Designing an Inverted Pendulum Exhibit for

The Ann Arbor Hands-On Museum

ME 450, Section 2
Design Review 3
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Sponsors: Ann Arbor Hands-On Museum, Prof. Shorya Awtar

Director: Prof. Hong Im

ABSTRACT

This project involves designing, building, and testing a new exhibit, representative of Mechatronic systems, for the Ann Arbor Hands-On Museum. The Design Team has been working on an Inverted Pendulum System that balances a free pendulum in its inverted position using a motor controlled arm, optical encoders, and feedback controls. In addition to this motor controlled system, two manually controlled inverted pendulums are also to be designed and built. These manual systems will be of different sizes to demonstrate the effect that size and mass have on the system. This exhibit will teach museum visitors about feedback controls and the field of Mechatronic systems.

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EXECUTIVE SUMMARY

To accommodate evolving interests in technology, the Ann Arbor Hands-On Museum has requested an informational exhibit that demonstrates the use of computer-controlled systems. To achieve this, a classic feedback-control problem has been selected which balances a short pendulum in an inverted position. This exhibit will provide three such devices, two of which will allow a museum patron to manually attempt balancing an inverted pendulum, and a third computer-controlled device. The first manual device will be large, making it simple to balance, while the second will be small, making it difficult to balance. The computer-controlled exhibit will be the same size as the smaller device, however should seem to balance simply, demonstrating the capabilities of Mechatronic systems.

In making a successful exhibit, five key aspects must be addressed, namely the aesthetics, interaction, electronics, mechanics, and safety of the device. Specifically, the sponsors of this project have requested an exhibit that is robust and stand-alone. It must also be safe, interesting, and intuitive for all ages of the general public to use. As a final specification, considerations of environmental impact both during use and after the functional lifetime will aid in the selection of electrical and mechanical components.

To meet these requirements, many basic specifications have been made. This includes only minimal maintenance for one year with no major repairs required for at least three. The exhibit must also operate without being connected to a computer, but rather be operated using on-board microcontrollers. Safety precautions must be taken to eliminate pinch points, sharp edges, and other dangers associated with the exhibits. Interaction with the devices should also be as simple as possible, such as a single button for the automatic system and a single control-wheel on each of the manual ones. To achieve these goals, the final design uses wireless communications across moving joints, properly sized bearings, and reinforcement on key supports. Sharp edges will be de-burred and chamfered, and polishing/sandblasting will be done to finish the exhibit.

Testing of the final design has verified the design. Mechanically, each device works as intended or will be made to with only minor modifications. This includes increasing the weight on the large manual system to make it simpler to balance and adjusting the torque limiter to reduce forces on the stops. Testing of the electrical system have shown proper communication between individual components, however noise seems to be affecting some of the data. Further testing of the system will be required to determine feedback coefficients and resolve timing issues. Techniques for reducing noise and further error-checking should also be implemented to further increase the reliability of the automatic system.

Testing of the exhibit validates the feasibility of the final design. With only minor changes, each of the manual systems should function fully as indented. For finishing, each device must be polished and sandblasted, with a few components requiring a complete remanufacture due to jammed or misaligned bolt holes. The functionality of the automatic system is presently limited to the "Swing-Up" mode, and is incapable of balancing. Further development of the control system, including the change to a current-controlling servo amplifier, should allow for completion of the electrical system. The final step in the electronics will be the ordering and assembly of custom printed-circuit boards (PCB's). The final mechanical steps will be the actual encasement and mounting of the devices in the museum. Upon completion of the tasks described in the Future Work (p. 43) section, the Inverted Pendulum Exhibit should be complete and fully functional for the Ann Arbor Hands-On Museum.

INTRODUCTION

The objective of this project is to produce a professional quality museum exhibit featuring Mechatronic systems and feedback controls through the use of inverted pendulums. Upon completion, this project will be placed on display in the Ann Arbor Hands-On Museum (AAHoM). This project has been inspired by increasing interest in new technologies and their applications, such as the Segway, vehicular guidance systems, and others. The purpose of this exhibit will be to inform and inspire museum patrons on the topic of Mechatronic.

Three inverted pendulum systems will be produced for this exhibit. The first will be an active system that balances a free pendulum in its inverted position using a motor-controlled wheel, optical encoders, and feedback controls. A prototype of this system already exists, so our focus will be to improve upon its safety, functionality, and aesthetics. Two passive systems must also be constructed, which will be manually controlled by the museum visitors. The Design Team will work extensively with the sponsors, Professor Shorya Awtar and the Ann Arbor Hands-On Museum staff, to ensure their requirements are met.

