Inverted Pendulum Exhibit for the Ann Arbor Hands-On Museum

ME 450, Section 2
Final Report
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Sponsors: Ann Arbor Hands-On Museum, Prof. Shorya Awtar
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ABSTRACT

This project involves designing and building a mechatronics exhibit for the Ann Arbor Hands-On museum. The exhibit consists of an inverted pendulum system that utilizes feedback controls in order to balance a free pendulum in its inverted state. The exhibit will be made up of a manual pendulum system, in which patrons will attempt to balance the pendulum on their own, and automatic pendulum system that will use a microprocessor and feedback controls to balance the pendulum. The purpose of the exhibit is for the patrons of the museum to gain an understanding of how a mechatronics system and feedback controls work.

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EXECUTIVE SUMMARY

As technology advances in leaps and bounds, the need to educate people in society has also grown. The Ann Arbor Hands-On Museum (AAHoM) sets out to educate children, and the general public, about science and technology in a fun and interactive way. Our sponsor, the Ann Arbor Hands-On Museum, and Professor Shorya Awtar have asked our team to create an exhibit to educate the museum's patrons about mechatronics and feedback controls.

The underlying problem is to create a system that conveys the idea of feedback control for the environment of the Ann Arbor Hands-On Museum. The exhibit we create will consist of an inverted pendulum system that will explain to patrons how the concept of feedback controls works. Before creating the design for our system, we established parameters that we needed to meet based upon the sponsor's requirements. The system we design needs to be attractive, with continuity between all parts of the design, yet be based upon an inherently simple design. Also, it has to be durable, create a sense of wonderment, be engaging for the patrons, and cost less than $2000 to build. Additionally, to match with the rest of the museum's exhibits, the project must be aesthetically pleasing. Finally, we expect this exhibit to be part of the museum for ten years, so the exhibit must be robust and easy to repair. All of these goals must be accomplished with the upmost concern for user safety.

After receiving the sponsor requirements we established engineering specifications that we needed to meet. These requirements dealt with the size, functionality and safety of the system we would create. At this point in the design process we have established detailed engineering specifications that will be used in our final design.

In order to complete our final design by the design expo, we first set out to create a project plan. Being in the final manufacturing phase now, we will begin this week – March 22-26 – to manufacture the components for our inverted pendulum system. All manufacturing processes will be completed by Design Review 4 on Monday, April 5. The remaining time before the Design Expo will constitute testing of the system with the microcontroller and magnetic agitator as well as anodizing the metal components. For the Design Expo our team will deliver a finished, functioning mechatronic inverted pendulum system with an assembled and functional magnetic agitator.

In order to create an ideal design for the Museum we developed a variety of concepts through brainstorming. In each of these concepts we had a manual system in which the user could try to balance a pendulum, and an automatic system which would exhibit the power of a microprocessor by performing the task of balancing the pendulum. Also, a method of interaction with the mechatronic design was identified for each of our design concepts. After discussion with our sponsors and after analyzing the strengths and weaknesses of each concept, we generated an alpha design. From analysis of this alpha design, we arrived at a final design concept. The details of this final design will be provided in the following report.

The purpose of this report is to present our design problem, background research, customer objectives, specific challenges, engineering specifications, concepts, our alpha design and our plan for the future.

PROBLEM DESCRIPTION

The project we are to design, manufacture and polish will be an exhibit at the Ann Arbor Hands-on Museum (AAHoM). The AAHoM is the project sponsor and our contacts at the museum are John Bowditch, the Exhibits Manager and Mel Drumm, the Museum Director. Our task is to take the concept of feedback controls and create a functional, attractive and interactive inverted pendulum exhibit for the AAHoM. The final design we create must be exhibit-ready at completion. In addition, our team will create a comprehensive assembly, maintenance and troubleshooting manual.

PROJECT BACKGROUND

Feedback Control

The inverted pendulum system is a closed loop feedback control system. In such a system, a set value or goal is set, and a computer or some other control device tries to maintain this target as outside forces act on the system. Humans are the ultimate example of feedback control systems, as we can adapt to changing conditions very rapidly. Some common feedback control systems are the Segway, automobile cruise control, and aviation auto-pilot. These systems attempt to hold a target value, such as a set speed, and have to vary the input to the system (engine power) to compensate for changing environmental conditions (hills or wind).

Figure 1 on page 3 shows a simplified version of the control loop for the inverted pendulum. This control loop is demonstrated from an inverted pendulum built by an ME 350 team, shown in Figure 2 on page 4. The target (reference) position is the vertically balanced position, which the controller compares to the current position. The error between these values is used by the controller, in our case a computer running LabVIEW (not shown in Fig. 1) or dedicated microchip, to decide how much to turn the servo motor. The system input is the spinning of the servo motor (#5 in Fig. 2), which spins the horizontal shaft (#2), which in turn swings the pendulum (#3). The position and velocity of the swinging pendulum is constantly monitored by the optical encoder (#6) and then fed back to the controller to compare to the ideal balanced position. This cycle is repeated many times per second in an effort to balance the pendulum.

Figure 1: Simple Description of Inverted Pendulum Feedback Control System

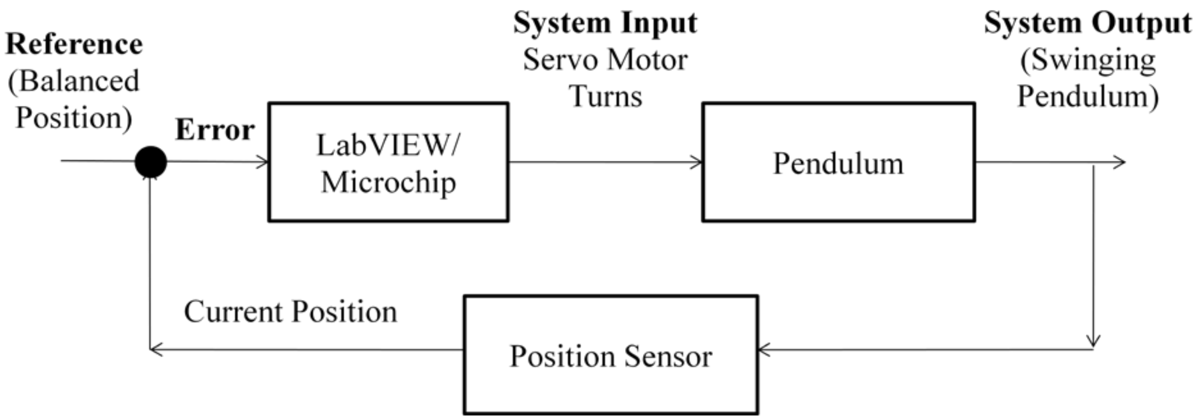
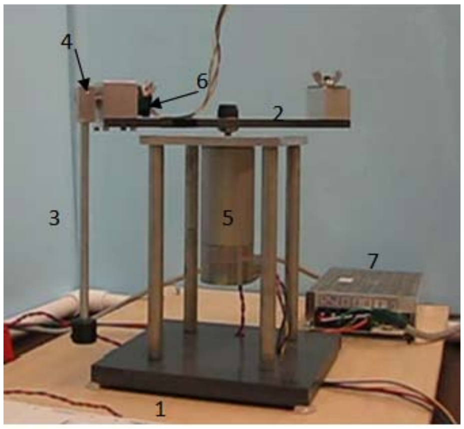


Figure 2: ME 350 Inverted Pendulum



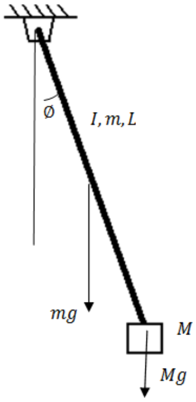
System Modeling

The concept behind balancing a pendulum in the unstable inverted position is complicated. However it is not that difficult to balance a broom stick on the palm of your hand. The first step in understanding how the physics of an inverted pendulum work, we must begin with modeling the system.

We know from Newton’s Laws that everything is pulled towards the earth equally due to gravity. And that any object dropped in a vacuum will fall at the same speed and acceleration. But when one end of a long object is constrained everything changes. Now rotational inertia is involved. Not all objects will tip over at the same speed and acceleration. Rotational inertia depends of how height the center of mass is relative to the pivot of rotation.

Rotational inertia explains how a tall shaft is easier to balance on your finger then a short one. It all depends on where the center of mass is located. If the center of mass is higher up on the shaft it has a longer distance to fall then one with a lower center of mass. Because the shaft falls in a circular path the distance traveled increased exponentially. This phenomenon makes this display possible, with relative small changes in height increases the time it takes to fall exponentially. The threshold between a human being able to balance a pendulum and not balancing it are close, therefore a computer controlled feedback loop is necessary to balance the small system.

Figure 3: Simple Pendulum Model



The mathematical model is shown below

$$(ML^2 + I)\ddot{\emptyset} + mg\frac{L}{2} + MgL(\emptyset) = 0 \qquad \text{Eq. 1}$$

M and *m* are the mass of the ball weight at the end of the pendulum and the pendulum arm respectively. L was the length of the pendulum arm, l is the inertia and φ is the angle to the neutral axis. Solving for the period of the pendulum arm you end up with the equation below.

$$T = 2\pi \cdot \sqrt{\frac{2L}{3g}\left(\frac{1}{-\frac{1}{3+\frac{m}{M}}+1}\right)} \qquad \text{Eq. 2}$$

The larger the period the longer the pendulum lingers in the air and the easier it is to balance.

Ann Arbor Hands-On Museum

To get an idea of what type of exhibits are in the Ann Arbor Hands-On Museum, we visited the museum and spoke with the Exhibit Manager, Mr. John Bowditch. The museum features interactive exhibits designed to teach people about science and technology, while being engaging and fun. The museum caters to both young children and adults, so while many of the controls of the exhibits are very simple, there is always detailed information about the science behind the exhibit on display for anyone interested in learning more.

Figure 4: Exhibits at the Ann Arbor Hands-On Museum

Sponsor Requirements

John Bowditch gave us some general guidelines to follow in designing an exhibit for the Hands-On Museum.

- Bright Colors

  As the museum is generally designed for a younger audience, most of the exhibits are brightly colored. We should either anodize, paint, or do some other sort of surface treatment to make our exhibit as eye-catching as possible.

- Simple Design
  We are attempting to teach the kids about mechatronics and feedback control, so we don’t want a design that is overly complicated, as it may draw the users attention away from learning about the science behind the exhibit. A simple design is also usually easier to build and maintain.
- Longevity
  Many exhibits are in the museum for years at a time, so we are to target a ten year life span. The display will need to be robust, as kids of all sizes will be using the exhibit.
- Sense of Wonderment
  John felt that a museum exhibit is kind of like theater, in that it should impress and amaze its user. Therefore we want to design our exhibit so that a user will be impressed that a computer and servo motor can balance a pendulum.
- Continuity of Design
  The exhibit will have multiple parts, but these parts should be visually tied together so that a patron walking by will instantly recognize that the different parts of the exhibit are all related.
- Engaing
  Children tend to have short attention spans, so our exhibit needs to be engaing. If the devices are impossible to operate, then people will quickly lose interest. We need to desing something that is easy to use, and will be very fun to use.
- Under $2,000
  The museum would like us to attemp to keep our budget under $2,000.

PRIOR WORK

The task of creating an inverted pendulum for the Hands on Museum was attempted by an ME 450 group in the winter of 2009. They were partially successful, so we will try to build off of their successes. Their vision for the display involved three different systems, seen in Figure 5 on page 8.

Large Manual System

The first part of the exhibit, Figure 5 (A), is a large manual system. This system consists of a 30 inch long pendulum that is constrained to within 10 degress left or right of vertically balanced. The user is able to turn the base of this exhibit and balance the pendulum. Due to the large moment of inertia of the large a human is able to easy balance it.

Small Manual System

Figure 5 (B) shows the small manual system that was to be part of the exhibit. This system is also constrained to about 10 degrees left or right of vertical, and can be turned manually by a person in order to balance it. Due to the small moment of inertia of they short pendulum, it is virtually impossible to balance this system.

Small Mechatronic System

The third system, Figure 5 (C), is very similar to the small manual system, but incorporates mechatronics to balance. In theory, what is nearly impossible for a human to do, is accomplished very quickly by the mechatronic system. This should show the users that while the human brain is usually superior to computers, when it comes to performing a repetetive task, such as moving the pendulum to balance it, a computer can operate much more quickly than a person.

In reality, the mechatronic prototype is unable to balance. The system uses a complicated solar-powered infrared LED data transmission system, which never worked. The optical encoder that senses the pendulum position was supposed to send data to a decoder chip that would convert the data into pulses of an LED. An infrared reciever at the base of the prototype would receive these pulses and send the information to the computer program running the pendulum, which would then send commands to the motor. The infrared transmission system was not quick enough to keep up with the pendulum when it was swinging quickly, hence the system could not balance itself. The finished mechatronic pendulum nees to run off a dedicated microprossor that is neatly integrated as part of the display. This prototype still has to be connected to an outside computer that is running LabVIEW.

Figure 5: Winter 2009 ME 450 Group's Exhibit Prototypes

A B C

Existing Prototypes Strengths and Weaknesses

Most of the strengths of the prototypes are centered on the large manual system, which was well received by the museum staff. It is very well built and easy to balance for users of all ages. John Bowditch has requested that we do not make major changes to the large system and instead concentrate on the small systems. The continuity shown between the three systems with the circular wheel theme was also a strength of the pendulums.

Most of the complaints about the prototypes deal with the small mechatronic system. The previous team attempted to implement a very complicated solar-powered infrared LED transmission system in order to eliminate a wire connection that could wear out. While this system was very clever, it also never worked. We will attempt to use a simpler setup that will allow us to actually finish the exhibit, and make it easier for the museum to repair. All the wires and solar panels on top of the mechatronic prototype also detracted from the aesthetics of the system. People pay money to get into the Hands-On Museum, so we have to produce a product that looks very professional and attractive.

SPECIFIC CHALLENGES

The goal of this project is create an exhibit-ready inverted pendulum system. The basic concept we plan to implement includes a large manual system, a small manual system and a small mechatronic system. There are specific challenges that lie within this goal because the inverted pendulum will be in a museum that is interactive and that is made for children. It is completely different to design a project for an engineering lab as opposed to a polished, professional system for a museum. The project solution we develop has to be functional, yet it has to be polished and placed in an learning environment for children. This being said, our team established six specific challenges that we will focus on with our project solution.

Firstly, the exhibit has to be a learning experience for the patrons of the museum. The museum is mainly for children, but there are also the children's parents and people of various ages that visit the museum as well. Our focus is to create an exhibit that a child can interact with and take something away from. We want the children to observe that it is very difficult for them to balance a small pendulum, while it is very easy for a computer to do the same task. For older and more mature patrons, the learning experience is that feedback control can be used to perform a specific task that a human cannot do because a human does not have a quick enough response time.

In addition to the project being a learning experience for all patrons, it has to be an aesthetically pleasing and attractive exhibit. From visiting the museum, one can see that all the exhibits are brightly colored and eye-catching. There has to be a certain visual element that draws the patrons to our exhibit. In order to do this we will use bright colors, possibly by anodizing the metal, to create an attractive professional look for all of our final system components.

Additionally, the system we create has to be functional. The automatic mechatronic design has to work well and balance the pendulum to illustrate the idea of feedback control. Also, the manual large design and and manual small design have to be possible to balance for the patron. The large design will be easier to balance, but the small design has to also give the patron a chance to be able to balance the pendulum; it cannot be impossible or the patrons will lose interest in the exhibit.

One of the most important aspects of our design – and biggest challenges – is to create a completely safe exhibit. The exhibit is in a hands-on museum where there are many children and children inherently will want to touch the systems. For this reason, the small manual system and small mechatronic system will be behind a plexiglass shield so that the patrons cannot damage them or be injured in any way. The large manual system will be outside of the plexiglass so that users may touch and interact with it. As a result of this, the large system has been designed (by the previous Winter '09 IP Team) to have no pinch points, sharp edges or chances of impact. The large pendulum is restricted in its movement and all edges are chamfered and pinch points covered. Also, the mechatronic system utilizes electrical components that carry current and voltage. In order to eliminate electric shock, any high voltage wires will not be close to the patrons at all and any buttons that the patrons can use to interact with the system will use safe voltage levels. To avoid electrical fire, GFCIs will be used as needed to limit current flow to the circuit board being used to run the system.

Finally, the system we create must be robust and easily maintained. The systems are exposed to wear constantly and must be overbuilt with high safety factors because of constant interaction with the patrons. Specifically, the large manual system that is in direct contact with the patrons is built robustly and designed so that no patron can harm themselves or destroy the system. Although our system will be overdesigned, there are still components that can wear or that will need to be replaced in the lifetime of the exhibit. The idea is that the components of the system that do need to be replaced will be basic, off the shelf components that can be bought easily and installed without much difficulty. It is much easier for the museum staff to replace a battery than to rewire the circuit board. Our system will take this into consideration when finalizing our design.

ENGINEERING SPECIFICATIONS

Safety

Safety is our upmost concern when designing our project. The project being placed in a children's museum brings up unique design challenges. Children are still developing the notion of a safe and unsafe situation. A dangerous situation that seems obvious to an adult might not occur to a child. Life lessons about safety are best learned through example, and therefore these lessons are best left to the parents. With law suits running rampant, parents don't need an incentive to blame someone other than themselves. When given the incentive, they can and will pounce. Therefore the responsibility falls onto us to provide a safe product. And more importantly, any injury that occurs cannot be traced back to engineering incompetence.

1. Sharp edges: Machined surfaces and edges tend to be sharp. Special attention will be given to surfaces, and edges that can be touched by patrons. There will be a 0.1" chamfer applied to any such surface.
2. Hot surfaces: Some of the electrical components have the potential to get hot. Any components that are hot will be out of reach of the patrons.
3. Pinch points: This is probable the most common injury that occurs at the museum simply because it is impossible to eliminate all possible pinch points. But that doesn't mean we will not try. Our goal is to eliminate every pinch to the best of our ability that a patron can reach.
4. Impact: Because our project is automated, the possibility that someone could get hit from a swinging pendulum is high. For this reason any system we build that is directly interacted with will have a limited range of motion. Anything that has a full range of motion will be behind Plexiglas. The big system pendulum is constrained to about ±10 degrees off of vertical currently.

Electrical

Electrical safety is of the upmost importance, as the danger will be invisible to young children. There will be minimal human contact with the electrical portion of the exhibit, so most electrical specifications relate to reliability and aesthetic concerns.

1. Electrical shocks: Some components will carry large potentials with the capability to shock someone. Wet skin will conduct electricity at about 50 volts. Any wire carrying 24 volts or more will not be routed where patrons can come in contact with them.
2. Electrical Fire: An electrical fire is a real danger when dealing with electronics. All wiring should be 24 gauge or thicker. All of the circuits that we build will be protected with GFI circuit breakers. These breakers will be designed to break the circuit when the allotted amperage for the individual circuit is exceeded.

Interactive

Making the display interactive is going to be challenging because the mechanical system display will be behind Plexiglas. Being interactive is an essential part of the AAHoM experience, so interaction with the mechanical system is a given. Many children learn from hands on experiences, this is essential to their learning style. A simple display that you cannot interact with doesn't appeal to a lot of kids. Our goal is to make the project interactive and engaging. To simply make the project interactive isn't enough - if the exhibit is not engaging it will go unnoticed and unappreciated.

1. Success Rate: Our project will be easy to interact with, meaning that is intuitive and quick to pick up. From observing at the AAHoM we found that children have relatively short attention spans. Therefore our goal is for every patron that touches the project, 80% of them will use it correctly.
2. Automatic System: Interaction with the automatic system is mandatory. Because this display will be behind Plexiglas we have to come up with a unique way of interacting with the system while keeping it safe.
3. Calibration Time: The automatic system should be able to calibrate itself (in case it loses its sense of position) in less than 25 seconds. It should take less than five seconds for the system to go from its calibrated state to a balanced state.

Aesthetically Pleasing

Above all the AAHoM is a learning experience for children. The project has to convey the message clearly, and intuitively. This is a unique challenge because our project has to appeal to children. John Bowditch was quoted saying "engineers are not creative these days." We would like to prove him wrong. In order to create a good learning experience our project must fit into the other displays at the museum. Therefore our project has to be creatively colorful, along with having intuitive markings.

1. Finish and coating: The primary material we will be using is aluminum; this gives us an interesting solution for coloring: anodizing. Anodizing is an extremely vivid bright way to color normally very boring aluminum.
2. Correlations: Color coding different parts shows children connections, and correlations between different parts on the project. Also it makes the project interesting to look at. The more connections we make between the manual and automatic systems, the better understanding the patron will have of the concepts.

Functionality and Longevity

The previous group that attempted this project tried to eliminate one major wear part – a slip ring. Because there is a sensor mounted on a rotating arm, routing wires back to the computer is a problem. Instead of using a simple slip ring the previous team opted for a more complex approach that would eliminate that major wear part. This proved fatal because introducing another degree of complexity made their project harder to finish, and inevitably they didn't finish. Our plan is to make the project simpler - the philosophy Myth Busters uses is "the simpler design is always the better one."

1. Functionality: John Bowditch told us in our first meeting that he just wanted a project that utilized slip rings and a bushing. We were more than happy to accept that proposition. We are planning to keep this project as simple as possible.
2. Longevity: From our understanding, the museum wants to keep our project for 10 years. The only maintenance that the museum wants to do is replacing simple to access wear parts. Therefore, our design has to be easily taken apart, and use easily obtainable parts.

Budget

The budget was left open ended but John Bowditch was quoted as saying "keep it under a couple thousand." Our budget goal is therefore a maximum of $2000. There will be a few large purchases, for instance, the precision slip rings cost on the order of $400.

Dimensions

When talking to John Bowditch he gave us a rough idea of space constraints. He said the smaller the better obviously, but this is not strictly enforced. He told us that the large *Bob the Builder* display on the first floor was just temporary. After it leaves later in the spring a lot of room would be opening up. Because the big display is being used, and we are only concentrating on the smaller system, we will not be building something taller than the big system.

1. Height Constraint: Because we will not be building anything bigger than the big project we can safely assuming that the tallest thing we will build will be less than 36" tall.
2. Width and Depth: The museum is roughly looking for something that will fit on a 3' X 3' table. The big system will sit separately on a table next to our display.

Table 1: Engineering Specifications for AAHoM Inverted Pendulum Exhibit

Engineering Spec	**Value**	**Unit**
Electrical		
Button voltage	<24	V
Wiring gauge	<24	ga
Unbundled wiring	2	in
Mechanical		
Big system restraint from vertical	±10	degrees
Lifespan	10	years
Yield strength	200	lbs
Manual system weight	30	lbs
Chamfer on sharp edges	0.1	in
Interaction		
Magnetic handle height above ground	48	in
Pivot point of manual system above ground	36	in
Calibration time	<25	sec
Calibration to balanced time	<5	sec
Pinch points	0	#
General		
Price	<2,000	$

DESIGN IDEAS

At this early stage of our design process, we have come up with a few preliminary design ideas that we will do further research on and expand future ideas from.

Mechanical/Mechatronic Systems

The previous team's design transferred the signal from the pendulum arm position sensor to the computer through an infrared signal. While this was a clever design, it complicated the system and in the end, the mechatronic system did not work. To fix this problem, our team is attempting to possibly use precision slip rings on the mechatronic system to transfer data with a much simpler design. Also, to make sure the electronics in our system are safe, we will use GFI's as circuit breakers in the system. To make the mechatronic system more engaging, our team is planning on creating a "toggle" button that will disturb the system to the left or right, depending on the user input. This will disturb the system slightly, to prove to the user that the computer can overcome disturbances and keep the pendulum balanced.

CONCEPT GENERATION AND METHODOLOGY

To begin our design process, we first began brainstorming possible features for both the manual and automatic system.

Manual system

One of the main points for the manual systems is to help the patrons of the museum understand what the computer is doing when it is balancing the pendulum. The patrons must understand how difficult it is to balance a pendulum in the inverted position, and therefore will be more amazed when they see how easily a computer can accomplish this feat. Therefore, a manual system is absolutely necessary in order to enrich the patron's learning experience.

Pendulum Variables

In order to make the manual system more engaging and interactive, we came up with features that would add different variables to the system. These would include changing the pendulum length, changing the pendulum arm length, and incorporating a moveable mass onto the pendulum. These variables would allow for an additional learning experience.

Damper

A small manual system would be impossible to balance. Since having a small manual system that is impossible to balance seems unnecessary, to make the system more engaging and less discouraging, we thought a damping system could be implemented in order to make the small manual system difficult, but not impossible to balance. Therefore balancing the small manual system will be a challenge, but not impossible.

Swing up

Additionally, allowing for the manual system to have a swing-up motion would be another feature that could be implemented. Instead of restricting the pendulum motion to ±10 degrees from vertical, allowing the patrons to swing up the pendulum and then attempt to balance it would offer a direct parallel between the automatic system and the manual system.

Automatic System

In order to make the automatic system more engaging and interactive, our team was adamant about implementing a way to disturb the automatic system to make it easier for patrons of the museum understand what the feedback control is actually doing. When a person physically disturbs the system and sees the system respond and keep the pendulum balanced, the idea of feedback controls can be better visualized. A few features that could make this possible are described below.

Foam Noodle/Sword

One idea was to have a foam noodle that could enter the Plexiglas case and could knock the automatic pendulum down. This would allow the patron to hit the pendulum indirectly, without actually touching it themselves. (page 37)

Projectiles

Another idea was to use foam balls that patrons would throw at the pendulum. There would be a ramp below the pendulum that would return the balls to their original position. Besides actually throwing the balls, there could be a shooting mechanism that would shoot out the foam balls at the pendulum (page 32)

Magnets

Using a magnet mechanism could also disturb the automatic system. To make this work, we would install a magnet at the top of the pendulum, and an opposing magnet would be either outside the Plexiglas case, or inside but controlled by a handle that is outside. (page 35)

Buttons

Instead of having physical contact with the pendulum, an alternate option is to have electronic buttons that will control the pendulum from outside. One option is a “drop” button that will stop the signal to the motor, and essentially drop the pendulum. Another option is to have “jogging” buttons that will disturb the system by jogging the system to the right or to the left. (page 37)

Concepts

Once we brainstormed a list of features, we compiled the features into different concepts. Our concepts put different features together to come up with an idea of the exhibit as a whole. Each concept outlines how the exhibit will look, what features will be implemented, and the engineering challenges for each concept.

Old System

In this system, implemented by the team from the Winter 2009 semester, there would be three systems. There will be two manual systems- one large, one small, in which the users will interact with the system in order to get a feel for how difficult it is to balance a small pendulum versus a large pendulum. The automatic system will balance the pendulum. Features include infrared transmission to transmit the signal for the automatic system. (page 44)

Ball Throwing/Adjustable Length

In this concept, (page 42) there would only be two systems, a manual system and an automatic system. The manual system would be the same big system that was developed in Winter 2009, with a few additional features. The features would include a telescopic pendulum that would allow the patron to make the pendulum longer or shorter. The telescopic pendulum will help patrons understand that changing the length of the pendulum (which in turn is changing the inertia) effects how easy it is to balance the system. For the Automatic system, the feature we would implement is that the exhibit would have foam balls where the patrons of the museum could throw at the pendulum in order to disturb it. Once they do, they will see how the pendulum is able to recover quickly and stay balanced.

Challenges that would occur in this design are mainly based on safety. Having kids throw objects is the main safety concern. The museum does not want to encourage patrons of the museum to throw things, as they could pickup something heavier then the foam balls and throw and destroy the pendulum. Also, the telescoping arm on the manual system can cause additional pinch points.

Behind-the-Wall System

In this system, (page 43) there will be three systems. There will be two manual systems, which will operate behind a wall and will be connected to a patron accessible handle. The patrons will first go to the large manual system, swing it up and try to balance it. They will repeat the same process for the small manual system, which will be near impossible to balance. Last there will be an automatic system. The main feature in this system is the consistent design- each system will be behind the same Plexiglas wall and will look similar. Also, the manual systems will be able to swing up.

The challenges in this system will be the size of the exhibit; it will take up a lot of space and will be hard to move around. Also with the full swing up motion, the pendulum will be very difficult to balance, even if it has a large moment of inertia.

Hanging from Ceiling Manual System

This concept will have three systems. The difference between this concept and the rest is that the manual system will consist of two rods, one smaller and one larger, that will be attached to a wire and will be hanging from the ceiling. The patrons can walk up to these rods and attempt to balance them in their hands. The automatic system will be similar to the previous. (page 46)

In this concept, the main concern again is safety. Having two rods hanging could cause a multitude of unsafe situations, including children hanging from them.

