene. The bolts are screwed into the pod stops using a wrench with no bigger than a 2 inch lever arm to prevent thread stripping. Initially, only one side of each neoprene strap should be secured since the pod must be placed in first. For the roller assembly, the roller pins are inserted between pieces of neoprene inside the roller frame slots to cushion the rollers. The pins are a two piece binding post and have a slot on one piece which must face outward so it is easier to screw it in with a flathead screwdriver. These pins are placed through the roller frame with the roller with bushings in place. The eyebolts are secured in the holes in the top FRP plate using two nuts. The cable is passed through both eyebolts and the grip eyebolts on the data cable before being clamped together to form a loop with the stainless steel cable clamps. Figure 27 shows the complete assembly of the cart. Refer to the drawings in Appendix B for more detail.

Figure 27: Cart fully assembled without the pod.

Components list

The following lists the components of the pod and the quantity of each.

- FRP plate support pieces. (2)
- FRP plate pod holders [one with holes for cable eyebolts]. (2)
- Delrin roller frames. (4)
- UHMWPE pod stops. (4)
- Delrin bushings. (8)
- Rollerblade wheels. (8)
- Stainless steel binding posts 1 ¼" barrel length, 8-32 thread size. (8)
- 316 stainless steel hex cap screw 5/16"-18 thread, 2" length. (12)
- 316 stainless steel hex cap screw 5/16"-18 thread, 2 ½" length. (8)
- 316 stainless steel hex cap screw 5/16"-18 thread, 1 ¾" length. (8)
- 316 stainless steel hex nut, 5/16"-18 thread, ½" width, 17/64" height. (28)
- Stainless steel 5/16"-18 eyebolts. (2)
- Fiberglass cap screw, hex head, 5/16"-18 thread, 1-1/2" length. (16)
- Corrosion resistance acetal spring washer, 5/16" screw size. (16)
- High strength neoprene rubber strap, ¼" thick, 2" width. (2)
- Stainless steel cable clamps. (2)
- Vinyl coated steel cable. (1)
- Lead sheet 1/8" thickness, 32" length, 2 ½" width. (8)

Maintenance

It is not expected that any of the machined parts will fail over the course of the life of this project but in the event of unforeseen circumstances, drawings are provided to make new parts. What are expected to be in need of repair at some point are the rollers. These rollers were not chosen with regard to long life and they are the only contact surface with the track. These rollers can be replaced by similar rollerblade wheels. The roller bushings may be removed by pressing them out with an arbor press or similar and placed in new rollerblade wheels, given the wheels have the same inside hub dimensions.

Future improvements/iterations

The size of the pod cart will change if the camera pod is able to be compressed. Having a large pod greatly increased the buoyancy of the entire pod-cart assembly which required adding a lot of lead weight. Having a smaller cart requires less weight. The rollers chosen for the cart are still a first iteration since testing of the wheels will commence during the use of the system. More expensive and durable wheels with a more custom shape will improve the continued desired stability in the cart as it moves up and down the track.

Sheave and Frame

Implementing the final design of the sheave and frame is discussed in the following sections.

Manufacturing

The sheave frame was constructed with 3''x3''x.120''wall steel tubing donated to the project. A total of three 20ft. lengths were used for the frame. These lengths were cut to a rough length on the carbide tipped chop saw in Mustang 60 and then cut to the correct length and angle with the horizontal band saw. The band saw in Mustang 60 was used first, however after measuring the cut the blade had walked ¾'' over the 3'' cut. This was deemed to be highly unacceptable and the rest of the cuts were done with the band saw in the Hangar. After all the cuts were made and verified to the correct length, the bottom part of the frame was laid out on the floor and positioned using a slide square to ensure geometric accuracy. The bottom section (see fig 28) was held with a right angle magnet and tacked into place. The same process was utilized to tack the vertical section. The bottom and vertical section were then tacked together and the 45^{o} supports were tacked into place. Correct dimensions and square corners were once again verified while the frame was still soft assembled. Lastly, each seam was MIG welded. The seam between the tubes that were cut on the Mustang 60 band saw had an enormous gap and could not be welded easily. This problem was fixed by adding a 1/8'' TIG filler rod to fill the gap and then by MIG welding over it. These imperfect welds were then ground down. 3''x 3'' plates were added to close the hole at the bottom of the vertical section, and all gaps closed, to ensure that no corrosive air could enter the internals of the frame.

Figure 28: Sheave Frame

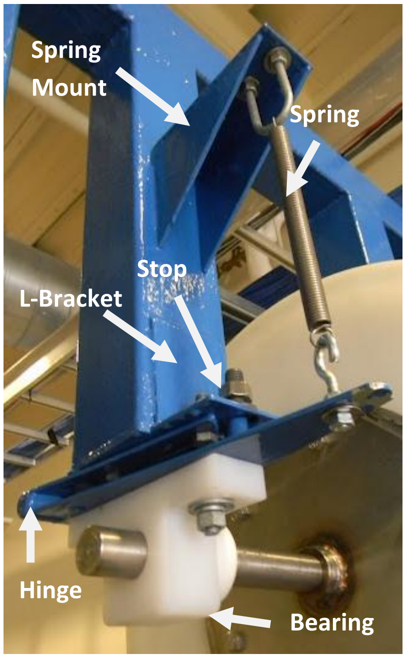


Figure 29: Bearing and Spring Assembly

The vertical sheave supports were added onto the frame later. These frame supports hold the sheave, spring mounts and hall-effect switch (see fig 29). The L-brackets and spring mounts were cut from a 10gauge sheet of steel, using the optical trace plasma cutter. This method allows any shape to be cut quickly and without any programming. The spring mounts and L-brackets were then formed by TIG welding the cut flat pieces into their 3D shapes. Three sets of holes were then drilled into the spring mounts so that there could be 3 different mounting positions in order to give adjustability to the sensitivity of the

load switch, by decreasing or increasing the effective moment arm. The L-brackets and spring supports were then TIG welded to a short section of 3’’x 3’’x.120’’wall tubing, which was also capped with 3’’x3’’ plates. Once assembled, holes for the hinges were then marked by transfer punching through the holes in the hinges then drilled. These vertical sheave supports were then TIG welded to the rest of the frame.

A 7/16’’ bolt was then TIG welded to each of the hinges to provide a travel stop. On one hinge an encoder housing mount was welded on to provide a press fit for the PVC encoder housing. A small plate was also welded to the L-bracket to hold the hall-effect housing. The hall-effect housing was made by boring out the inside of type 316 stainless steel 3/8’’ screw, which will thread onto a bolt welded onto the small plate. A small magnet secured to the hinge trips the hall-effect on and off.

Separate appendages had to be constructed to hold the two cable roller guides, designed to keep the cable from departing the sheave. These two attachments were constructed from 1.25’’x 1.25’’x.120’’ wall square steel tubing and TIG welded to the frame. Their position was carefully calculated however was subsequently adjusted after errors in the calculations were noticed. Large gaps were again filled with various scraps to make welding the joints possible and also to seal all openings to air.

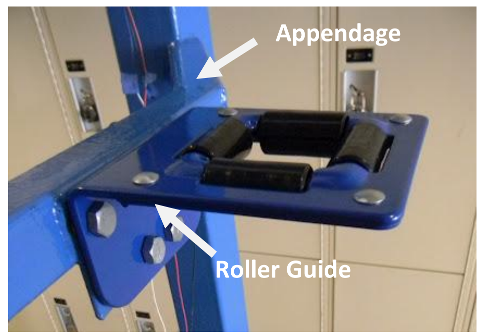


Figure 30: Roller Guide for the Cable

To protect the steel frame from corrosion, it was coated with Amershield, a polyurethane based industrial marine coating suggested by Rob Brewster. In order to prepare for painting, the entire frame was ground with a combination of wire brush and 36grit sand paper. After the frame was completely roughed, a chemical etching compound (Ospho, main ingredient is phosphoric acid) was applied to the entire surface of the frame. This reacted directly and turned some sections black while leaving a white powdery substance. The entire surface was then wiped down with mineral spirits and the first coat of Amershield was rolled onto the frame. A second coat was also applied and then left out for a couple days for the cure to fully harden the resin.

The sheave was constructed from two different parts, the sheave body and the hub plates. The sheave body was machined from a 2’ x 2’ , 1-1/2’’ thick sheet of UHMW polyethylene. This process was aided greatly by Rob Brewster from the Bio Sciences department. The 6’’diameter inner cutout circle was machined first. This first process used a hole-saw to get a rough under sized shape, and then a boring bar was used to get the precise 6’’ inner diameter. While the location of the center was still known, the 6 x 3/8’’ hole pattern, 8’’ bolt circle was drilled using a bolt circle tool on the digital read out. After this a 6’’ OD part was machined out of Delrin®, in order to locate the center of the sheave on the rotary table. With the sheave placed flat on the rotary table a flat end mill was plunged down and the rotary table turned to get the 20’’ outer diameter. The rotary table was then placed vertically with the edge of the sheave hanging off the

front of the mill table. The knee of the mill was then moved down as far as possible and the head the mill was turned at a 30^o angle because the knee would not retract far enough down. A ball end mill was then used to machine the curved groove that the cable would run on. After ten revolutions Rob connected an air motor to the crank of the rotary table so that the entire process was automated. The edges were then rounded and the sheave cleaned.

The hub plates were made from 10-gauge, type 316 stainless steel sheet and two type 316 stainless steel set screw hub collars. The hub plates were cut to a 10’’ OD using the optical trace plasma cutter as before. A 1’’ center hole was then drilled on the mill after using an edge finder to locate the center of the circle. Using the center location the same 6 3/8’’ holes, the 8’’ bolt circle hole pattern was created for each plate and edges created by the plasma cutter were ground smooth. The hub collars were then welded to the plates using the TIG welder and a type 316 1/16’’ filler rod provided by Rob Brewster. Afterwards, it was realized the exact location that the collars were welded to the plates was extremely critical because the shaft would not slide through both collars, however luckily this oversight did not result in a $100 loss of materials.

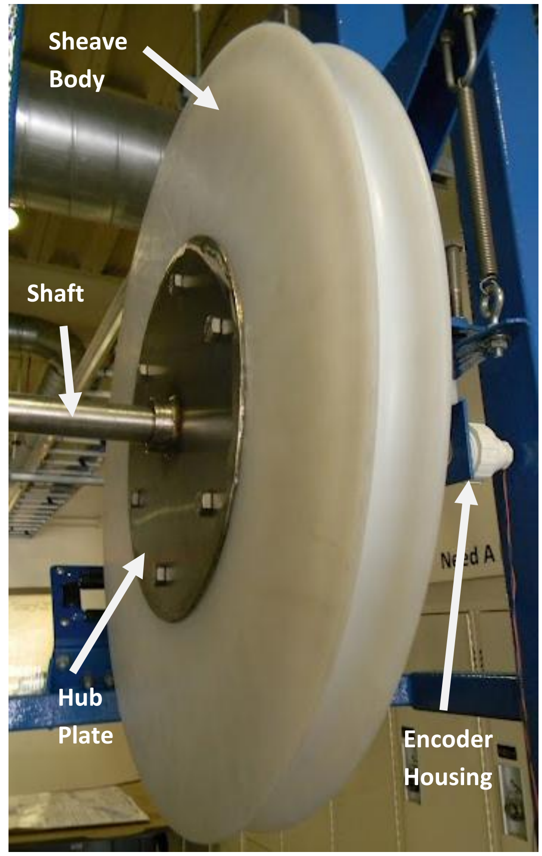


Figure 31: Sheave Assembly

Testing

The sheave and sheave frame have been tested with up to 30 lbs. of load, and the load switch design has also been tested and is operational. Both cable roller guides have been tested with a nylon rope and placed a fair amount of tension onto the cable, which was one of the goals of the roller guides.

Assembly

In order to assemble the sheave to the sheave frame, a list of steps should be followed.

1. Make sure to slide both UHMW shaft collars onto the sheave shaft.
2. Place all galvanized bolts onto the hinge without the encoder support, along with bearing and close the hinge. Then insert the hinge onto the L-brackets with all the bolts simultaneously otherwise there will be no way to insert further bolts. Tighten bolts and proceed.
3. Follow the same set up procedure as with the first hinge, but simply get it ready to install.
4. Insert the sheave shaft through the already installed bearing and slide the sheave as close to the bearing as possible.
5. Install the second hinge, same as before, with all the bolts entering their holes simultaneously. Tighten the nuts until hinge is in place.
6. Slide the sheave shaft through the second bearing and tighten UHMW shaft collars so that the sheave is in line with the cable roller guides.
7. Assemble the encoder housing (see encoder section)

Components

Table 6 below lists the components used to make the final sheave and frame assembly.

Table 6: Components List for Sheave and Frame Assembly

Component	Quantity	Part Number
Sheave Frame	1	Custom made
Sheave Body	1	Custom made
Hub Plates	2	McMaster 9943K29
Sheave Bolts	6	McMaster 92186A634
Sheave Nuts	6	McMaster 90715A145
Hinges	2	McMaster 1526A55
Bearings	2	McMaster 6254K24
Shaft	1	B&B 1'' type 316 round
Hinge bolts and nuts	8	Ace Hardware
Bearing Bolts and Nuts	4	Ace Hardware
Hose Roller Guide	2	Grainger item # 10C541
Roller Guide Hardware	8	Ace Hardware
Springs	2	McMaster 94135K36
Eyebolts	2	McMaster 9489T17
U-bolts	2	McMaster 8862T21
Shaft Collars	2	McMaster 9410T38

Repair

Over time, the load switch may need to be adjusted in order to ensure that its desired operation continues. This can be easily achieved by either tightening or loosening the U-bolts located on the spring mount above the sheave. Tightening the U-bolts will increase the amount of cable tension needed to open the load switch and vice-versa. If necessary, a stiffer or softer 6'' spring may be needed but this is only for extreme circumstances. The position of the U-bolt can also be changed so that the sensitivity of the load switch can be adjusted.

The sheave frame will need weekly supervision so that if any gaps in the paint form, then a quick application of either epoxy or Amershield will stop them from corroding and affecting the integrity of the structure.

The hall-effect switch might also need to be adjusted if changes in the spring tension don't give the desired result. This can be done by simply moving the hall-effect casing (thread) by turning it within the nut in order to make it actuate at different ranges.

Improvements

For future renovations, the sheave frame should be hot-dip galvanized instead of painted with a marine coating. The encoder should be completely sealed from the corrosive air, which also includes the shaft facing side of the encoder. The hinges should in the future be custom made, so that they incorporate all the features needed without adding odd appendages. The hose roller guides should be made of type 316 stainless steel instead of powder coated steel. The flexible shaft should be made of something other than clear plastic tubing, and have a more secure clamping method. The entire structure would ideally be covered by some type of weather proof housing.

Encoder and Housing

Implementing the encoder housing for the sheave is discussed below.

Manufacturing

The encoder housing is made from a three piece PVC ½" union. The non-threaded piece was turned down on the outside to fit snugly in a hole in a metal sheet using a lathe. This metal sheet was welded to the sheave frame. A lathe was also used to turn down an inset for a washer to hold the encoder. This washer was turned out of a piece of acetal stock. The washer was tapped with a 3/8" – 32 thread so the encoder could securely be attached to the washer. The washer fits into the inset on the union piece. A ½" cap was drilled on the end to allow the encoder wires to pass through. Epoxy was used to seal this hole. The encoder input shaft was glued into a flexible piece of plastic tubing. This tubing was cut to length to fit onto a metal rod welded to the sheave shaft.

Components List

- ½" cap
- 3 piece ½" union
- Threaded washer
- Encoder (see image to the right)
- Flexible plastic shaft

Assembly

The encoder housing is put together by following these steps:

1. The washer is first threaded on to the encoder.
2. The wires of the encoder are putted through the ½" cap.
3. The washer with the encoder is placed inside of the union with the wires coming out of the threaded piece.
4. Teflon thread seal tape is wrapped around the ½" cap and it is tightened into the threaded piece of the union.
5. The union is then tightened by twisting it together
6. The flexible shaft is glued to the input of the encoder.
7. The flexible shaft is pressed onto the sheave shaft while the union is pressed through the metal plate welded to the sheave frame.

Figure 32: Encoder used in the sheave assembly. The silver part on the bottom is the input shaft

Swoop Board

Among the many important mechatronics considerations for this project, the microcontroller on top of the pier deck is the key to determining the overall motion and maintenance of the camera pod. The microcontroller board, here on out referred to as the "Swoop" board, contains more than enough features for our application. Figure 33 shows an image of the entire Swoop board.

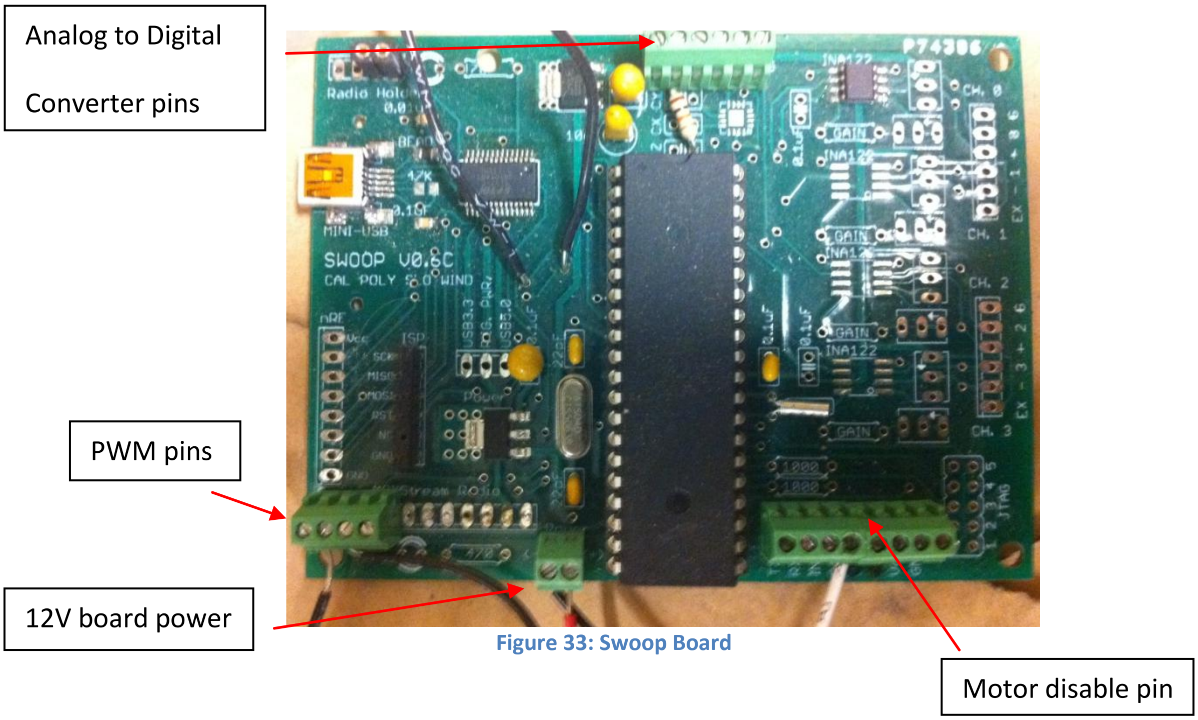


Figure 33: Swoop Board

The key ingredients are the Swoop's Analog to Digital Converter (ADC), general input/output (I/O) pins, and its pulse-width modulation (PWM) capabilities. The ADC is essential for getting readings from the absolute angular encoder that we are using for position control of the up and down motion of the pod. The general I/O pins are responsible for various signals required to run the motor, open and close the rinse valve, and read the hall-effect sensor. Lastly, the PWM capability is required in order to control the direction and speed of the motor that runs the winch. Assembly, testing of circuit components, a components list, and repair notes will be included in the following sections. Also, there will be a discussion of possible improvements and future design ideas that could be considered later on with additional iterations.