INFORMATION SOURCES

In order to fully define the requirements and direction of the project, background information was gathered from a broad range of resources. The intent is to ensure that the deliverables meet the requirements of the project in all aspects.

Visits to the Ann Arbor Hands-On Museum

Unlike many ME450 projects, the goal here is not to simply build a functional prototype, but rather three professional devices that are ready for long-term exhibition. In order to get an idea of how exhibits work, and fail, the Design Team went on a guided tour of the AAHoM on Jan 7th and again on Feb 6th of 2009. During these visits, John Bowditch, the Exhibit Manager, showed the team around the museum and provided a great deal of insight into what makes a successful exhibit. Discussion of key concepts also took place, allowing the Design Team to gain valuable information for the development of the project. Following in Figure 1 are just two of the many exhibits at the AAHoM, showing the type of quality that will be expected with this project.

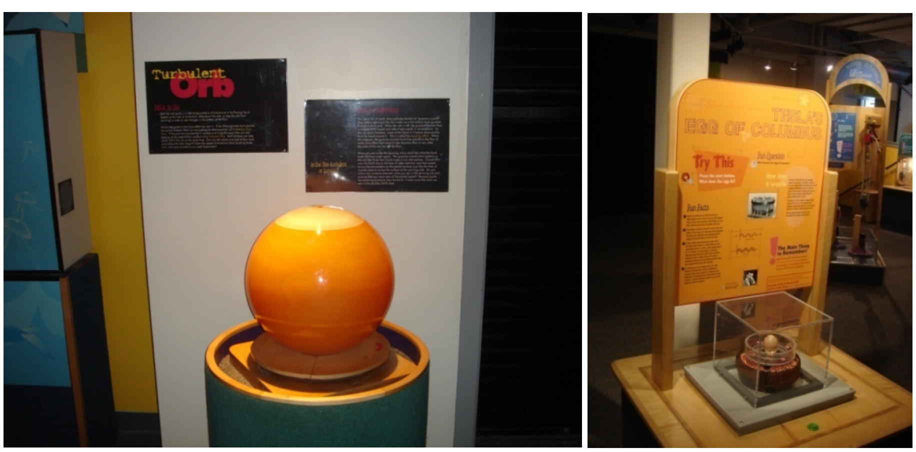


Figure 1: Example Exhibits from AAHoM Showing Expected Quality

History of Feedback Control

In order to learn more about the history of feedback control and as its applications, the team searched the IEEE Xplore database, Wikipedia, and Google Scholar, finding a number of papers and web pages. These may prove to be useful resources for developing the exhibit graphics and labeling. Some main points from the literature research on this topic:

- Feedback control is not a human invention and exists in many forms naturally.
- The earliest usage of feedback control by humans is believed to be the water clock invented by Ktesibios in approximately 300 B.C.[1]
- James C. Maxwell, E. John Rout, and Adolf Hurwitz did the earliest formal analysis on feedback control in the late 19th century. [1]

Previous Research on Inverted Pendulum Systems

A good deal of research has been done on inverted pendulum systems in recent years, resulting in many variations on the theme. One paper written by Professor Awtar et al [2] describes a case for dynamic modeling of these systems. Since this project is to build an exhibit based on the existing prototype, it was decided that this research would not cover all types of inverted pendulums in depth. Other models, however, were incorporated in lateral benchmarking. Figure 2 shows some examples of inverted pendulum systems from past research.