Other Concepts

Segway - A possible idea was turning the manual system into a Segway type system. This way patrons can automatically connect feedback s systems to a real life application: the Segway. However, this adds extra complication to the project, building a Segway adds more complexity then needed for this application. Also having a Segway system run for years in a museum is not practical. (page 38)

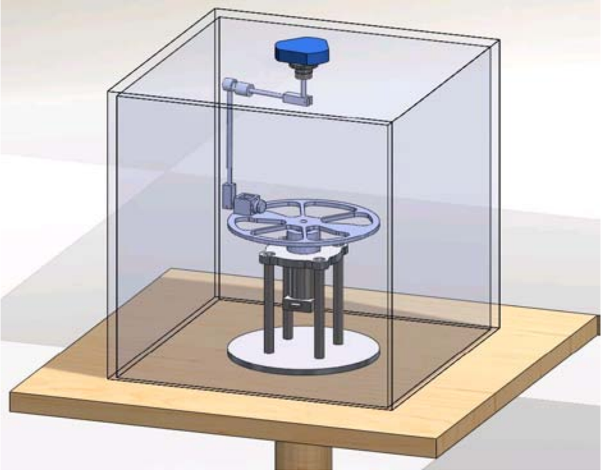
Double-inverted pendulum - Instead of having just one pendulum swing up and balance, through research we found it was possible to attach two pendulums together and have a double pendulum system. Although this system is impressive and creates an automatic sense of wonderment, the system will add more variables that would make the system more complicated and harder to make robust. (page 31)

ALPHA DESIGN

In choosing our alpha design for the mechatronic system – which is our focus – we analyzed the merits of the previous team's design along with the various concepts we generated as a team. The main concept we will keep from the previous team's design is the idea of a rotary system for the pendulum. This allows infinite travel and is a simple way to exemplify the concept of the inverted pendulum. Further, we will improve on the design and incorporate a slip ring assembly to keep the system clean and functional.

In general, we will use the same form of the previous team's mechatronic design, but the components and method of control are very different. Through extensive brainstorming and analysis of the sponsor's requirements as well as various engineering constraints, we feel a mechatronic design using a slip ring is the ideal solution to our design problem. Our system will have a heavy cylindrical aluminum base similar to the previous team as well as the same columns to support the system. The upper plate where the wheel, motor and slip ring attach is of our own design and is rectangular in shape, with round corners. This gives an attractive, aesthetically pleasing look to our system. The motor we will use is a similar Pittman motor, but one designed for heavier mass. The integral difference in the design lies in the slip ring assembly. This assembly will be on top of the plate, above the motor, and beneath the wheel. The motor shaft will pass through the slip-ring in order to power the wheel. The slip ring, however, allows us to transmit the signal from the encoder on the pendulum shaft down to the microcontroller. This simple, elegant design, disposes of the need for extraneous wires and preserves an attractive clean look to our system. The other component that was modified from the previous teams design is the bearing housing. This was redesigned to be more robust and to increase the lifetime of our system.

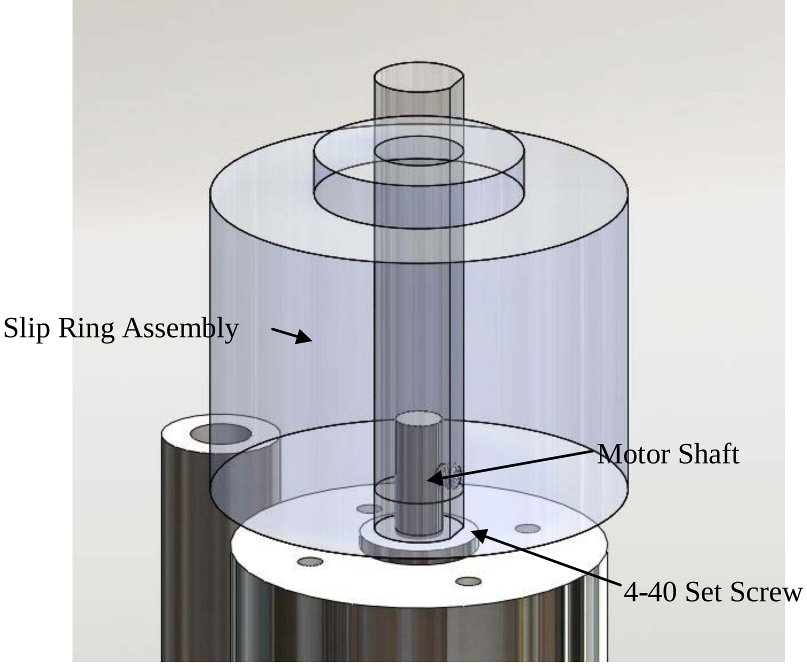
Figure 6: Alpha Design 3D Model



Signal Transmission

Last year’s design used an optical signal sent from a light on the rotating wheel to a stationary sensor underneath the motor. This design introduces new levels of complication that we feel are unnecessary for this system. Our choice for signal transmission is a simple slip ring assembly. We have looked at a few different companies, and a few different styles. We decided that for simplicity we would like a slip ring assembly that has a bore-through design. Transferring power through the slip ring assembly prevents power transfer issues like back lash in gear assemblies. One company we are interested in is IEC, located in Texas - they produce a slip ring assembly that meets the criteria we specified. Another company we are looking at – Moog – is an international company but has an office in Virginia which we are currently contacting for a quote on their bore-through slip ring design. Mechanical power transfers through the middle, and the signal is transferred along the outside of the cylinder around that shaft. We will also create a shaft adapter (located in Figure 7 below) that fits over the motor shaft and has an outer diameter that fits in the slip ring.

Figure 7: Position of Adapter Inside Slip Ring

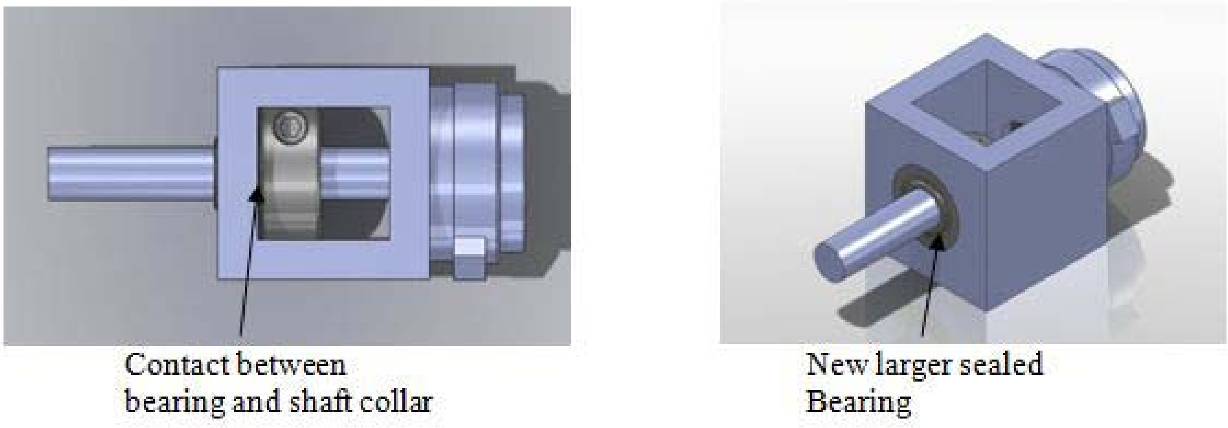


Bearing Housing

The current bearing housing at the pendulum shaft joint used on last year’s project is the same housing used in the ME 350 inverted pendulum project. Some of the problems we found with this design are that the bearings are not suited for long term use. We determined through testing of the previous project that the bearings were not smooth when the pendulum rotated and seemed to have a substantial amount of friction. As a result of these problems, the pendulum can be manually inverted and it will stick in that position. Another problem is keeping the horizontal pendulum shaft inside the bearing housing. Currently the optical encoder located on the back of the bearing carrier holds the shaft from sliding out in the radial direction with a press fit. This shaft is subjected to substantial forces in the radial direction. This shaft from last year’s design has worn out its press fit and slips out of the bearing carrier.

The solution to this problem is to upgrade the bearings from the small open ball bearings to larger sealed ball bearings. We are looking at bearings with an extended inner race that would contact a collar shaft which is secured to the horizontal shaft. With these bearings the horizontal shaft would be constrained from any radial motion. The larger sealed bearings are robust and will provide superior longevity for the project.

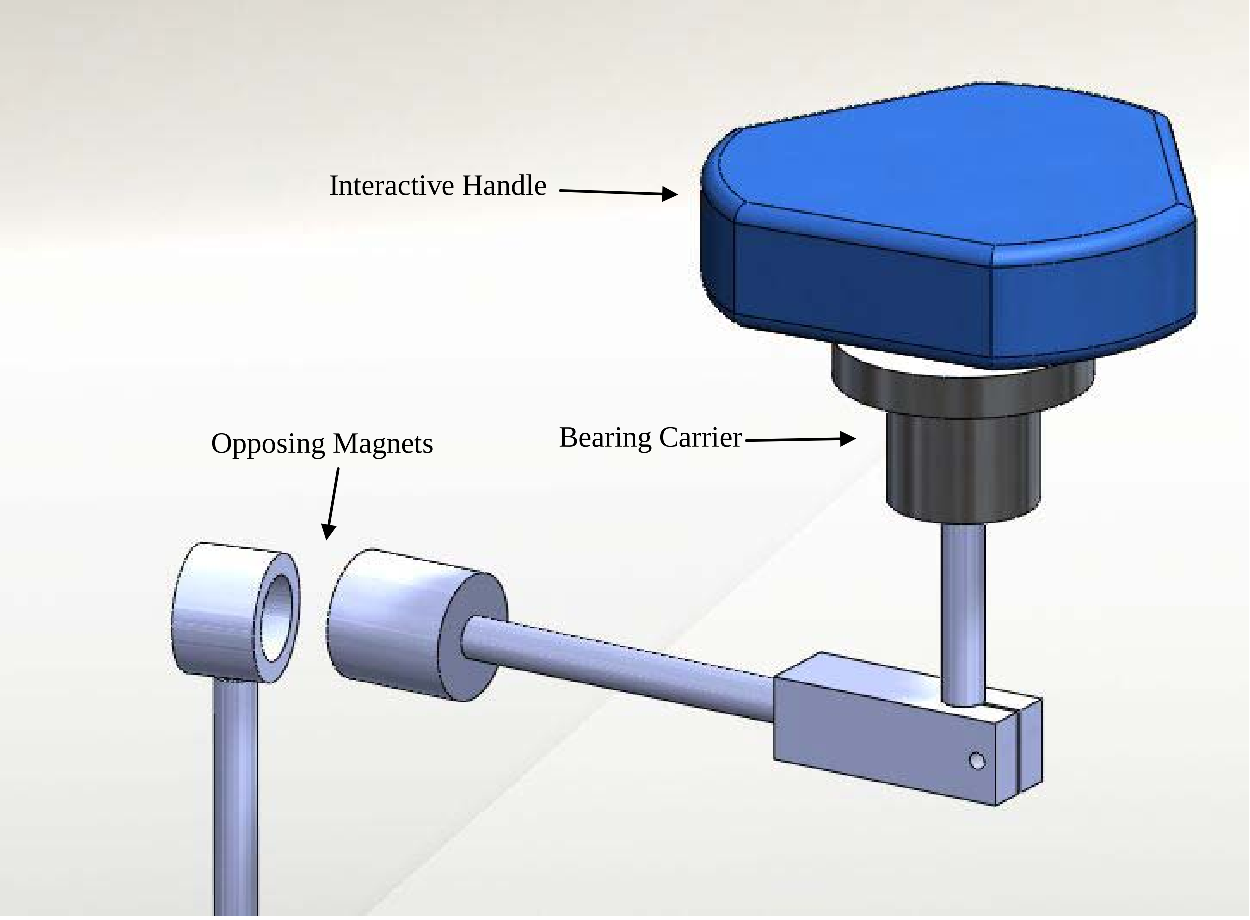
Figure 8 Improvements to Bearing Carrier



Interaction With the Mechatronic System

Our team felt that physical interaction with the mechatronic system was a necessary to give the user the hands-on experience that is the theme of the Museum. Last year's team concentrated on the data transfer system and less on the interaction. They did however have a "Drop" button which would interrupt the feedback loop and let the pendulum drop to its stable neutral position. This is feature that we would also like to incorporate into our design, but we feel that it is not enough. We have decided to incorporate a magnet in addition to the "Drop" button. There will be a magnet placed at the tip of the pendulum and at the end of the agitator arm. The same poles of the magnet will be facing each other, causing them to oppose each other. This gives the patrons a chance to really interact with the display in a similar manner as flicking the pendulum. At the prompting of the Museum Exhibit Manager, John Bowditch, we will use a cylindrical knob with three sides cut off for use as a handle. It's easy to make, does not have a large moment of inertia and is small therefore preventing patrons from spinning it too fast.

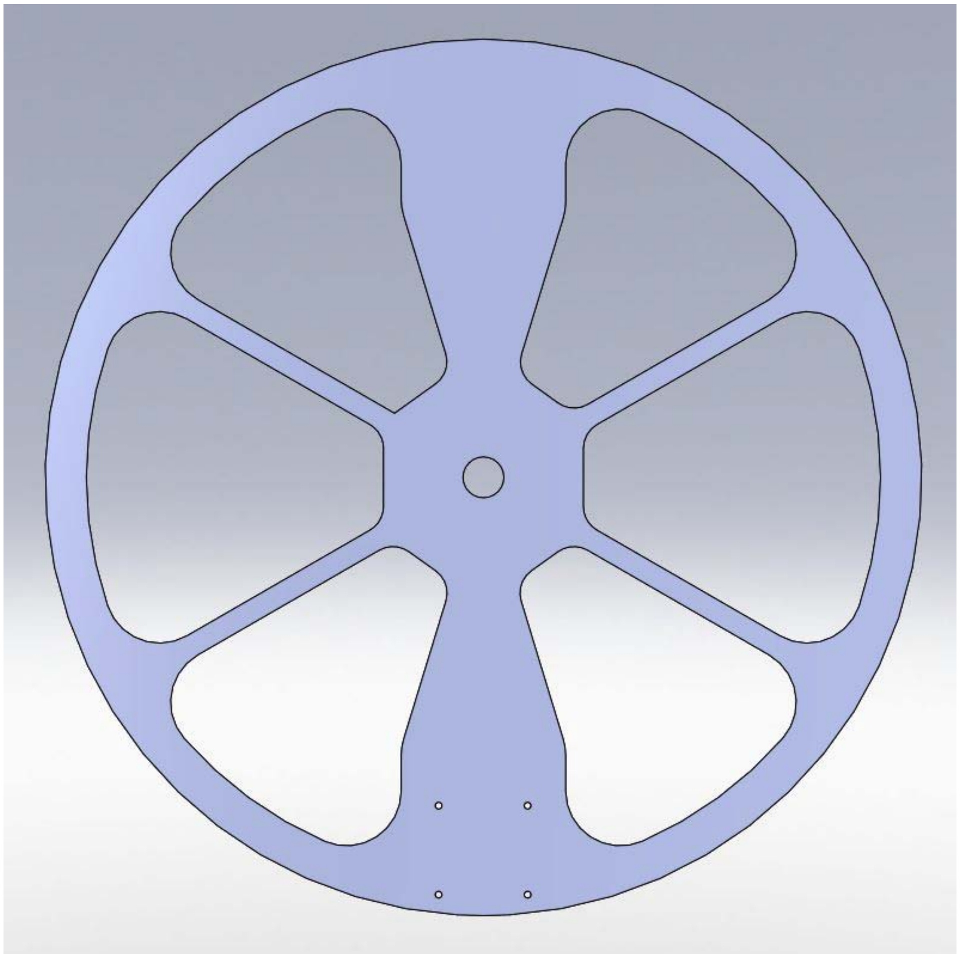
Figure 9: Magnetic Agitator



Horizontal Wheel

Our main concern when manufacturing the wheel was aesthetics. The shape of the wheel – seeing as it is on top of the mechanism - is an essential part of how the project will look. We want the mechantroic system and the large manual system to look similar in their design so a wheel shape is important. Sticking with last year's design we are going to make a six spoke design. Because the shape is two dimensional we can really get interesting with the shapes, and leave the hard work to the water jet.

Figure 10: Wheel



ENGINEERING ANALYSIS

Slip Ring Assembly Life Span

We have contacted four companies about slip ring assemblies. It seems that the industry standard for life span is ten million revolutions. Our conservative estimate of how many revolutions the pendulum motor will spin on average is five revolutions per minute. Considering museum hours and days the museum is closed, we predict that the slip ring assembly will last thirteen years. We considered the fact that the pendulum will spend most of the time in the upright position. This causes the need for the motor to rapidly change direction causing the slip ring to slide back and forth in the same spot repeatedly for long periods at a time. We figure in an infinite amount of time all spots on the slip ring will see the same amount of wear. That means we have to make sure that the forces around the rotation of the arm are even. Setting up the pendulum level will be essential so that the pendulum will not be biased to one balancing point over another.

Motor Selection

The motor selection is a critical part to the success of our project. Simply using the motor that was selected for the ME 350 project will not be sufficient. Masses and inertias have changed as well as critical length dimensions. Even if the old motor works we want there to be safety factor involved that ensures success and safety. An interesting part about the Pitman Motor selected for the ME 350 project is that the torque constant changes as the length of the motor changes. Meaning there will be no changes in the design of our project if the motor constant needs to change. There is ample room for the motor to expand, and the mounting bolt pattern stays constant.

In finding the motor constant, we have MATLAB code, thanks to professor Awtar, which calculates the motor constant based on variable of the physical system. The physical system is broken down into critical components that define the system. These variables are mass, center of mass, inertia around axis of rotation, and critical length. The components are the pendulum arm, swing arm, and motor. Using Solid Works, and Adams we can determine these variables based on the physical system that we are building.

Magnetic Agitator

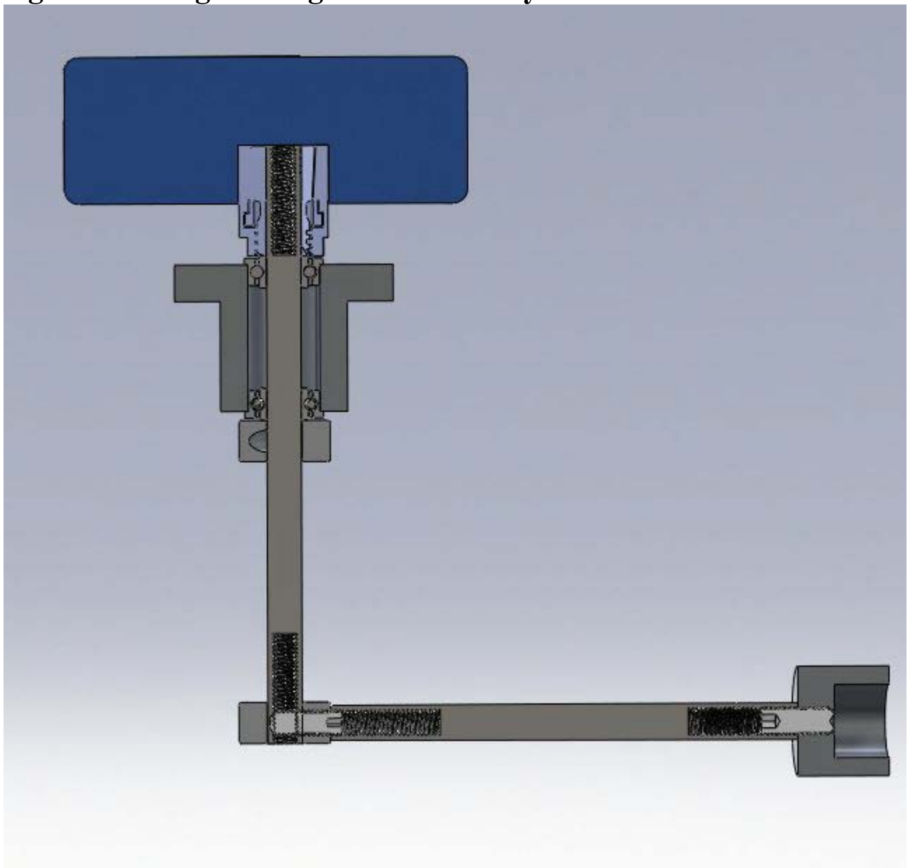
Our goal is to create a fun and interesting system. The magnetic interaction is a key feature of our project and in order to make it interesting in has to be a challenge to knock over the pendulum. There are a few variables we can play with in order to fine tune this experience. One is the size of the magnets, second is the distance between the two magnets. Using Adams we can back out the amount of force needed to push over the pendulum. Then we will calculate the peak force generated between the two magnets in the radial direction. To change the amount of force applied by the magnets we would adjust (d) the distance of the horizontal magnetic support. The force increases exponentially as the magnets get closer, but the force in the radial direction decreases by sin(φ) as φ (the angle between the two magnets) decreases. We will match the force needed to knock the pendulum to the peak force generated between the magnets. Finding the zone where the force due to the magnet is a maximum will be the challenge at the museum.

FINAL DESIGN DESCRIPTION

Magnetic Agitator Assembly

In order to create an interactive exhibit for the patrons of the museum, we needed to develop a system that would provide a connection to the user while being appropriate for a museum environment. The system we developed for this application is a setup that uses magnets that are of the same pole and will repel each other when they are close to each other. There will be one magnet placed at the tip of the pendulum while the other magnet will be placed in a rotating arm that moves in a circle horizontally as seen in Figure 11. Outside of the Plexiglas case that houses our inverted pendulum system, a simple handle is attached through a keyless bushing and shaft to the arm inside the case that houses the magnet. The shaft runs through two bearings housed in a bearing fixture that attaches to the Plexiglas case through a threaded nut. The shaft and magnet agitator arm are both steel shafts of ¼” diameter. The shaft from the handle has a shaft collar at the end of it which is drilled and tapped on one side to house a set screw to accommodate the internally threaded rod which is the agitator arm. At the tip of the agitator arm is a cylindrical housing which encases the magnet – which is attached using glue. This agitator arm rotates on the same axis as the inverted pendulum wheel, and is slightly shorter than the radius of the wheel. As a result of this, the agitator arm can rotate freely and be in close vicinity of the inverted pendulum to jar the pendulum without direct contact. This design was found to be the best interactive system based upon our extensive brainstorming, analysis and through discussion with the AAHoM exhibit manager.

Figure 11: Magnetic Agitator Assembly Cross-Section



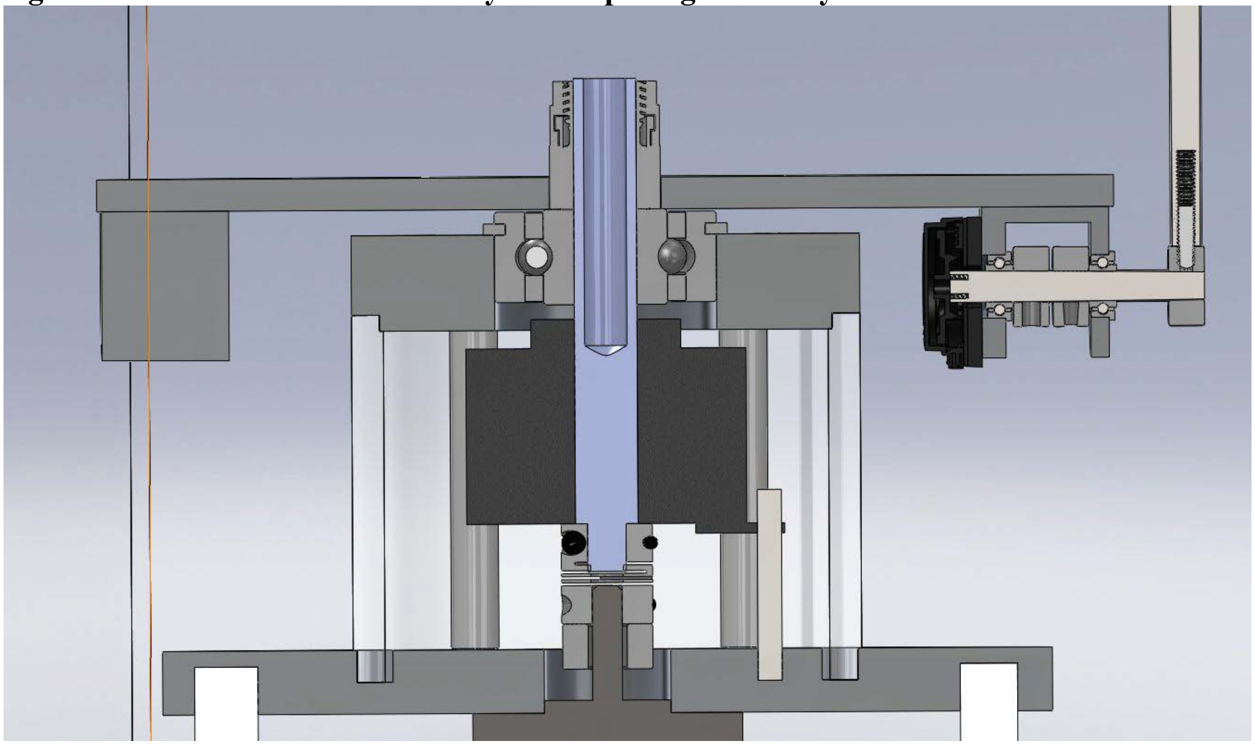
Pendulum Arm Assembly

After careful analysis of the ME 350 inverted pendulum and the previous Winter 2009 inverted pendulum, we arrived at our concept of the pendulum arm assembly. This component of our inverted pendulum system attaches at the edge of the wheel on underside of the wheel. The bearing and encoder housing is made from a 1" aluminum plate with walls 1/8" thick – the counterweight will be made from the 1" solid square block of aluminum. One side of the tube will be milled out and the edges rounded to create an arch-like shape to the housing as shown in Figure XX. A hole will be drilled in each of the sides to house flanged double shielded ABEC-5 ball bearings to accommodate the ¼" shaft of the pendulum. The side of the housing closest to the center of the wheel houses the encoder on the outside of the bearing housing. Two shaft collars will be placed on the shaft as it is pressed through the bearings and into the encoder. These shaft collars will constrain the pendulum shaft axially, but still allow the shaft to rotate freely. The outside end of the pendulum shaft will have a shaft collar as well. This shaft collar will be drilled and tapped on one side for a set screw that will accommodate the internally threaded rod used as the pendulum. At the tip of the pendulum is a cylindrical housing that faces the center axis of the wheel. This housing encases the second magnet which will provide a repelling force when it is in close vicinity with the magnet in the agitator arm. This setup for the pendulum arm assembly was determined to have both the robustness and aesthetics to appeal to the museum environment.

Slip Ring Assembly

In order to transmit the position of the pendulum to the controller from the encoder in the bearing and encoder housing, we needed to develop a method to conduct the signal. Through extensive research and discussion with John Bowditch, we concluded that a slip ring setup was ideal for our application (this setup is shown if Figure XX below). The slip ring selected for our application was a Jinpat through-bore slip ring. At the top of the system the wheel of the inverted pendulum connects to the main shaft through a keyless bushing. This main shaft will be a ½" steel shaft that is hollow at the top and solid through the slip ring. The shaft is constrained at the top of the by a double sealed ball bearing pressed into an aluminum plate. In addition, the main shaft is connected to the inner cylinder of the slip ring through four set screws. The wires from the encoder will run down the hollow shaft and out of the side of the shaft and then proceed into the inner rotating cylinder of the slip ring. Below the slip ring the main shaft connects to a flexible shaft connection which in turn is connected to the motor shaft. The slip ring is constrained from rotating by a dowel pin that is fixed in the motor plate below the slip ring. This allows the slip ring to "float" and only be constrained by the four set screws to the main shaft and the dowel pin on the side. The reason for this method of attachment is to keep from fully constraining both the inner cylinder of the slip ring and the outer ring of the slip ring. If both parts are fully constrained, the brushes inside of the slip ring can be subject inconsistent wear and therefore fail before the lifetime of the product. By allowing the slip ring to float, we avoid this earlier failure and prolong the life of the slip ring. The bearing plate at the top of the system which constrains the main shaft will be attached below to the motor plate through four shoulder bolts. An acrylic cylinder will surround the design and allow the patrons a view of the inner workings of the system.