Assembly

The Swoop board is a pre-fabricated ATmega 644p microcontroller. Because no assembly of the Swoop itself was required, the assembly of the overall pier deck circuit is fairly simple. The main components are the Swoop board, absolute angular encoder, H-bridge circuit board, motor, and power supply. It is important to note that there are safety hazards involved in powering and operating this circuit and these will be documented throughout this report. Also, there was analysis done in order to verify that 1) the motor could handle the design load, and 2) that the additional gear ratio added to the system gave enough additional torque. These calculations are provided in APPENDIX E. The following are assembly instructions for the

entire Swoop board circuit. While permanent wires will be soldered together for long term use, the necessary information is included in case these wires need to be changed or repairs require a reconstruction of the overall circuit. Reference diagrams for pin breakouts and general assembly are provided in APPENDIX D.

CAUTION: Before doing any disassembly or repairs, make sure all power is turned off. The motor can draw up to 75A and simply touching the motor or power leads could be deadly. Also take great care to ensure that no bare wires are touching that don't belong with each other. This could short out the board and possibly cause it to break.

- Connect the AHI (Pin 7) and BHI (Pin 2) of the H-bridge circuit to the 12V H-bridge circuit board power (see 4801A truth table in APPENDIX D for more information on why these pins are tied high)
- Connect the ALI (Pin 6) and BLI (Pin 5) of the H-bridge circuit to the Swoop board Port D Pins 4 and 5 respectively (these are the PWM signals)
- Connect the DIS (Pin 3) of the H-bridge circuit to the Swoop board Port B Pin 1
- Connect the orange wire (power) of the encoder to the V_{cc} of the ADC pins (right next to ADC7)
- Connect the brown wire (ground) of the encoder to the GND of the ADC pins (right next to ADC4)
- Connect the blue wire (signal) of the encoder to ADC4
- Connect one motor lead to MOT+ and the other lead to MOT- on the H-bridge circuit. NOTE: If during initial setup the pod is moving in the opposite direction that it should, either switch the PWM signals or switch the motor terminals. It is highly recommended, however, to simply switch the PWM signals. In either case, make sure to power off everything before touching or removing any leads from the circuit.
- Connect the main power lead (yellow) of the power supply to the BAT terminal on the H-bridge board.
- Connect the main ground lead (black) of the power supply to the GND terminal on the H-bridge board. NOTE: The power supply leads should be diagonally across each other. The same should be true of the motor leads. If this is NOT the case, recheck the wiring. Do NOT attempt to power the circuit before all four of these wires are hooked up the in the correct locations.
- Connect the 12V power wire of the fan to the FAN+ terminal.
- Connect the ground wire of the fan to the FAN- terminal. NOTE: If these are hooked up backwards, the fan will not run.
- Leave the white signal wire coming out of the fan unwired. This is an RPM sensor that is not currently programmed to be used.
- On one node, connect the 12V power of the power supply with the 12V power terminal on the Swoop board as well as the 12V power terminal on the H-bridge board.
- Repeat the above step for the GND terminals. There should be 3 wires at the ground node if done correctly.

Testing

Once the encoder was hooked up to the circuit and its signal was adequately calibrated by the program, the PID controller code for the motor could be combined into one master program to run the H-bridge circuit. The H-bridge had two versions: the original one was fabricated out of six half-bridges, an aluminum heat sync, and a proto-board to route additional wires. The mounting pin of each half bridge also serves as an output, so they could be directly screwed on to the heat sink to provide conductivity. Figure 34 shows the assembly of the circuit.

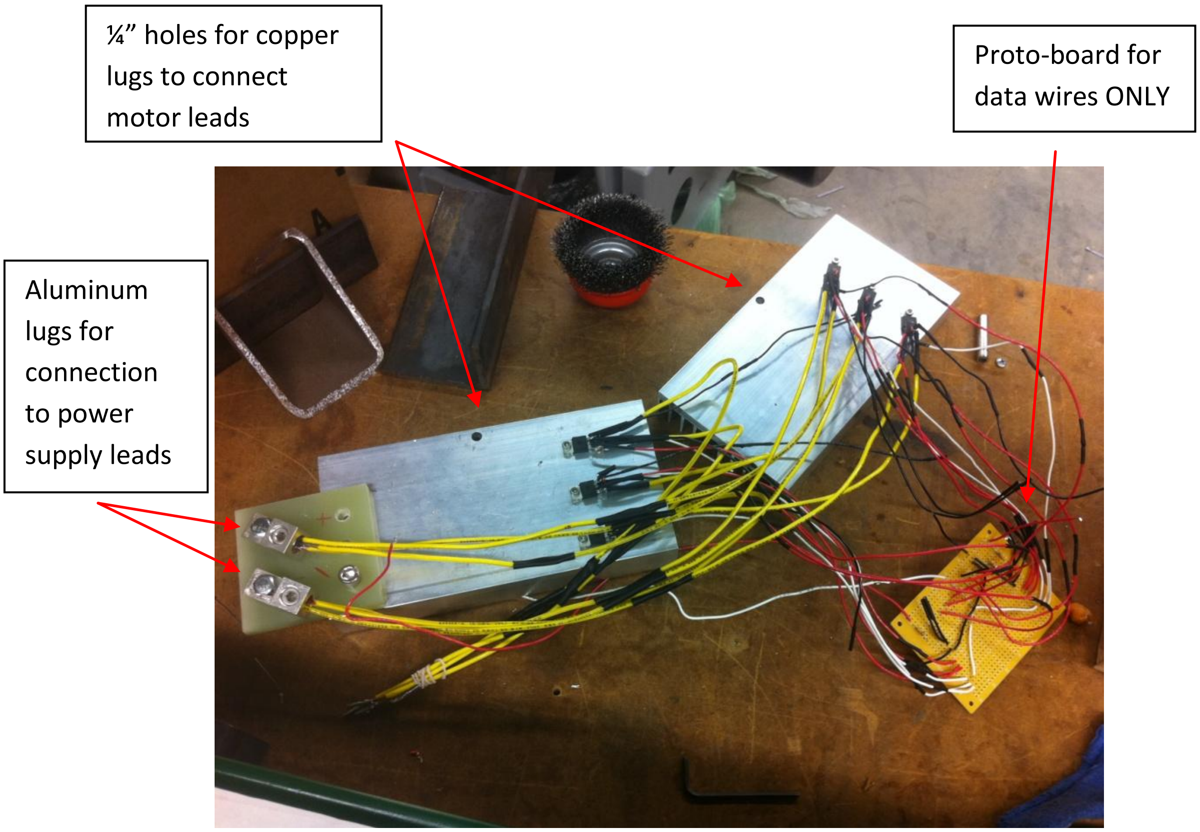


Figure 34: Assembled H-Bridge Circuit

Stranded 14 awg copper wires were used for all power connections, whereas 22 awg single strand data wires were used for all signal connections. The 6 half bridges were electrically connected to the heat sink, so the heat sink acted as a conductor that carried the PWM signal to the motor. If the circuit had worked, thermal paste would have been used to solidify the connection between the half-bridge output pin and the heat sync. The heat sink was 4.23" x 16", overdesigned to give more than sufficient surface area for heat dissipation.

The second design is a high-current H-bridge circuit which was specifically designed for this type of application. We ended up purchasing this H-bridge and using it for the final product. The testing of this high-current circuit focused on using the winch to raise and lower a weight (never more than 15lbs.) connected to a rope over the sheave. The PID controller that was designed is a generic state/task program that runs cooperatively (every 10ms) with the other features of the Swoop board. Figure 35 shows the actual H-bridge circuit being used for our project.

Figure 35: OSMC H-Bridge Circuit with Fan Mounted

The very first tests that were conducted with the simple rope/weight setup used P-only control. This was because integral and derivative gain can cause shakiness which could quickly and easily harm the additional gear train which was added to the winch to increase the torque. These initial tests were also conducted before the polarity-switch delay loop was functioning properly. This meant that the power supply's over-current protection would shut of the power supply as soon as the motor wanted to switch directions to reach its desired target after it had overshot. This allowed the exact value where the motor overshot to be found. Many values of K_P were tested to see if the overshoot could be either eliminated or greatly reduced. The following test results revealed the tendency of the motor to overshoot its desired position.

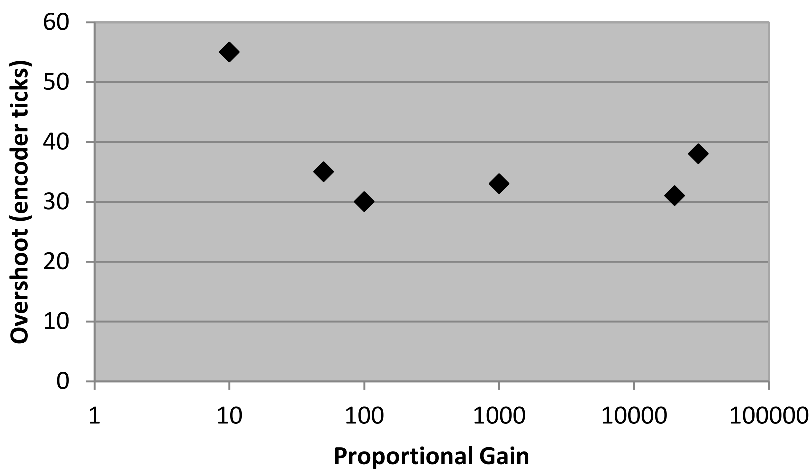


Figure 36: Overshoot of Winch Motor in Terms of Encoder Ticks

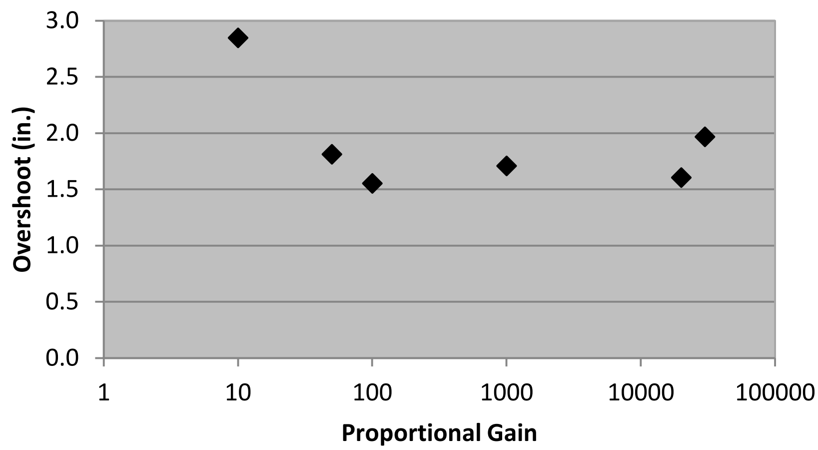


Figure 37: Overshoot of Winch Motor in Terms of Inches

The data shows two important facts about the first round of tests. First, the data shows that large changes in proportional gain had negligible impact on the overshoot of the system. Second, that overshoot never went beyond 3 in., and mostly stayed between 1.5 and 2 in. K_P had to be kept above a certain threshold in order for the error to be greater than 1. There was also no reason to make it large, however, because the effects of small gains were just as good as large ones.

The final round of testing prior to installation at the pier demonstrated the need for additional features to be added. After it was discovered that changing K_P had negligible effect on the tendency of the system to overshoot, it was necessary to add an entirely new feature to solve this problem. This feature involves program logic that put the motor in brake mode as soon as the error came within ±15 encoder ticks of the desired value. This additional feature was necessary as a substitute for velocity control because the motor simply wouldn't run the system at noticeably different speeds (duty cycles). As the weight approached its desired position, the program was written to instruct the duty cycle to decrease and therefore decrease the speed of the motor as the error got smaller. Changing speeds didn't work, however, because backlash occurred when the motor would move the weight downward. Before the ±15 tick feature was added, the motor would overshoot, pause, and then overshoot in the other direction. It kept doing this indefinitely, not getting any closer to the target value and slipping downward each time. Because of the non-linear nature of this system, additional testing will have to be done once the cable and pod are attached to the winch. The amount of weight moved by the motor will be a major factor in the final tuning of the system. Slippage, however, should be eliminated because the normal force between the cable and the sheave will greatly increase with the weight of the pod.

Components List

Table 7 shows a list of all major components required to assemble the Swoop circuit.

Table 7: Components List for Swoop Board Assembly

Component	Quantity
ATmega 644p "Swoop" Microcontroller Board	1
HIP4081A/OSMC H-bridge Circuit	1
MA3 Miniature Absolute Magnetic Shaft Encoder	1
12V/75A Imperial P.M. Motor	1
Zalman 1000W Power Supply	1
Aluminum lug (motor)	2
Copper lug (power supply)	2

The Imperial P.M. motor used for this application is no longer manufactured. If a replacement is needed, Imperial Motors does sell similar motors.

Future Iterations/Additional Features

There are three important components that have not been incorporated into the Swoop circuit at this time. They are the fresh water rinse valve, the hall-effect load sensor, and the push button. The rinse valve is a simple solenoid valve that opens and closes depending if the signal is high or low. The main program runs an interrupt service routine that will open the valve if the pod reaches the pier deck. The valve will stay open for some interval of time (likely about 30 seconds) and will spray fresh water on the pod to clean off the salt water and deposits on the pod and cart. After it is closed, it will not open again unless the pod goes below the deck and comes back. The valve circuit is mostly ready for integration with the rest of the system, but because the easiest way to test its functionality is by testing it with an actual hose at the pier, it hasn't been hooked up to the Swoop board yet.

The hall-effect sensor will determine whether or not there is sufficient load in the cable. A simple spring and hinge system will set off the hall-effect switch if the spring loses most of its tension. This would only happen if the pod either hit the bottom of the ocean floor or was stuck in the tidal zone and was oscillating in the waves. In the case of the pod hitting the sea floor, the program will instruct the motor to stop. The encoder reading reach its max value at that point, so the program will know that the only way the sensor could have gone off was by hitting the bottom. The motor controller will ensure that the pod never stays lingering in the tidal zone. If it needs to travel through the waves it will, but it will not be allowed to stay in that specified range.

The push button will be placed at the max height the pod could reach. When the push button is pressed, the total encoder value will reset. This is very useful in the case of maintenance or repairs, because the pod location can simply be recalibrated when the power is turned back on. Any time the position is not what it is supposed to be for whatever reason, the pod can be reeled up and the encoder will be reset.

Most of the suggested additional features have already been discussed in the previous sections. However, in consideration of future improvements, it is important to mention that at the time of the writing of this report the winch components have not been installed at the pier. This means additional rounds of testing and tuning must be conducted before the system can go into

full service. It is possible that adding integral and derivative gain might actually improve system performance, although at the current time it does not look likely that they will be needed. Because of the backlash in the motor and gearing, there may need to be some redesigning or enhancing of the additional ratio in order to eliminate this issue.

Cable

In order to keep the camera pod waterproof, special connectors were needed to attach to the main cable. Because this cable and especially its molding are designed to be permanent on the winch/sheave setup, there will only be a short section included on assembly and repair. The cable itself contains a total of 21 conductors: 3 sets of 22 awg TS data quads, 6 16 awg conductors, and 3 coaxial wires. A Y-mold was used to separate the components into 6 different legs. Figure 38 shows the cable grip and the central Y-mold, and Figure 39 shows each of the legs.

Figure 38: Y-Mold and Cable Grip

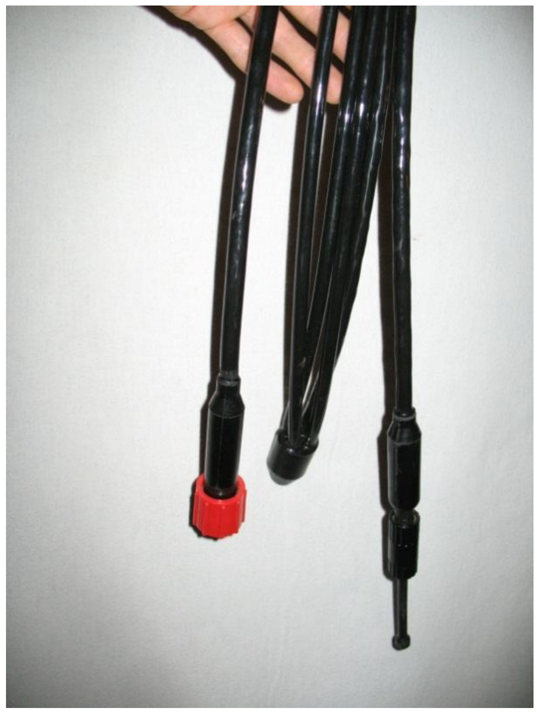


Figure 39: All 6 Legs of Cable

The legs can't individually handle load, so it was necessary to place a grip just above the molding that would take care of attaching to the pod cart. The grip functions similar to a Chinese finger trap, and is rated for 2160 lbs of axial load. The breakdown and function of each leg is listed below.

- Leg 1 contains 12 total conductors: 4 16 awg for power and 8 22 awg for data signals. This leg goes directly to the camera pod and is connected using MCBH12M and MCBH12F micro series bulk head connectors.

- Leg 2 contains 4 total conductors: 2 16 awg for power and 2 22 awg for data signals. This leg was made for a temperature/pressure sensor and is currently plugged for future use by a MCDC4M micro series dummy plug.
- Leg 3 is exactly the same as Leg 2 and is plugged by a Subconn® Poly Plug.
- Legs 4-6 each contain just 1 coax cable. They are plugged in the same junction as Leg 3.

  NOTE: Since the cable originally only had 6 16 awg wires, we requested to have 2 of the 16 awg split off into 2 more. This gives us an equivalent total of 8 16 awg wires.

Assembly and Repair

The cable itself only needs to be reeled to the winch, with certain connections made to the slip ring. The slip ring will have two main components: the circular brass connectors already attached to the winch with 4 leads coming out, and an additional printer cable that is being used for the remaining data wires. The brass slip ring will be used for the 4 power wires coming directly from the pod. The remaining 7 data wires actually used by the pod will be soldered to the printer cable. This printer cable is long enough and has been tested to withstand over 20 full rotations of the winch. Reeling all the way down requires approximately 11.5 full rotations of the 20" diameter winch drum. The simple idea employed here is that the printer cable is capable of twisting as the winch drum rotates, and thus performs the function of a slip ring without actually "slipping." Which data wires are soldered to which printer cable leads and which power wires are soldered to which power wire leads will depend on the way the wires are installed at the pier. Because this hasn't happened yet, there are no specific assembly instructions for this portion. The general discussion in the section regarding the setup of the cable and winch wires should be sufficient as a starting point, however. Additional, more detailed information will come soon.

Future Iterations/Additional Ideas

A simpler, cheaper solution could have been hand-made by our team that could have provided basic functionality. The professional work done on the cable does provide reassurance of robustness, as well as the blueprints to repair or re-designate certain wires for different use in the future. The cable also contains many more wires than are needed for this project, but steps were taken with this design to ensure that these wires could easily be used for other purposes in the future. Addition of a hydrophone and a temperature/pressure sensor are two likely candidates for these additional legs.