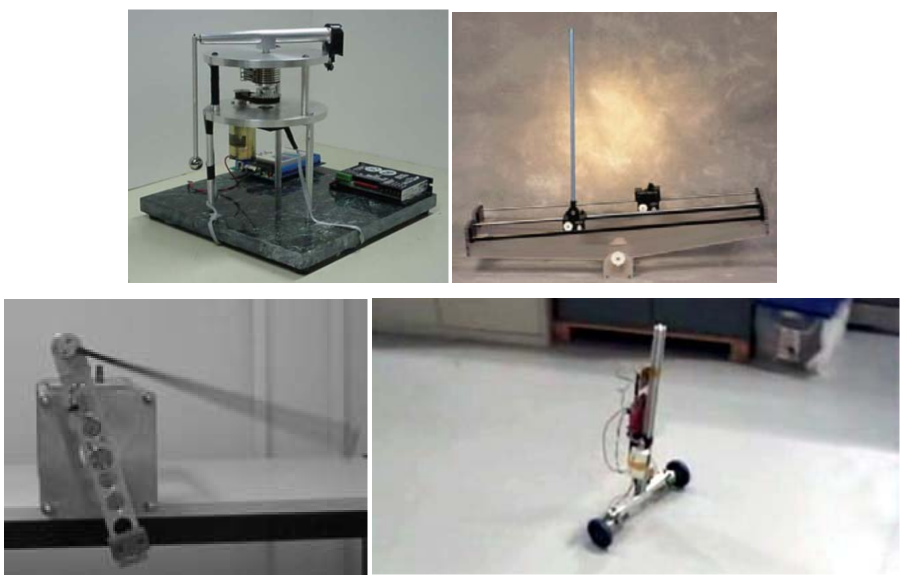


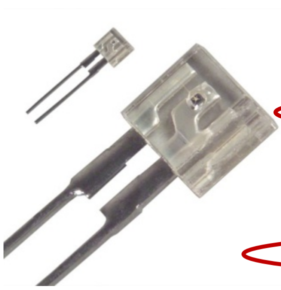
Figure 2: Examples of Inverted Pendulum Systems

Other Literature Research

The Design Team also did some research on human response time for our design of passive systems. A paper on driver's response time was reviewed [3], which is valuable for this project, since one would expect the response time to be of the same order of magnitude despite the different conditions in these two cases. A paper on the effect of human response time for the stabilization of a two-wheeled suitcase was also reviewed [4].

Features of Infrared LEDs and Detectors

To solve the problem of transmitting encoder signals from the swing arm down to the controller in the small passive system, the Design Team has investigated infrared LED solutions. The idea is to use infrared LED emitters and detectors to transmit the signals (schematics of the preliminary transmitter and receiver are in Appendix E). The team therefore researched features of infrared LEDs and detectors. The major source of this information comes from manufacturer datasheets located primarily through Digikey. The team was especially interested in the follow features: the voltage and current needed to power the LED and detectors, the half-power transmission/viewing angle of the LED and detectors respectively, and the emitting/receiving wavelength. Figure 3 shows an example of the LEDs that the team found.



Parameter	Conditions	Typ	Unit
Forward voltage	$I_F = 100$ mA	1.3	V
Reverse current	$V_R = 3$ V		µA
Radiant power *	$I_F = 50$ mA	6.0	mW
Peak emission wavelength	$I_F = 50$ mA	940	nm
Spectral half band width	$I_F = 50$ mA	50	nm
Terminal capacitance	$V_R = 0$ V, f = 1 MHz	45	pF
Half-power angle	The angle when the radiant power is halved	80	°

Figure 3: LNA2603F Infrared Emitter Produced by Panasonic[5]

Solar Cells

One way to power the encoder and LEDs on the rotating wheel (figure 10 page 15) would be using solar cells. The team has been investigating different solar cell manufacturers and their products through supplier websites. Most of the solar cells the team found, which are suitable in size, can only produce about 0.5 volts. It is almost 10 times lower than what is needed. However, given that they can provide more than sufficient current (more than 1 Amp compared to the need of only a few hundred milliamps), the team should be able to raise the voltage to the required value (5V). One possible way is to put several cells in series.

Benchmarking System Construction

As shown in Figure 4, the prototype uses a DC motor to rotate a swinging arm to which the pendulum is attached. It can swing the pendulum up and balance it in an inverted position. The detailed descriptions of the parts are listed below Figure 4.

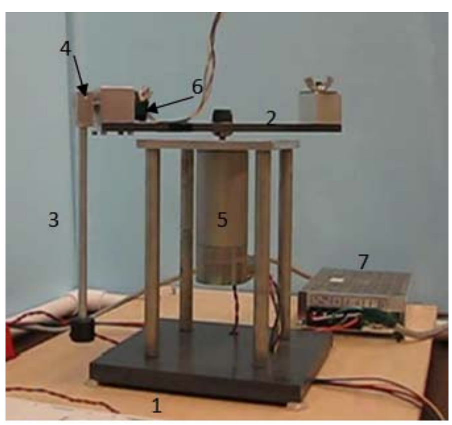


Figure 4: Current Prototype

1. *Base:* The base is made of a PVC sheet at the bottom, four aluminum rods and a squared aluminum piece at the top.
2. *Rotating arm:* The rotating arm is made of an aluminum alloy. A counterweight mass is added at one end to balance the pendulum weight.
3. *Pendulum:* The pendulum is attached to the rotating arm using a precision ball bearing listed below.
4. *Precision Ball Bearing:* Miniature Precision SS Ball Bearing - ABEC-5 Flanged Shielded, .25" ID, .375" OD, .125" W, McMaster Part#57155K322.
5. *DC motor:* Pittman Lo-Cog DC Servo Motor, 24V, 77 oz-in peak torque, PittmanExpress Part # 9237S011.
6. *Miniature Optical Kit Encoder:* US Digital E4P OEM Miniature Optical Kit Encoder, US Digital Part # E4P-300-250.