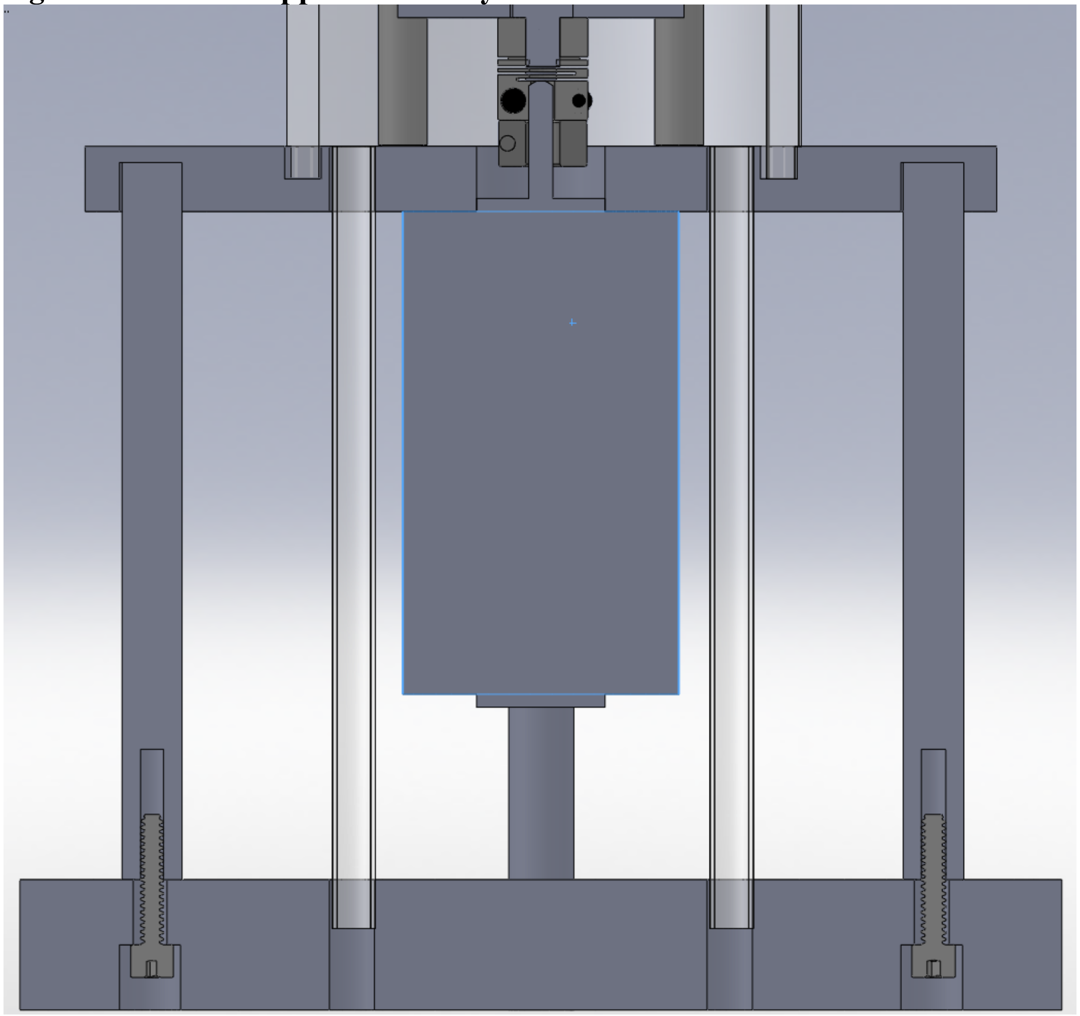
Figure 12: Pendulum Arm Assembly and Slip Ring Assembly



Motor Support Assembly

The motor plate assembly is detailed in the cross section in Figure XX below. The plate itself is connected to the base plate through four steel studs which are externally threaded. These studs are recessed into the plate to provide a secure stable connection. The motor itself will bolt to motor plate through oversized holes in the motor plate. This design allows the motor, and therefore the motor shaft, to solely be aligned through circular motor pilot. A single acrylic tube will conduct the wires from the slip ring down through the motor plate and out the bottom of the base plate to the controller. The base plate is a solid 1” thick 8” diameter aluminum plate. The studs are connected through four cap screws countersunk into the bottom of the base plate. The large base plate provides a strong foundation for the inverted pendulum design.

Figure 13: Motor Support Assembly and Base Plate



FINAL COMPONENT SELECTION

Slip Ring Selection

After deciding through extensive brainstorming and research that a slip ring was the ideal solution to sending the encoder signal to the controller, we needed to select the right slip ring for our application. We found several companies that had slip rings we felt met our needs and these various companies and slip ring models are detailed in Table 2 below. The first company we talked to was Michigan Scientific. This local company makes a variety of slip rings for various applications and was attractive to us for the very fact that they were a local company. The problem, however was that the slip ring they made within our price range ($200-$700) was not a through bore slip ring. We need a through bore design to have the main shaft transmit the torque from the motor to the wheel. Michigan Scientific makes a through-bore slip ring, but it is for a 2 inch diameter shaft – which is much too large for our application – and it cost upwards of $1,000. For these reasons, we had to eliminate the Michigan Scientific slip rings from consideration.

The next company we inquired into about a slip ring was IEC based out of Texas. IEC had a high temperature slip ring that met our engineering specifications of minimal electronic noise, ideal shaft diameter and number of circuits but cost $1,500. Despite the ideal engineering specifications of the IEC slip ring design, the enormous cost could not be justified for our application.

Moog is a company that manufactures precision instruments for flight systems and various other applications. Moog had several slip ring models that we analyzed as possible options for our system. The model we looked at from Moog was the AC6349 through bore model. This model was ideal for our system but there was a four week ship time for all Moog slip rings including the AC6349. Though the AC6340 slip met our engineering requirements, we could not wait for the slip ring to ship for the four week period. As a result, we had to eliminate all Moog products from consideration.

The final company our team analyzed for use of their slip ring products was Jinpat based out of China. We found out about Jinpat through a professor in California that modeled his inverted pendulum system off of the inverted pendulum system developed by Professor Awtar and his graduate students. This professor used a slip ring from Jinpat that worked well for his application. We, however, chose a slightly different model – the Jinpat LPT012 – shown below in Figure 14. This slip ring met the engineering requirements for minimal noise, shaft size, slip ring size and number of circuits. After contacting the company, we found the slip ring would arrive within one week of placing the order. Based upon these specific reasons, we selected the JinPat LPT012 as the slip ring to use for our inverted pendulum system.

Figure 14: Jinpat LPT012 Slip Ring

Table 2: Slip Ring Selection Specifications

Manufacture	Model #	Price	Shaft Diameter (in)	Outside Diameter (in)	# of circuits	Electronic Noise (mΩ)	RPM (continuous)	Amperage (A)	Voltage (V)	Quality of Engineering Drawing
Moog	AC6438	$423.00	0.50	2.080	6	100	250	5	250	poor
Moog	SRA-73683	$330.00	0.50	1.375	6	10	120	5	210	poor
Moog	AC6349	$700.00	1.00	3.070	6	60	250	15	440	Moderate
Michigan Scientific	S4	$450.00	N/A	2.000	4	100	12000	0.5		Great
JINPAT	LPT012A	$301.00	0.50	1.375	6	10	300	2	380	Bad
JINPAT	LPT012	$244.00	0.50	2.205	6	10	500	5	380	Moderate
IEC	TBVS-HT-.375	$1,500.00	0.375	1.750	6	1		3.5	500	Moderate

Microprocessor Selection

The current prototype is hooked up to a computer, and balances itself by running a LabVIEW program which sends power to the motor. The LabVIEW program uses equations of motion and other live position readings from the pendulum to decide which way to spin the motor, and how much torque to supply. The museum exhibit will require something smaller and more reliable than a desktop PC or laptop to run the pendulum. A dedicated microprocessor will be required.

After researching available options and talking to University faculty, we narrowed our search down to two options. The Arduino Duemilanove is a very basic microprocessor that can be programmed and used in various applications. The Duemilanove is used by hobbyists and professionals alike to mechanize projects. While the Duemilanove chip itself is very small, we would need to add external power supplies and amplifiers, just as we have with the prototype setup. The NI cRIO is basically just a very compact computer. It runs LabVIEW code just like a PC and has all the power supply, input/output connections, and amplifiers we would need built into one chassis. Table 3 explains some of the main differences between our two microprocessor options.

Table 3: Electronic Systems Summary

Manufacturer	**NI**	**Arduino**
Model	cRIO 9074	Duemilanove
Base Cost	$400	$30
Language	LabVIEW	Modified C++
Programming Environment	LabVIEW	Open Source Arduino Specific
PC Connection	USB/Serial/Ethernet	USB
Additional Parts		
Power Supply	Included in 9074 Chassis	MW S-60-24
		$25
		MW T-60C
		$35
Input/Output Ports	NI 9401	Included in Chip
	Included in Discount Price	
Amplifier	NI 9505	AMC 12A8
	Included in Discount Price	$275
Total Cost	**$400**	**$365**

The NI cRIO is extremely overpowered for what type of processing power our exhibit requires. A typical setup utilizing the devices shown Fig. 15 would cost around $3,000. The shown I/O and amplifier devices plug into the 9074 chassis. NI is willing to offer us a large discount on top of their typical educational discount, bringing the total price down to about $400. Using an Arduino chip would require that we purchase additional power supplies and amplifiers. The prices and devices listed in Table 3 are based on what was used for the ME 350 prototypes. A total cost of about $365 is slightly less than that of the NI setup.

The main benefit the NI cRIO would provide would be its ease of programming. While the Arduino would require that we write a program in a modified version of C++ (all members of our team have minimal programming experience), the cRIO uses LabVIEW code. As the current program that runs our prototype pendulum is written in LabVIEW this would mean we would have to do very little editing to adapt the current program to our final design. The LabVIEW code is written on a PC and uploaded to the cRIO via USB, serial, or Ethernet ports.

Figure 15: NI Devices Required for Exhibit

NI cRIO-9074 Chassis

NI-9401
Digital I/O

NI-9505
Amplifier

<http://sine.ni.com/np/app/main/p/ap/daq/lang/en/pg/1/sn/n17:daq,n24:cRIO>

We feel that the reduced programming time offered by the NI cRIO is more than worth its slightly higher price when compared to the Arduino Duemilanove. We will somehow incorporate NI into our museum exhibit to thank them for the large price discount they are giving us. We may have the cRIO on display or have some type of NI logo on the case. We are currently in the process of ordering the cRIO and all the necessary components.

Motor Selection

The current prototype uses a Pittman 9237S011 24V DC servo motor. This motor seems to struggle balancing the pendulum quickly when used with the ME 350 inverted pendulum setup. Our exhibit will have a lot more inertia than the ME 350 setup, due mainly to the aluminum wheel replacing the small pendulum arm connecting the pendulum to the motor. So choosing a stronger motor for our exhibit seemed like a good idea to consider. Various replacement motors that we considered are listed below in Table 4. The colors correspond with rankings within a category; dark green is the best, and dark pink is the worst. Our ratings of the motors are given in the right-most column, with higher numbers relating to better motors.

Table 4: Motor Selection Summary

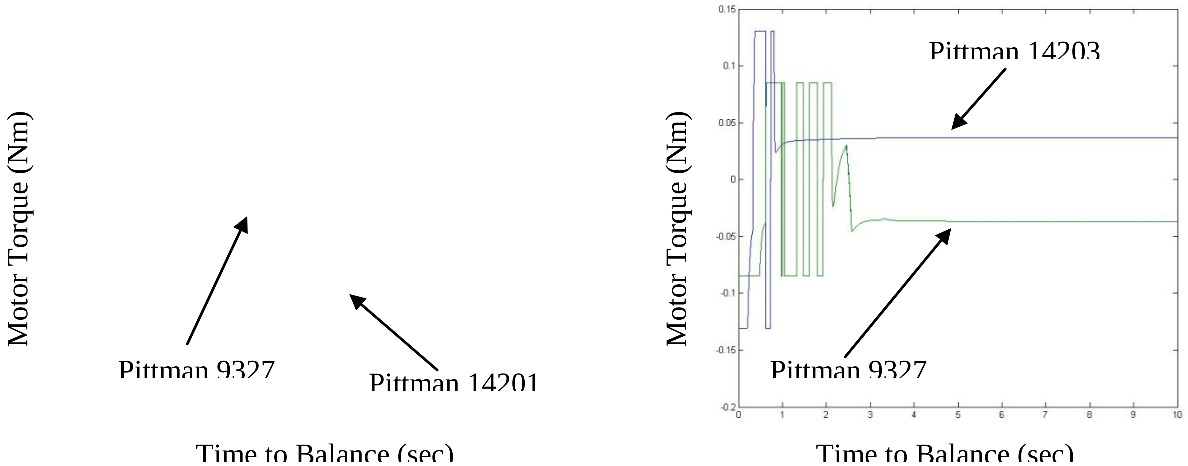
Ordering Data			Motor Data				Physical Properties					
Company	Model Number	Price	Torque Constant (mNm/A)	Stall Torque (mNm)	Nominal Torque (mNm)	(V)	Type	Inertia (g-cm^2)	Shaft Diameter (mm)	Motor Diameter (mm)	Motor Length (mm)	Overall rating
Pittman	9237S011 w\Encoder	$221.56	42.4	540.0	81.0	24	Brushed	85.0	5	40.0	84.4	99
Pittman	3441S002-R3 w\Encoder	$249.98	31.6	94.0	29.0	24	Brushless	9.9	5	29.9	60.5	43
Pittman	4443S013 w\Encoder	$297.39	39.2	1100.0	130.0	24	Brushless	61.0	6	39.5	82.7	57
Pittman	5441S006 w\Encoder	$322.13	45.6	1200.0	180.0	24	Brushless	170.0	8	48.0	80.2	133
Pittman	14201	$138.48	52.5	438	71	24	Brushed	110	6.35	51.9	75.0	79
Pittman	14202	$140.38	55.1	751	99	24	Brushed	160	6.35	51.9	81.4	131
Pittman	14203	$146.12	65.4	1120	150	24	Brushed	210	6.35	51.9	94.1	183
Pittman	14204	$152.45	61.2	1440	180	24	Brushed	260	6.35	51.9	103.6	149
Maxon	EC-max 283867	$255.09	28.0	497.0	88.0	24	Brushless	51.2	6	40.0	58.0	33
Maxon	EC-max 283869	$155.80	50.0	636.0	92.9	48	Brushless	51.2	6	40.0	58.0	85
Maxon	EC-powermax 305013	$678.30	13.5	3180.0	114.0	24	Brushless	33.3	5	30.0	64.0	-25
Maxon	Flat 251601	$102.89	33.5	822.0	84.3	24	Brushless	135.0	4	42.8	21.3	47

Our first major decision in choosing a motor was to go with a brushed or brushless model. Brushless motors offer increased reliability, due to the lack of mechanical brushes, but at a higher cost. It was decided that since our slip ring, with its mechanical brushes, would probably be the limiting factor in exhibit lifetime there was no need to spend extra money on a brushless motor.

The major difference between the possible motors was the torque constant. This is the amount of torque the motor supplies per amp of electricity sent to it. A higher torque constant means that the motor can supply a lot of torque at relatively low electrical currents. Supplying low electrical currents (below even the nominal motor rating) will extend motor brush life, so the less power we need to send to the motor, the better.

We were provided a mathematical MATLAB model of our inverted pendulum system by Professor Awtar. With this model we could change system inertias, motor parameters, and other physical properties and see how this affected the balancing time of the system. We got inertias of different parts of our system from our SolidWorks models and the motor parameters came from manufacture data sheets. In the current prototype system the current sent to the motor is limited to 0.75A. After simulating the current Pittman 9237 motor in the new pendulum system with a maximum of 0.75A we found that it would never balance. This was also the case with nearly all of the possible motors at only 0.75A. Shown below in Fig. 16 are a couple graphs of various motor performances when restricted to a maximum current of 2A.

Figure 16: Comparison of Pendulum Balancing Time with Motor Current of 2A



It can be seen that at a maximum of 2A some motors, such as the Pittman 14201 still can't balance the pendulum. Generally the higher the torque constant of the motor, the quicker it can balance the motor for a given current. This simulation did not take into account the friction of the slip ring, which when actually spinning the slip ring we purchased, does not feel negligible. After running several simulations and seeing the trends for motors with different torque constants we feel that the Pittman 14203 24V motor would be best suited to our application. It had the highest torque constant of the motors we compared, which will be beneficial for our heavier system. While the 14203 balanced the pendulum the quickest in the simulation at 2A, its nominal current is 2.77A, so we could probably increase the power even more without much reliability concerns. It would be better for us to overestimate our motor torque needs, as there are some frictions (such as the slip ring) that are not currently included in the MATLAB model. We would need to buy an encoder for the Pittman 14203 (talked about in the next section), which would add about $100 to the purchase price.

Optical Encoder Selection

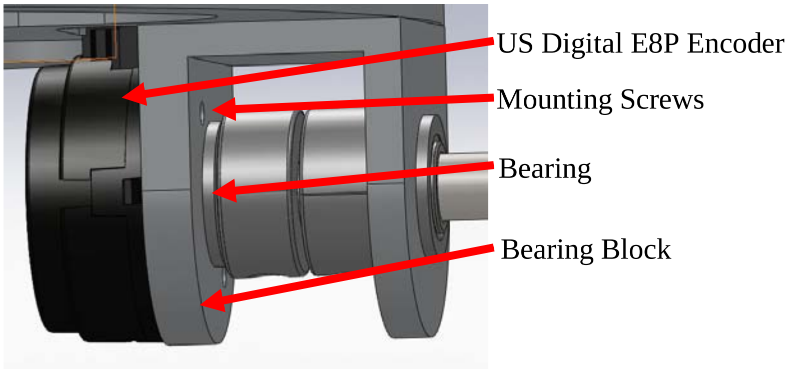
Pendulum Arm Encoder

The current prototype uses a US Digital E4P optical encoder on the pendulum are which has a resolution of 300 counts per revolution and quadrature output. The current encoder performs adequately on the current prototype and we wanted to keep it. Due to a bearing size increase in the bearing block to which the encoder is attached, we needed to choose an encoder with its mounting screws spread farther apart. We will use the US Digital E8P encoder (as shown in Fig. 17), which is also capable of 300 CPR or more and has quadrature output, but is slightly larger than the E4P, with mounting screws that will clear our new bearings. The final mounting setup can be seen in Fig. 18.

Figure 17: US Digital E8P Optical Encoder

<http://usdigital.com/products/encoders/incremental/rotary/kit/e8p/>

Figure 18: Optical Encoder Mounted to Pendulum Arm Bearing Block



Motor Encoder

Our proposed motor, the Pittman 14203, does not come with an optical encoder, but instead one must be purchased separately. The encoder on the current motor has a resolution of 500 counts per revolution with quadrature output. We will purchase either the Pittman E30A or E30B optical encoder for our new motor. Both encoders can achieve 500 CPR, or higher and have quadrature output.

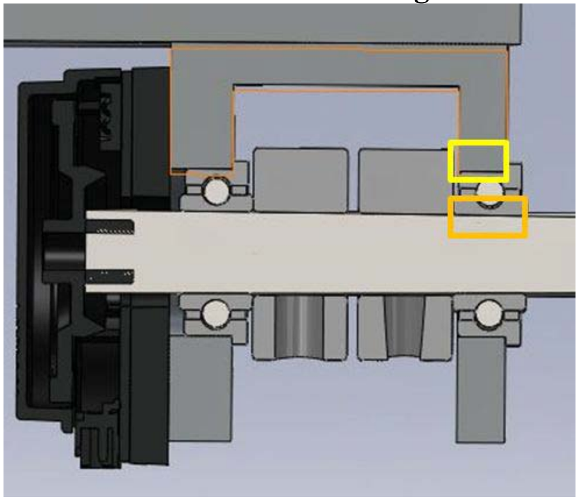
The difference between the two encoders is that the E30B has a zero index while the E30A does not. This means that the E30B always knows where it is at in relation to a fixed position on the encoder wheel. This may be advantageous over a unit without an index in the event of the pendulum exhibit being jarred. If the non-indexed encoder experiences a large force, it may skip a few slits in the optical wheel and lose track of its position. It would then try to balance to a position that is not vertical, and thereby impossible. If the indexed encoder is jarred and skips a few slits in the wheel, it would still know it was position-wise, due to the fixed index. Our team will have to determine if the advantages of an indexed encoder outweigh its higher cost.

IMPORTANT TOLERANCES

While our exhibit may not be on a nano-scale, holding tolerances during manufacturing will be essential in making sure our assembly fits together securely. Some of our tolerances appear on the dimensioned drawings of manufactured parts, in Appendix B, while others are still being determined by our engineering team as we learn more about the machines available for our use in surrounding machine shops.

There are several tolerances on our design that are critical to the functionality and durability of our design. The first critical tolerance is the fit between the pendulum mounting shaft, the bearings that hold the shaft, and the bearing block; as seen below in Figure 19. Using the Machinery's Handbook, the fits between the shaft, bearing, and housing were determined (shown next to orange and yellow box in Figure 19). If we have a hard time holding one of the fits, we want to at least make sure that there is not an interference fit on both the shaft and the housing. This would compress the ball bearings from both sides and reduce their lifespan.

Figure 19: Pendulum Arm Bearing Block Tolerances



🟧 Shaft Fit (h5) 0.0 to -0.0002"

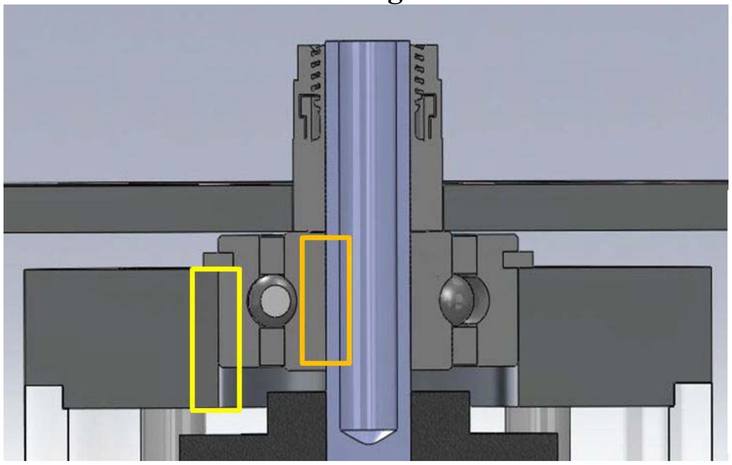
🟨 Housing Fit (J6) 0.0003 to -0.0002"

Bearing Diameter Tolerances (McMaster Carr #57155K337):
Inner Race 0.0 to -0.0002"
Outer Race 0.0 to -0.0002"

Shaft Diameter Tolerance (McMaster Carr #1257K116: 0.0 to -0.0002"

Another critical tolerance is the fit between the pendulum assembly's central shaft, its bearing, and the motor plate; this is shown below in Figure 20. Using the Machinery's Handbook, the fits between the shaft, bearing, and housing were determined (shown next to orange and yellow box in Figure 20). If we have a hard time holding one of the fits, we want to at least make sure that there is not an interference fit on both the shaft and the housing. This would compress the ball bearings from both sides and reduce their lifespan. We are currently searching for a ½" diameter precision shaft with tighter tolerances than the one that we currently have.

Figure 20: Central Shaft Bearing Tolerances



🟧 Shaft Fit (h5) 0.0 to -0.0003"

🟨 Housing Fit (J6) 0.0004 to -0.0002"

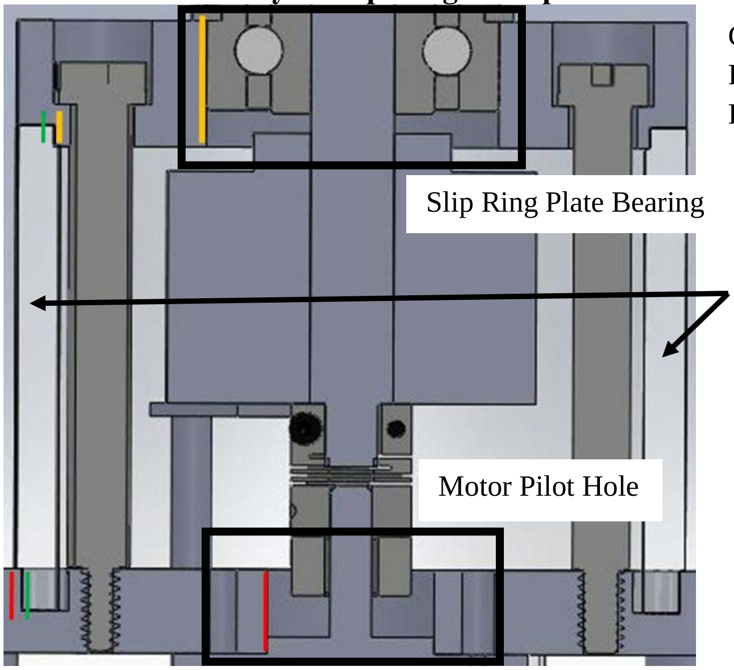
Bearing Diameter Tolerances (McMaster Carr #2782T81):
Inner Race 0.0 to -0.0005"
Outer Race 0.0 to -0.0005"

Shaft Diameter Tolerance (McMaster Carr #1346K17): 0.0 to -0.003"

While we have a flexible coupling connecting the motor shaft and central shaft, which will correct small misalignments between the two shafts, we still want the motor pilot hole and the central shaft bearing hole to be aligned. A section view of the area in question is shown below in Figure 21. The flexible coupling can withstand a misalignment of one degree between the two shafts, which corresponds to a difference of 0.03" between the centers of the motor pilot hole and the bearing hole. In an effort to preserve the bearing life (by keeping the shaft running as close to vertical as possible) we would like to keep the motor pilot hole and central shaft bearing hole concentric to within 0.005"

When machining the slip ring plate, we want to machine both the center bearing hole and the outer groove at the same time (highlighted in yellow in Figure 21), so they have the same center point. We would also like to machine both the motor pilot hole and outer groove (highlighted in green in Figure 21) into the motor plate at the same time so they have the same center point.

Figure 21: Concentricity of Slip Ring Set-Up

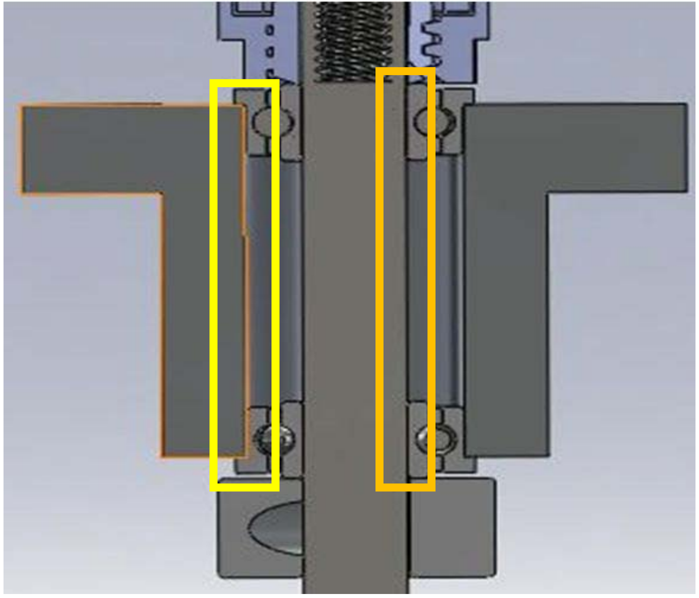


Concentric Tolerance (Motor Plate Pilot Hole to Slip Ring Plate Bearing Hole) ±0.005”

Acrylic Tube

The agitator arm bearings and shaft require the same fits as the pendulum arm bearings. This is shown in Figure 22 below.

Figure 22: Agitator Arm Bearing Tolerances



🟧 Shaft Fit (h5) 0.0 to -0.0002”

🟨 Housing Fit (J6) 0.0003 to -0.0002”

Bearing Diameter Tolerances (McMaster Carr #57155K324):
Inner Race 0.0 to -0.0002”
Outer Race 0.0 to -0.0002”

Shaft Diameter Tolerance (McMaster Carr #1257K116: 0.0 to -0.0002”

MANUFACTURING PLAN

CNC Mill

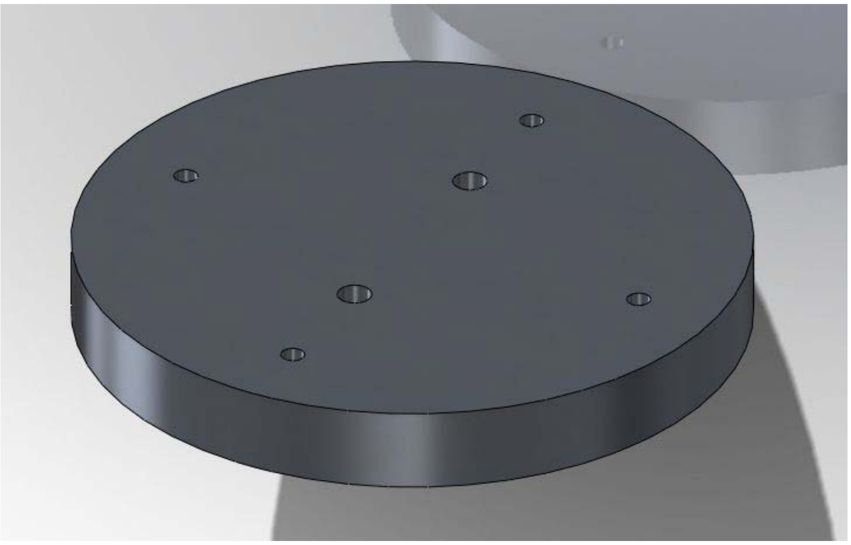
For the three aluminum plates the CNC Mill in the U of M graduate shop is a perfect choice. The tolerances and geometry are easily achievable using the Partner CNC Mill. Also all of our cutting processes can be taken care of on one machine. The machine cuts circles with relatively simple commands that you program right at the machines interface.