Building the pod

Construction of the camera pod includes physical manufacture of the waterproof enclosure, the internal structure, and the structure's subcomponents. It also includes electronics assembly, construction of a wiring harness, and writing code to operate the onboard electronics.

Figure 40: The Pod

Waterproof enclosure

The waterproof enclosure is comprised of three main pieces, two of which are assemblies unto themselves. These pieces are: the tube, the upper cap, and the lower cap.

The tube

The simplest component, the tube, is installed as is from the manufacturer, Reynolds Polymer. It is an 8" diameter acrylic tube with a 0.25" wall thickness.

The lower cap

The lower cap, machined from an 8" diameter solid acrylic cylinder is the main piece of the lower cap assembly.

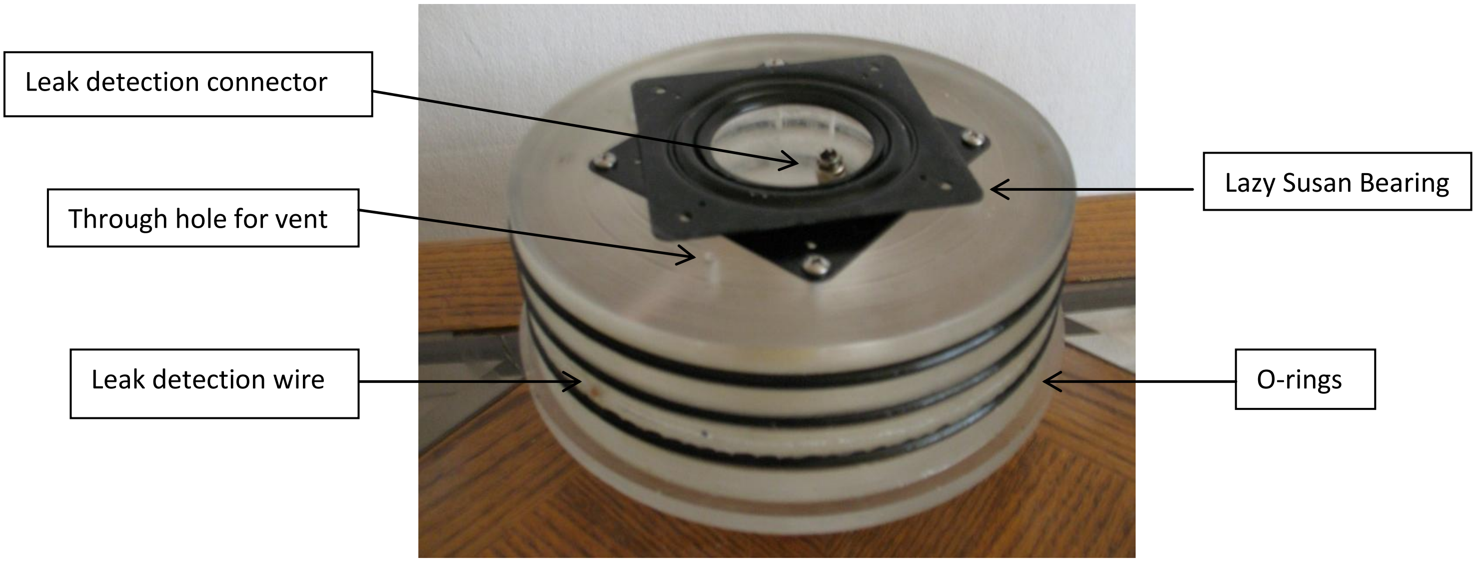


Figure 41: The Lower cap assembly

Additional components include a Lazy Susan bearing for the internal structure to rotate on, a vent plug to allow cap installation without having to compress the air inside the tube, three O-rings, and a simple circuit to detect leakage past the O-rings. The vent plug has the added bonus that a moisture free gas, such as nitrogen, could easily be installed in the tube, replacing the moist air at the pier, to alleviate any fogging issues should they occur. The circuit installed on the cap is simply two wires and a waterproof plug to enable easy cap removal. The wires each run through a hole drilled radially in the cap in between the first and second O-ring lands 180° apart. After installation of the wires, the holes were filled with acrylic epoxy. A small groove is machined on the outer cap diameter between the two. If water were to breach the first O-ring, a short would be induced which can be instantly detected by the onboard microcontroller. The deck-side computer can then be notified, and the assembly can be raised out of the water for maintenance before damage occurs. The physical manufacture of the caps was the most difficult part of the pod.

The pod caps were machined from a solid 50 lb. acrylic rod, 2 ft. long. The first task was to cut out workable lengths. A band saw was thought to be the best option for such a large piece; however the Mustang 60 band saw has such a large error that it cuts a straight cut at 20^{o} and the Hangar band saw would take 1hour per cut while still walking a half a foot. Rob Brewster was contacted for advice and he suggested that the cuts be done at his shop. Rob's band saw was used to make the initial cuts and then a jig was made to run the parts through the table saw in order to make both faces parallel. This method was not ideal, so the parts were placed on a rotary table on the mill, shimmed till it was level and then clamped to the rotary table. A large diameter end mill was then utilized to thoroughly plane one side of each of the 5 discs (1 extra for mistakes). Only one side was squared off because the other would be machined away in the process of making the pod caps.

The still very large cap stock was then placed in an old Clausing lathe at the Hangar and turned to dimensions specified in the drawings. At first, a sharp nose tool was used, which produced an undesirable surface finish and large amounts of chatter. Next a large radius cutter was used and long, stringy, quiet chips ensued. The depth of cut that could be taken was increased tremendously; in fact, .25'' depth of cuts were being taken by the end of the project. This allowed the material needed to be removed to get from an 8''OD to a 2''OD much more manageable. The large center cavity was taken on with another rotary table. The rotary table used had lathe chuck jaws therefore centering the part on the rotary table was not an issue however find the center of the part in relation to the tool was still difficult. This was solved using an edge finder to locate the approximate center. A ¾'' flat end mill was then used to machine out the material in the cavity. The last portion called for a greater surface finish in order to increase clarity for the sonar. To achieve this, the spindle speed was increased and the feed rate was decreased on the last passes.

The O-ring grooves were taken on next. An O-ring design guide from Parker Hannifin's website was used to select the correct O-ring size and groove dimensions for tube ID (see data sheets in appendix). An O-ring groove tool (square shaped cutter) was used to cut the grooves on a lathe. The lathe unfortunately accidentally shifted into auto-feed and damaged one of the corners of the groove. The bottommost groove was also cut too deep.

<u>The upper cap</u>

The upper cap consists of seven components: the cap itself, a waterproof plug (with O-ring), a 3' data/power cable, a hollow shaft, a gear, a bearing, and a magnet. The cap was again machined on campus on a lathe. A concentric through hole is centrally located to allow the entry of wires and the mounting of the gear and bearing for the inner structure's rotational movement. The hole is tapped on the outside to allow a waterproof plug from Subconn to be installed and is reamed to a step from the inside to allow precise shaft installation, a 0.001" interference fit. The gear and bearing each fit to the shaft with a 0.001" interference fit as well with the gear additionally having a hub with 2 set screws. These parts needed no additional tolerancing and are installed as is received from SDP.com. The magnet is installed inset into the caps inner face at a diameter in between that of the pinion gear and that of the internal structure's support rods and is used by a hall effect switch on the structure as a rotational limit switch. The last component is a 3' segment of printer cable outfitted with low profile connectors so as to be able to thread through the inner structure to the lower chamber for installation. Of the 32 conductors inside the cable, 24 are used to pass through power and 6 are used as data lines. This turned out to be a major ordeal as the 24 wires needed to be soldered to 10 pins on the inside of the waterproof plugs which lie inside an area of less than half of a pinkie nail. Two pins are used for power and two are used for ground, with three conductors per pin, while each data line uses two conductors and one pin. All individual connections are shielded with shrink wrap and the connection to the Subconn plug is bolstered with a brace made from 0.010" music wire to distribute axial loads during installation around the soldered connections.

Figure 72: The Upper Cap Assembly

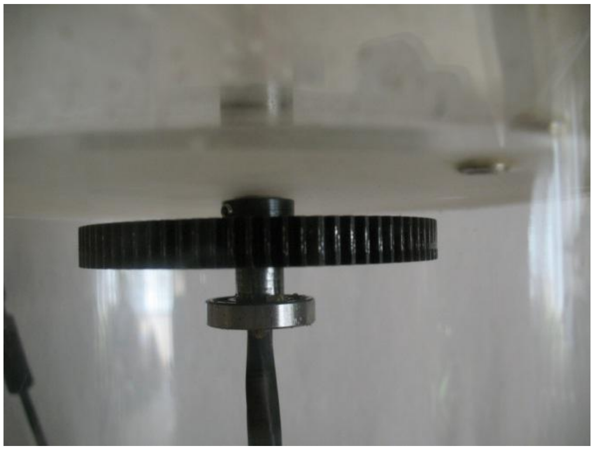


Figure 43: Gear and Bearing in Upper Cap

The internal structure

The internal structure is comprised of 4 discs, 3 threaded rods, 18 standard nuts, 6 jam nuts, 2 felt strips, a cable routing block, a motor and pinion, and mounts for the lights, electronics, and camera.

Discs

The discs that make the individual platforms of the structure were machined on campus from a 0.5” thick Delrin sheet. Oversized circles of 7.75” were scribed around an indentation and the circles were roughly cut out using a vertical band saw. A drill press was then used to create a mounting hole at the indentation so as to be able to mount the discs on a lathe. A 1” diameter shaft was concentrically drilled and tapped to allow the discs to be mounted to it, and the discs were bolted to the shaft and turned down to a diameter of 7.38” The motor mounts on the topmost disc and all planned through holes were then located and machined on a mill.

Structure

The four discs are assembled with three 30” threaded rods with nuts above and below each disc at each rod location (90°, 180°, and 270°), where one 90° increment is left open for unobstructed camera viewing. Jam nuts are used at the outside of the structure to allow clearance between the structure and caps. Felt strips are then glued to the two central discs to provide light insulation to the central camera chamber.

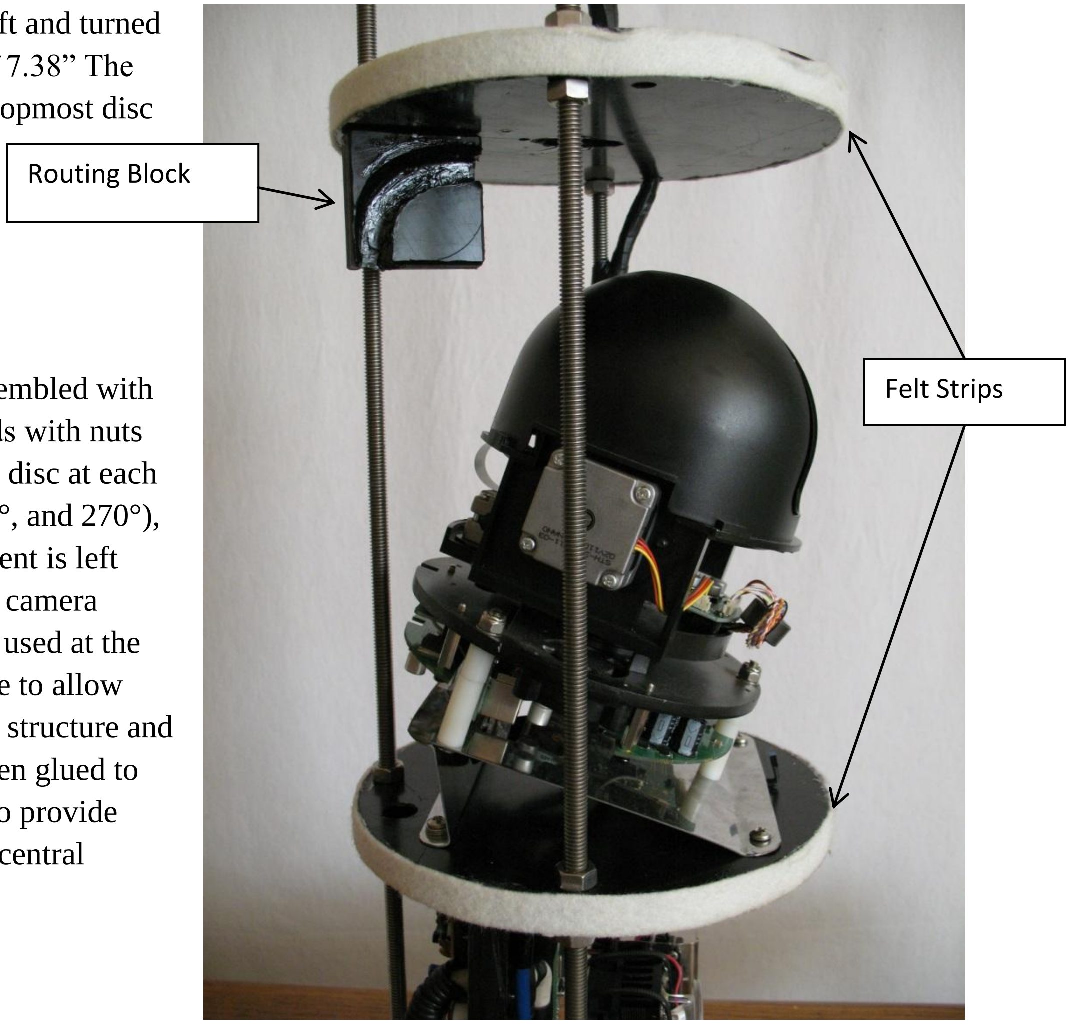


Figure 44: Central chamber of pod structure

Routing Block

Because the routing block features an internal curve and was planned late in the game, it was decided to freehand this piece using a Dremel® tool. Constructed from Delrin, an arced path roughly larger than the printer cable was first carved out using a scribed line from a compass. The block was then cut to size using a miter box and hand saw. The rounded features were then machined into the side of the arced path using a pear-shaped Dremel bit until the cable diameter was slightly exceeded and all rough surfaces were removed. The block was then mounted to the structure using the cable itself in order to achieve a proper radially mounted fit.

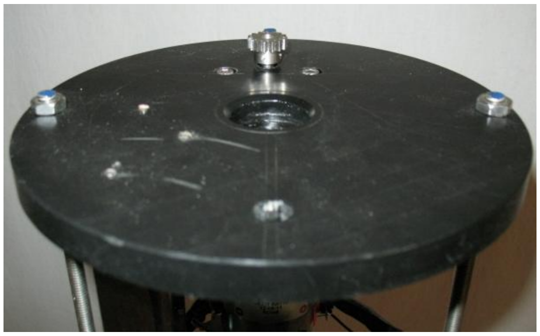


Figure 45: Upper disc with motor and pinion gear

Motor and pinion

The motor, severely discounted from Ametek®, is mounted to the underside of the topmost disc and is fitted with a pinion gear purchased from SDP.com. Slotted motor mounts were considered for adjustability, but the high precision of parts from SDP allowed all designed spacings from our solid models to function equally smoothly in physical form.

Mounts

Four mounts for additional subassemblies are attached to the pod's inner structure. Two of these are towers which hold the LED arrays. These pieces are made from 0.12" stainless sheet metal and were bent partially in a brake and partially in a vise with wooden jaws. Through holes for the servos to fit in were cut using a small Dremel mounted cutting wheel. A ramp for the camera to mount on is also constructed from stainless sheet metal, but a 0.020" thickness gives greater support and weldability. The ramp is comprised of 2 pieces, each bent in a brake and then TIG welded together. The hole for the camera's wiring access was also cut out using a Dremel mounted cutting wheel. The electronics mount is a Delrin slab with through holes to allow wire passage between the two boards in the pod. This slab is mounted to the ceiling of the lowermost compartment using an ell bracket made of leftover 0.020" stainless sheet metal.


Figure 46: Light Mount with Servo and LED Array

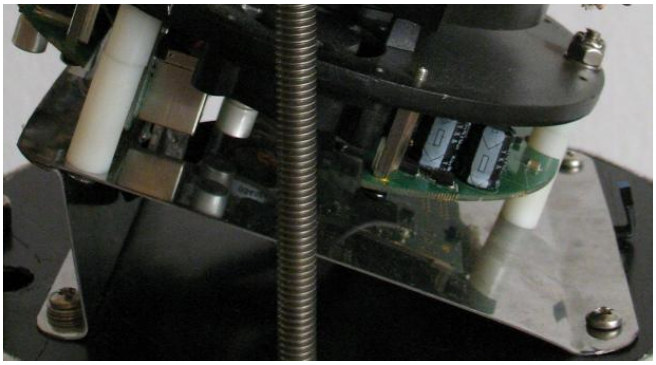


Figure 47: Camera ramp mount

Electronics Assembly

The electronics in the pod revolve around a first generation Cal Poly ME405 board but also include a handmade board, a hall effect switch, a phototransistor, two servos, two fans, six LEDs, an encoder, and, of course, the camera. A wiring schematic for the pod assembly can be found in Appendix J.

ME405 board

The ME405 board, graciously provided by Dr. Ridgely, was altered in six ways to suit our needs. An early wiring error caused the ATMEGA128L, originally mounted, to burn up. The microcontroller was replaced by an ATMEGA1281, which turned out to be greatly beneficial due to greater number of timers and the presence of pin change interrupts. Additional modifications included breaking out microcontroller pins which were not already accessible on

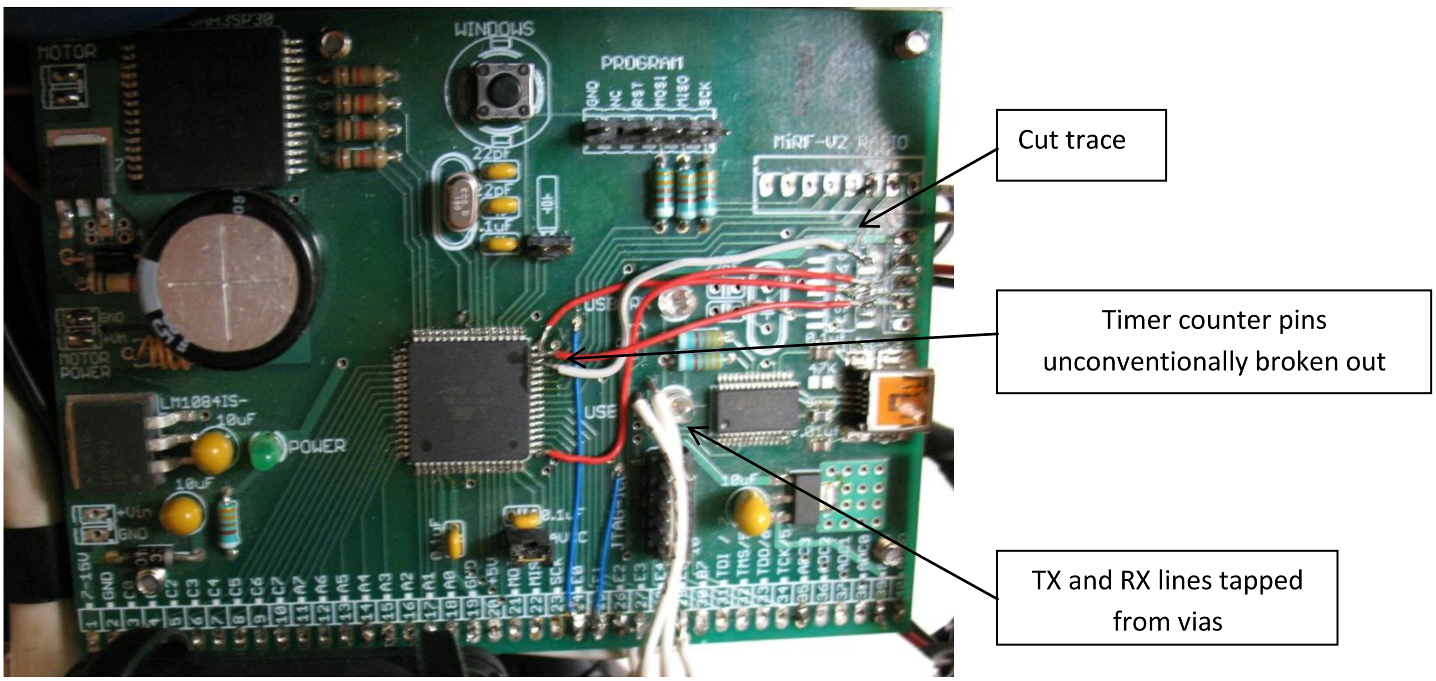


Figure 48: ME405 board with alterations

the ME405 board. This was done by soldering 30 gauge wires directly to legs of the microcontroller at one end and to pads for an encoder driver which was not mounted on our board. We were then able to access the four pins which were not otherwise available. Further discussion of this can be found under the heading “future iterations.” Also to make the above hack work, a trace to power had to be cut to allow an additional pad for wire soldering and data transfer lines were tapped into through in-board vias rather than at proper breakouts. The ME405 board does breakout the other set of data transfer lines, but if those are connected to a communication device such as the FT232, like is mounted on our RS485 breakout board, you can no longer flash code onto the microcontroller without desoldering one of the communication lines. Figure 48 shows the alterations to the board.

Handmade board

An additional board of electronic components and junctions is mounted on the opposite side of the Delrin mounting plate. Due to time constraints, this board is constructed from protoboard and includes some circuitry which is not used. Most of the function of this board is power supply and electronic noise absorption, but additional circuitry for the phototransistor and LEDs are also located on this board. A large switching voltage regulator, Texas Instruments model PT6304, supplies three 12 volt outputs, each capable of 3 Amps. This is fed into one large power node which is then used to power fans, the ME405 board, and the camera. A separate 5 volt voltage regulator on the ME 405 board supplies another power node on this board which feeds the servos, hall effect switch and phototransistor. The 2 LED drivers, Lightline model RCD-24-1.20, are each fed 24 volts directly and their outputs are controlled via PWM signals generated on the ATMEGA1281. The motor driver chip on the ME405 board is also supplied 24 volts directly. The phototransistor is wired with a 513 kΩ resistor between its emitter and ground, 5 volts to its collector and is read by the ATMEGA 1281 at the emitter/resistor junction. A potentiometer was used to calibrate the phototransistor in order to select the proper resistance value. Figure 50, showing the back of the handmade board, illustrates the complexity of this circuit much better than the purposefully simplistic front side of the board. Unused circuits installed on this board include circuitry to read fan rpm and a sensor to read temperature and humidity. The humidity function of our selected sensor and the fan rpm reading capabilities each require a microcontroller timer/counter, and it turned out that we had only enough to generate the necessary PWM signals to drive vital components. Furthermore, the temperature component of our selected sensor varies its resistance value proportional to temperature. This would require a constant current source exclusively for it, so the sensor was left unused on the board.

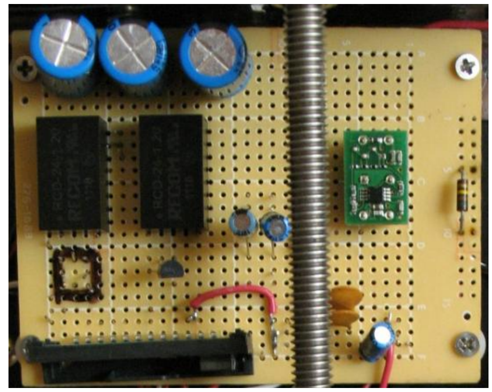


Figure 49: Front of handmade board

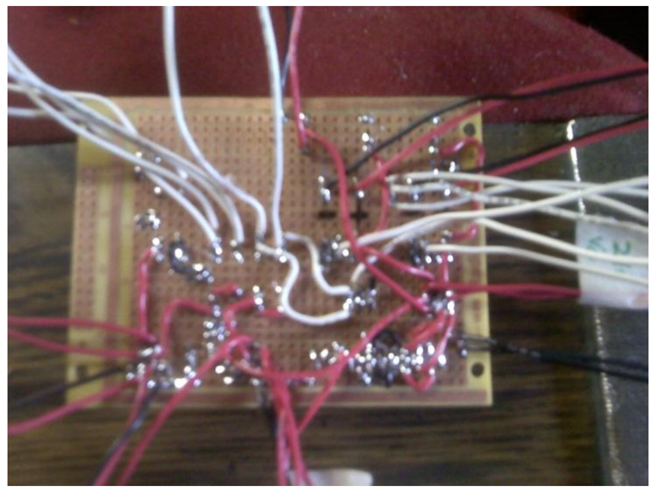


Figure 50: The back side of the handmade board

Wiring Harness

The wiring harness inside the pod is separated into three groups. The first and simplest piece of the harness is the wiring and connector attached to the lower cap for the detection of leakage past the O-rings. The second piece of harness is permanently installed in the pod and connects the two boards to each other and to the sensors, lights, servos, motor, and encoder. Except as a result of a harness failure, these wires are attached tightly to the structure out of harm's way and should not need to be touched. The third section of the harness is attached to the upper cap assembly and is used to connect the internal pod structure to the outside world. Because it was decided to permanently attach the upper cap to the tube, this piece of harness is slightly longer than the tube and is made to be threaded down through each platform, avoiding all other components, until it can be threaded together with its mating waterproof connector in the lower chamber of the pod. The assembly/disassembly section below makes this process infinitely more clear. This last piece of harness, previously discussed in the upper cap assembly section above, is soldered to the leads of a Subconn underwater connector threaded into the outside of the upper cap and is bolstered with music wire to keep from stretching or kinking during assembly/disassembly. The most difficult part of this assembly was the connections between the cable and the waterproof connectors. In order to have minimally sized holes for the harness' path through the platforms, Hirose® 12 pin connectors were chosen for their 14 mm maximum diameter. Acting on this decision required soldering 24 of the 32 conductors in the printer cable we were using to a set of pins which could easily fit on Lincoln's head on a US penny. Figure 52 shows a picture of the soldered connections with a car key for perspective. Unfortunate conditions required this process to be repeated three times in what has been dubbed "the saga of the cable." The first occurrence was due to attaching a female jack when there was no male socket to be had to attach to it. The second occurrence was when the proper set of pins were connected and it was then realized that the base of the socket could not slide freely over the cable housing except where trimming had occurred. A third iteration of micro-soldering was forced by a short which melted the two power pins after the pod was rinsed following its first pressure test. Table 9 shows wire colors and pin numbers for each conductor. Figure 53 shows pin configurations for each connector.

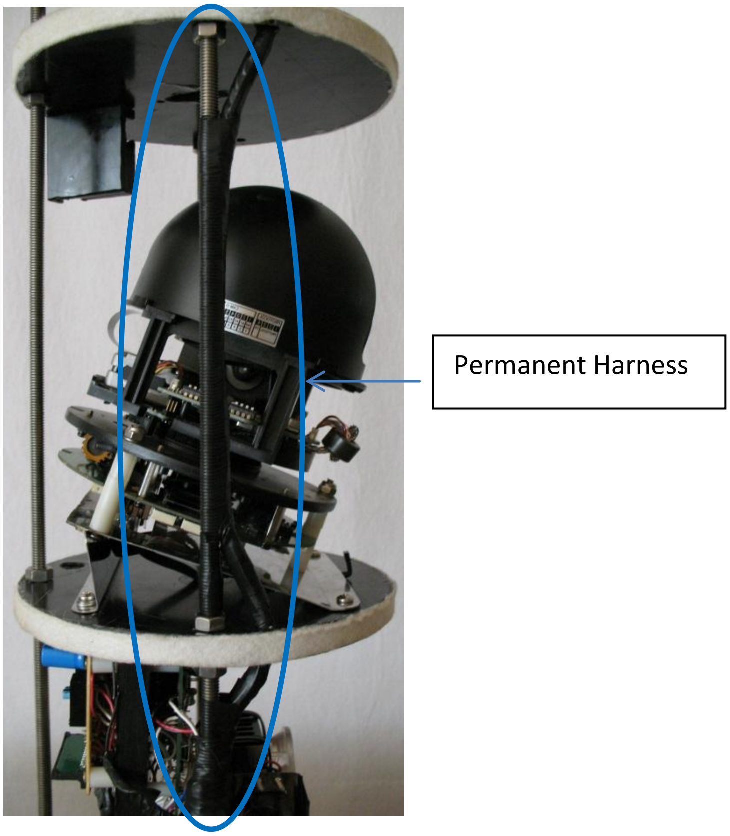


Figure 51: Permanent in-pod wiring harness

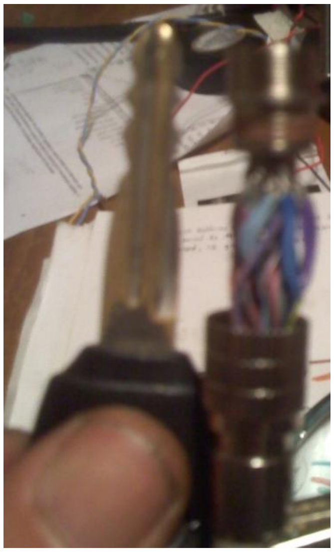


Figure 52: Solderd microconnector joint

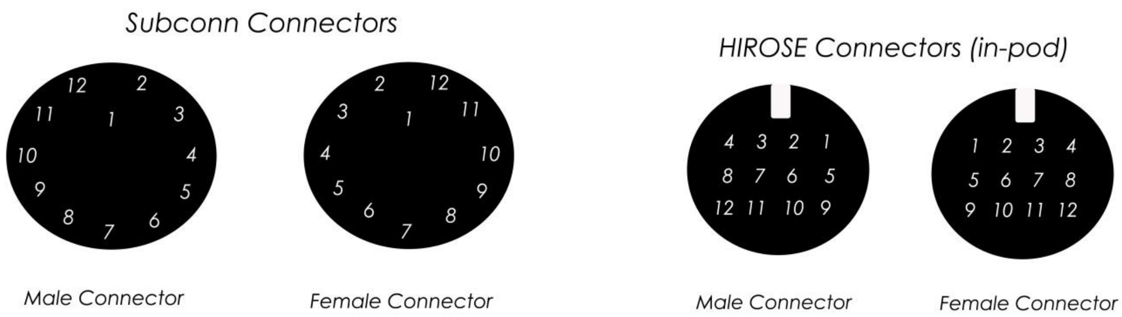


Figure 53. Connector pin configurations

Table 8. Wire color and pin chart

Conductor Name	Subconn Connector	Hirose Connector	Nuclear Cable	In-pod Cable
	pin #	pin #	wire color	wire color
Cam1	1	5	Bk	Y, Y/Bk
Cam2	2	6	W	W, Bk/W
Cam3	3	9	R/Bk	B, B/Bk
Cam4	4	8	G	Br, Br/W
RS485 "B"	5	10	O	Gy, Gy/Bk
RS485 "A"	6	7	B	Pi/R, Pi/B
x	7	1	W/Bk	many
x	8	2	R	many
+24 volt	9	3	G/Bk	R, R/W, R/Bk
+24 volt	10	4	O/Bk	O, O/W, O/Bk
Gnd	11	11	B/Bk	G, G/W, G/Bk
Gnd	12	12	Bk/W	P, P/W, P/Bk

Table 9. Color Abbreviations

B	blue
Br	brown
Bk	black
G	green
Gy	gray
O	orange
P	purple
Pi	pink
R	red
W	white
Y	yellow

Code

The code running inside the pod consists of ten files working together. Appendix H contains doxygen generated summaries of each file and a table of contents of available class methods (functions). The full source code can be found at http://pierportal.csc.calpoly.edu/repos. At this point, the code is not finished to our satisfaction and will continue to be developed through July of 2012 when all group members will have left the area. However, nearly all functionality is present and will be discussed below. The ten files used can be broken into three categories: mains, state machines, and drivers. Additional files are located in a library which is used but files were not written by our group members. Each type of file written for the camera pod is discussed in the following subsections.

Mains

Each program uses only one main, ours is currently LIGHT_CAM_v6.cpp, but the version number is sure to change as the software evolves. The role of the main is to create objects of each type necessary to perform the tasks desired and then run those objects at a speed fast enough to perform the necessary duties, but slow enough that the processor has time to complete all tasks. In LIGHT_CAM, 14 objects are created and then run by the four state machines, which are discussed in the next section. Before proceeding, Table 10 shows each object created by LIGHT_CAM, its file name, its type, and its role.

Table 10: Software files running inside camera pod

File	Object name	Object type	Role
LIGHT_CAM	N/A	Main	Create objects, schedule state machines
avr_adc	avr_adc	Driver	Reads analog voltages and converts to digital numbers.
da_encoder	da_encoder	Driver	Interrupt driven software tracks angular position of a motor.
da_motor	da_motor	Driver	Controls voltage levels and direction to a motor by sending logic and PWM signals to H-bridge.
dats_bright	dats_bright	State Machine	Simple P-only controller to maintain appropriate lighting levels. Driver functionality controls light similar to da_motor.
fan	fan	Driver	Turns fans on/off via logical signal to a transisistor and governs fan speed with PWM signal.
servo	servo	Driver	Controls servo position angles with PWM signals
task_PID	task_PID	State Machine	PID control for motor rotation
task_print	task_print	State Machine	Control all screen output longer than 1 character
task_read	task_read	State Machine	Mastermind. Receives all inputs and initiates appropriate actions.
STL_task	time_stamp, task_timer	Library	Both object types used to schedule state machine run intervals.

Drivers

In order to be able to better discuss state machines, we will first detail the driver classes implemented and the class members (functions) contained within them.

avr_adc

This driver reads an analog voltage at a pin on the microcontroller and converts the voltage level to a digital number so that it can be used for comparisons. In our project, a phototransistor's collector voltage is read in order to determine available light. This driver has 3 methods (another name for function): read_once, read_afew, and TenBit_to_mV. The only method used in our project is read_once, which reads a voltage at whichever ADC [analog to digital converter] pin you specify and returns a 16 bit value.

da_encoder

This driver has very simple methods as its main purpose is to track encoder readings via pin-change interrupts. Two of the three methods return a value, number of tick or number of errors. The third method clears both of those values at a local level.

da_motor

This driver controls the voltage output of a VNH1 H-bridge through the use of four methods. Two simple methods increase_duty_cycle and decrease_duty_cycle allow simple testing of the motors. Method set_mode configures the H-bridge to set the motor brake function or spin the motor forward or backward. The final method set_duty_cycle allows you to enter a specific duty cycle to control the motor's speed. In all cases where motor duty_cycle is concerned, a PWM signal to the H-bridge is used to control voltage output.

fan

The fan driver works very similarly to da_motor. Again, increase_duty_cycle and decrease_duty_cycle allow simple testing of the fans, while set_speed allows specific speeds to be entered. In each case, the fan speed is governed at the fans by a PWM signal. Two other methods fan_on and fan_off control a logical signal to an npn bipolar junction transistor to complete or break the power circuit to the fans.

servo

The servo method contains three methods which work the same way as in da_motor or fan. Methods look_up and look_down allow incremental adjustments of the servo angle for simple testing, and set_angle allows you to enter a specific angle you would like the servos to aim to. In all cases, servo position is governed by PWM signals.

State machines

State machines describe a type of program organization which allows a computer to multi-task. Because the processor runs at 16 MHz (1 line of code runs every 0.0000000625 second) and real-world actions take considerably longer than that, the processor is able to initiate actions and then go manage another task in order to run smoother and faster. The drawback to this programming style is that the complexity of the program is greatly increased and variables must be added so that each time the processor checks in on a task it can quickly resume what it was doing and check to see if the initiated action is completed before evaluating the situation and taking another action. Three of the four state machines used in this software are relatively simple and will be discussed first. Two of the state machines, dats_bright and task_PID, also include methods common to driver files. The simplest machine, task_print, is discussed first, and the mastermind state machine, task_read, will close the discussion of code in the pod.

task_print

Because sending characters out from the computer to a screen or another computer is a slow process in terms of processor time, this state machine is implemented to print out any messages longer than one character. Operating based on the condition of variable print_mode, a global variable shared between task_read and task_print, appropriate messages are loaded into a buffer whenever print_mode becomes non-zero. This process is very fast. A transition is then made to another state where one character from the buffer is printed each time the processor comes to check in on task_print. The end of a message is recognized by a null character, something not

used in human language. When the null character is seen, task_print returns to its hub state and sets print_mode to zero. In this way, task_read can see when task_print has finished. A final state can be entered in the case that the pod is interfacing with a computer, which it will be in normal conditions. The computer has no need for menus and prompts which say please and thank you, so state 2 was created as a dead end which disables task_print from sending anything out over the serial lines. A state-transition diagram for task_print is shown below in Figure 54. Along each transition line is written the conditions necessary to induce the state change (cause) and any variables which are changed as a result of the state change (result). They appear in the format CAUSE/RESULT, where if there is no slash, no results take place other than the state transition itself.

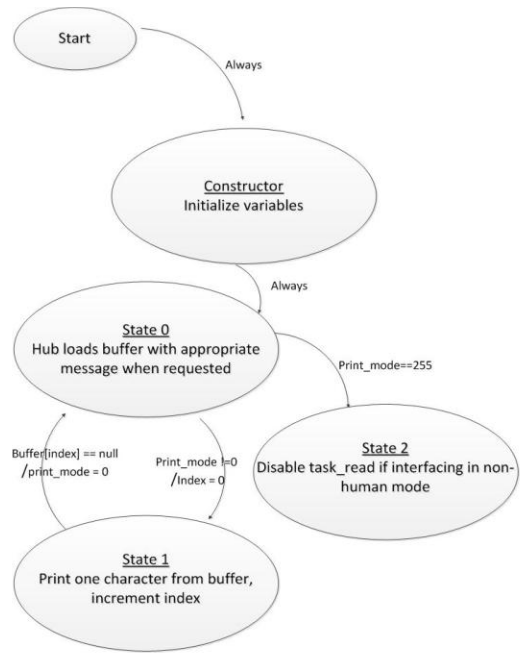


Figure 54: State-transition diagram for task_print

dats_bright

The dats_bright class creates an object which is both a driver for the LEDs in our project and a controller which handles the light intensity and fan speed based upon the ambient light available. Beginning with the driver functions, dats_bright has six methods. Two of the methods again allow simple up/down control of the light intensity for either individual set of lights (upper OR lower). Another method takes a reading of the ambient light and returns the voltage measured at the phototransistor's collector in millivolts. Another two methods, each named set_light, allow a user to set one or both lights to a specific intensity between 0 and 100%. In all cases where light intensity is adjusted over 10%, the fans are turned on to the same percentage as the lights are operating at. The final method, run, is the state machine which is always operating as scheduled by LIGHT_CAM. After construction, there are two operational states. State 0 is inactive and just waits until variable Control_On is set to true, as shown in Figure 55. In state 1, run takes a reading of the ambient light each time and puts in an array of ten measurements. On every tenth measurement, which occurs every 0.2 seconds, the measurements are averaged to remove noise and used to set the lights to an appropriate level. If at any time Control_On is set to false, the lights and fans are turned off and dats_bright returns to state 0.