Base Plate (Figure 23)

Machining from 1" plate aluminum. We will start with the bottom of the part. Here is a step by step plan on how we will make this part.

1. Zero x, y, and z axis's
2. Drill out the four holes and counter sink them with a plunging mill bit.
3. Then we will cut the finished part out with a circular cutting command making sure that the tool never hits the chuck, and that the usable piece doesn't fall before the cut is fully made.
4. All holes that need to be tapedwill be tapped.

Figure 23: Top of Base Plate Finished Part



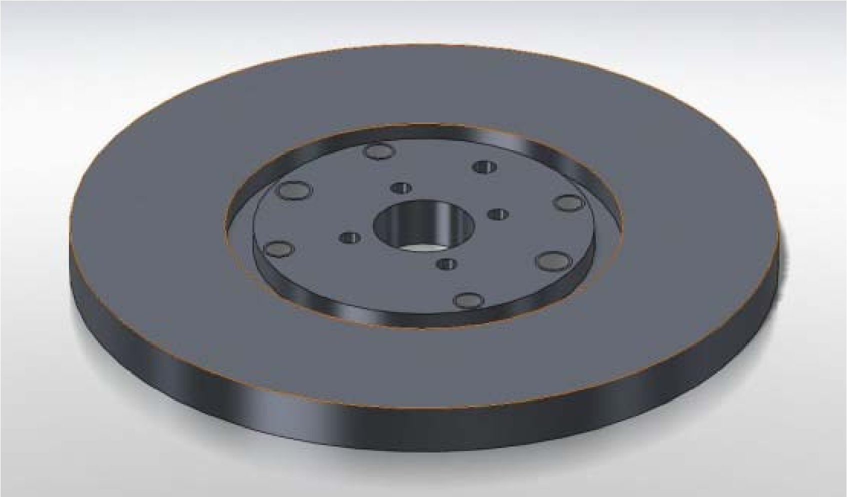
Motor Plate (Figure 24)

Machining from ½" aluminum plate. This part has some tighter tolerances.

1. Zero x, y, and z axis's
2. Drill holes for upright supports from bottom side of part, we will use a plunging mill bit in order to create a flat bottomed hole.
3. We will have to flip the part in order to machine features on the top side. When doing these processes special attention to where the zero of the part is. This means that when we flip the part we have to zero the part on the same edge. And then use negative number for the one of the planer axis's.
4. On the top side the grove and the motor pilot hole will be milled. These two processes will be performed without removing the part from the chuck to ensure concentricity. In order to get the tolerance we want we will leave a small amount of material and then incrementally mill and measure the groove and pilot hole until it meets our specification.

5. Drill holes for anti roll pin, wire tubes, motor bolts, and shoulder bolts.
5. Then we will cut the finished part out with a circular cutting command making sure that the tool never hits the chuck, and that the usable piece doesn't fall before the cut is fully made.
6. All holes that need to be taped get will be tapped.

Figure 24: Top of Motor Plate finished part

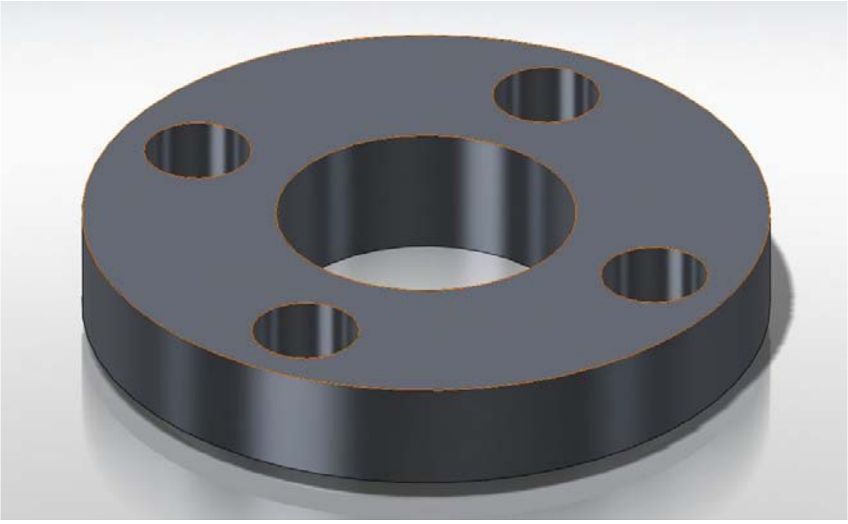


Bearing Plate (Figure 25)

Machined from 1" aluminum plate. A very similar method to the Motor Plate will be used to machine this part.

1. Zero x, y, and z axis's
2. Drill and counter sink holes from top of part for shoulder bolts.
3. Flip part making sure to zero part using same edge.
4. Mill groove and bearing hole using circle command. These two processes will be performed without removing the part from the chuck to ensure concentricity. In order to get the tolerance we want we will leave a small amount of material and then incrementally mill and measure the groove and pilot hole until it meets our specification.

Figure 25: Top Bearing Plate finished part



Water Jet

For lots of complicated geometry the water jet is the perfect tool. It is located in the Reconfigurable Manufacturing Lab at the U of M. Our team has experience using the water cutter and knows the procedure.

Inverted Pendulum Wheel (Figure 26)

The wheel that supports the Pendulum has a lot of complicated geometry that does not need extreme tolerances. The wheel is made out of ¼" aluminum plate.

1. The geometry for the wheel gets saved in a .dfx format and brought down to the lab.
2. Then we will create a tool path on a computer provided in the shop.
3. It is then converted into a file that is compatible with the water jet machine.
4. From there the technician on staff runs the machine, ensuring proper usage.

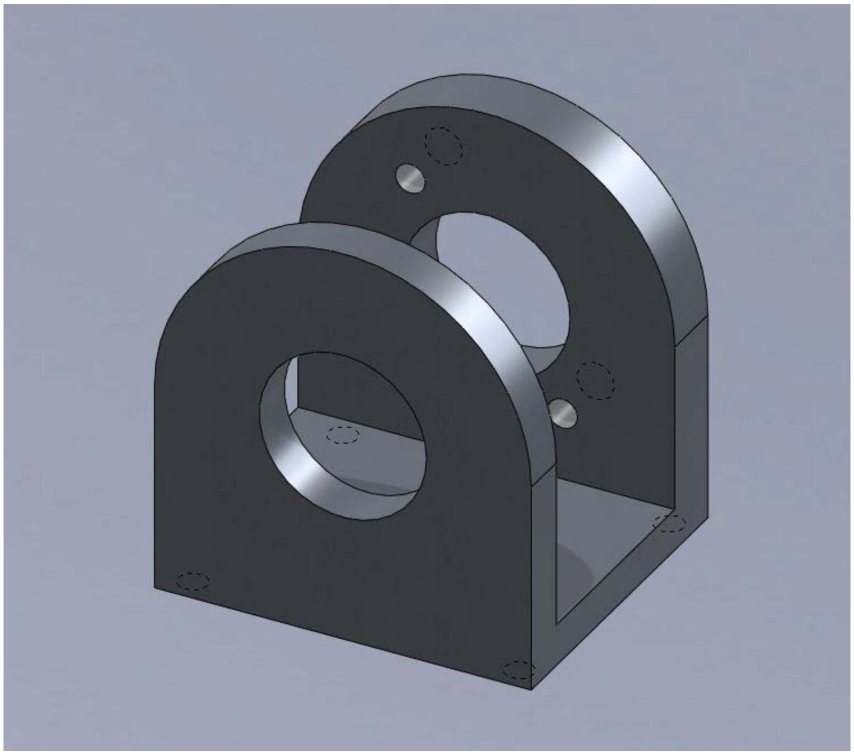
Figure 26: Wheel finished part

Bearing Block (Figure 27)

The bearing block provides bearing support and encoder mounting. The bearing block is made form 1” aluminum plate.

1. The geometry for the Bearing Block gets saved in a .dfx format and brought down to the lab.
2. Then we will create a tool path on a computer provided in the shop.
3. It is then converted into a file that is compatible with the water jet machine.
4. From there the technician on staff runs the machine, ensuring proper usage.
5. Then the part needs milling, so it will be moved over to the Wilson center.
6. Part will be placed bearing face up, and zeroed in the x, and y direction.
7. The through hole for the bearing will be drilled out then reamed with a ½” reamer.
8. Next the holes for encoder will be drilled, the depth will be roughly ½”.
9. Then the part will be oriented upside down, leveled, and zeroed in the x, y, and z direction.
10. The four mounting holes will be drilled next, roughly 5/8” deep.
11. Then the part will be oriented up right and zeroed in the y, and z direction.
12. The middle part of the block will be milled out to spec’s.
13. Any holes that need tapping will be tapped.

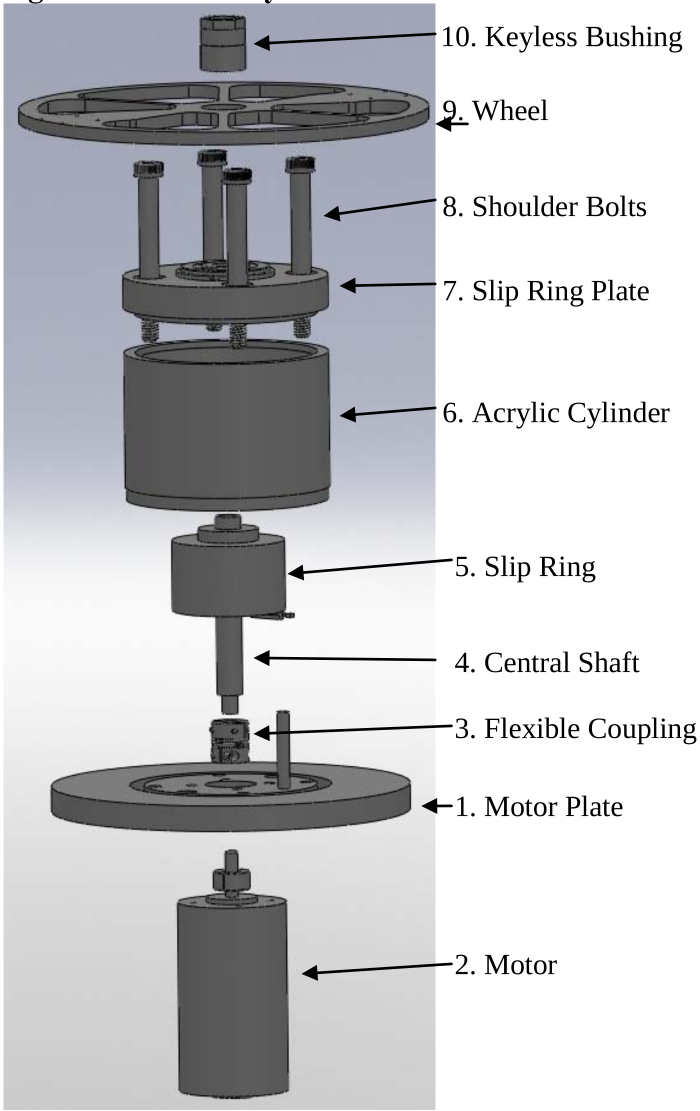
Figure 27: Bearing Block Finished Part



ASSEMBLY

We designed our exhibit to be as simple to assemble as possible. Shown below in Figure 19 is the assembly order of the core of the inverted pendulum. All items in the core assembly just set on top of each other, so there is no need to measure the distances between components during assembly.

Figure 19: Assembly Order of Pendulum Core



The primary step in assembling the pendulum is securing with the motor plate, with the permanently secured dowel pin, to the base plate by screwing in the four 5.5" threaded studs (not shown) and the acrylic wire tubes (also not shown). Once that initial step is complete the core of the assembly can be put together.

The motor, with permanently attached shaft collar, will bolt to the base of the motor plate. Then the flexible coupling will be clamped onto the motor shaft, with the central shaft clamping into the other end of the coupling. The slip ring will slide down the central shaft and the four set screws in the top flange of the slip ring will be tightened onto the shaft. The acrylic cylinder will then slide over the slip ring and sit in a groove on the motor plate. After the acrylic cylinder is in place, the slip ring plate, with permanently pressed-in bearing, will sit on top of the acrylic in a groove cut out of the bottom of the slip ring plate. Four shoulder bolts are used to tighten the slip ring plate down on top of the acrylic. They should be tightened until they stop turning, as the shoulders prevent over tightening onto the acrylic. The central shaft will now be sticking through the bearing and the wheel should fit onto this shaft. A keyless bushing is used to tighten the wheel onto the central shaft.

After these assembly steps are preformed the counter weight and pendulum arm bearing block, with assembled pendulum arm and bearings, can be screwed into the wheel. Routing the wires may prove to be a little tricky. The wires from the slip ring to the pendulum encoder will need to be routed through the central shaft prior to assembly. The wires from the slip ring to the microprocessor can be routed through the acrylic wire tubes before they are screwed into the motor plate. We will have to develop further electrical wiring details once our electronic components arrive.

This assembly is designed to reduce assembly errors by eliminating any steps that require much skill. The person assembling the device just has to slide components until they touch the component below it, and then tighten a fastener; there is no measuring required.

PROJECT PLAN

To successfully complete our project, we had to organize our time into three stages. The first stage, which is a sort of planning phase, is where we will develop solutions and ultimately end up with our design. This phase is taking place from January 12-Feburary 18, 2010. To begin this phase, planning and research have to be done. Our team created a Gantt chart to have a visual timeline. In addition, we created QFDs to organize our engineering specifications that will assist us in developing solutions for this project. In order to better understand the project, we have begun some background research through analyzing the Winter 2009 project's previous work. Also, we visited the Ann Arbor Hands-On museum and met with the exhibit manager, John Bowditch. Additional literature research will be conducted in this stage. Toward the end of this phase, we will develop our engineering drawings and finalize our design.

Stage two of our project plan is a manufacturing process. This phase will take place from February 19 to March 19, 2010. During this stage, we will implement our design solutions into a prototype. Much of this stage will be taking place in the shop, using CAD drawing to manufacture and put together the parts we need. The goal for this stage is to have a completed, working prototype for both the mechatronic and manual systems. However, they will not be exhibit ready at this time.

Lastly, stage three of the project plan, which will take place from Mach 20, to April 15 2010, will consist of polishing and finishing our design and prototype into a museum-ready exhibit. He we will complete the final product, anodize the product, and bring the separate components into one cohesive exhibit. IN addition, it will be during this time that we will have to develop a design manual for the AAHoM, which will consist of engineering drawings, part specifications sheets, assembly instructions and troubleshooting/maintenance instructions. At the end of this stage, the entire product should be ready for the design expo, and to be installed in the museum. See page 54-57 for a detailed project plan.

FUTURE CHALLENGES

Now that the design expo is over and nearly all of the final work is complete, the main future challenge is fine-tuning the NI cRIO microcontroller. At the design expo, the Inverted Pendulum was operated by a Dell desktop computer in conjunction with a USB DAQ. For the Inverted Pendulum on the Ann Arbor Hands-On Museum exhibit floor, the system will be controlled by the NI controller. There are still a few minor issues that need to be finalized before the system is exhibit ready, but these small issues will be fixed within the next week. The only other future work for our team is to hand over an operation and troubleshooting manual – all other work will be done by the museum itself. Several aluminum parts from the inverted pendulum are being sent out by the exhibit manager to be anodized while some of the wood for the exhibit itself is constructed by the museum. After all of these things are completed, the Inverted Pendulum will be on exhibit to the public on the museum floor.

SUMMARY AND CONCLUSIONS

The Ann Arbor Hands-On museum has requested for an exhibit focusing on feedback controls and mechatronic systems to be built. The project sponsors, The Ann Arbor Hands-On museum and Professor Awtar specifically requested for the exhibit to consist of an inverted pendulum system. This system will be made up of an automatic (mechatronic) system and a manual inverted pendulum system. The manual systems will be controlled by patrons of the museum, as they will attempt to balance the pendulum with only their reflexes. The automatic system will sit alongside the manual systems, and will prove to the patrons that given a specific task a computer can react much more quickly than a human can and accomplish the task much more effectively. We have set up a timeline to guide us through the design and manufacturing process and will complete and have the project exhibit-ready by April 15, 2010.

REFERENCES

[1] Arduino Open Source Hardware/Software, accessed 18 February 2010. <http://arduino.cc/>.

APPENDIX A: BIOGRAPHIES OF THE INVERTED PENDULUM TEAM MEMBERS

Alex Barrus

I was born on January 14, 1987 in Sturgis, MI, where I have lived for my entire life. I always loved playing with Legos, Tinker-Toys, Lincoln Logs, and other toys that allowed creative design. As I got older I enjoyed learning about cars and other mechanical device. I have complete four co-op rotations at the Toyota Technical Center in Ann Arbor and Saline. I will graduate in May with a BSE in Mechanical Engineering. Originally I had wanted to get a job in the automotive industry after school, but after seeing the turmoil in the auto industry over the last two years, I'm not sure if that will become a reality.

I have been a student transit coach operator for UM Transportation Services (I drive the blue UM buses) for four years. Interestingly, Max Bajcz, a member of the previous ME 450 group that tried to build this inverted pendulum, is my boss. I am also part of the Solar Car team. I was on the mechanical division for my first couple years, experimenting with carbon fiber layups and working on wheel fairing designs. For the last couple years I have been on the operations division, taking more of a support role in driving the team race trailer to events and doing random jobs for the team as they pop up.

Isabel Czarnocki

I was born June 24, 1988 in Detroit, Michigan. I have lived in Michigan my entire life, and attribute my interest in engineering mainly from the influence of the Detroit area. I am planning of graduating with a degree in Mechanical Engineering in December 2010. After graduating, I am hoping to find a full time job in the engineering industry, and eventually plan on continuing my education for a Masters degree.

I love to travel. I spent a couple months studying abroad in Shanghai, China at SJTU. Alex Barrus, a fellow teammate on this project was on the same trip. Both of my parents are from Poland, and I speak Polish fluently. Most of my family is there and I visit as often as my wallet allows. I am an active person that loves sports such as skiing snowboarding and soccer.

Garrett Gonzalo

The night was cold and wet – not pleasant by any means, but no one could affect it. I was born on that cold night – January 22, 1988 – in Vallejo, California to my parents – Michelle and Dennis Gonzalo. Ironically enough, the night (the day as well) was my father's birthday – I can not help but remind him that I am the best birthday present that he could ever get.

I have always had an affinity for design and engineering. As a child I drew house plans and did math for fun – it was a hobby for me. In high school my interest grew into wanting to pursue a degree in engineering and then in college here at the University of Michigan my want turned into pursuing a BSE in Mechanical Engineering. I have worked at the University of Michigan's Utility and Plant Engineering Department for 2 years and have developed a keen interest in Energy. As of now, I am an intern at Process Results, Inc. – a small engineering consulting firm. After graduation in May I plan to work as Mechanical Engineer in the Energy field.

In my spare time – as rare as it is – I play intramural sports and workout as much as possible. I was a gymnast for 5 years of my life and played soccer and ran track throughout high school. I am passionate about sports and physical fitness and try to stay in the best shape possible with my busy schedule. I also am a busboy at the - one and only - Alpha Phi Sorority on campus.

Daniel Ponstein

Born and raised in Ann Arbor since Oct, 10 1986, and despite strong Ann Arbor 1960 hippy undercurrents I don't think I turned out too far on the left side of every political argument. Ever sense I was little I tinkered with everything. Never being satisfied with how things work, I liked to improve upon what was already there. Growing up, people around me always said that I would be an engineer so much that I believed them. When it came to school I was not the greatest student, with very average grades. I didn't realize what my learning style was until I was in college at WCC. When school became less language oriented and more conceptual and math oriented my grades improved. My grades improved so much that that when I applied to the U of M school of Engineering I was accepted. Since then I have been balancing my out of school projects with my huge U of M work load.

APPENDIX B: DIMENSIONED DRAWINGS

Appendix B.1: Slip Ring Assembly

Fig B.1.1: Slip Ring Plate

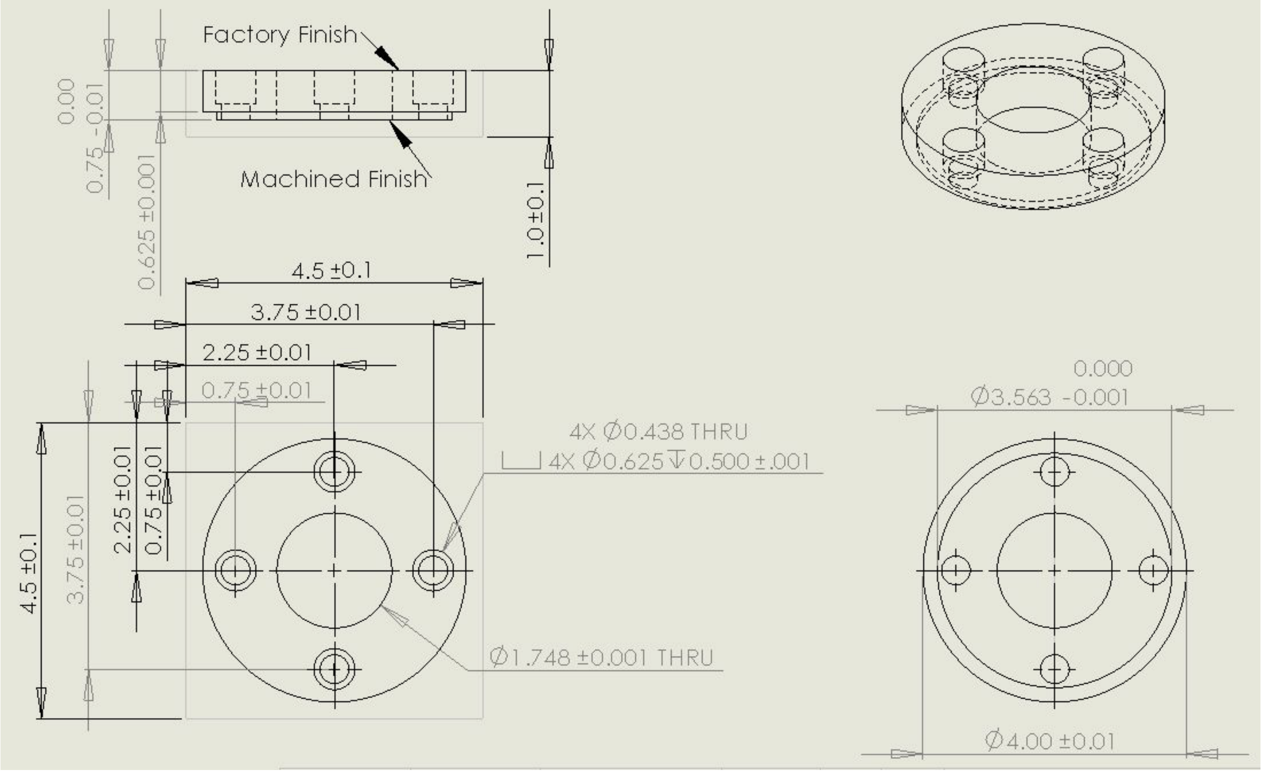


Figure B.1.2: Slip Ring Acrylic Enclosure

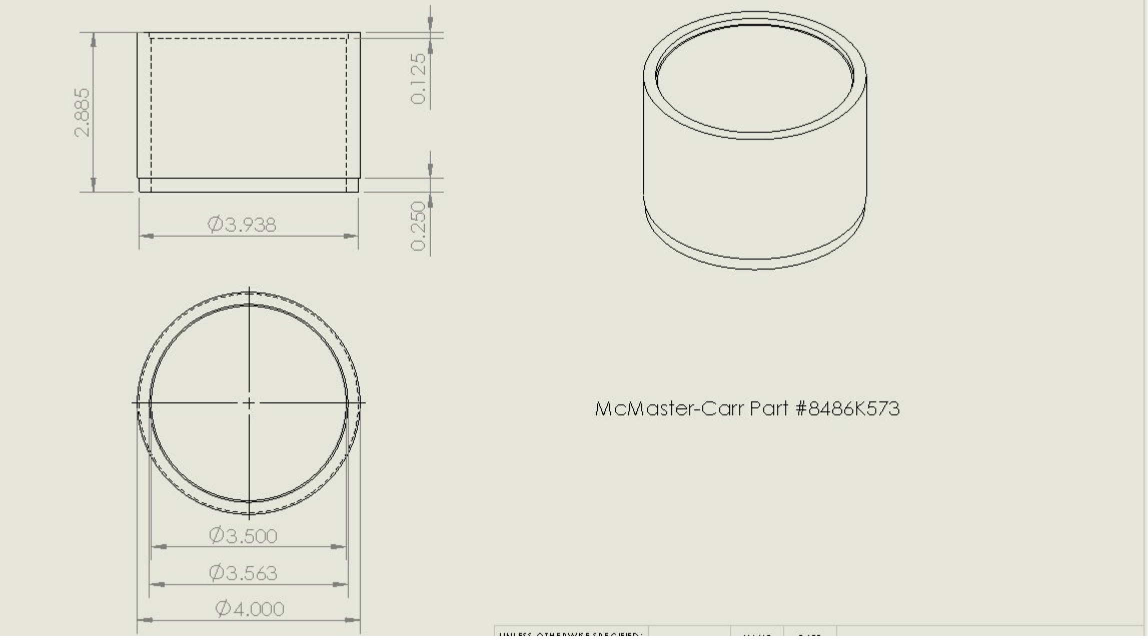
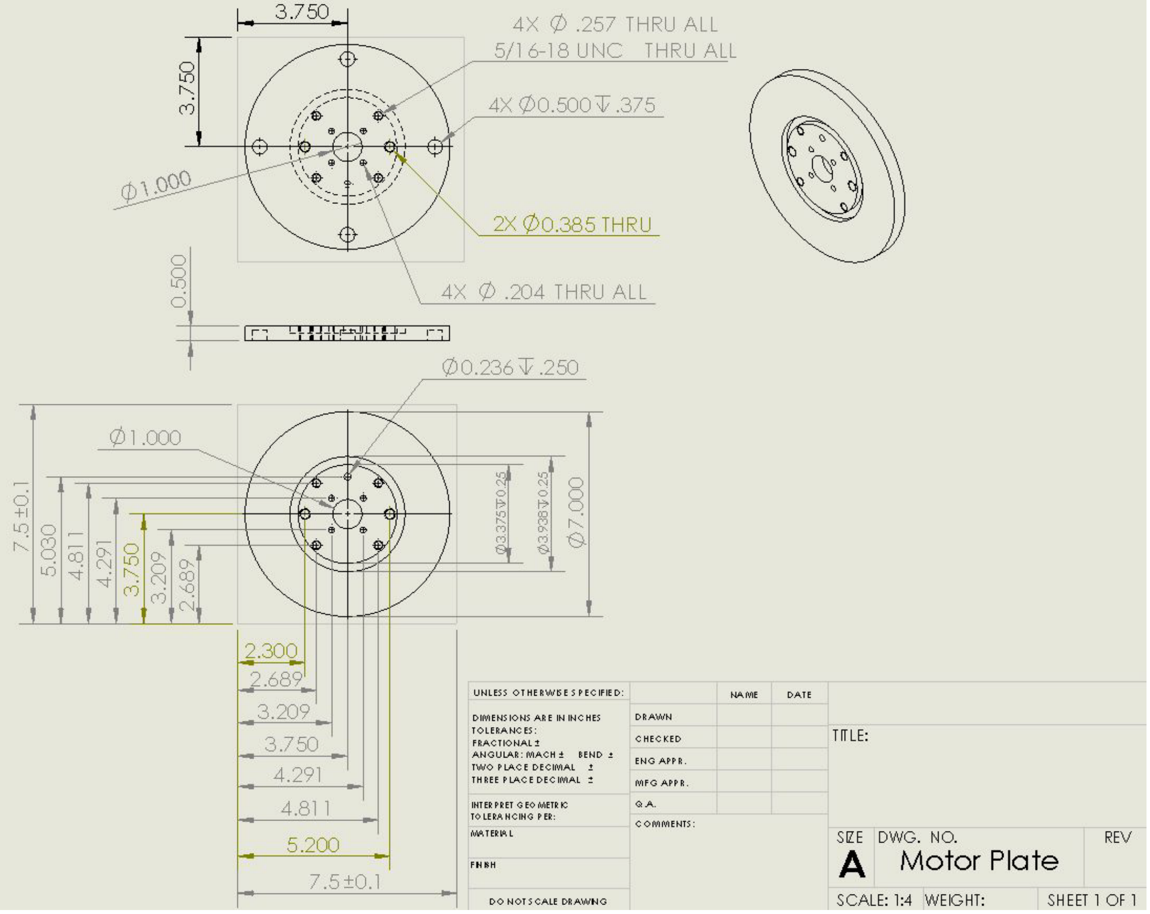


Figure B.1.3: Motor Plate



Appendix B.2: Base Support Assembly

Figure B.2.1: Base Plate

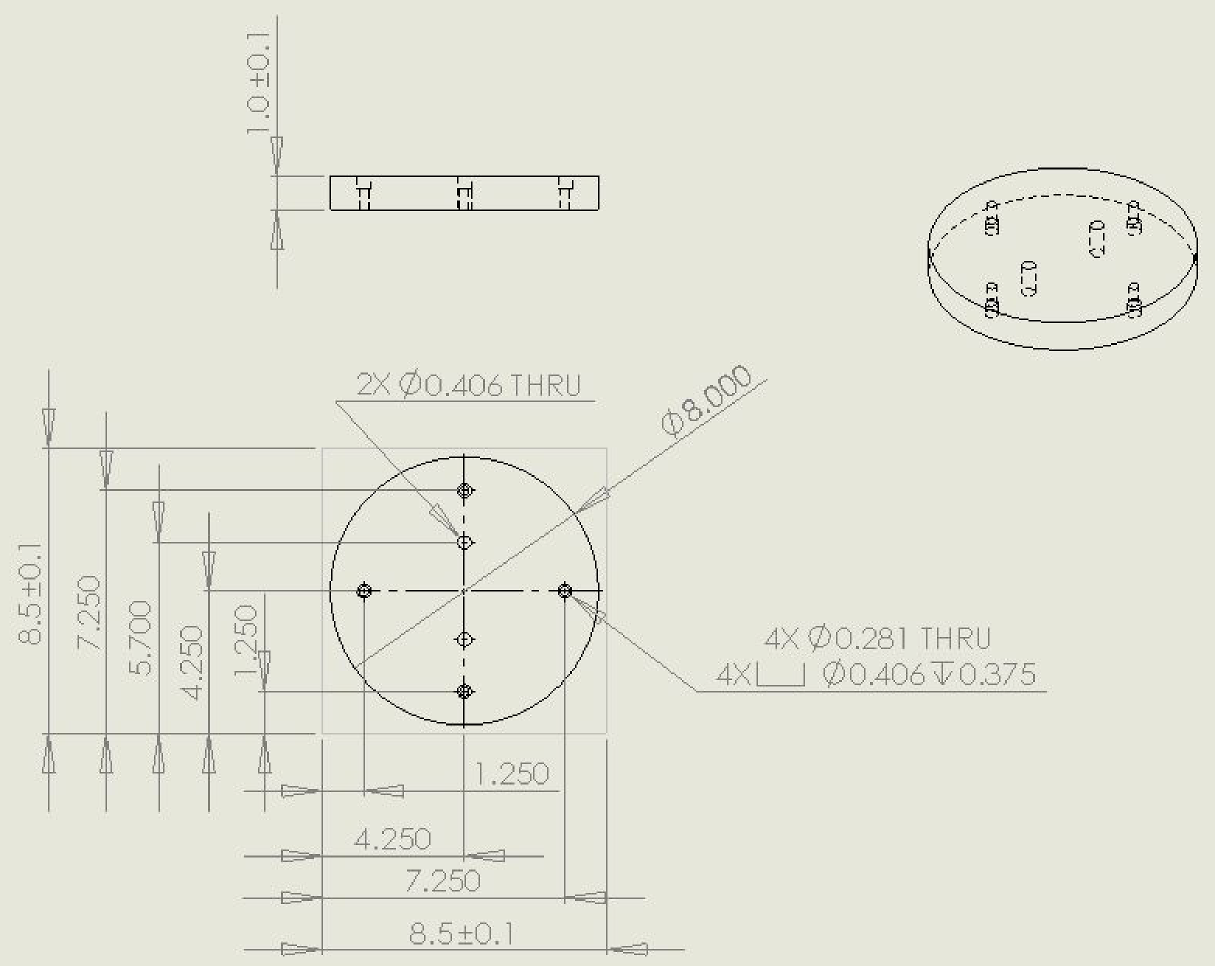
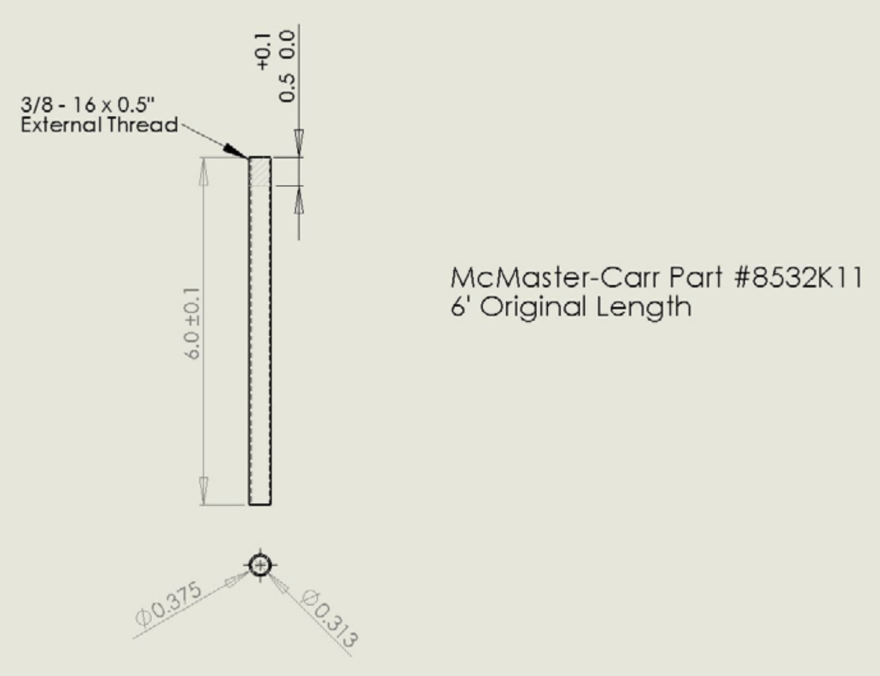
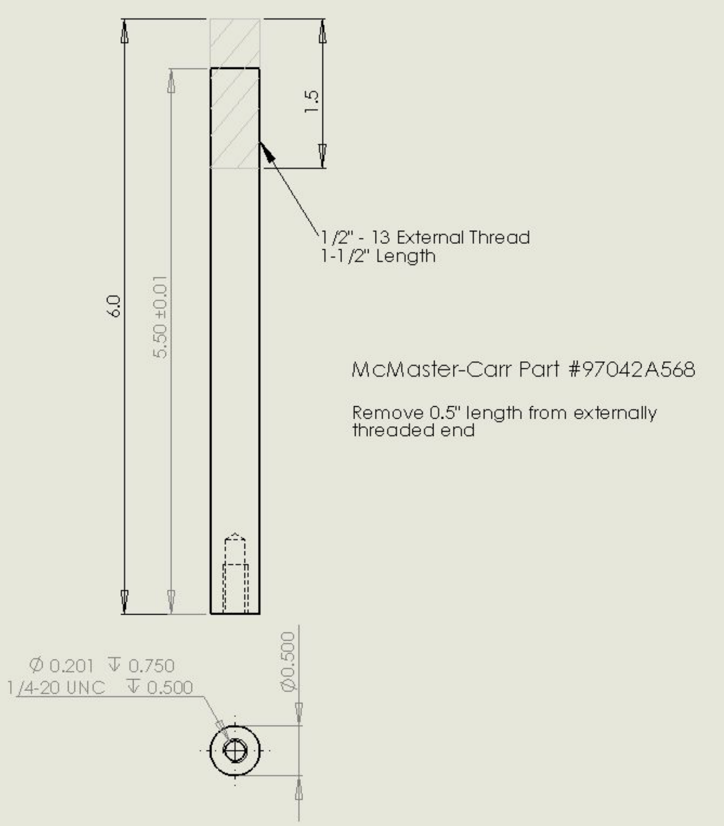


Figure B.2.2: Acrylic Wire Tube



McMaster-Carr Part #8532K11
6' Original Length

Figure B.2.3: Base Support Stud

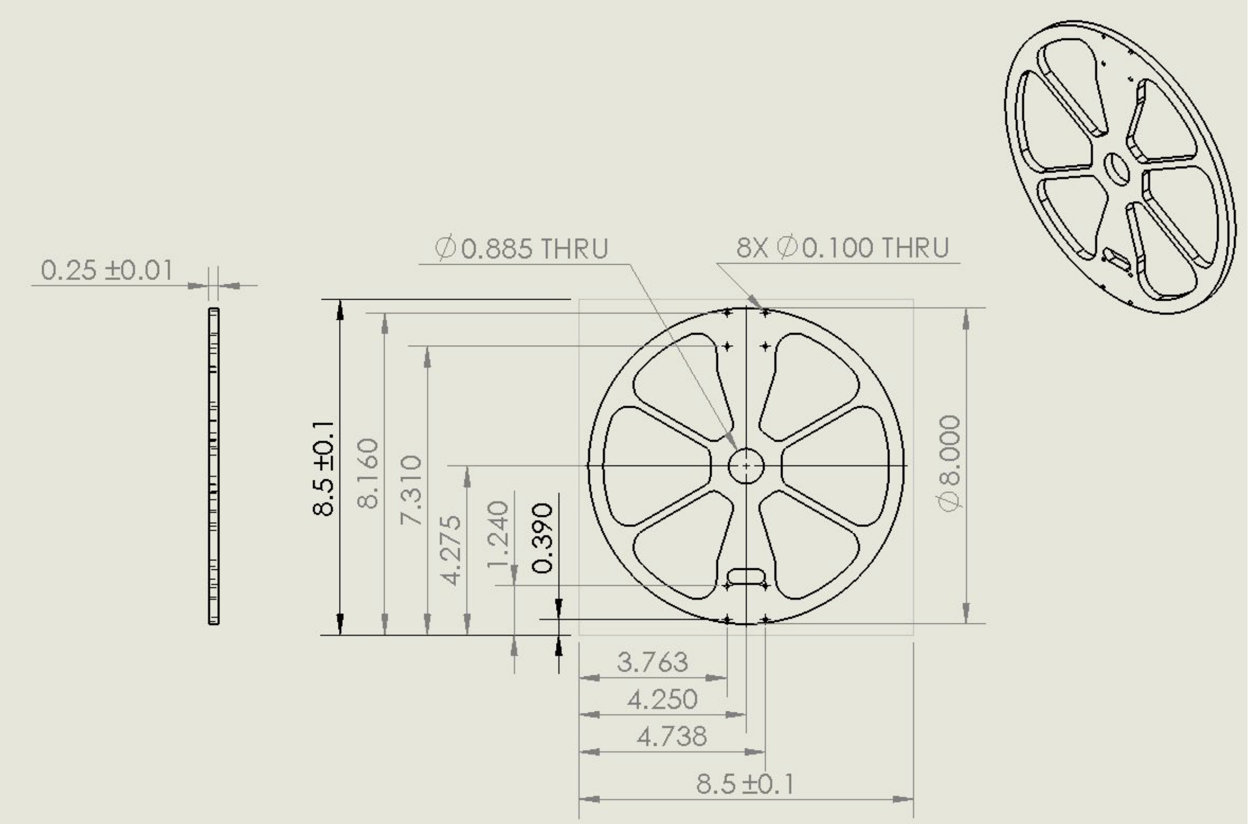


McMaster-Carr Part #97042A568

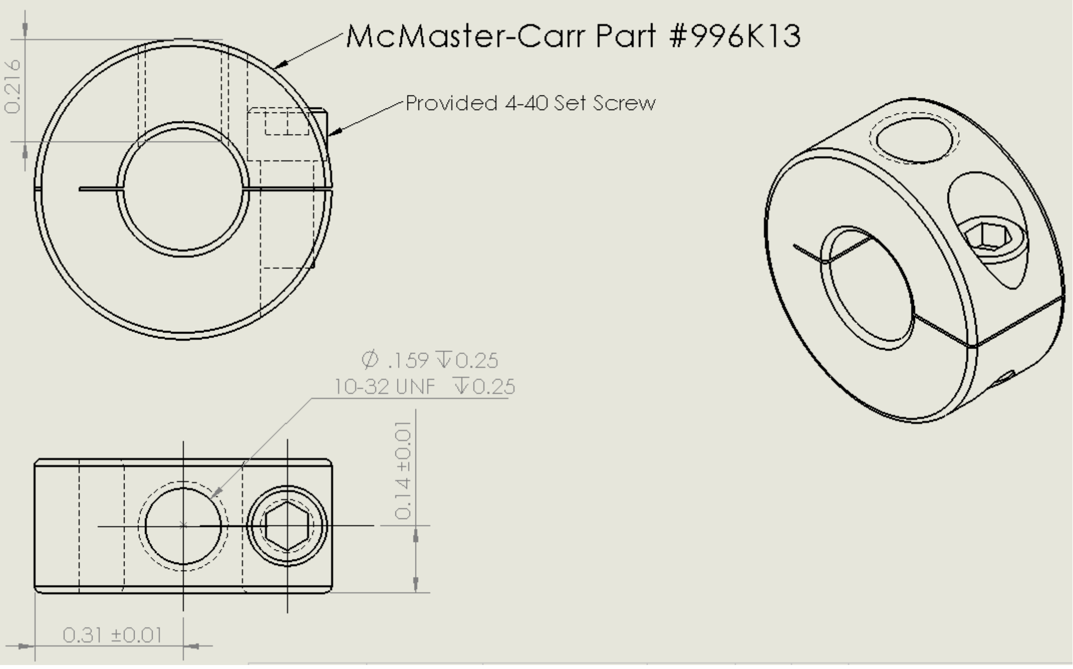
Remove 0.5" length from externally threaded end

Appendix B.3: Pendulum Support Assembly

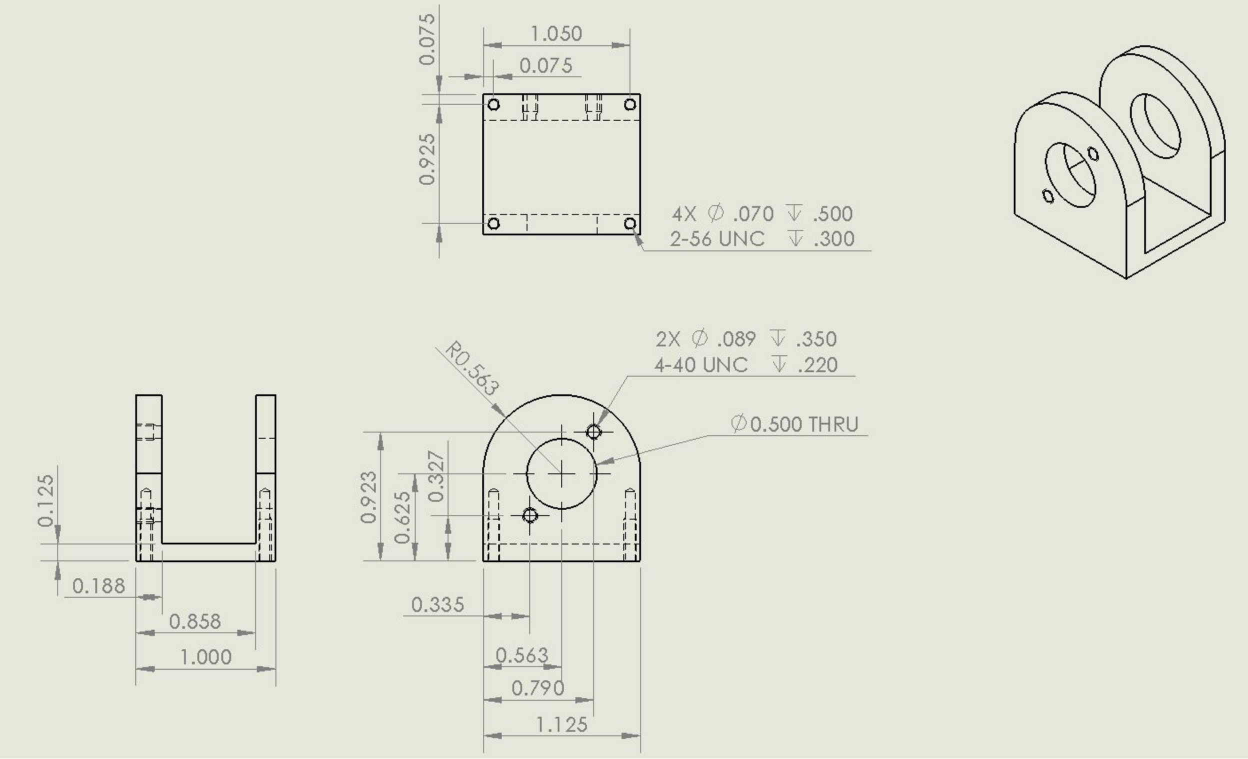
Appendix B.3.1: Pendulum Wheel



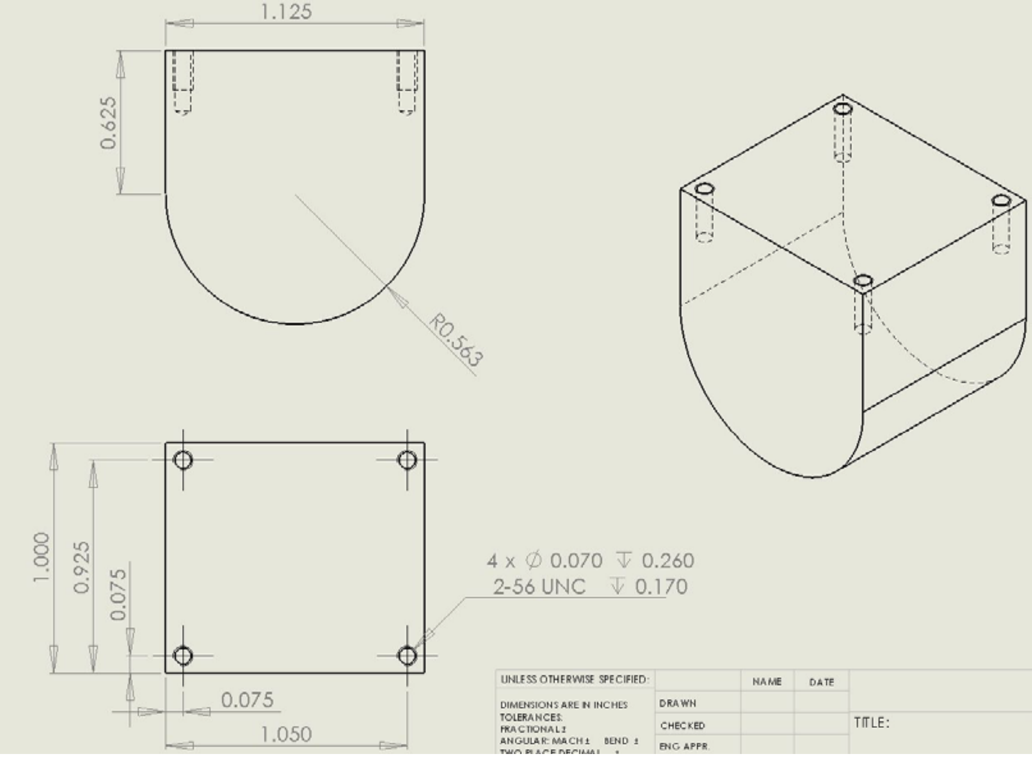
Appendix B. 3.2: Shaft Collar with Hole



Appendix B.3.3: Pendulum Bearing Holder

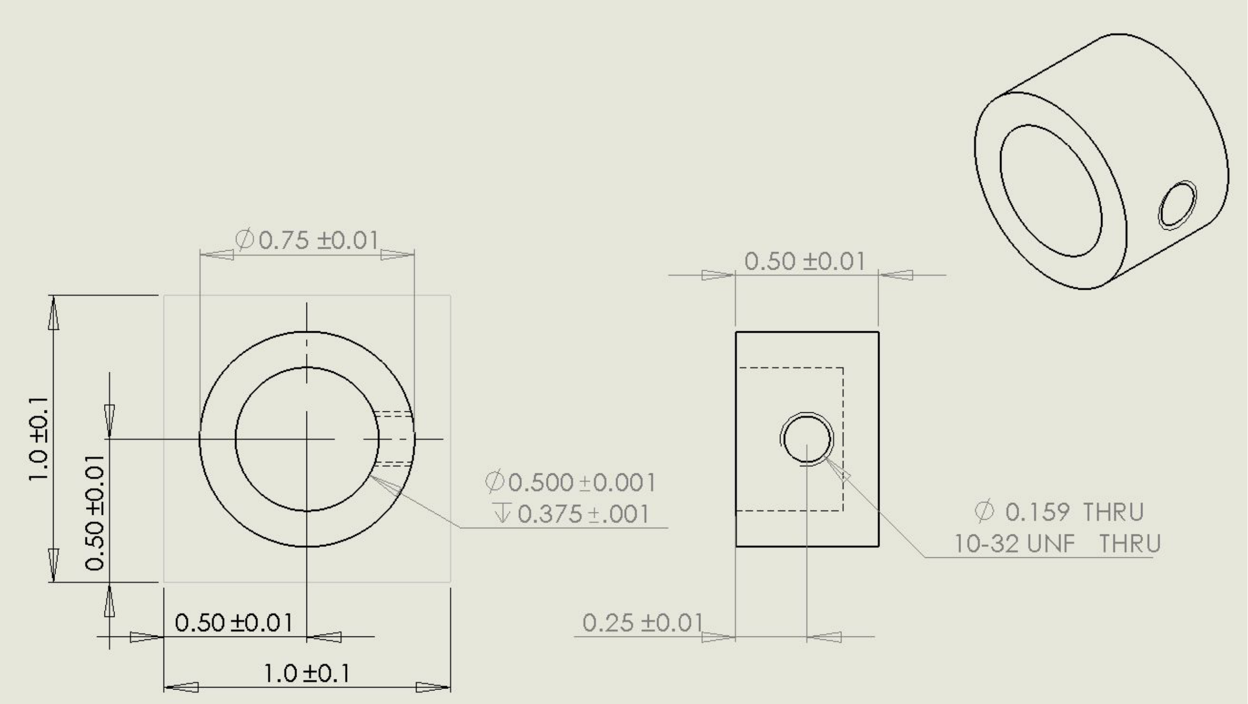


Appendix B.3.4: Counter Weight

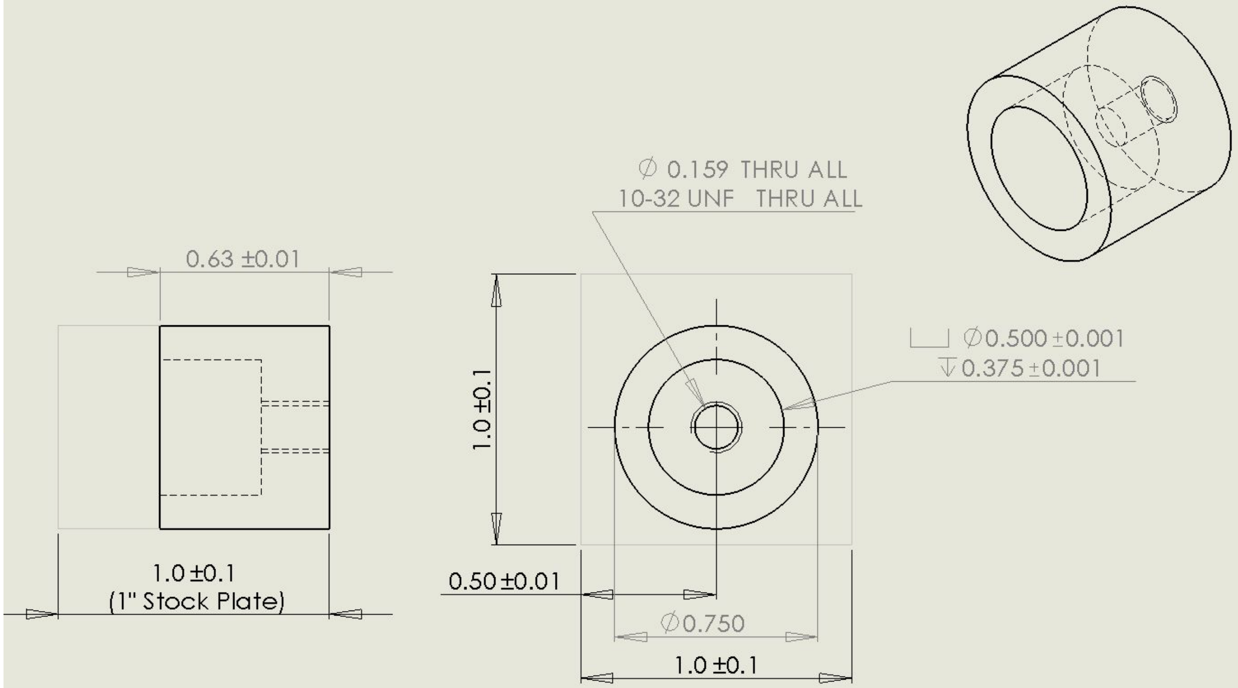


Appendix B.4: Magnet Interaction Assembly

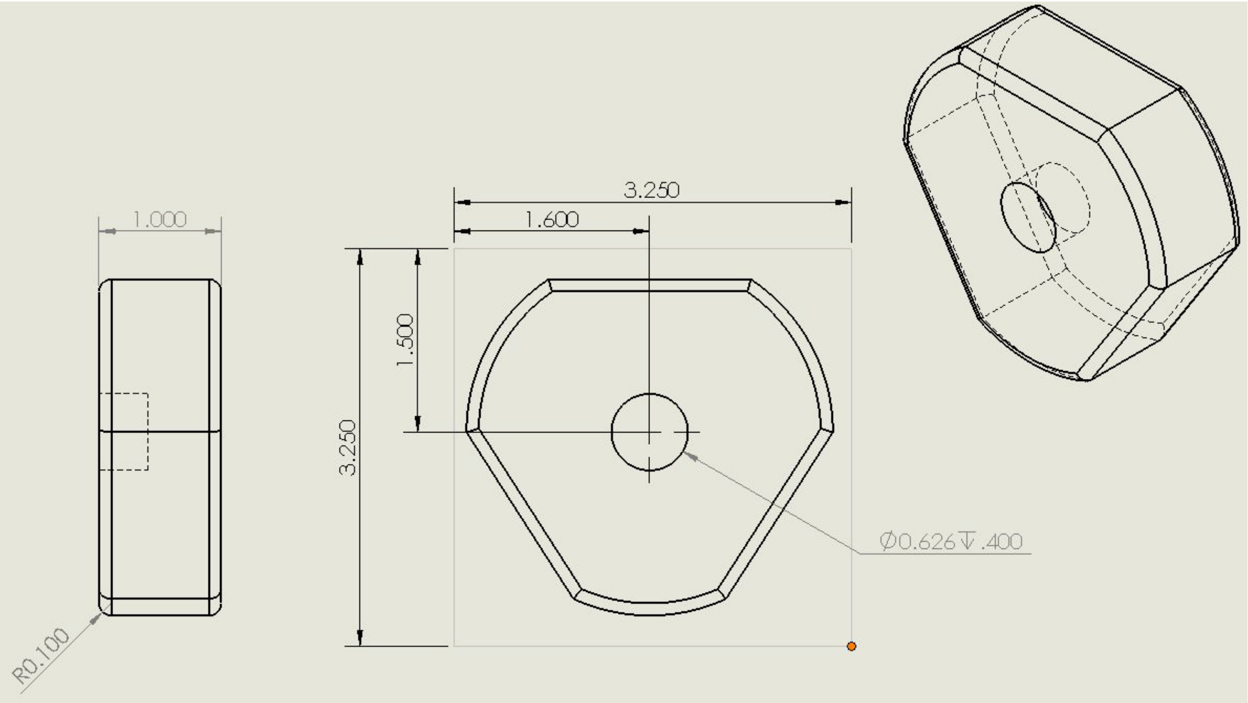
Appendix B.4.1: Pendulum Arm Magnet Holder