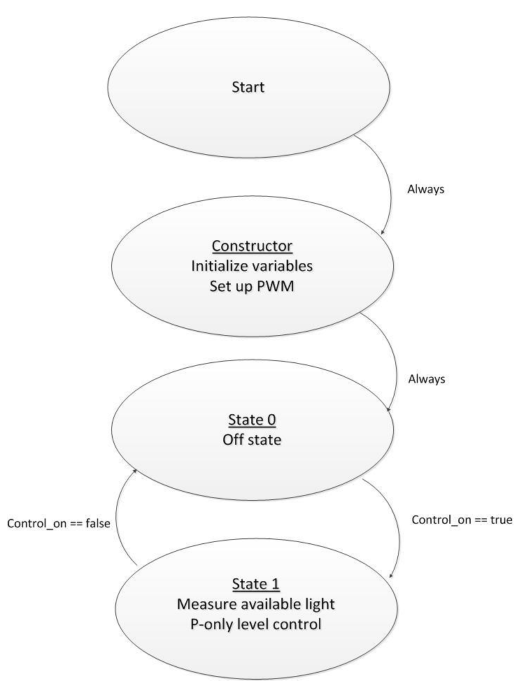


Figure 55: State-transition diagram for dats_bright

task_PID

The task_PID class has four methods and one interrupt driven subroutine. Two of the methods, simply named stop and go, are used to disable or enable motor control. This is done by setting variable giddyup to false or true, respectively. The motor is always stopped with brakes on if giddyup is set to false. The third method allows resetting of the PID by clearing archive values and triggering a clear command in the encoder function. The fourth method is again called run and is set up identically to the way that dats_bright.run is, as is shown in Figure 56. The differences between the two run methods are the types of controllers. task_PID offers full PID control and reliably spins the motor into position with very little error. As discussed in the manufacture of the gear system on the motor, a rotation of 180° of the pod's internal structure relates to roughly 110,000 ticks to the encoder. This value can be duplicated reliably by the PID controller to within 10 ticks. The final piece of task_PID is an interrupt subroutine which is triggered by a hall effect sensor located at the top of the pod. By locating the magnet directly away from the pier piling, the pod can reset its tick count to ±180° (based on direction of travel) as appropriate anytime the pod is driven to that extreme. Movement of the pod is limited to ±180° to prevent damage to the wires tying the structure to the inside of the upper cap. This interrupt also allows a homing method for after a power outage.

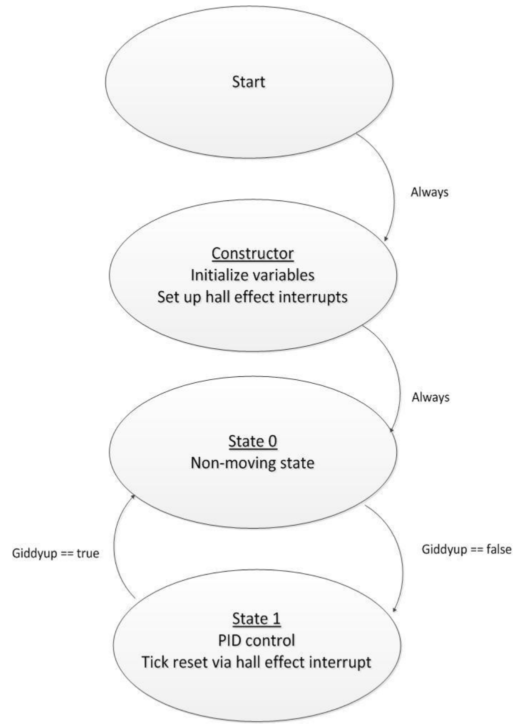


Figure 56: State-transition diagram for task_PID

task_read

The task_read class is the mastermind of the software package running in the pod. It offers two separate user interfaces, one for direct human interaction and one for while it is being controlled through the network by the website. At this point, the second interface is not completely finished, but the groundwork is laid out and agreed upon by the mechatronics and computer engineering team members. It will be discussed as if finished in this report.

The first state decision occurs while the constructor of task_read runs. A message "If you are human, press y within 10 seconds" is displayed and a dummy loop is cycled through in the code to repetitively check if a 'y' has been pressed for 10 seconds. If operating as part of the network, no 'y' will come and task_read will skip to state 11. As a result of this transition, print_mode is set to 255, which disables task_print. If a 'y' is detected, the processor responds with "thank you human" and proceeds into the human interface. As is shown in the state-transition diagram of task_print in Figure 57, the networking interface will be a simple 1 state procedure while the human interface is an 11 state complex octopus of transitions. The reasons for this are twofold.

Firstly, the network interface will not have full functionality. There is no reason to allow PID gains to be set and help menus here will not be applicable to the GUI that the user sees. Secondly, much of the human interface's complication stems from the fact that printing to the screen is a slow process in computer time. By using a 4 byte data packet structure to communicate between the deck-side computer and the pod, time lags due to communication become negligible. Because the diagram helps understand maneuvering the interface, we will begin with the human interface and finish with the network interface.

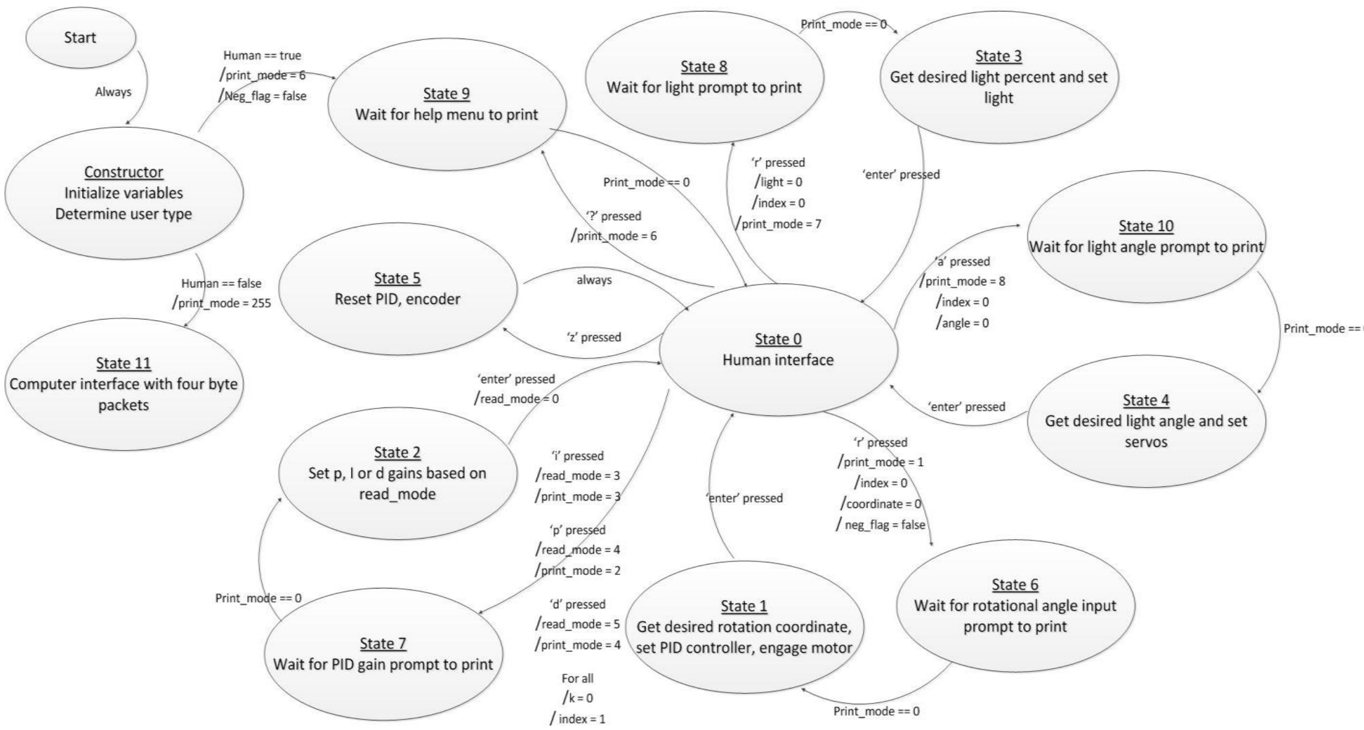


Figure 57: State-transition diagram for task_print

The human interface

If a person presses 'y' as the pod is initialized, the human interface is entered. The first step the processor takes is to print out the help menu and wait until it is completely displayed before entering the hub state 0. Similar states which wait for prompts to display are found with each state performing a data input task. Table 11 shows all the commands possible in human interface mode.

Table 11: Commands while in human interface mode

Button	Command	Button	Command
a	Set angle of servos [0° - 110°]	p	Set K_p [0 – 65535]
r	Set angle of structure rotation [-180° - 180°]	i	Set K_i [0 – 65535]
l	Set light intensity [0% - 100%]	d	Set K_d [0 – 65535]
z	Reset PIDS and encoder	1	+/- mode: upper servo
q	Display: K_p, K_i, K_d, set_point, ticks, error	2	+/- mode: lower servo
g	Enable motor	4	+/- mode: upper light intensity
s	Disable motor	5	+/- mode: lower light intensity
n	Enable light controller	9	+/- mode: fan speed
f	Disable light controller	+/-	Increase or decrease the selected item
t	Get reading from phototransistor	?	Print help menu

In set modes 'a', 'r', 'l', 'p', 'i', and 'd', the user is allowed to enter up to 3 or 5 digits as appropriate for the mode's range. If too large of a number is entered, it is saturated to the largest acceptable value as shown in Table 11. If no digits are pressed before enter is pressed, zero is entered as the set value. In the case of 'r' mode, a negative sign can be typed as the first character only. This triggers a flag, neg_flag, which is applied to the input value when the user presses enter. Pressing enter initiates movement of motors or servos in 'r' and 'a' modes and changes light and fan settings in 'l' mode. Pressing 'n' enables the controller described in the dats_bright subsection above to begin taking readings from the phototransistor and adjusting light levels based upon ambient light conditions. Fan speeds are again adjusted proportional to light intensity.

Network interface

The network interface is designed currently into a single state where it receives a 4 byte data packet, responds with a 4 byte data packet and then initiates the command. The next step will be to expand this interface slightly so that the response will not occur until after the action is completed. This will require at least one more state to be added to task_print but will be mostly copy and paste programming. The order of operations currently is:

1. Receive the 0^{th} byte [command byte]
2. Receive 1^{st} and 2^{nd} bytes and insert into union
3. Receive 3^{rd} byte and store in variable checksum
4. Calculate checksum in pod
5. If checksums match, proceed
6. Use command byte in switch-case
7. Implement command appropriately
8. Return data packet

The pod will not initiate communication, but will be constantly responding to the deck-side computer. Table 12 shows the packet structures which occur along with their commands. OHB is

short for “the Oh heck byte,” which will be sent as response to anything if the pod discovers a leak via its short detection system in the lower cap. This is intended to flag to the deck-side computer to pull the pod out of the water immediately and not let it re-submerge until maintenance has been performed and a network administrator clears the fault.

Table 12: Command structure for network interface

Command	Deck-side computer				Pod			
	0^{th} byte	1^{st} byte	2^{nd} byte	3^{rd} byte	0^{th} byte	1^{st} byte	2^{nd} byte	3^{rd} byte
Set pan angle	0x01	HI byte	LO byte	checksum	x	x	x	x
Set light angle	0x02	HI byte	LO byte	checksum	x	x	x	x
Enable Light Control	0x03	0	0	checksum	x	x	x	x
Disable Light Control	0x04	0	0	checksum	x	x	x	x
Increase Light setpoint	0x05	HI byte	LO byte	checksum	x	x	x	x
Decrease Light Setpoint	0x06	HI byte	LO byte	checksum	x	x	x	x
Get pan angle	0x07	0	0	checksum	0x07	HI byte	LO byte	checksum
Get light angle	0x08	0	0	checksum	0x08	HI byte	LO byte	checksum
reset	0x09	0	0	checksum	x	x	x	x
OHB	N/A	N/A	N/A	N/A	0x0A	0x0A	0x0A	checksum
completed task	N/A	N/A	N/A	N/A	0x0B	cmd 0^{th} byte	0	checksum

Two “Get” commands are responded to by reiterating the command, then sending the requested data before the checksum. All other commands, marked with x, are responded to similarly. A task completed byte is sent, followed by the original command that was just completed, then a zero and the checksum. The agreed upon checksum at this point has been chosen as exclusive OR due to quick calculation and reportedly high reliability.

Testing the pod

Major concerns about the pod’s ability to perform as specified include: visibility if scratched and while lit, overheating, smooth internal motions, water leakage, and code reliability.

Visibility Testing

Dr. John Ridgely, our advisor, supplied a 6.5” acrylic tube left over from the creation of an experiment for the controls lab. This particular piece of tubing had been used as a canister for a vacuum and was severely scratched with evidence of gluing. An early test involved taking video through the walls of this tube with a 1500 lumen Streamlight flashlight oriented in a variety of positions. While a slight haze was visible as the video camera looked through the walls, no distinct scratches could be seen and the video quality was deemed acceptable by the group and Dr. Ridgely. Furthermore, the refraction index of acrylic is similar to that of water so once water fills the scratches, the effects should be further diminished. Until complete sealing is accomplished, discussed momentarily, this statement cannot be verified. The other visibility concerns involve light from the outer chambers either reflecting off of the inner walls into the camera chamber or refracting into the tube wall and lighting the wall like a fiber optic cable. The effects of internal reflection were nonexistent once a cloth seal was introduced between the light

and camera. This function is achieved in our final design by felt strips surrounding the camera chamber. Illumination of the tube wall itself proved to be negligible unless the light was aimed directly at the end of the tube wall normal to the diameter, a situation not possible in our design.

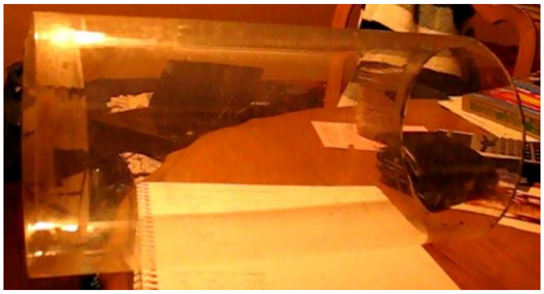


Figure 58: Scratched up test tube

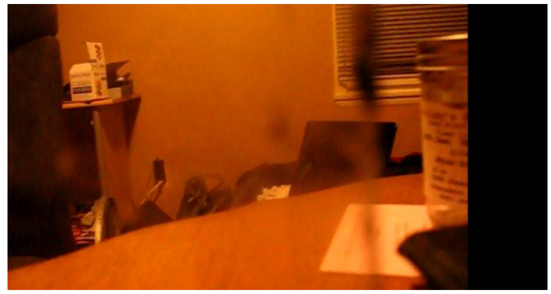


Figure 59: Looking through wall of test tube

Overheating

Being that acrylic is a poor conductor of heat, the team was concerned over residual heat buildup from the voltage regulators, motor and LED drivers, lights and camera. Precautions taken include the use of a switching FET voltage regulator and the use of fans in each chamber. Once fans were installed, the sealed pod was exposed to maximum heat output for a 2.5 hour block with a mercury thermometer in the central chamber and it was seen that the internal temperature did not exceed 90°F, where the room temperature was 69°F.

Smooth Internal Motions

The motor driving the pod structure's pan function is driven by a PID (Proportional, Integral, Differential) controller to ensure accuracy and smooth motion. Speed limiting of the motor is implemented by limiting the voltage output from the VNH1 H-bridge motor driver chip. Testing without the camera yielded best results with a P only controller. Error upon rotation would consistently be less than 10 ticks when rotated through 0 to 110,000 ticks. Additionally, movement was successfully tuned to the goal of not making a human motion sick. However, slightly abrupt endings to the motion were found to disturb the security camera's internal pan position. As the final assembly took longer than anticipated to complete, further testing and tuning will be required. The camera does have a function to lock into a given position, which we hope will correct this issue, but a velocity based controller might also need to be implemented to ramp rotation speed up and down more smoothly. Additionally, closed source coding for the security camera makes it difficult to extract any specific commands for the camera itself. With assistance from a technician at A-1 webcams, the source of our camera, we hope to extract the ability to lock the camera position soon.

Water Leakage

The final and most crucial test for the pod to undergo was a pressure test to 100' of depth in salt water, a factor of safety of 2.5 for our application. For this test, our sponsor, Tom Moylan, took two of our members roughly 1.5 miles offshore in a Zodiac to achieve the maximum depth required. In order to pinpoint failure, if it occurred, the lowering rope was marked at 40', 60' 80'

and 100’ positions, and our test procedure involved lowering and raising the pod for inspection at each increasing interval. Unfortunately, the glued seam between the upper cap and the tube failed at 60’, as evidenced by roughly 2 Tablespoons of water inside the pod after the test. Plans to improve the seal will be implemented in the coming weeks and this test will be reiterated after the following repairs have taken place:

1. The pod will be placed on a lathe with both caps installed and a V-groove will be machined at the external interface between the upper cap and pod.
2. The inside of the pod will be half filled with fresh water, inverted, and pressurized to flush salt water residuals and verify leak location.
3. After drying, Acrylic glue, a solvent with water-like consistency, will be liberally puddled in the inside of the tube and again the pod will be pressurized to push the solvent into any remaining voids. The acrylic glue will then be applied to the innermost portion of the V-groove from the outside.
4. Once cured, a marine rated epoxy will then be applied to the outside of the pod, filling the V-groove.

Code reliability

While many code unreliabilities would be nothing more than a nuisance, certain aspects are crucial to prevent system damage. The most primary example of this is that if the leak detection system is triggered, the pod must be pulled out of the water quickly. This test will be simulated on the pier deck by shorting the wires manually to ensure appropriate responses occur. A second redundant failure check which must be further tested to ensure functionality is the hall effect sensor’s interrupt subroutine. This system guarantees that the pod cannot twist its cable beyond 180°, which is vital for the longevity of the wire. Additionally, further twisting the cable could damage the LED array in the upper chamber by pulling or constricting about the lens or servo arm. Another important issue lies in the fact that we have shown some unreliability in communications over the lengths of cable we are using. While it seems to be a moot point when only sending a few bytes, further testing will need to happen to ensure optimal performance.

Maintenance

The camera pod has a minimal amount of scheduled maintenance and will mostly be performed on an as-needed or an as-opened basis. Table 13 lists the foreseeable maintenance items and suggests timelines and suitable products.