Appendix B.4.2: Interaction Arm Magnet Holder



Appendix B.4.3: Magnet Interaction Handle



APPENDIX C

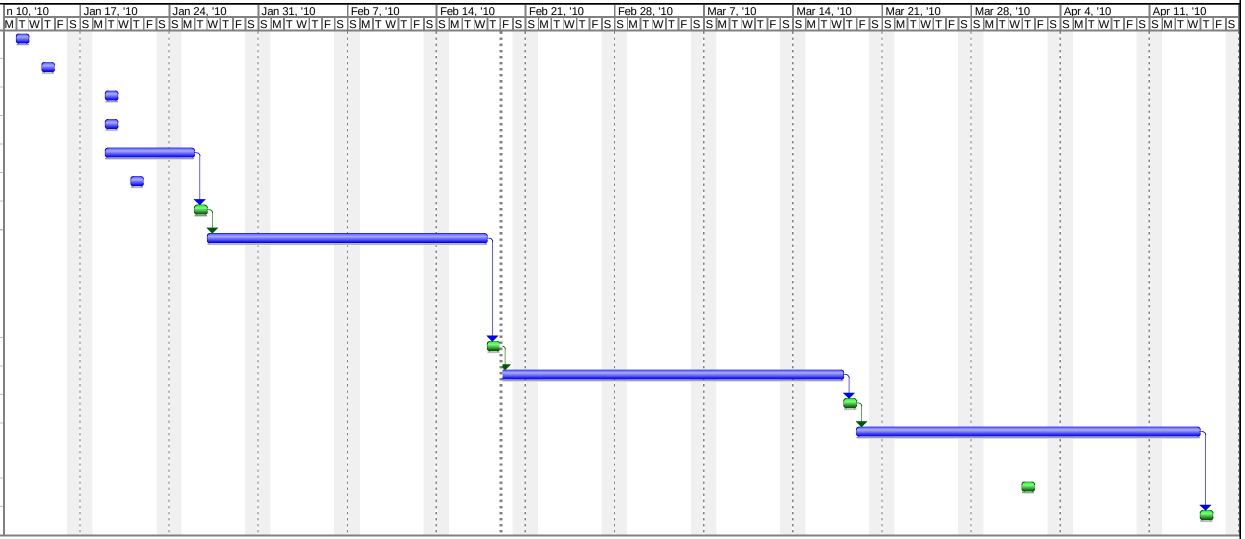
Inverted Pendulum Bill of Materials

Item Description	Manufacturer	Part #	Unit Cost	Units	Total Cost
Shaft collar for 1/4" shaft, 11/16" OD	McMaster-Carr	6435K12	$1.74	6	$10.44
Set Screws (10-32) 3/32" Hex, 1/2" L (per 100)	McMaster-Carr	92311A429	$5.38	1	$5.38
Jin-Pat Slip Ring - 1/2" Through-bore	Jin-Pat	LPT012	$244.00	1	$244.00
Acrylic 4" OD Tube 3.5" ID 12" Length	McMaster-Carr	8486K573	$25.04	1	$25.04
Acrylic 1/16" Wall Thickness 3/8" OD 6' Length	McMaster-Carr	8532K11	$2.04	1	$2.04
Steel Ball Bearing for 1/2" shaft, 3/4" W, 1 3/4" OD	McMaster-Carr	2782T81	$23.01	1	$23.01
Trantorque Keyless Coupling, 1/2" Shaft Dia, Max Torque 350 In/Lbs 1" Length	Amazon or http://www.smallparts.com	6202112 or TTQ-08/14	$25.88	1	$25.88
Trantorque Keyless Coupling, 1/4" Shaft Dia, Max Torque 150 In/Lbs .75" Length	Amazon or http://www.smallparts.com	6202105 or TTQ-04/10	$28.19	1	$28.19
Shoulder Bolts 3/8" D 2 3/4" Shoulder	McMaster-Carr	90298A635	$6.68	4	$26.72
1/2" 6061 Al plate, 12"x12"	McMaster-Carr	89155K44	$60.38	1	$60.38
1" 6061 Al plate, 8"x8"	McMaster-Carr	89155K72	$49.38	1	$49.38
1/4" 6061 Al plate, 8"x8"	McMaster-Carr	89155K22	$17.95	1	$17.95
1" cap screw 1/4"-20	McMaster-Carr	92488A225	$1.30	4	$5.20
Sealed Ball Bearing for 1/4" shaft, 1/2" OD, .547" flange	McMaster-Carr	57155K337	$7.00	2	$14.00
Stainless Steel One-End Threaded Stud 1/2"-13 Thread 6" Length	McMaster-Carr	97042A568	$9.58	4	$38.32
Internally Threaded Rod 6" L, 1/4" OD, 3/4" thread (10-32 thread)	McMaster-Carr	6516K51	$8.11	2	$16.22
1/4" OD 7" Precision Shaft 303 Stainless	McMaster-Carr	1257K116	$4.53	1	$4.53
1/2" OD 12" Length Precision Shaft Plain Carbon Steel	McMaster-Carr	1346K17	$6.90	1	$6.90
Socket Cap Screws	McMaster-Carr	92949A081	$7.68	1	$7.68
Flanged Double Shieled Ball Bearing	McMaster-Carr	57155K324	$5.85	2	$11.70
E8P Optical Encoder US Digital	US Digital	E8P	$37.35	1	$37.35
Motor (Pittman 14203 24V)	Pittmann	14203-24V	$146.12	1	$146.12
Encoder	Pittmann		$100.00	1	$100.00
Microprocessor	NI		$400.00	1	$400.00
		Total			$1,306.43

APPENDIX D: Project Plan

Project Plan Overview: January 12-April 15

ID		Task Name	Duration	Start	Finish	Predecessors
1		Project Assigned	1 day	Tue 1/12/10	Tue 1/12/10	
2		Initial Meeting with Professor Awtar	1 day	Thu 1/14/10	Thu 1/14/10	
3		Meeting with Max Bajcz	1 day	Tue 1/19/10	Tue 1/19/10	
4		Meeting with Professor Awtar: Project Plan	1 day	Tue 1/19/10	Tue 1/19/10	
5		Develop Project Plan, Challenges and Timeline	5 days	Tue 1/19/10	Mon 1/25/10	
6		Visit Museum: Meet John Bowditch	1 day	Thu 1/21/10	Thu 1/21/10	
7		Design Review 1	1 day	Tue 1/26/10	Tue 1/26/10	5
8		Finalize Detailed Project Plan, develop engineering drawings and create list of materials	16 days	Wed 1/27/10	Wed 2/17/10	7
9		Design Review 2	1 day	Thu 2/18/10	Thu 2/18/10	8
10		Build and Assemble Functional Prototype	19 days	Fri 2/19/10	Wed 3/17/10	9
11		Design Review 3	1 day	Thu 3/18/10	Thu 3/18/10	10
12		Refine prototype to create functional, aesthetically pleasing final product	19 days	Fri 3/19/10	Wed 4/14/10	11
13		Design Review 4	1 day	Thu 4/1/10	Thu 4/1/10	
14		Design Expo	1 day	Thu 4/15/10	Thu 4/15/10	12



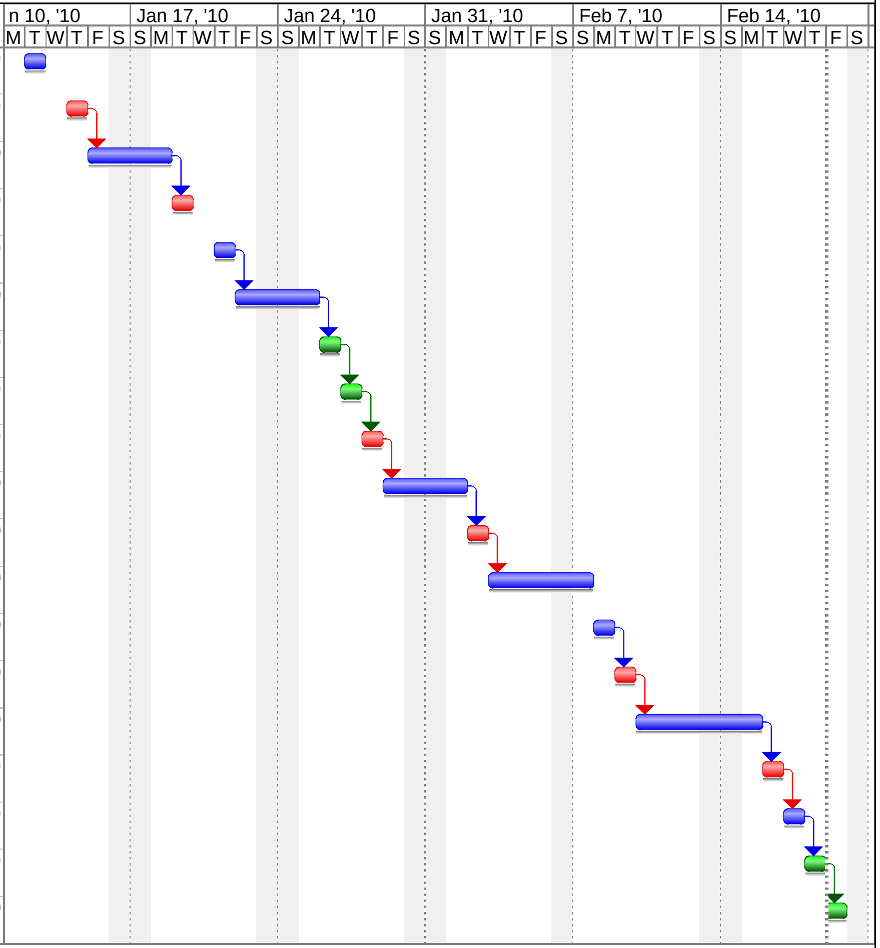
Project: Project Plan Overview v1.0
Date: Fri 2/19/10

Task	▬	Progress	▬	Summary	▬	External Tasks	▬	Deadline	⇩
Split	⋯	Milestone	◆	Project Summary	▬	External Milestone	◆		

APPENDIX D: Project Plan

Stage 1 Project Plan: January 12 - February 18

ID	ℹ	Task Name	Duration	Start	Finish
1	▦	Inverted Pendulum Assigned	1 day	Tue 1/12/10	Tue 1/12/10
2	▦	Meeting with Professor Awtar	1 day	Thu 1/14/10	Thu 1/14/10
3	▦	Back Research of W09 IP Team	2 days	Fri 1/15/10	Mon 1/18/10
4		Meeting with Professor Awtar	1 day	Tue 1/19/10	Tue 1/19/10
5	▦	Visit AAHoM: Meet John Bowditch	1 day	Thu 1/21/10	Thu 1/21/10
6	▦	Prepare for Design Review I	2 days	Fri 1/22/10	Mon 1/25/10
7		Design Review 1	1 day	Tue 1/26/10	Tue 1/26/10
8		Design Review 1 Report Due	1 day	Wed 1/27/10	Wed 1/27/10
9		Meeting with Professor Awtar	1 day	Thu 1/28/10	Thu 1/28/10
10	▦	Concept Generation	2 days	Fri 1/29/10	Mon 2/1/10
11		Meeting with Professor Awtar	1 day	Tue 2/2/10	Tue 2/2/10
12	▦	Choose alpha design: begin drawings	4 days	Wed 2/3/10	Sun 2/7/10
13	▦	Meeting with Russ Pitts	1 day	Mon 2/8/10	Mon 2/8/10
14		Meeting with Professor Awtar	1 day	Tue 2/9/10	Tue 2/9/10
15	▦	Engineering Specifications, Drawings and Materials	4 days	Wed 2/10/10	Mon 2/15/10
16		Meeting with Professor Awtar	1 day	Tue 2/16/10	Tue 2/16/10
17		Prepare for Design Review 2	1 day	Wed 2/17/10	Wed 2/17/10
18		Design Review 2	1 day	Thu 2/18/10	Thu 2/18/10
19		Design Review 2 Report Due	1 day	Fri 2/19/10	Fri 2/19/10



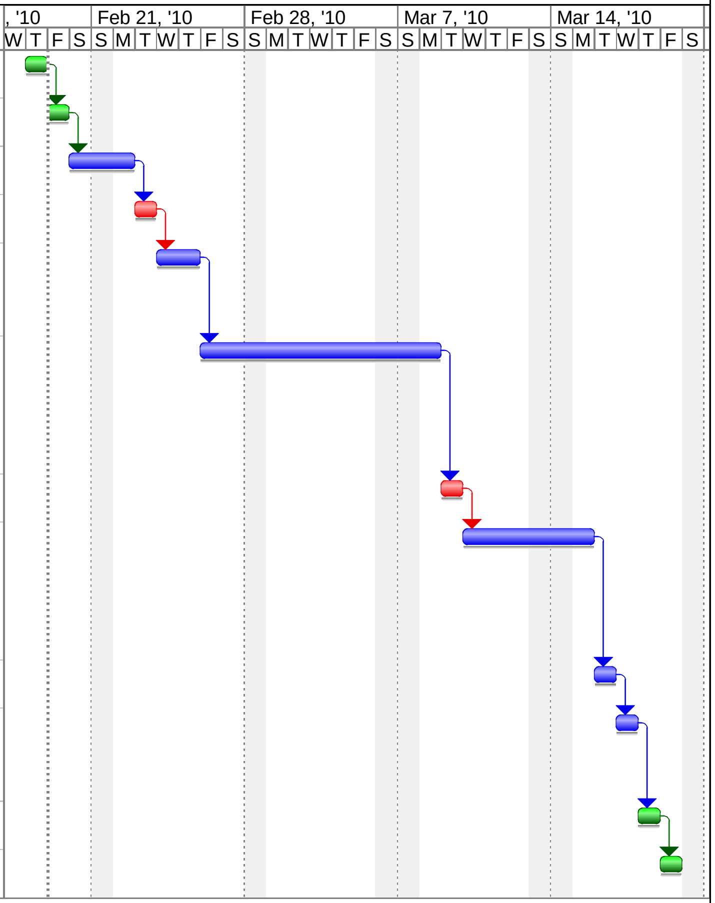
Project: Stage 1 Chart v2.0
Date: Fri 2/19/10

Task
Split
Progress
Milestone ◆
Summary
Project Summary
External Tasks
External Milestone ◆
Deadline ⇩

APPENDIX D: Project Plan

Stage 2 Project Plan: February 18 - March 18

ID	ℹ	Task Name	Duration	Start	Finish	Predecessors
1		Design Review 2 Presentation	1 day	Thu 2/18/10	Thu 2/18/10	
2		Design Review 2 Report Due	1 day	Fri 2/19/10	Fri 2/19/10	1
3	▦	Choose components, Finalize Engineering Drawings	2 days	Sat 2/20/10	Mon 2/22/10	2
4		Meeting with Professor Awtar	1 day	Tue 2/23/10	Tue 2/23/10	3
5		Order materials, complete safety report and process sheets.	2 days	Wed 2/24/10	Thu 2/25/10	4
6	▦	Begin programming of microchip and manufacturing of materials.	8 days	Fri 2/26/10	Mon 3/8/10	5
7		Meeting with Professor Awtar	1 day	Tue 3/9/10	Tue 3/9/10	6
8	▦	Finishing manufacturing of components, Finish programming of microprocessor, Begin assembly of prototype.	4 days	Wed 3/10/10	Mon 3/15/10	7
9		Meeting with Professor Awtar	1 day	Tue 3/16/10	Tue 3/16/10	8
10		Complete Assembly of Prototype, prepare for Design Review 3	1 day	Wed 3/17/10	Wed 3/17/10	9
11		Design Review 3 Presentation	1 day	Thu 3/18/10	Thu 3/18/10	10
12		Design Review 3 Report Due	1 day	Fri 3/19/10	Fri 3/19/10	11



Project: Stage 2 Chart v2.0
Date: Fri 2/19/10

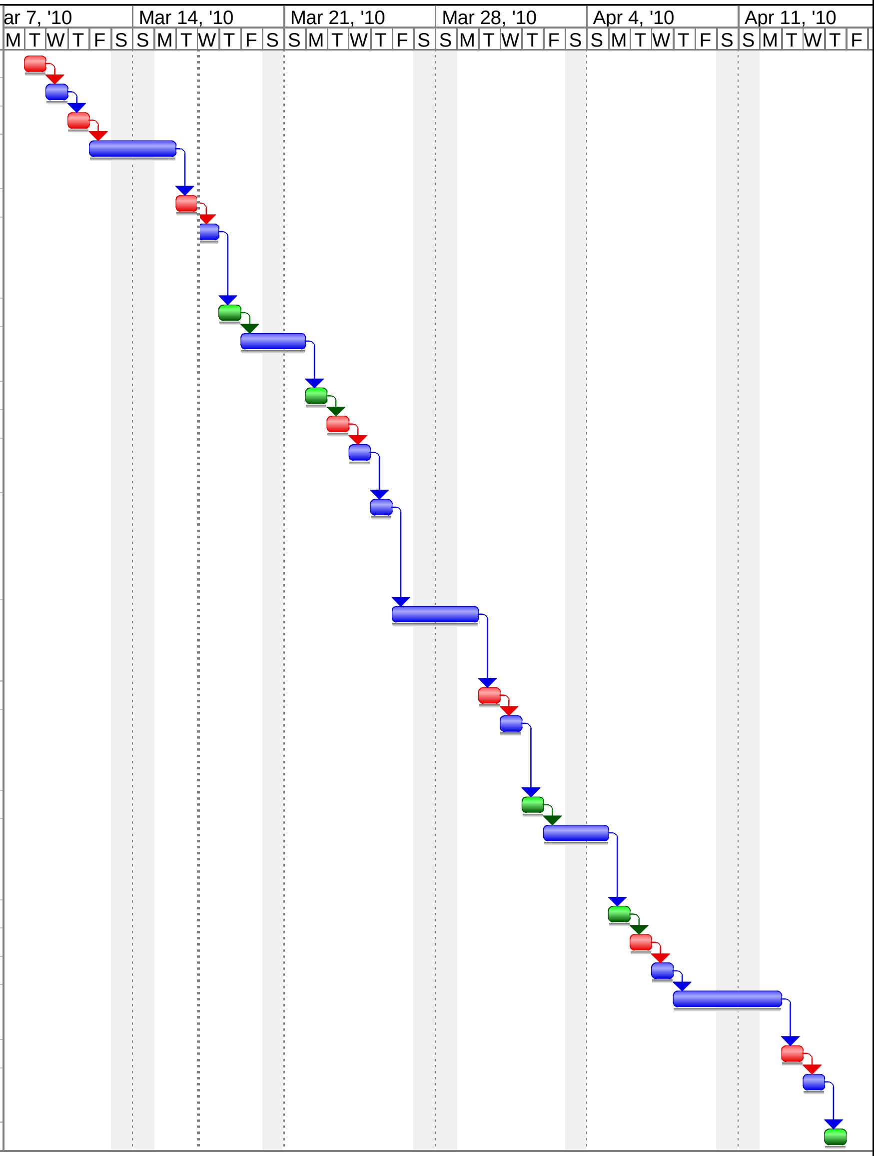
Task	▬	Milestone	◆	External Tasks	▬
Split	┊┊┊┊┊┊	Summary	▬	External Milestone	◇
Progress	▬	Project Summary	▬	Deadline	⇩

Page 1

APPENDIX D: Project Plan

Stage 3 Project Plan

ID	ℹ	Task Name	Duration	Start	Finish
1	▦	Meeting with Professor Awtar	1 day	Tue 3/9/10	Tue 3/9/10
2		Order slip ring, complete motor analysis, tune design	1 day	Wed 3/10/10	Wed 3/10/10
3		Meeting with Professor Awtar	1 day	Thu 3/11/10	Thu 3/11/10
4	▦	Tune design, choose motor, complete engineering drawings	2 days	Fri 3/12/10	Mon 3/15/10
5		Meeting with Professor Awtar	1 day	Tue 3/16/10	Tue 3/16/10
6		Finalize all aspects of design, complete safety report and engineering drawings, prepare for Design Review 3	1 day	Wed 3/17/10	Wed 3/17/10
7		Design Review 3 Presentation	1 day	Thu 3/18/10	Thu 3/18/10
8	▦	Get safety report and engineering drawings approved: begin manufacturing.	2 days	Fri 3/19/10	Sun 3/21/10
9		Design Review 3 Report Due	1 day	Mon 3/22/10	Mon 3/22/10
10		Meeting with Professor Awtar	1 day	Tue 3/23/10	Tue 3/23/10
11		Manufacturing Day 1: Cut stock metal plates, face, and drill and ream holes	1 day	Wed 3/24/10	Wed 3/24/10
12		Manufacturing Day 2: Perform lathe operations on shaft, drill holes in metal studs Programming Day 1: Program NI controller, experiment with setup	1 day	Thu 3/25/10	Thu 3/25/10
13	▦	Manufacturing Day 3-6: Use water-jet to cut out wheel from 1/4" Al plate Programming Day 2: Finish programming microcontroller	2 days	Fri 3/26/10	Mon 3/29/10
14		Meeting with Professor Awtar	1 day	Tue 3/30/10	Tue 3/30/10
15		Manufacturing Day 7: Use water-jet to cut out circle plates from square stock, also prepare for Design Review 4	1 day	Wed 3/31/10	Wed 3/31/10
16		Design Review 4 Presentation	1 day	Thu 4/1/10	Thu 4/1/10
17	▦	Manufacturing Day 8: Drill holes in shaft collars and use mill to trim acrylic sleeve, manufacture pendulum joint	2 days	Fri 4/2/10	Sun 4/4/10
18		Design Review 4 Report Due	1 day	Mon 4/5/10	Mon 4/5/10
19		Meeting with Professor Awtar	1 day	Tue 4/6/10	Tue 4/6/10
20		Final manufacturing and assembly, test setup with microcontr	1 day	Wed 4/7/10	Wed 4/7/10
21	▦	Anodize, polish, clean materials to look professional and finished	3 days	Thu 4/8/10	Mon 4/12/10
22		Meeting with Professor Awtar	1 day	Tue 4/13/10	Tue 4/13/10
23		Prepare for Design Expo, Assemble final product with anodized metals, re-verify controller operation	1 day	Wed 4/14/10	Wed 4/14/10
24		Design Expo	1 day	Thu 4/15/10	Thu 4/15/10



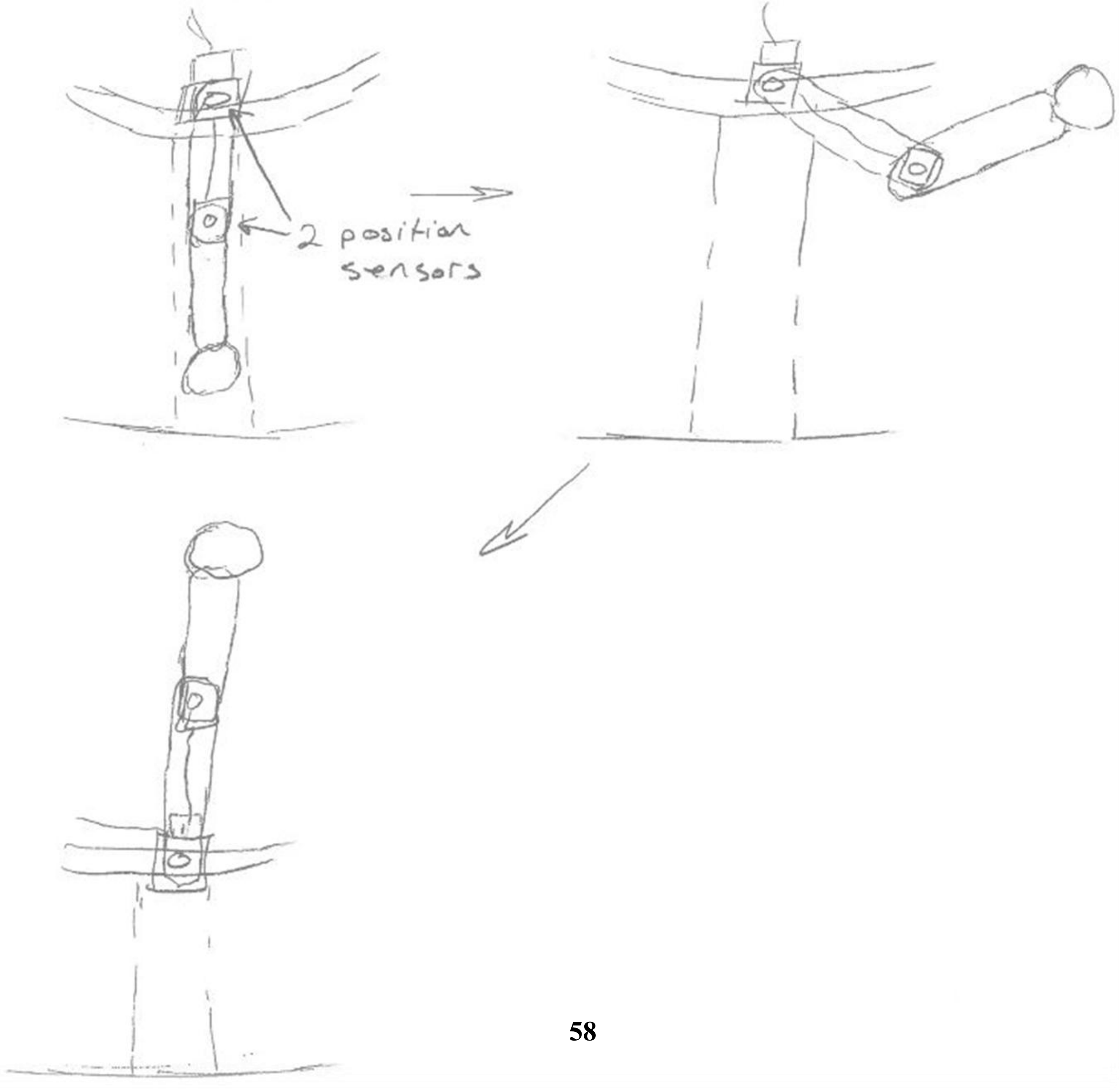
Project: Stage 3 Chart v3.0
Date: Wed 3/17/10

Task	▬	Milestone	◆	External Tasks	▬
Split	┆┆┆┆┆┆┆	Summary	▬	External Milestone	◇
Progress	▬	Project Summary	▬	Deadline	⇩

APPENDIX E: Features and Concepts Sketches

Alex Barrus 1-31-10

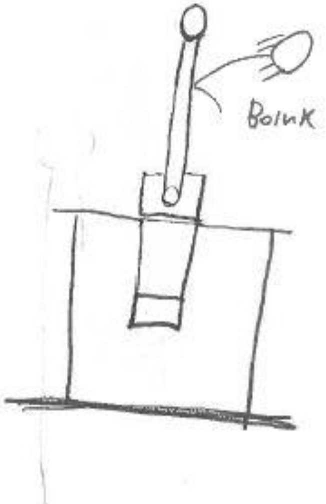
Double Inverted Pendulum

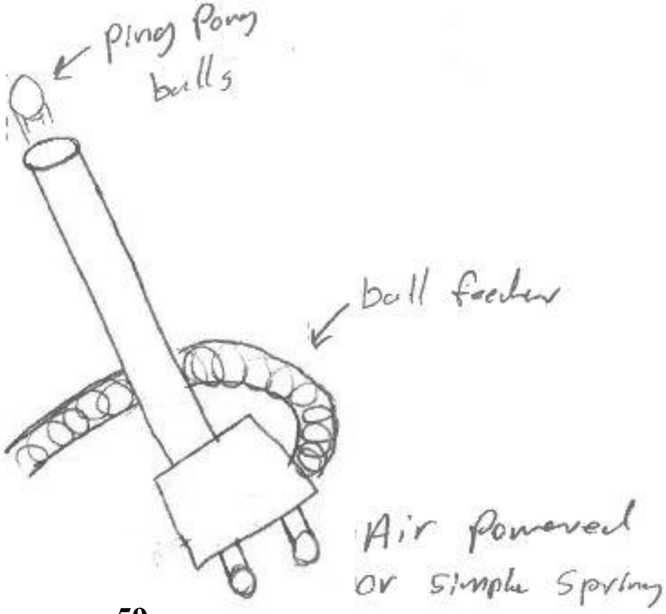


APPENDIX E: Features and Concepts Sketches

Daniel Ponstein
1/31/10

Disturbances: Ball shooter



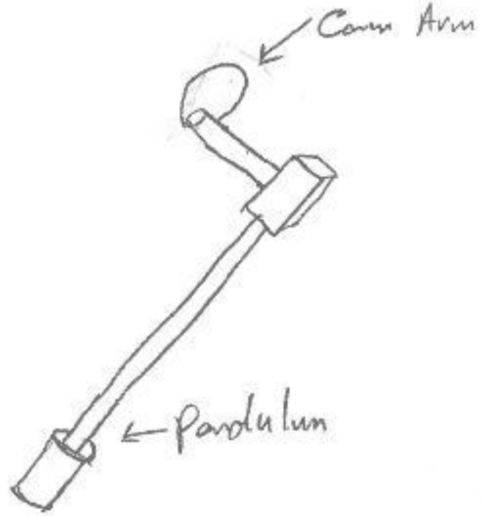


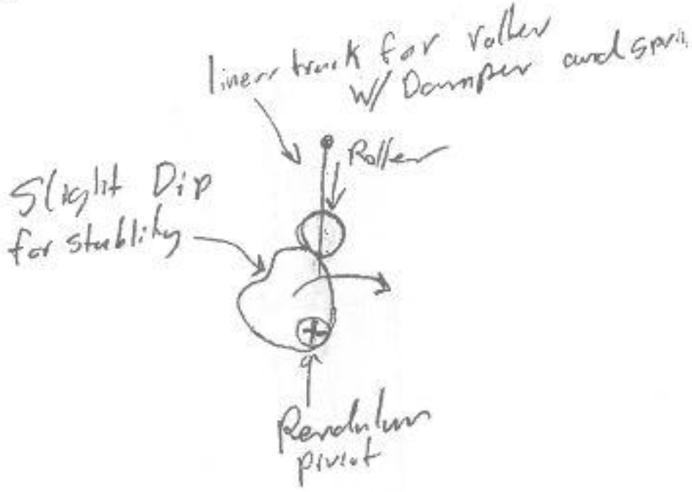
APPENDIX E: Features and Concepts Sketches

Daniel Jordan

1/31/10

Damper / Friction @ Top of Swing

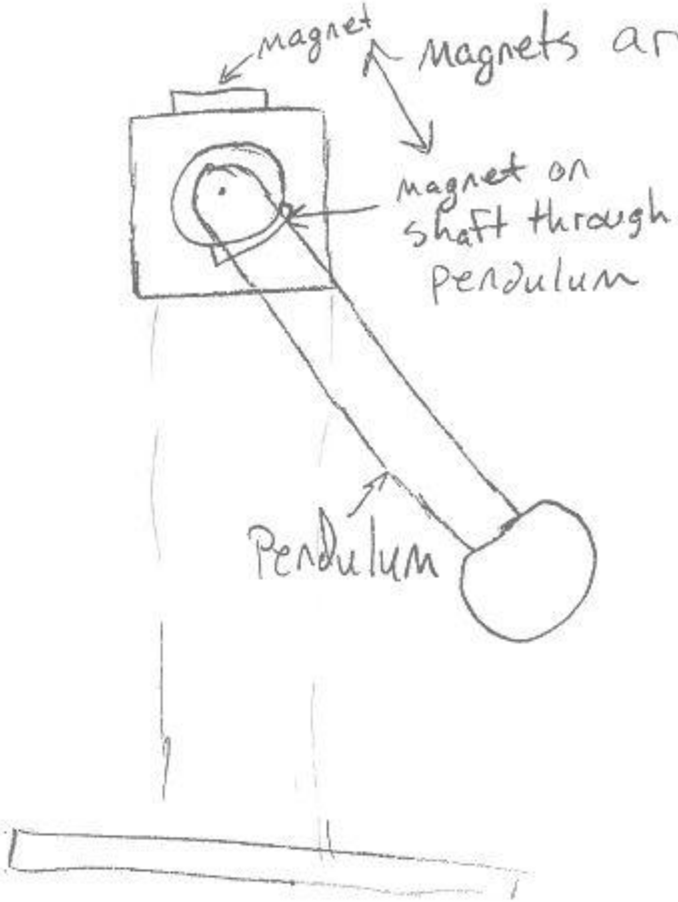




APPENDIX E: Features and Concepts Sketches

Alex Barrus 1/31/10

Magnetic Damping

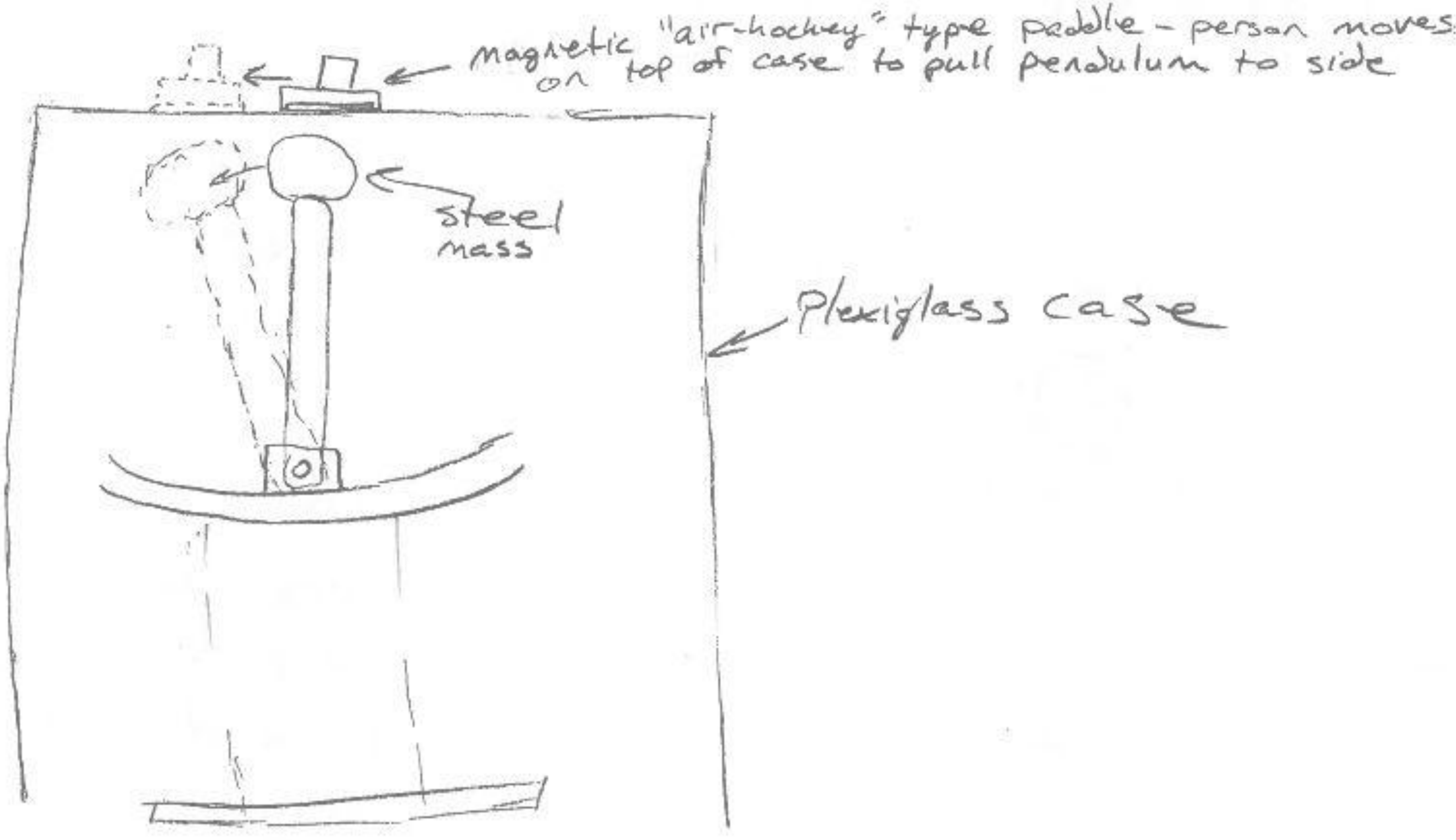


when pendulum nears upright balanced position; magnets attract, slowing pendulum down.

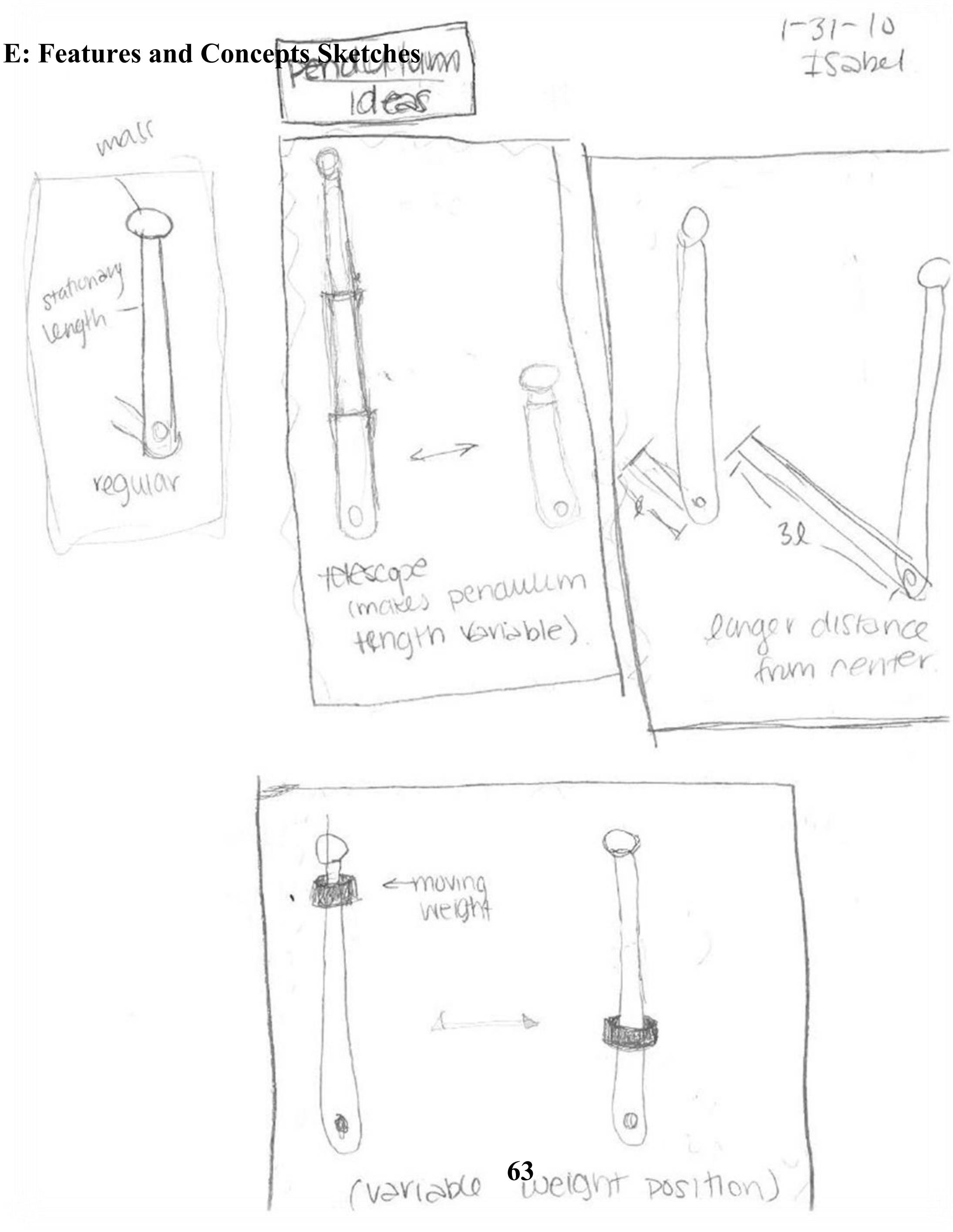
APPENDIX E: Features and Concepts Sketches

Alex Barrus 1-31-10

Magnetic Manual Interaction System



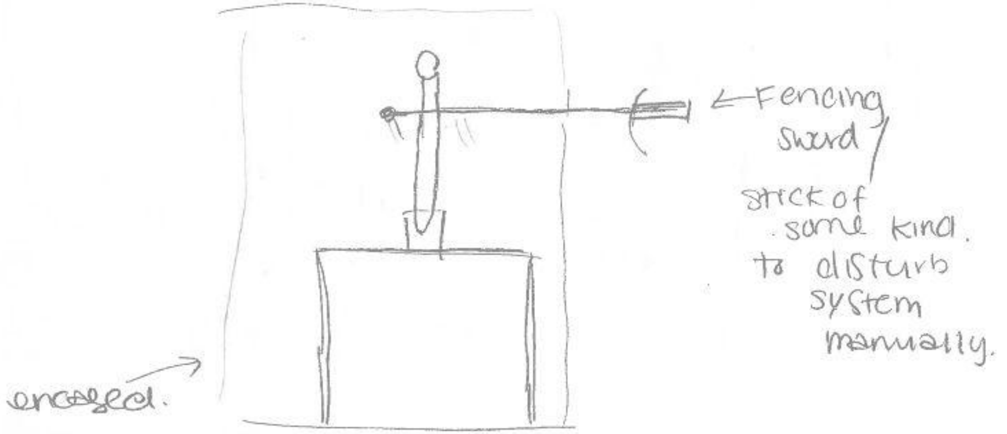
APPENDIX E: Features and Concepts Sketches



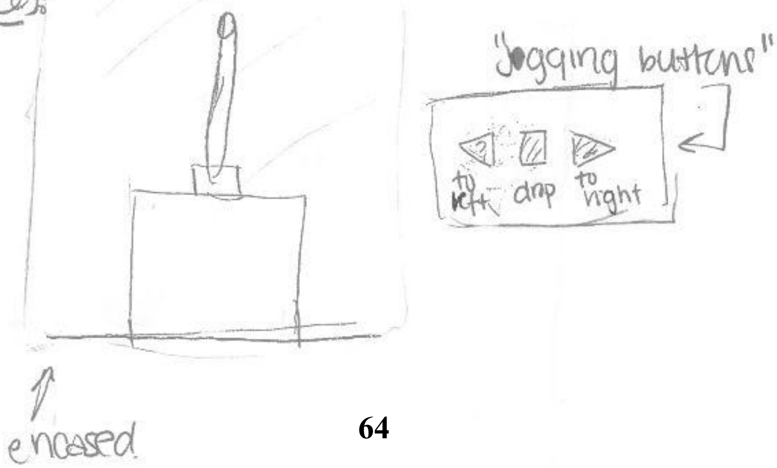
APPENDIX E: Features and Concepts Sketches

1-31-10
Isabel
@ Dude

Disturbances: Manual "Fencing" Idea.



Disturbances:
Electrical



APPENDIX E: Features and Concepts Sketches

physical system

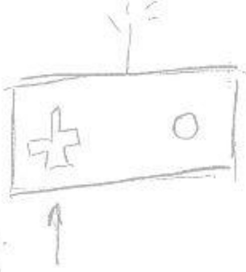
Segway

inspired:
A inverted pendulum

1-31-10

Isabel Czarnock

mechatronic system



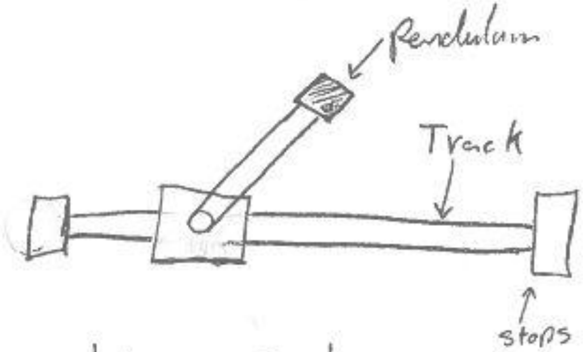
APPENDIX E: Features and Concepts Sketches

Daniel Panstein
1/31/10

physical system

Horizontal System

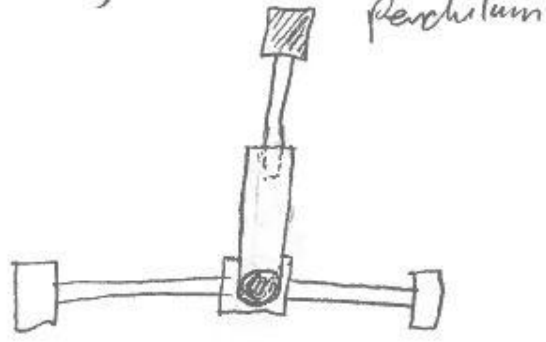
(AS)



Linear Position System

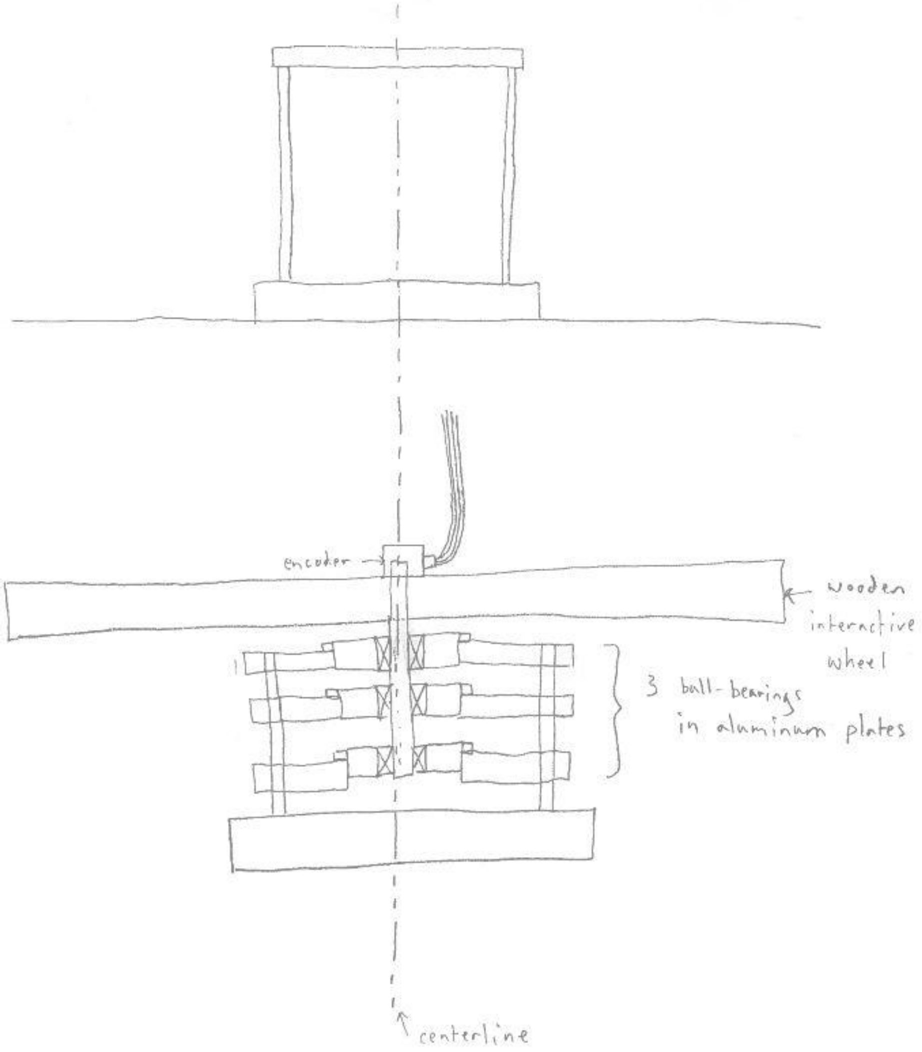
Linear motor
- Screw Drive
- Gear track

(MS)



APPENDIX E: Features and Concepts Sketches

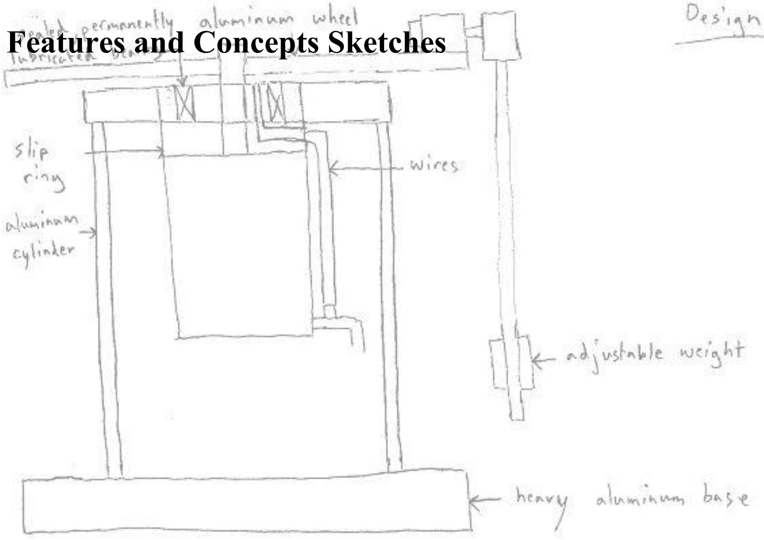
Interactive Idea



ME450 W10 : IP Garrett Gonzalo 1/31/10

APPENDIX E: Features and Concepts Sketches

Design Concept #1



ME450W10 : IP

Garrett Gonzalo 1/31/10

APPENDIX E: Features and Concepts Sketches

Features

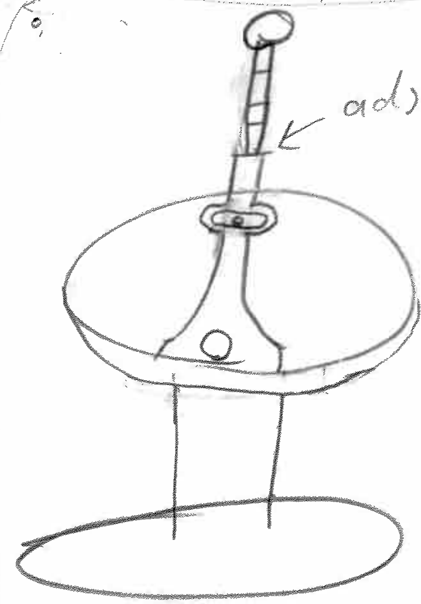
- adjustable length.
- ramp & ball return.
- disturbing automatic design.
- modified big system
- movable mechanical system.

Activities

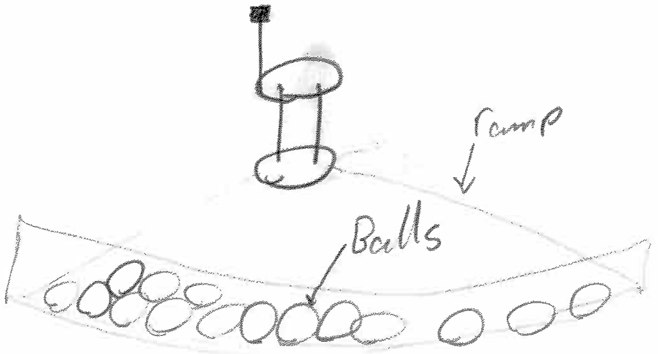
- go up to manual system & understand length of pendulum effects level of difficulty.
- see motor balancing automatic system - with drop button.

Engineering Challenges

- safety of big system.
- adjustable length (telescoping).



mechanical



automatic.

- distrupt system by throwing lightweight balls at pendulum.

APPENDIX E: Features and Concepts Sketches

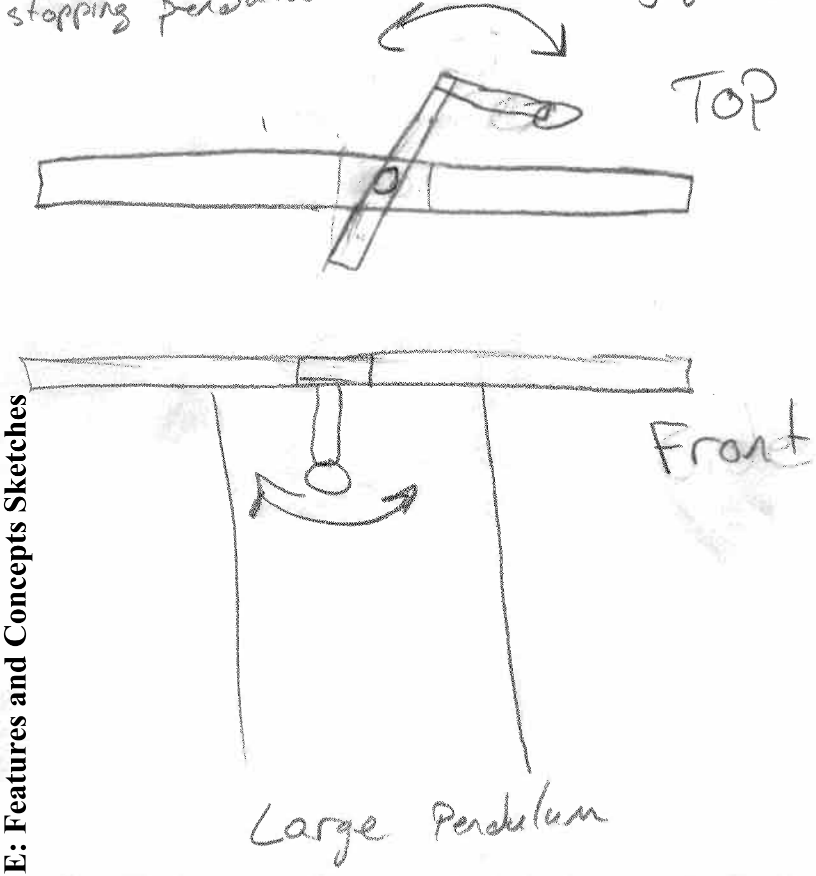
Activities

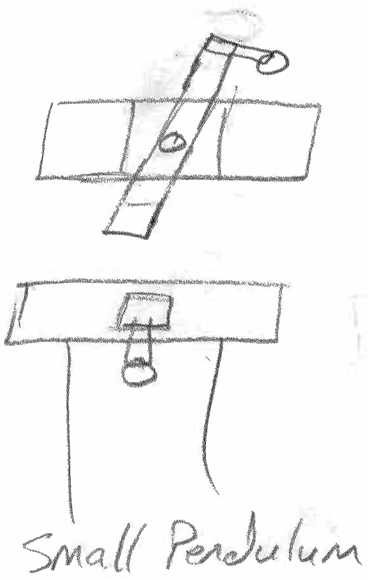
- Pivot large manual system
- Attempt to balance pendulum in vertical position
- See difficulty of swinging up & stopping pendulum

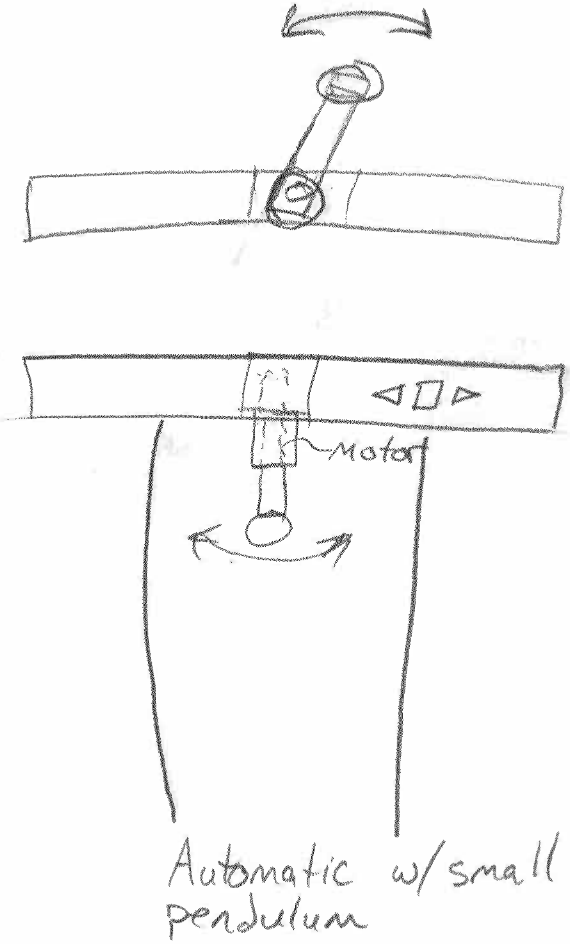
- pivot / balance small manual pendulum
- watch automatic system balance
- can push left/right jog buttons to interact

Features

- Horizontal arm pivots, pendulum has full 360° spinning motion







Engineering Challanges

- Pendulum may hit side wall

APPENDIX E: Features and Concepts Sketches

Past group.

Features

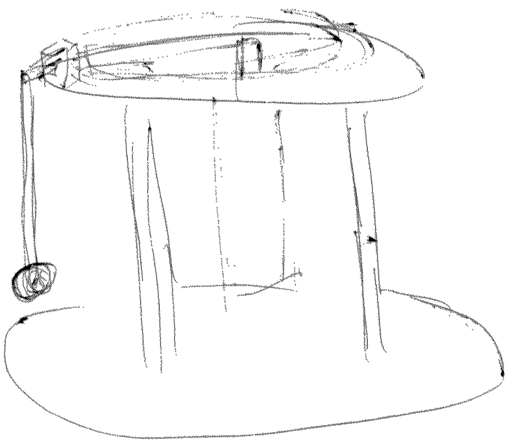
- corralation between manual & automatic.
- small manual - is difficult but not imposs.

Activities

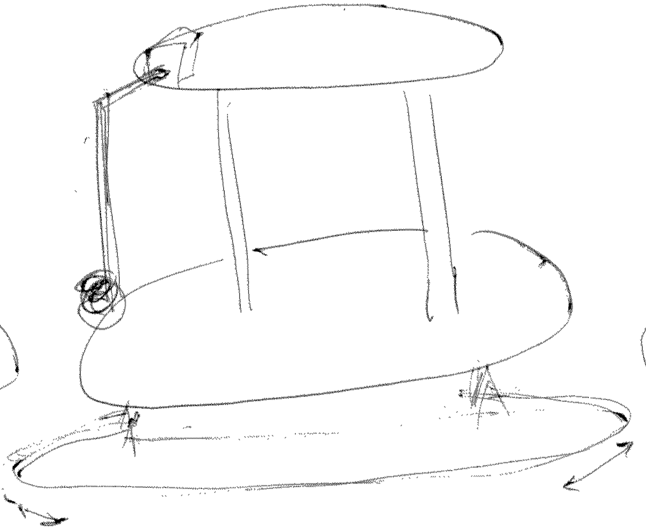
- balance big manual system (without swing up
- try - and with great difficulty - balance small manual system
- see - amazingly - how automatic system easily balances small system.