Table 13: Suggested maintenance chart for camera pod

Type	Part	Job	Frequency	Product
Clean	Outside of Tube	Wipe with gentle cleaner and chamois cloth	Weekly or as needed	Windex
	Inside of Tube	Wipe with gentle cleaner and chamois cloth	When opened or as needed	Windex
Lubricate	Cable routing points	Apply lube to cable routing points	When opened or monthly (less of the two)	Vasoline
	O-rings	Apply lube to O-rings	When opened or monthly (less of the two)	Pure Silicon lube
	Upper Bearing	Apply lube to upper bearing	Yearly	Bearing grease
	Lower Bearing	Apply lube to lower bearing	When opened or biannually (less of the two)	Silicon spray lube
	Gears	Apply lube to pinion gear face	When opened or monthly (less of the two)	Silicon spray lube
Check	O-rings	Check for tears, ensure pliable	When opened or annually (less of the two)	N/A
	Pinion set screw	Ensure tight. Blue Loc-Tite if retightening	When opened	N/A
	LED function	All 6 LEDs come on	Monthly	N/A
	Felt strips	No tearing, excessive fraying, or mildewing	Monthly	N/A
Replace	Thread tape on vent plug	Remove old thread tape and reapply new	When opened	plumber's tape
	Felt strips	Remove old felt and glue. Cut strips 0.5" x 23.25" and glue to discs surrounding camera chamber.	As needed	Standard felt - Betty's Fabric donated Brushed on adhesive.
	O-rings	Replace	As needed	O-ring part # EPDM O-Ring AS568A Dash Number 366 McMaster part # 9557K344
	LEDs	Remove Lens with razor blade. Desolder leads and remove screws from LED heat sink board with bad LED. Remove LED heat sink board to workbench and desolder bad LED. Reverse procedure to install. Install new thermal paste.	As needed	CREE LED # XMLAWT-00-0000-000LT20E7CT Arctic Silver Thermal Paste

Assembly/Disassembly

The following sections detail the process to remove and install the internal pod structure from the tube. Installation is nearly the reverse of disassembly with minor differences which will be addressed. Please see attached maintenance chart for specific component replacement procedures as needed.

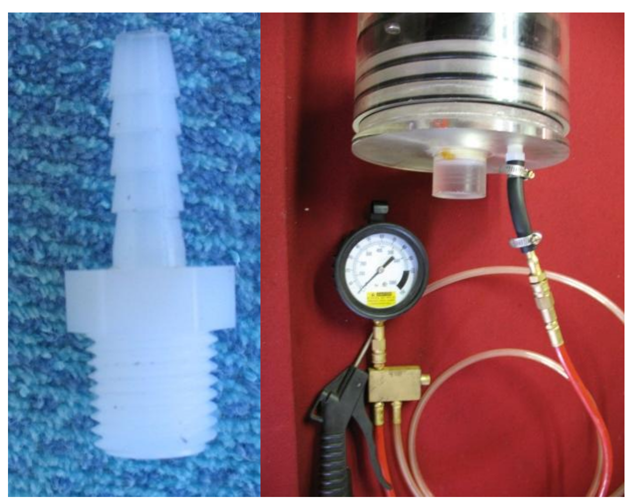
Disassembly

The following steps should be followed carefully to remove pod inner structure without damage.

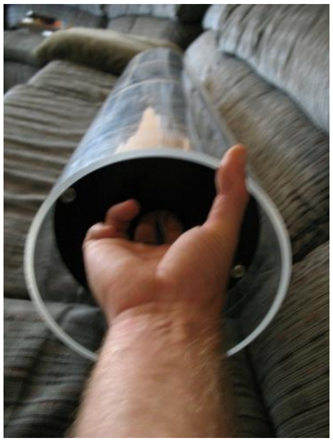
1. Place pod horizontally on floor or table on top of a towel or blanket.

2. Remove vent plug from lower cap using a 5/8” or 16mm wrench.

3. While an assistant holds the tube, firmly grasp the button on the lower cap and pull straight out. If pod has been sealed long enough for this to be overly difficult, thread a pipe tapped (1/4” pipe threads) plug with barbed nipple into the threaded vent hole into the lower cap and raise internal pod pressure to 5 - 10 psi or until the cap begins to move slowly.
   Caution: Do not let the cap come off quickly! Wires connect the lower cap to the structure and allow only 5 to 6 inches of extension.



4. Unscrew threaded wiring connection between internal structure and lower cap. Set the lower cap aside.



5. Rotate tube such that the motor and pinion are at the 6 o'clock position (straight down). Insert fingers into large hole in the lowest platform and pull straight out firmly and evenly until the pinion gear separates from the stationary gear at the top of the pod. While watching the cable in the upper chamber, continue pulling the structure with an even force until the lower chamber is out of the tube.
   Caution: Cable in upper chamber can snag on upper light array. If this happens, push structure back in to release snag and rotate structure inside of the tube until the cable is safely oriented.

6. Unscrew threaded wiring connector between structure permanent harness and cable pigtail from the upper cap. Orient the cable so that it lies relatively straight.

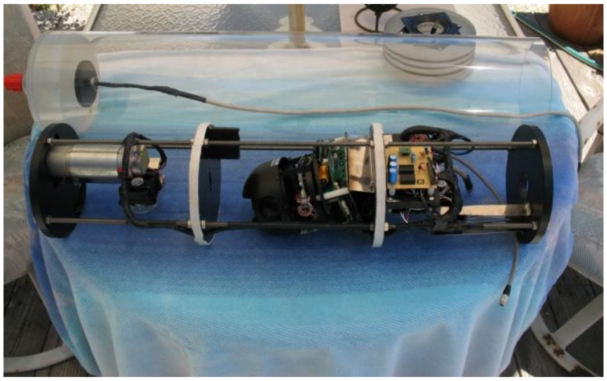
7. Ensuring the remaining portion of cable or its connector do not snag on the lower portion of the structure or any of the electronics therein, continue pulling the structure with a straight even force from the tube. Continue to watch for snags in the upper chamber also. Continue pulling the structure out of the tube until the camera chamber is roughly hallway exposed. Pull the harness connector through the access hole in the lower camera chamber platform and remove the cable from the routing block.

8. The structure will now slide freely from the tube. Ensure the cable does not wrap around the upper LED array or wire connections to the motor/encoder on its way out.
9. Perform inspections of parts as specified in the above maintenance chart, Table 13. Clean, lubricate, and replace parts as necessary. Table 13 suggests frequency, products, and procedures for all foreseen maintenance tasks.

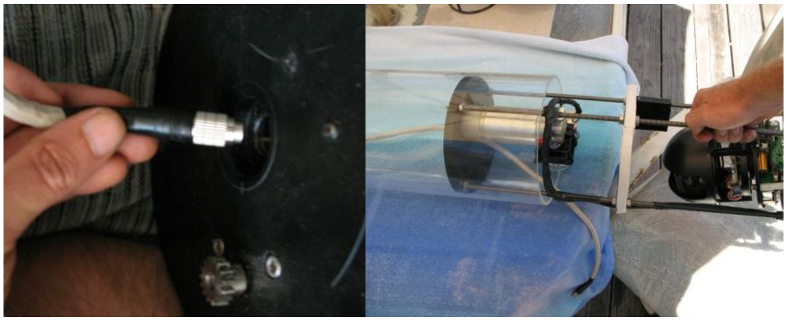
<u>Installation</u>

The following section describes the differences between disassembly and installation.

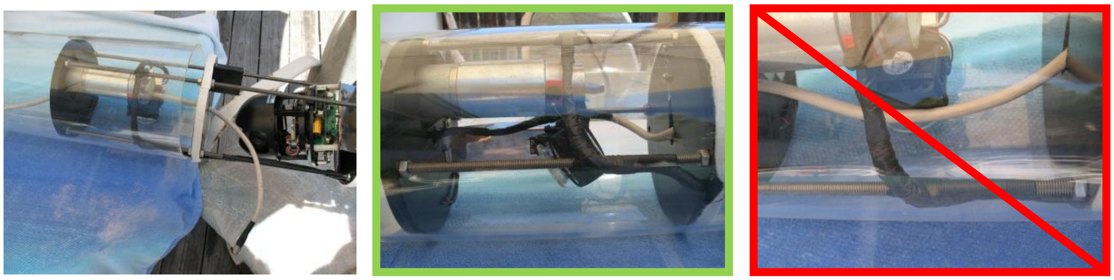
1. Orient the tube horizontally on floor or table on top of a towel or blanket with the magnet inset in the upper cap in the 12 o'clock position (straight up).



2. Thread the cable through the hole in the upper platform and insert upper platform into the tube. Orient the structure so that the motor is also in the 12 o'clock position.

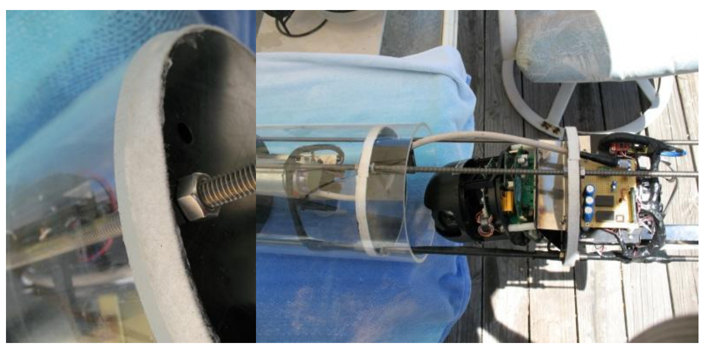


3. Thread cable between motor and the upper light array and through the central hole in the second platform. As the structure is inserted, the cable will attempt to come out of this position. Keep the cable in this position by always keeping the cable taut while pushing the structure into the tube.

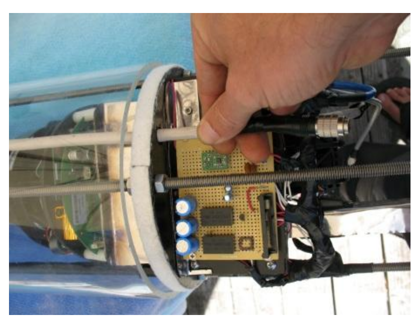


4. Ensuring that cable routing surfaces are well coated with Vasoline or equivalent, thread cable through upper camera chamber platform and around cable routing block.

5. Insert upper camera chamber platform slowly into tube, ensuring that felt does not snag or tear. Press the felt into the tube as necessary for insertion. If felt was just replaced, two sets of hands are useful for this.

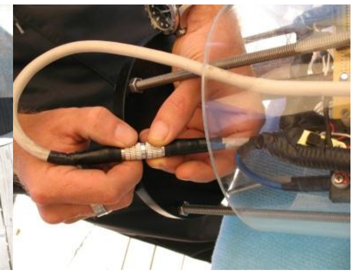


6. While pulling gently on the cable, push structure into tube until camera chamber is halfway exposed. Slowly pull all slack from cable, ensuring that the cable is not binding around upper LED array. Thread cable connector into lower chamber.
Caution: Do not pull directly on cable connector! Instead, grasp cable body firmly.

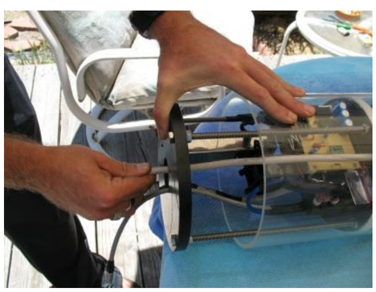


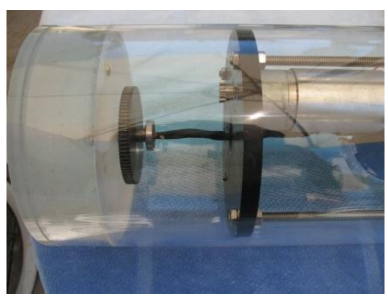
7. Insert lower camera chamber platform slowly into tube, ensuring that felt does not snag or tear. Press the felt into the tube as necessary for insertion. If felt was just replaced, two sets of hands are useful for this. Continue to pull gently on the cable so that the cable is still routed between the motor and upper light array in the upper chamber.

8. Insert structure until lower chamber is roughly halfway exposed. Gently pull all slack from cable, again watching for snags in the upper chamber. The structure can be rotated 180° inside the tube to alleviate snagging or undesired friction points. Connect cable connector to permanent harness connector in lower chamber gently screw them together.



9. Thread small harness connection for lower cap assembly through large hole in lower platform. Then pull the main cable straight down (from the hole in the lower platform of the camera chamber) accessing the cable from the edge of the lower platform for as long as possible as the lower chamber is inserted into the tube. Further pulling can then be applied by reaching the main cable through the large access hole in the lower platform. Pull slack as needed to insert structure so that cable does not kink in between upper cap and structure. Insert structure in this fashion until gears are just shy of being coplanar.



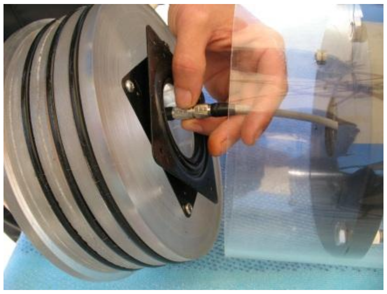


10. Ensure magnet (in upper cap) and motor are still oriented at 12 o'clock. Gently press structure into tube and rotate slightly as necessary to allow gears to mesh.

11. Push any portion of main cable exposed into the lower chamber and fish out the cable for the lower cap as necessary.

12. Ensure lower cap O-rings are in good condition and are well lubed with Moly lube or equivalent. Connect wiring connectors and thread them together gently. Insert cap slowly

while pressing the O-rings into their lands as they enter the tube. If O-rings have just been replaced, this takes a lot of force.
Caution: Ensure O-rings do not bulge out and get pinched/torn as cap is pressed in.
Caution: Subconn wiring plug on top of pod is long and semi-fragile. Be careful with it when applying large forces to lower cap.



13. Remove old thread tape from vent plug and re-apply new thread tape. Insert plug and tighten with a 5/8" or 16mm wrench.

Future iterations

One of the most important items for a future iteration of this board would be to create the entire circuit for the project with its custom needs in mind. The ME405 board we used saved enough time to where we were able to get a functional result, but there were some major drawbacks. In future iterations, a custom PCB board which includes all components in the present circuit would help clean up the wiring a lot. Additionally, it would be good to step up the microcontroller to an ATMEGA1280, which has 100 pins and double the timer/counters. This would have allowed the fan speeds to be monitored by the microcontroller and the humidity sensor to be read.

Another thing inside the pod that did not come to fruition is temperature monitoring. Measuring pod ambient temperature and temperatures directly at LED heat sinks would allow for greater safety factors for the electronics on board the pod.

An additional electronic device that did not work out was a sonar sensor in the lower cap to detect the sea floor. It turned out that the sonar waves could not penetrate the acrylic cap. A future iteration should include some means of bottom detection, whether it be a stronger sonar, an external sonar, a laser, or some way of waterproofing a mechanical bump-stop switch.

The cable to the lower chamber creates a huge ordeal for both repair and assembly. The threat of twisting is also a potential issue. Future iterations would do well to redesign this aspect. Possibilities include adding a clockspring or similar conductor at the top of the structure or making the upper cap removable. Downfalls of the removable upper cap lie in the fact that the structure place a torque on the cap as it rotates.

Winch Gear Ratio

The following sections describe the implementation of a gear system added to the winch.

Manufacturing

The need for a larger ratio than the 12.9:1 gear ratio already on the winch was discovered late in the manufacturing phase of the project. It was decided to quickly design and build an additional gear ratio into the winch to slow the travel speed and increase the load capacity. The gear ratio was made by mounting a bearing and a shaft with a pinion connected to the winch chain and a sprocket connected to a set of 2 additional chains mounted into an aluminum block that is mounted to the winch. The additional chains connect to the motor pinion. Figure 60 shows the new layout of the gear train.

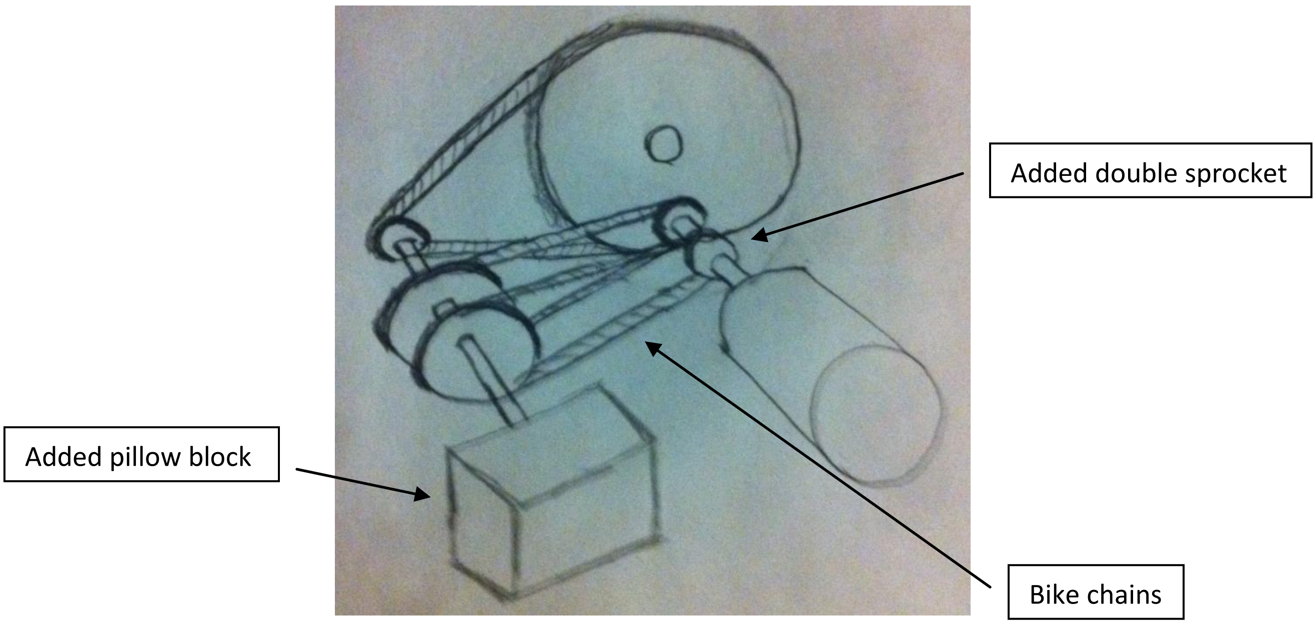


Figure 60: Sketch of gear system added to the winch

Aluminum block

The aluminum block was machined on a manual mill. A turntable was used to clear out a large amount of material for the large bearing to be placed. This process is pictured in Figure 61. Four holes were drilled in each corner of the block that matches up with the holes on the mounting plate of the winch. Initially, these holes were tapped but it was decided to remove these threads and place bolts through each hole to secure the block to the winch.

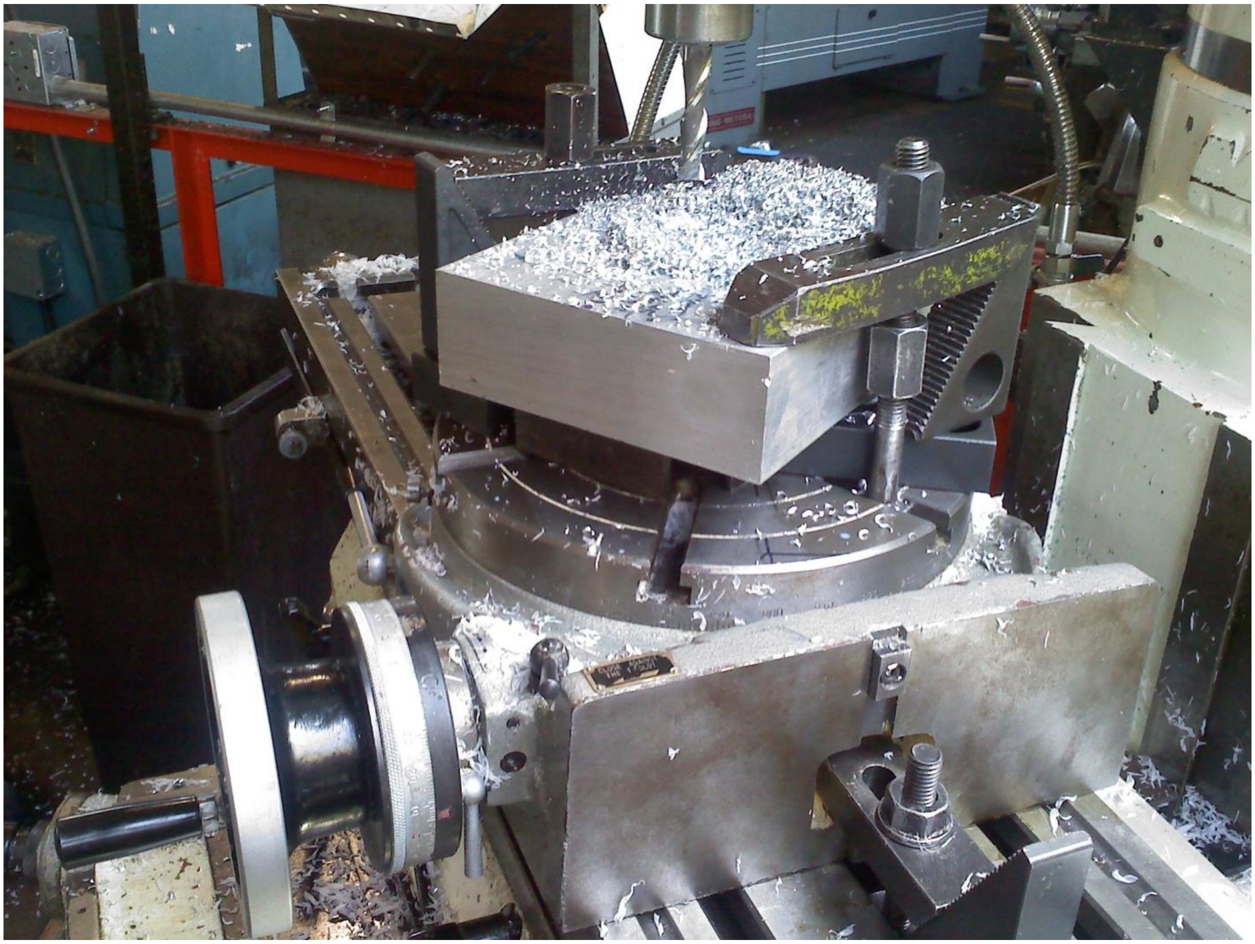


Figure 61: Mill setup on a turntable in order to clear material for the bearing to be set

Hub

The 2 sprockets were placed on a bike hub pulled from an old bike. The hub was placed on a mill and machined flat on the narrow side. A 1" diameter hole was drilled through the center of the hub using a drill press to fit around the shaft. Both the machined flat face and the position of the hole were critical to centering the attached sprockets on the shaft. A ¼" broach was then used to make a keyway in the hub. This was done using a hydraulic press. A second pass was done using shims to make a deeper slot so the key would fit. The hub was discovered to wobble slightly due to bending from its previous use and from when it was clamped in a vise on the mill. This was corrected by bending each arm of the hub individually using the press.

Shaft

The shaft that fits in the bearing and holds the winch pinion and the sprockets was initially turned down from a stock of hardened steel. This proved exceedingly difficult and time consuming. The decision was made to make the shaft from aluminum – a material much easier to machine than hardened steel. After the shaft was turned down to the correct diameter to fit inside

the bearing, it was turned down on one end to fit the pinion that originally came with the motor and that mates with the chain already on the winch. Two slots for keys were machined into the shaft on a manual mill.

Pinions

The pinion that came with the motor was broached with a small sized broach. This size fit the key and the machined slot on the shaft. The motor shaft was fitted with two sprockets to mate with the 2 additional chains. This was assembled onto a metal collar and fitted onto the motor shaft.

Chains and Winch

The chains are standard bike chains that mate with the sprockets. In assembly it was discovered these chains would interfere with part of the winch mounting plate. Those parts of the mounting plate were cut away using a reciprocating saw.

Assembly

The assembly for the winch gear system is complex due to the tight spaces and specific order in which it must be assembled. The following is a step by step instruction of how to assemble the gear system.

1. Move the winch onto its side with the mounting plate facing up.
2. Place the small key into the small pinion
3. Place the pinion with the chain underneath the center hole.
4. Place the 2 chains around the pinion.
5. Place the large key into the crank hub
6. Place the hub with the narrow side up. The assembly should like Figure 62 at this point.
7. Place the aluminum block into the pinion. Use force and spacers to accomplish this.
8. Loosely bolt in the block to the mounting plate. Use a prybar to move the pinion up as far as possible.
9. Using Loctite, put in the set screws for the pinion with a 1/8’’ Allen wrench. Rotate the drum to make the set screws accessible.
10. Loosely place the small chains on the sprockets.
11. Tension the big chain and tighten down the block in place.
12. Using Loctite, place the setscrews in the motor shaft pinion.
13. Place the motor pinion loosely onto the 2 chains.
14. Place the motor bolts head-side down and tighten while pushing the motor to the far side to tension the chains. Spacers are inserted between the motor and the mounting plate.

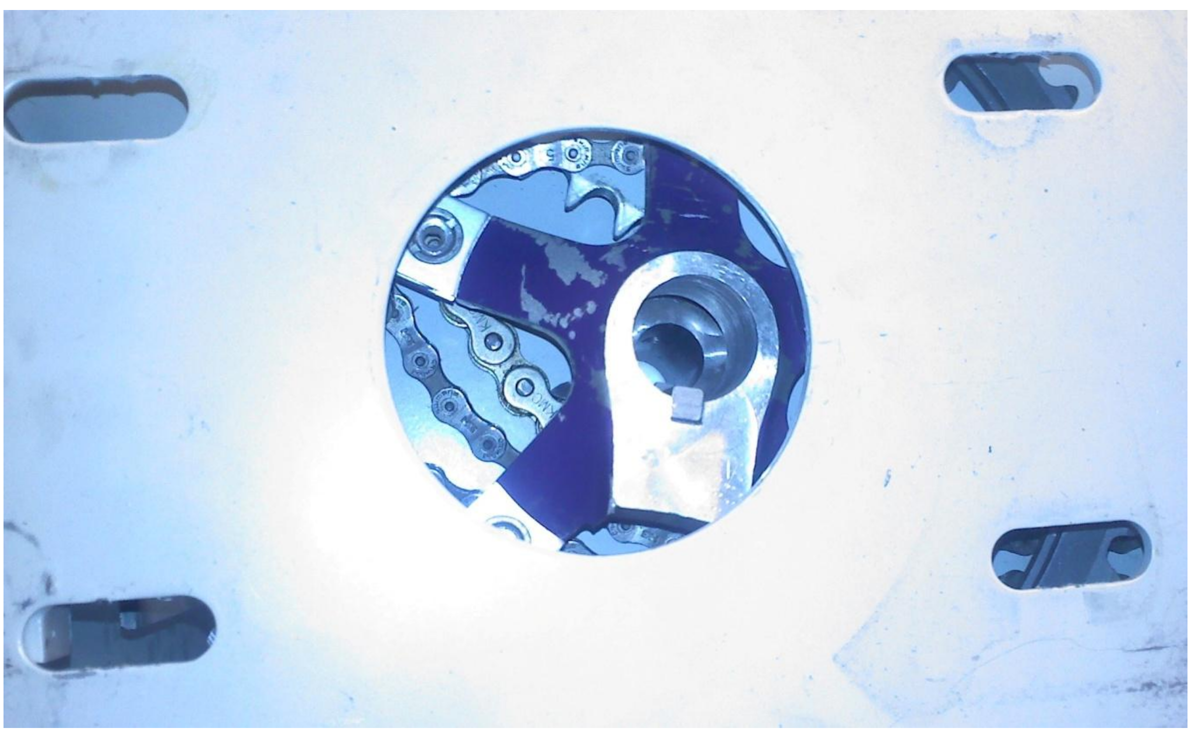


Figure 62: View through the mounting plate of the assembly at the end of step 6

The parts needed to mount the aluminum block and the motor are pictured in Figure 63.

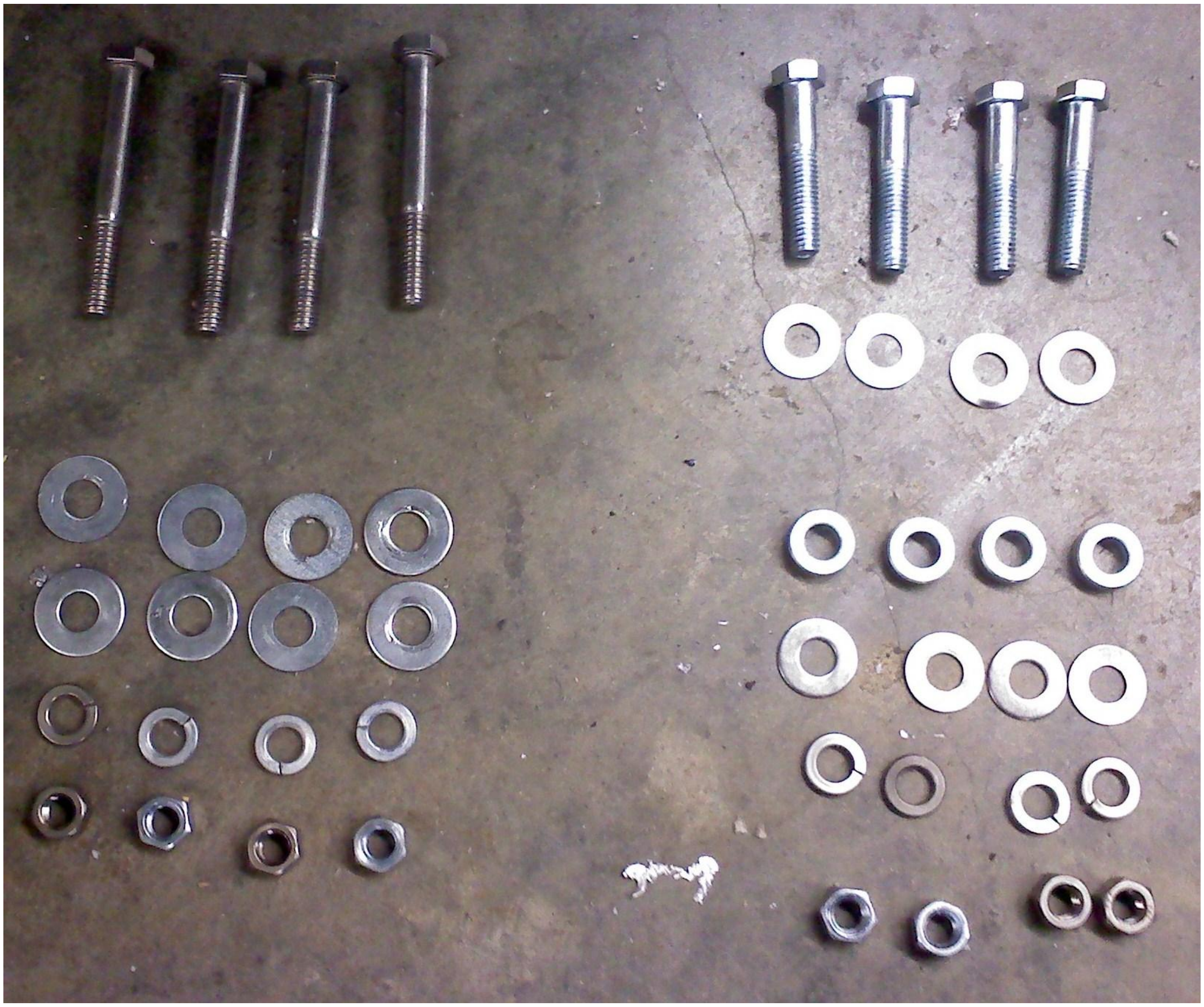


Figure 63: Bolts, washers, and nuts used to mount the aluminum block (left) and motor (right)

Appendix A: Technical Specification List

1. Protection for materials will be used and replaced no more frequently than once a year.
2. A fresh water rinse will occur upon camera surfacing each time.
3. The camera pod will be able to apply scraping force of 6N to the track.
4. Routine maintenance occurs daily. If not performed by use, procedure will start automatically.
5. Camera will have the ability to adjust pitch at least 90°
6. Camera will be able to adjust yaw at least 270°
7. Camera will have at least 3x optical zoom.
8. Maximum distance from camera pod to pier piling will be 7 feet.
9. Lighting must provide lighting temperatures from 4000-5500 Kelvin to the camera lens
10. Lighting must provide at least 900 lumens
11. Lighting must track camera movement to within ±5°
12. Lighting focal point automatically adjusts according to zoom and remains at a constant 6 inches from the camera focal point ±0.25 inch.
13. System travel will have jerk of less than 0.1 $^{ft}/_{s^3}$
14. Video feed will display temperature from 0°C to 50°C ±1°C
15. Video feed will display depth ±0.5m
16. System will be aware of seafloor at distance of 1m with at least 5 cm resolution
17. Zero substances defined as toxic by the EPA will be released.
18. The camera pod will be sealed to max external pressure of 40psi
19. The camera pod will remain airtight under impact force of 3.6kN
20. The structural supports will retain functionality after impact force of 3.6kN
21. Automatic shutdown of motor at 90% of max current rating
22. A manual override shut-off switch will be within arm's reach of any dangerous mechanism.
23. The Camera pod's controls can be seized by the system administrator at any time remotely or from the site.
24. No component of the system should require more than four divers to install.
25. The camera pod will be able to reach the maximum annual depth
26. Annual maintenance can be performed by 2 people in one working day (8hrs)
27. Any link between camera pod and above water system must be interchangeable by 2 people in less than one working day (8hrs)
28. Program code will be modular and will conform to current standards.

<u>Appendix B</u>: Drawing Packet

Appendix C: Bibliography

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<u>Appendix D:</u> Vendor Supplied Specifications and Data Sheets

Appendix E: Detailed Supporting Analysis

```
% Structural Analysis code for Track
%
% Pier Portal
% Michael Machado
% 1/11/12
%
% Assuming 800lb impact from elephant seal
% Assuming 10ft between spans
% Assuming weak point is track, not brackets or rungs
% Assuming impact is at the midpoint between rungs
% Assuming beam theory can be used
% Assuning simple supports to be consrevative. Moment generated by
% simple supports is double that of fixed supports because rung rigidity
% takes up some of the load.
% Does not account for fatigue stress from variable loading by waves

% constants
M= 24000; % (in-lbs) moment due to impact, calculated from Shigley's
Mechanical Engineering Design 9th edition, Appendix A, table A-9 #5
k=3; % 1 for circular hollow cross section, 2 for square hollow cross
section, 3 for round cross section, 4 for square cross section
t=.25; %(in.) material thickness
D=3; % (in.) circular outer diameter
d=D-2*t; % "         " inner diameter
B=2; % (in.) square outer wall
b=B-2*t; % "           " inner wall
sig_all = 40000; % (psi) 316 stainless steel yeild strength

%Moments of Inertia
if      k==1;
    I=(pi/64)*((D^4)-(d^4));
    y=D/2; % (in.) radius of tubing or bar stock
elseif k==2
    I=((B^4)-(b^4))/12;
    y=B/2; % (in.) radius of tubing or bar stock
elseif k==3
    I=(pi/64)*(D^4);
    y=D/2; % (in.) radius of tubing or bar stock
elseif k==4
    I=(B^4)/12;
    y=B/2; % (in.) radius of tubing or bar stock
end

%Stresses
sig=(M*y)/I;
sf=sig_all/sig
```

```
%% Calculation of Spring force due to cable load

% Michael Machado
% Pier Portal Senior Project group
% Last Update 5/1/12
%% Initial Geometry Variables

sh=87;              %top of sheave (in)
wh=24.5;            %top of whinch drum (in)
wd=63;              %distance from sheave to whinch (in)
dp=3;               %distance from hinge to bearing CL (in)
dh=1.5;             %height of bearing CL (in)
ds=8;               %distance from hinge to spring attach point (in)
s=sh-wh;
hc=sqrt(s^2+wd^2);

%% Force Calculation

Fc=230;              %tension on cable (lbs)
Fs=((Fc*dp*(s/hc+1)+Fc*dh*(wd/hc))/ds)/2  %force onto spring lbs

%% Spring Constants

OD=1;                   %outer diameter
d=.060;                 %wire thickness
G=10e6;                 %stainless steel shear modulus (psi)
E=28e6;                 %modulus of elasticity
Nb=12;                  %number of body turns

%% Spring Calculations
Fi=5;                    %spring preload
D=OD-d;
C=D/d;
Kb=(4*C+2)/(4*C-3);
Na=Nb+G/E;              %number of equivalent turns
k=(d^4*G)/(8*D^3*Na)    %Spring constant
L0=(2*C-1+Nb)*d        %spring free length
y=(Fs-Fi)/k             %spring deflection
L=L0+y;                 %spring lenght
```

11/6 Researching plastic tubing

~~Int~~ Interstate plastics.com
Specifications available for many different plastics

Tube choices to analyze

Polycarbonate (Lexan)] Specifications
Clear Cast Acrylic] attached on back

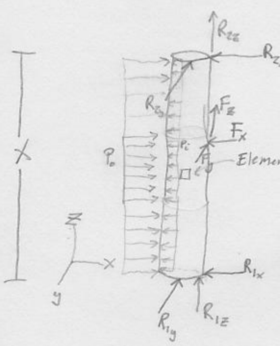
Poly Carbonate (Lexan)

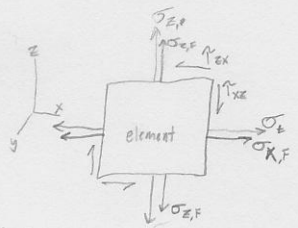
ID (inch)	OD (inch)	$/8ft stick
11.75	12.0	$2086.80
9.75	10.0	$1591.44
8.75	9.0	$1300.56
7.75	8.0	$1040.16
6.75	7.0	$805.92
5.75	6.0	$473.76

Clear Cast acrylic

6.0	6.25	$389.39
6.0	6.5	$473.11
7.0	7.25	$412.85
7.0	7.5	$570.17
~~8.0~~	~~8.25~~	N/A
8.0	8.5	$855.60

11/7 Tube analysis...