Engineering challenges

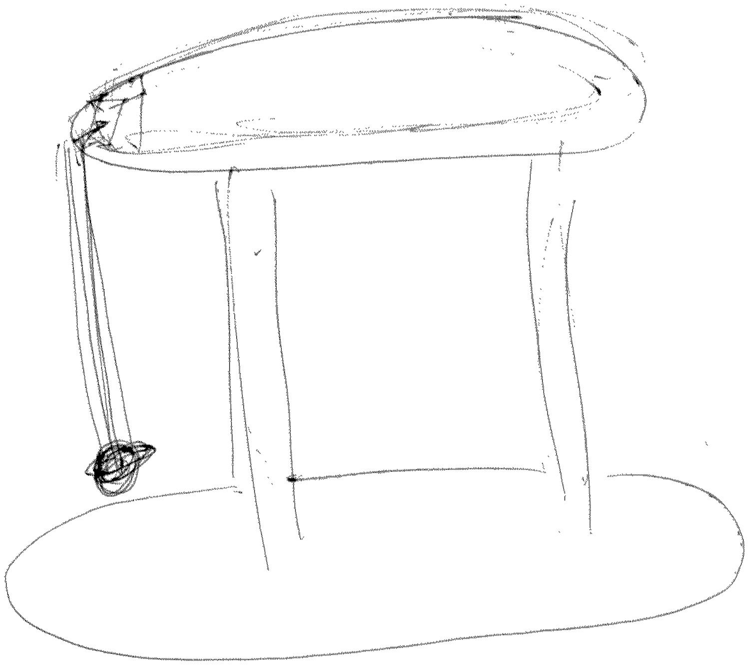
- wiring in the automatic system
- chosing a microprocessor/ controller.
- safety.



automatic

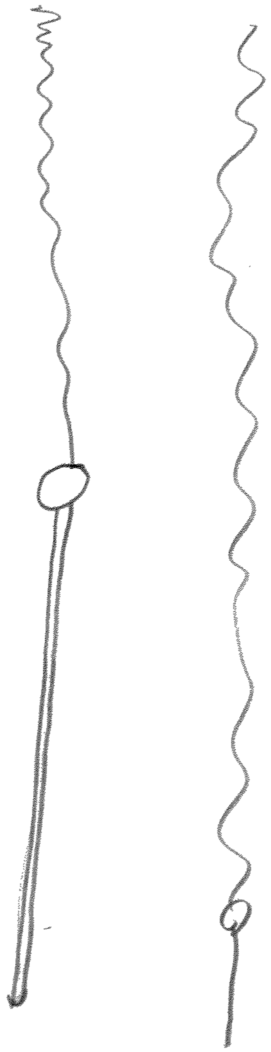


manual



manual. (constrained).

APPENDIX E: Features and Concepts Sketches



Fetures

- Can blance in the upright position.
- shows How inncompitant you are balancing

Actions

Balance an pendulum at your hand

Can't Blance small one

Watch Automatic

APPENDIX E: Features and Concepts Sketches

Features

difference in sizes of manual pendulum.

- can disturb automatic system physically!

Activities

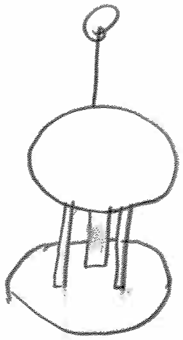
- try to balance - successfully - the large manual system
- try to balance - with difficulty small pendulum.
- see automatic system balance disturb with noodle.

Engineering Challenges

- safety of pendulums - ristrict so they cant hit anyone.
- ristrict amount of disturbance to automatic system, so that it doesn't have to re-zero all the time.

1

2



3

APPENDIX F: Design Analysis Assignment

F.1: Material Selection

Component 1: Support Post

1. Function: support top of pendulum

   Objective: minimize weight

   Constraints: hold 2.5 lbs per post (~23 psi), cheap

2. Material index: $M = \frac{\sigma_f}{\rho}$

3. From strongest to weakest: Stainless Steel, Zinc-Aluminum Alloy, Aluminum (6061), Aromatic Polyamide (plastic), Cardboard

4. Winner: **Aluminum (6061), $0.713 - $0.785 /lb, Vickers Hardness: 1.47e5 – 1.59e5 psi**
   Easy to machine and sand by hand, local availability

   Losers:
   Cardboard: Flammable
   Aromatic Polyamide: Too expensive ($2.47 - $3.60 /lb)
   Zinc-Aluminum Alloy: Similar specs to 6061 Al, but limited local availability
   Stainless Steel: Too hard (Vickers Hardness: 2.73e5 – 3.27e5)

Component 2: Acrylic

1. Function: support motor plate and pendulum

   Objective: maximize visibility

   Constraints: hold 5 lbs ~ 1.7 psi

2. Material index: $M = \frac{Transparency}{\sigma_f}$

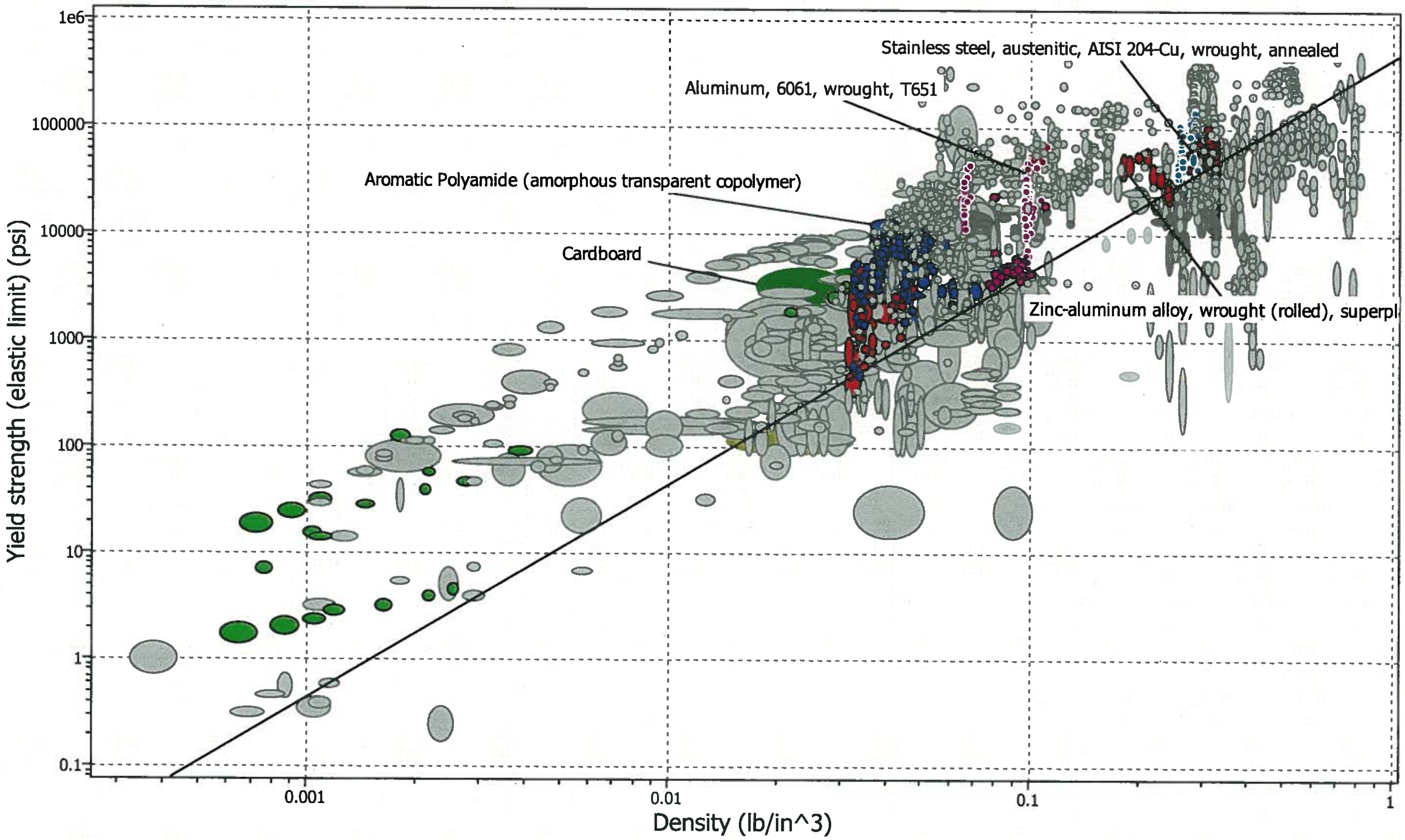
3. From clearest to more opaque: PMP, PMMA, Potash Soda Lead Glass, Sapphire, Diamond

4. Winner: **PMMA (Acrylic), $1.17 - $1.29 /lb, Vickers Hardness: 2.29e4 – 3.11e4 psi**
   Clear, hard (scratch resistant), available on McMaster-Carr

   Losers:
   PMP: Too expensive and soft ($4.57 - $5.59 /lb, Vickers Hardness: 6.54e3 – 9.96e3)
   Potash soda lead glass: Dangerous (broken glass), lack of availability
   Sapphire (single crystal): Too expensive ($3.1e4 – $3.3e4 /lb), lack of availability
   Diamond: Too expensive ($1.4e5 - $2.8e5 /lb), lack of availability

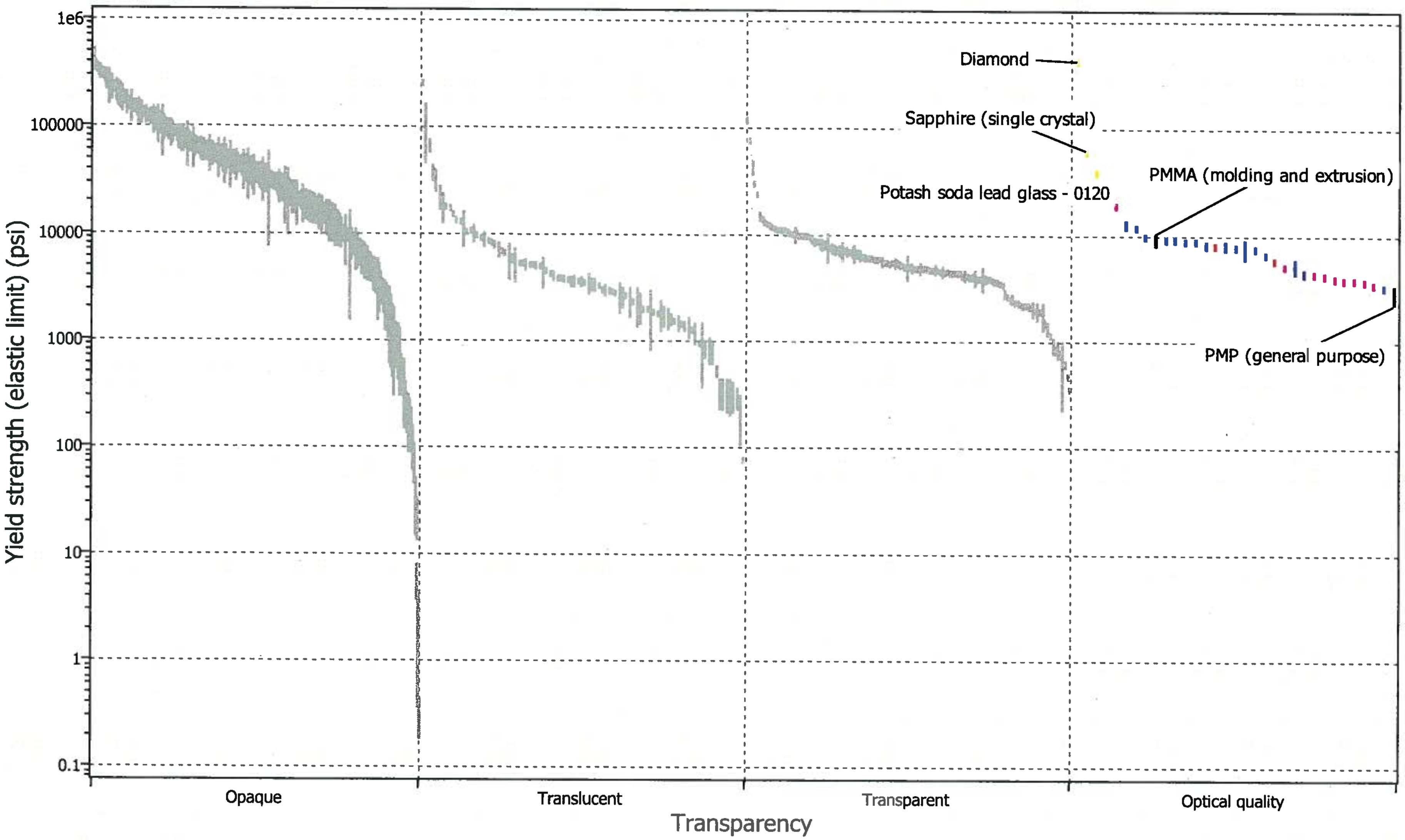
Support Post

Stage 1



Slip Ring Cylinder

Stage 1



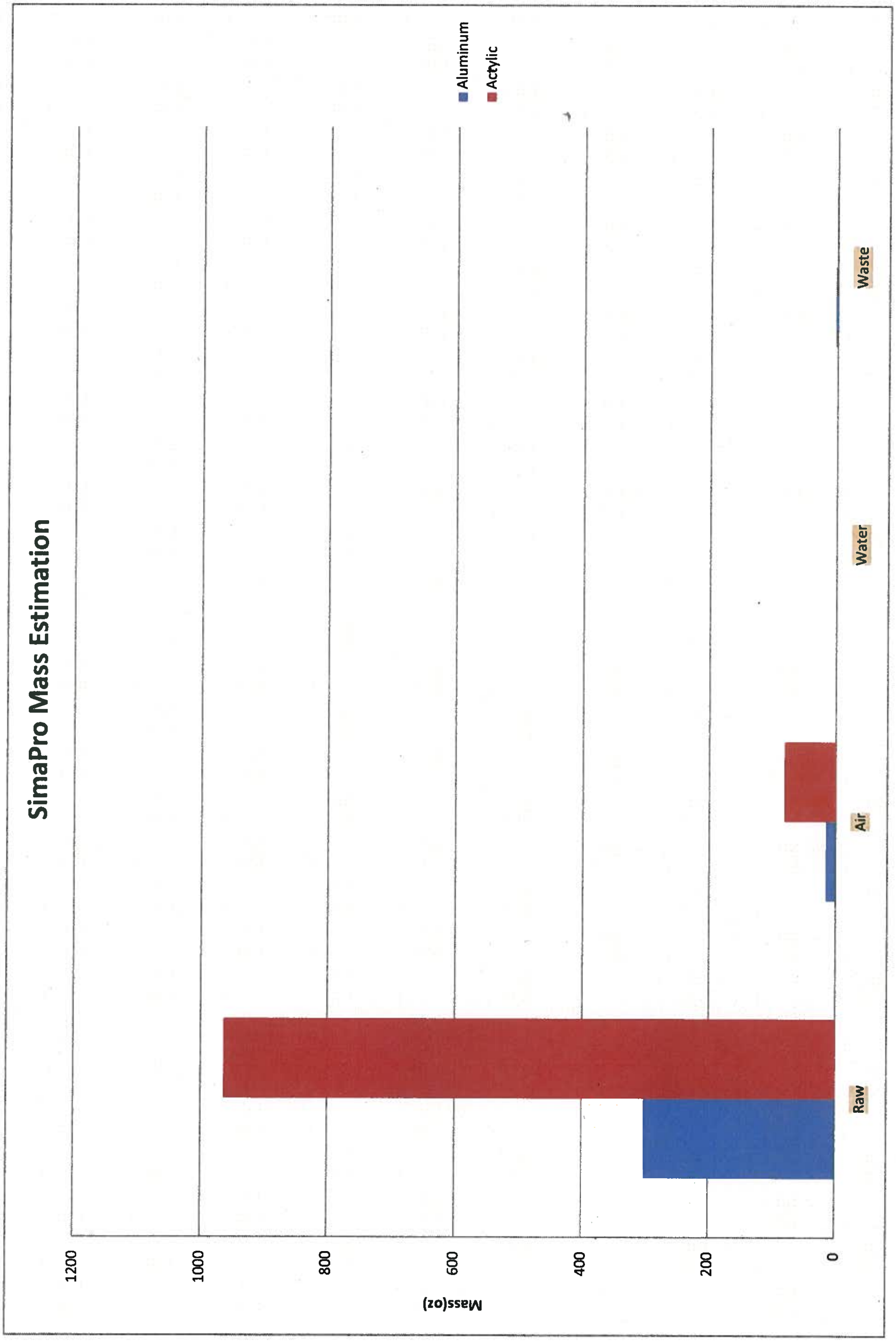
No warranty is given for the accuracy of this data. Values marked * are estimates.

F.2: Environmental Performance

We compared the environmental performance of our aluminum posts (6061) and acrylic cylinder (PMMA). Without any analysis we assumed that the aluminum would be more harmful to the environment. Aluminum uses a large amount of electricity during smelting, which we assumed would be more detrimental to the environment than production of the acrylic part.

To our surprise the acrylic was more damaging than the aluminum on almost every count. We assume this happened because nine times more acrylic is used than aluminum for these two parts. Acrylic is produced from petroleum, which has a large environmental impact. This product is a one-off part that is going into a museum; therefore, when this project finally gets disassembled the recyclable parts will be disposed of properly. Both aluminum and acrylic are recyclable, which leaves the analysis intact and unchanged when considering the full life-cycle impact of the project.

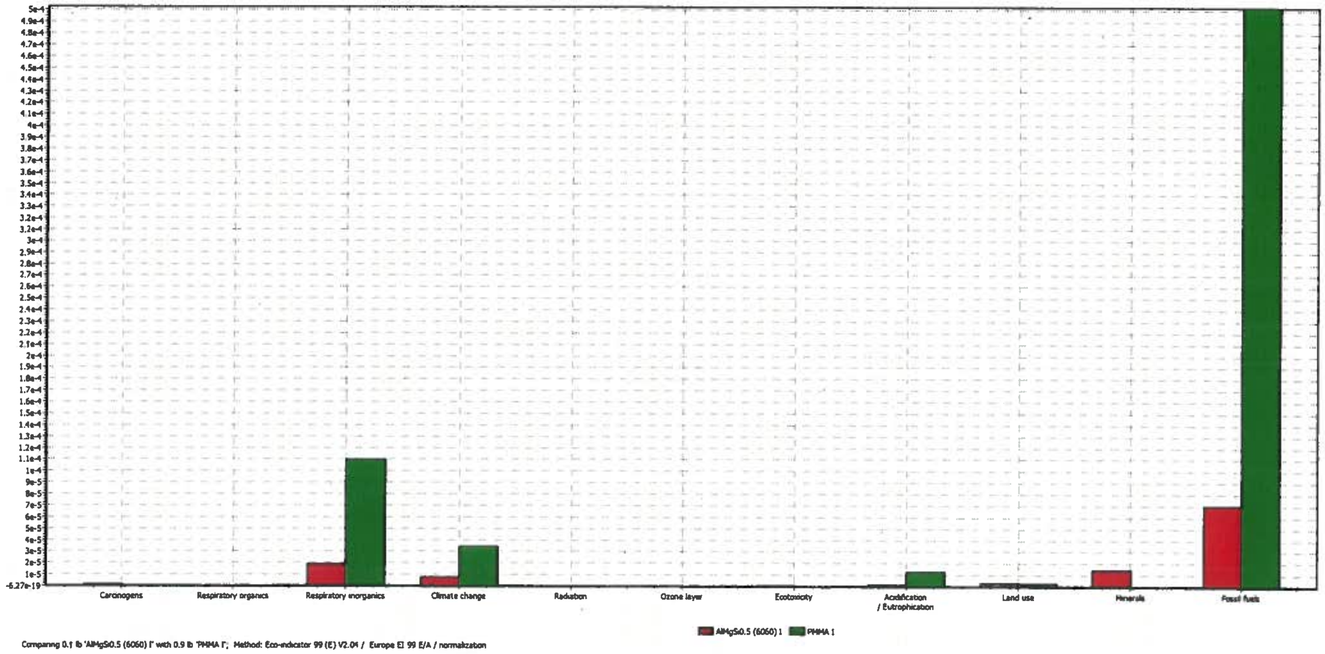
Would we keep this decision if we had to produce our pendulum again, based on environmental impact? Yes, probably, because this is a one off part so the environmental impact is extremely small. If this product was mass produced, other materials would be considered. PVC, although not as transparent, might be an acceptable replacement with a lower environmental impact.


SimaPro Mass Estimation
Aluminum
Actylic
Mass(oz)
1200
1000
800
600
400
200
0
Raw
Air
Water
Waste

Impact assessment

Date: 4/20/2010 Time: 12:12:03 AM

Title:	Comparing 0.1 lb 'AlMgSi0.5 (6060) I' with 0.9 lb 'PMMA I'
Method:	Eco-indicator 99 (E) V2.04 / Europe EI 99 E/A
Indicator:	Normalization
Per impact category:	Yes
Skip categories:	Never
Relative mode:	Non

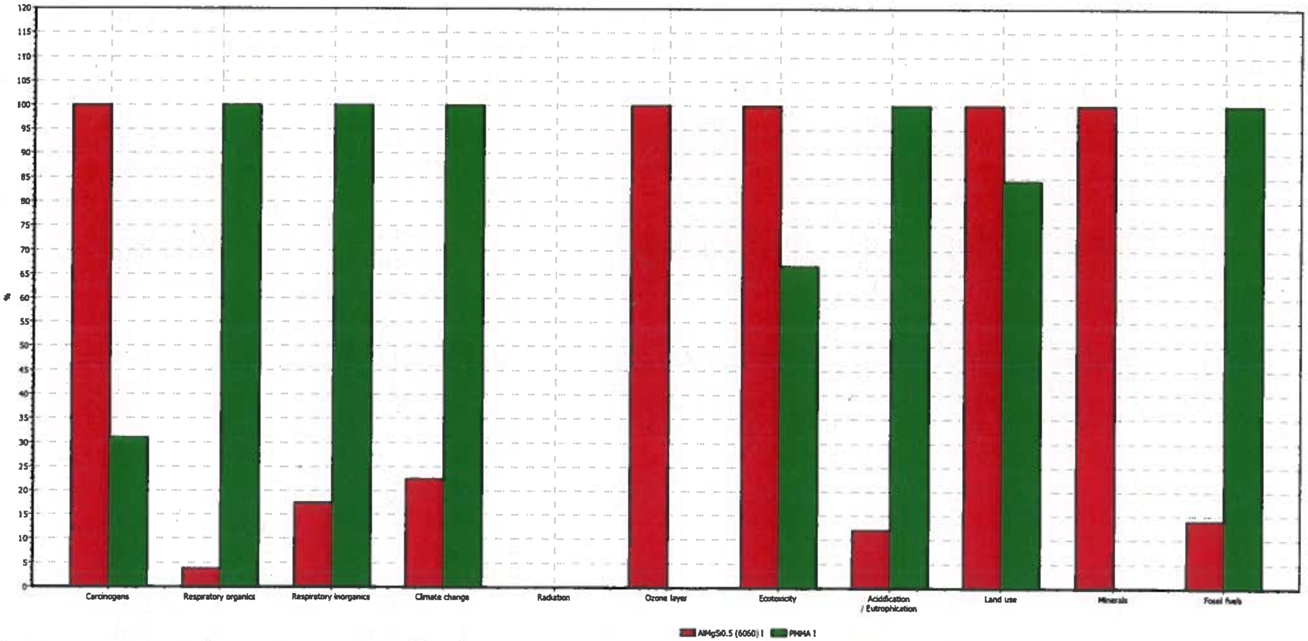


SimaPro 7.1 Educational
Project: poop3

Impact assessment

Date: 4/20/2010 Time: 12:11:52 AM

Title:	Comparing 0.1 lb 'AlMgSi0.5 (6060) I' with 0.9 lb 'PMMA I'
Method:	Eco-indicator 99 (E) V2.04 / Europe EI 99 E/A
Indicator:	Damage assessment
Per impact category:	Yes
Skip categories:	Never
Relative mode:	Non



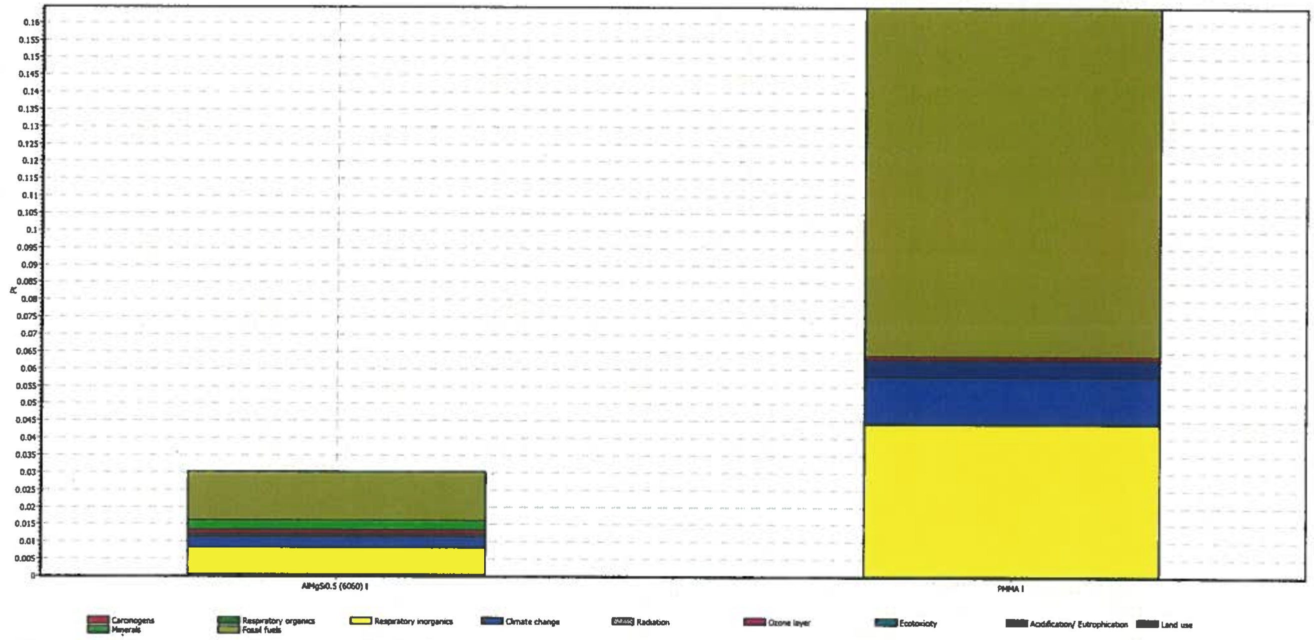
Comparing 0.1 lb 'AlMgSi0.5 (6060) I' with 0.9 lb 'PMMA I'; Method: Eco-indicator 99 (E) V2.04 / Europe EI 99 E/A / damage assessment

SimaPro 7.1 Educational
Project: poop3

Impact assessment

Date: 4/20/2010 Time: 12:12:46 AM

Title:	Comparing 0.1 lb 'AlMgSi0.5 (6060) I' with 0.9 lb 'PMMA I'
Method:	Eco-indicator 99 (E) V2.04 / Europe EI 99 E/A
Indicator:	Single score
Per impact category:	Yes
Skip categories:	Never
Relative mode:	Non



Comparing 0.1 lb 'AlMgSi0.5 (6060) I' with 0.9 lb 'PMMA I'; Method: Eco-indicator 99 (E) V2.04 / Europe EI 99 E/A / single score

F.3: Manufacturing Process Selection

1. The real-world production volume for our project would be around 1000 units. While professors would be interested in this product, we believe that other educational institutions, such as high school and museums would also be interested in purchasing a unit. The inverted pendulum is just so cool, and helps students of all ages acquire some sort of basic understanding of feedback controls. Therefore, 1000 units would be a safe estimate, but we do think that a business could manage to sell more units once the word spreads about how awesome our inverted pendulum.

2. The two materials that were selected using the CES Materials Selector were Aluminum and Acrylic. The best manufacturing approaches that can be used to produce the components at the production volume of 1000 is:

Acrylic cylinder- saw off stock hollow cylinder with a vertical or horizontal band saw.

Aluminum post- drill out and thread stock 6" posts

One way to improve the manufacturing process is to use a CNC process (a computer controlled process) instead of manually controlling the machines/tools manually. The two components will be produced using different manufacturing techniques because they are made of two different materials that require two different machining processes. The acrylic needs to be cut at a slow rpm because the material could fracture easily. Using a CNC process rather than manual labor would save time and prevent chances of human error in manufacturing.

Minimum feature size: The minimum feature size for the acrylic is a four inch diameter cylinder. For the Aluminum posts the minimum feature size is a 3/8" diameter cylinder. There are no necessary heat treatments or coatings for either component.

Tolerances:

Acrylic:

OD ± 0.03"

Wall thickness: 0.25'' ± 15%

Length: ±1/16''

Aluminum Posts:

Length: ± 0.1''

Costs: The CNC would take less machining time, therefore it may save labor costs in our project, but would have a significantly higher purchase cost than manual machines.