P_o, P_i are pressures inside/outside of tube
F is an impact force (based on seal)
Assume no torsional forces
X is distance between supports [brackets]

Assuming $P_i = P_{atm}$

and $P_o = \rho_{H_2O} g h + P_{atm}$

we will say $P_i = 0$, $P_o = \rho_{H_2O} g h$

due to this $\sigma_{z,P} = 0$

where ρ_{H_2O} = density of sea water

using www.csgnetwork.com density calculator with ocean temp = 51°F, salinity = 7296

$\rho_{H_2O} =$ ~~1000~~ $1005.364\ kg/m^3 = 1.951\ slug/ft^3 = 9.41E\text{-}5\ \frac{lbs^2}{in^4} = \rho_{H_2O}$

In Excel Spreadsheet →

$$\sigma_{t,inner} = \frac{2P_o d_o^2}{d_i^2 - d_o^2}$$

[Shigley 3.53]

$P_{o,max} = \rho_{H_2O} g h_{max}$ where max depth = 45ft = 540inch

$= \left(9.41E\text{-}5\ \frac{lb \cdot s^2}{in^4}\right)\left(32.174\ \frac{ft}{s^2}\right)\left(\frac{12in}{1ft}\right)(540\ in)$

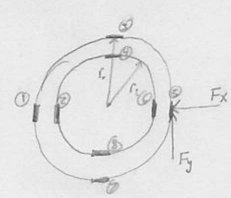
$P_{o,max} = 19.62$ psi

Note $\sigma_{t,max}$ symmetrical at any location (always at inner diameter of tube)

$$\sigma_{t,outer} = \frac{P_o(d_o^2 - d_i^2)}{d_i^2 - d_o^2}$$

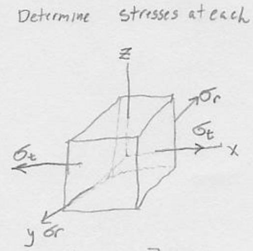
$\sigma_{r,inner} = 0$

$\sigma_{r,outer} = P_o$



Choose elements ①–⑧

Determine stresses at each



[Point 7 or 8]

11/11

Hoop stress from pressure

$$\sigma_t = \frac{p_i r_i^2 - p_o r_o^2 - \frac{r_i^2 r_o^2 (p_o - p_i)}{r^2}}{r_o^2 - r_i^2}$$

at r_i

$$\frac{p_o r_o^2 + r_o^2 p_o}{r_i^2 - r_o^2}$$

$$\frac{2 p_o r_o^2}{r_i^2 - r_o^2}$$

$$\frac{2 p_o \frac{d_o^2}{4}}{\frac{d_i^2}{4} - \frac{d_o^2}{4}}$$

$$\sigma_{t,inner} = \frac{2 p_o d_o^2}{d_i^2 - d_o^2}$$

at r_o

$$\frac{p_o r_o^2 + p_o r_i^2}{r_i^2 - r_o^2}$$

$$\sigma_{t,outer} = \frac{p_o (d_o^2 + d_i^2)}{d_i^2 - d_o^2}$$

radial stress from pressure

$$\sigma_r = \frac{p_i r_i^2 - p_o r_o^2 + \frac{r_i^2 r_o^2 (p_o - p_i)}{r^2}}{r_o^2 - r_i^2}$$

at r_i

$$\frac{-p_o r_o^2 + p_o r_o^2}{r_o^2 - r_i^2}$$

$$\sigma_{r,inner} = 0$$

at r_o

$$\frac{-p_o r_o^2 + p_o r_i^2}{r_o^2 - r_i^2}$$

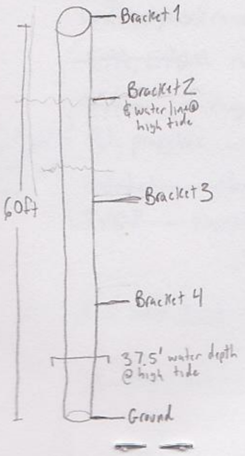
$$\frac{p_o (r_i^2 - r_o^2)}{-(r_i^2 - r_o^2)}$$

$$\sigma_{r,outer} = -p_o$$

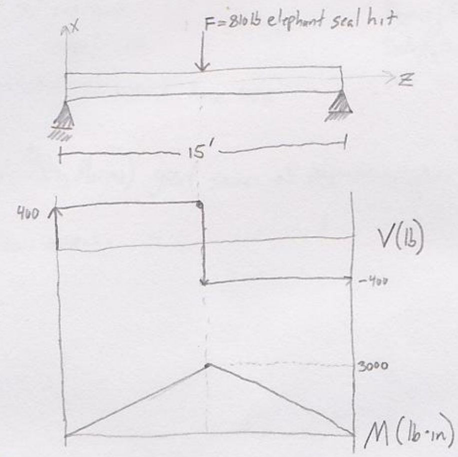
Treating a span of tube as a beam and dealing with only one span between brackets spaced at 15 feet, a bending moment is calculated based on an 800 lb_f impact force occurring at the center of the span. Stresses are again calculated in spreadsheet form.

11/12 Tube analysis con't

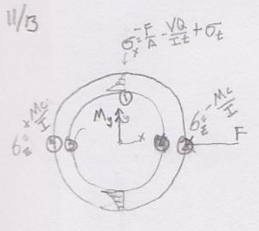
We currently have 4 brackets. Using the ground as a support point we have 5 supports



With an assumed spread of 15' between evenly spaced brackets, Analyze for an impact between brackets (1/2 way point = worse case scenario)

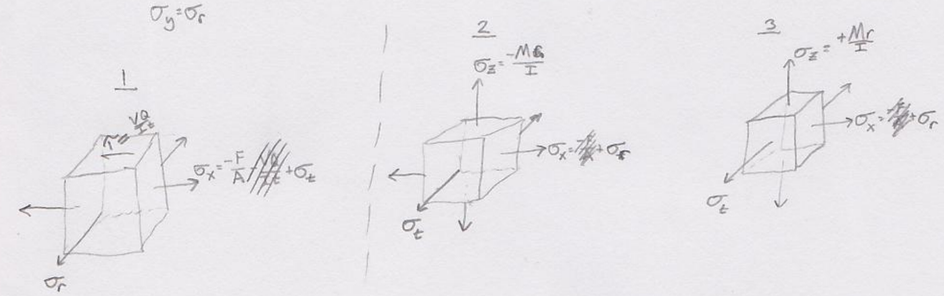


11/13



using pressure equation from page 25, @ 37.5' $P_o = 16.35$ psi

$\sigma_y = \sigma_r$



~~$Q = \pi r_o^2$~~ Max shear occurs at inner wall, point 1.

$$\frac{VQ}{It} = \frac{2V}{A}$$

$$\sigma_1, \sigma_2 = \frac{\sigma_x + \sigma_r}{2} \pm \sqrt{\left(\frac{\sigma_x - \sigma_r}{2}\right)^2 + \tau^2}$$

To be continued...

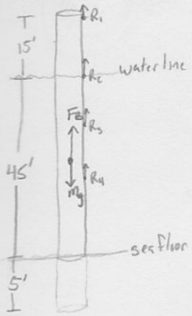
11/14 9:30 am

Met with Prof. J Mello to get help with above analysis. $\frac{F}{A}$ terms wrong - remove. σ_r terms negligible - remove. Local stress concentrations potentially major - revisit for FEA help when analysis preliminary done. <u>Chemical degredation is the driving issue!</u> Poly carbonate gets eaten by sea-water 2. Switch gears on analysis to begin with chemical compatibility. Also add forces on tube by brackets to counteract boyancy forces.

In this analysis, the weight of the tube and the buoyancy forces from an air filled tube are calculated and divided evenly between the four brackets we have access to, to connect to the pier. However, at the bottom of the tube, the entire axial load from that buoyancy force will be present and is accounted for in the following spreadsheet. In hindsight, this analysis is negligible.

11/16 More tube analysis – effect of weight & buoyancy

Static analysis



$$\sum F_y = m a_y = F_B - mg + R_1 + R_2 + R_3 + R_4 \quad O\ (a \to 0)$$

Assume bracket forces equal $R_1 = R_2 = R_3 = R_4$
&
ground provides no vertical force

$$0 = F_B - mg + R_{TTL}$$

$F_B = \rho_{seawater}\, g\, V_{tube}$

Assume constant density of seawater, $\rho_f = 9.41E{-5}\ \frac{lb \cdot s^2}{in^4}$

$$F_B = \left(9.41E{-5}\ \frac{lb \cdot s^2}{in^4}\right)\left(32.174\ \frac{ft}{s^2}\right)\left(\frac{12 in}{1 ft}\right)\left(45 ft\right)\left(\frac{12 in}{ft}\right)\left(\frac{\pi}{4} d_o^2\right)$$ where d_o is in inches

$$\underline{F_B = 15.408\, d_o^2\ lb}$$

$$mg = g\left(m_{tube} + m_{air}\right)$$
$$= g\left[\rho_{acrylic} L \left(d_o^2 - d_i^2\right)\frac{\pi}{4} + \rho_{air} L \left(d_i^2\right)\frac{\pi}{4}\right]$$
$$= \frac{\pi L g}{4}\left[\rho_{acrylic} d_o^2 + \left(\rho_{air} - \rho_{acrylic}\right) d_i^2\right]$$

$\rho_{sample} = SG_{sample}\, \rho_{H_2O}$

$\rho_{acrylic} = 1.19\left(1.94\ \frac{sl}{ft^3}\right)\left(\frac{1 ft^3}{12^3 in^3}\right)\left(\frac{1\ lb_f s^2/ft}{1 sl}\right)\left(\frac{1 ft}{12 in}\right)$

$\underline{\rho_{acrylic} = 1.1133E{-4}\ \frac{lb\, s^2}{in^4}}$

$\rho_{air} = 0.0774\ \frac{lb_m}{ft^3}$ @ sea level & 50°F

$= \left(0.0774\ \frac{lb_m}{ft^3}\right)\left(\frac{1 sl}{32.174\ lb_m}\right)\left(\frac{1\ lb_f s^2/ft}{1 sl}\right)\left(\frac{1 ft^4}{12^4 in^4}\right)$

$\underline{\rho_{air} = 0.116E{-6}\ \frac{lb\, s^2}{in^4}}$

$g = 32.174\ \frac{ft}{s^2}\left(\frac{12 in}{1 ft}\right)$

$\underline{g = 386.088\ in/s^2}$

$L = 65 ft$

$\underline{L = 780 in}$

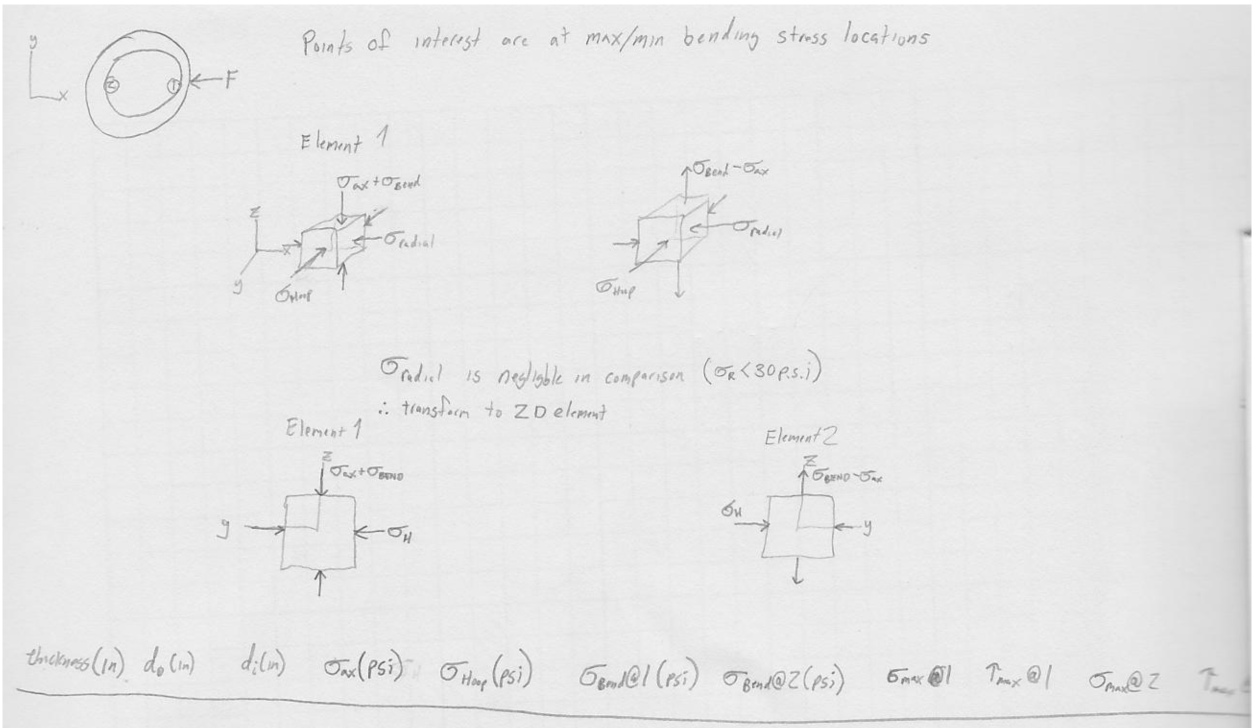
$$\underline{mg = 236521\left[\left(1.1133E{-4}\right) d_o^2 - \left(1.11214E{-4}\right) d_i^2\right]}$$

$$R_{TTL} = mg - F_B$$
$$= 236521\left(1.1133E{-4}\right) d_o^2 - 15.408\, d_o^2 - \left(1.11214E{-4}\right)\left(236521\right) d_i^2$$
$$R_{TTL} = 10.924\, d_o^2 - 26.304\, d_i^2$$

Assuming uniform distributions, this gives compressive stress in tube $-\frac{R_{TTL}}{A_{Tube}}$

t (in)	d_o (in)	d_i (in)	A_{tube} (in²)	R_{TTL} (lb)	σ_{ax} (psi)
1/4	8	7.5	24.347	-780.464	-32.055
3/16	8	7.625	18.467	-830.195	-45.100
1/4	7	6.5	21.206	-576.068	-27.166
3/16	7	6.625	16.052	-619.223	-38.577
1/4	6	5.5	18.064	-402.432	-22.278
3/16	6	5.625	13.645	-439.011	-32.055

The following elements show the location and orientation of the stresses on elements of the inner tube wall in line with the impact force at a cross section at the level of the impact force. Compressive stresses at this location are by far the dominant stresses.



The following spreadsheet analyzes tubing of two wall thicknesses and three diameters using all the stress analysis described to this point. We were shocked to see a factor of safety of 14 for the weakest tube as shown by this analysis.

Sheet1

psi

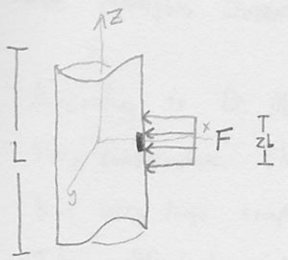
d_o (in)	d_i (in)	Area (in^2)	I (in^4)	Reaction (lb)	hoop stress	Bending stress	axial stress	axial max@1	axial max @2	Tau_max@1	Tau_max @2	Sigma_max @1	Sigma_max @2
8	7.5	24.347	45.746	-780.464	-324.046	262.316	-32.055	-294.371	230.260	309.209	46.893	-618.418	293.181
8	7.625	18.408	35.130	-830.195	-428.605	341.586	-45.100	-386.686	296.486	407.646	66.060	-815.292	385.096
7	6.5	21.206	30.235	-576.068	-284.853	347.282	-27.166	-374.448	320.117	329.651	17.632	-659.301	351.331
7	6.625	16.052	23.298	-619.223	-376.320	450.692	-38.577	-489.269	412.115	432.794	17.897	-865.589	449.301
6	5.5	18.064	18.699	-402.432	-245.677	481.303	-22.278	-503.581	459.025	374.629	106.674	-749.258	576.839
6	5.625	13.695	14.474	-439.011	-324.046	621.786	-32.055	-653.841	589.730	488.944	132.842	-977.888	738.600

Note on units: all stresses are in psi

$$\sigma_{1,2} = \frac{\sigma_x + \sigma_y}{2} \pm \underbrace{\sqrt{\left(\frac{\sigma_x - \sigma_y}{2}\right)^2 + \tau_{xy}^2}}_{\tau_{max}}$$

The final addition to the tube analysis was an examination of local stresses in the impact zone using Advanced Shell Theory. Dr. Joe Mello was of great assistance in this analysis and supplied the equations used on the following page to bypass Finite Element Analysis. According to Dr. Mello this analysis yields a conservative estimate of local impact stresses. As shown in the following spreadsheet, this analysis discovers stresses more than 10 times larger than anything previously examined.

11/22



$F \equiv$ applied force $= \underline{800\text{ lb} = F}$

$2b \equiv$ ~~area~~ distance of tube force applied over = estimate @ 16 inch → $\underline{b = 8\text{ inch}}$

$L \equiv$ length of tube = distance between supports = 15 ft = $\underline{180\text{ inch} = L}$

$R \equiv$ radius to impact, will consider these stresses as applied to a thin wall tube so $R = \frac{OD}{2}$.

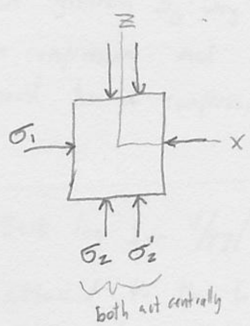
t = wall thickness. spreadsheet uses 1/4" & 3/16" wall tubes

Poisson's ratio $\quad G = \frac{E}{2(1+\gamma)}$ $\qquad E = G = 490{,}000$ psi for extruded acrylic as stated by Interstate Plastics [back of pg 25]

$\gamma = \frac{E}{2G} - 1$ (E = G)

$= \frac{1}{2} - 1$

$\gamma = -\frac{1}{2}$



$$B = \left[12(1-\gamma^2)\right]^{1/8}$$

$$= (12 \cdot \tfrac{3}{4})^{1/8}$$

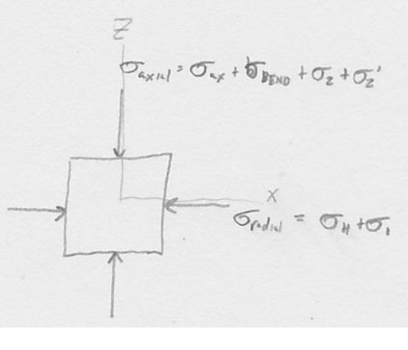
$$\underline{B = 1.3161}$$

$$\sigma_1 = -0.15 B^3 PR \tfrac{1}{4} b - \tfrac{1}{2} t - \tfrac{7}{4}$$

$$\sigma_2 = -0.13 BPR \tfrac{3}{4} b - \tfrac{3}{2} t - \tfrac{5}{4}$$

$$\sigma_2' = -B^{-1} PR \tfrac{1}{4} b - \tfrac{1}{2} t - \tfrac{7}{4}$$

Combined loading @ 1



d_o	d_i	Area	I	Reaction	hoop stress	Bending stress	axial stress	Sigma 1	Sigma 2	Sigma 2 Prime	Axial Total	Radial Total	max shear	primary stress 1
8	7.5	24.347	45.746	-780.464	-324.046	262.316	-32.055	-2190.33141	-3286.6106	-4864.7273668	-8445.70924043	-2514.37786020	2965.665690115	-8445.709240432
8	7.625	18.408	35.130	-830.195	-428.605	341.586	-45.100	-2190.30016	-3286.51685	-4864.6961168	-8537.89910092	-2618.90559859	2959.496751167	-8537.899100924
7	6.5	21.206	30.235	-576.068	-284.853	347.282	-27.166	-1916.77436	-2875.9874	-4256.8708210	-7507.30625548	-2201.62769085	2652.839282315	-7507.306255480
7	6.625	16.052	23.298	-619.223	-376.320	450.692	-38.577	-1916.74311	-2875.89365	-4256.8395710	-7622.00219101	-2293.06310752	2664.469541745	-7622.002191006
6	5.5	18.064	18.699	-402.432	-245.677	481.303	-22.278	-1643.21731	-2465.3642	-3649.0142751	-6617.95975163	-1888.89382818	2364.532961722	-6617.959751626
6	5.625	13.695	14.474	-439.011	-324.046	621.786	-32.055	-1643.18606	-2465.27045	-3648.9830251	-6768.09463949	-1967.23250806	2400.431065716	-6768.094639488

B	b	F
1.32	8	800

Appendix F: Gantt Chart

Appendix G: Beam Installation Plan

Appendix H: Doxygen Documentation

Appendix I: Final Costs

Appendix J: Wiring Diagrams

Appendix K: QFD