Benchmarking Controller Design

The angle and angular velocity of the pendulum and motor can be determined by the data output from the optical encoder and tachometer. This information is then feed into the LabView control code, which then sends control signals to the motor controller. Two types of control algorithms are used in this prototype, a swing-up controller and a balance controller, described by Equations 1 and 2.

$$T = 0.043 \times 0.75 \times \text{sign}[\dot{\theta} \cdot \cos(\theta)]$$ Eq.1 Swing-up controller

$$T = 0.4 \cdot \alpha + 0.5 \cdot \dot{\alpha} + 10 \cdot \theta + 2 \cdot \dot{\theta}$$ Eq. 2 Balance controller

T: Motor torque θ: Pendulum angle (zero when pointing up vertically)

α: Motor angle

As shown in Figure 5, one of the two controllers will be used depending on the position of the pendulum. When the pendulum is more than 25 degree away from the vertical position (θ>25º or <-25º), the swing-up controller is used. It adds energy to the system and swings the pendulum up to the inverted position. When the pendulum is within 25 degrees of vertical (-25º<θ<25º), the balance controller will be used. This balances the pendulum in its vertical position.

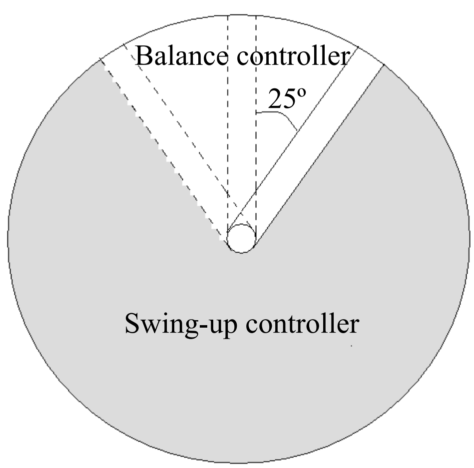


Figure 5: Usage of Controller Depending on the Position of the Pendulum

ENGINEERING SPECIFICATIONS

For this project, many of the technical specifications are obtained directly from the previous prototypes provided to the team. However, many specific technical challenges remain to be addressed. Of specific concern is the safety and robustness of the design. Equally important are the aesthetics of the exhibit. Unique from many other mechanical engineering projects, this one must be eye-catching and informative rather than a simple prototype. Another essential specification is that the project stays within a $1,500 budget. The following sections list the engineering specifications derived from our customer's requirements. A complete list showing detail of this derivation can be found in Appendix F.

Aesthetics

As the primary purpose of this project is to build a functional museum exhibit for the AAHoM, aesthetics are a key aspect of the design. As a top customer requirement, the exhibit must have a very technical look, which extends to many aspects of the mechanism such as finishing and coatings, material selection, and casement. The over-all layout of components, such as the location of motor and optical encoder, is also affected, making sure that their contribution to the system is clear.

While it is not particularly appropriate to quantify aesthetics, some technical specification has been added to the aesthetics:

Materials: Materials should be selected such that components and their interactions are clearly visible and emphasized. This should not, however, compromise the robustness of the system.

Finish and Coatings: All parts should be carefully machined to emphasize their purpose and distinguish them from other components within the system. Coatings, such as polishing, anodizing, painting, and sand-blasting, should also be considered to emphasize components. All sharp edges should be chamfered and de-burred to prevent injury.

Casement: This will be developed largely by the AAHoM; however considerations for safety and components that should remain visible will be communicated to the AAHoM staff.

Interaction

Equally important, interaction with the exhibit must be simple and intuitive. To facilitate this, the AAHoM has requested that the exhibit default to a "balancing" mode while not being interacted with. Further details are specified below.

Museum Visitor Interaction: The automatic exhibit should default to a "balancing" mode with appropriate feedback control parameters. A single button ("Drop Button") will temporarily disable the feedback control until the user releases the Drop Button or a specified time is reached. After release of the button or the specified time has elapsed, whichever comes first, the system will resume its default-balancing mode. This will require that the system can start from a stationary vertically downward position without physical interaction.

In addition to the automatic system, two manual systems will be developed. The interaction with these will be a single input via a moveable wheel. For the smaller manual system, a wheel will be placed beneath a table such that it protrudes just beyond the edge of the table for interaction. For the larger system, this wheel will be 16" in diameter and approximately 4" above a larger diameter table. This input will incorporate physical stops that will resist motion with a friction clutch after the input wheel travels more than 90 degrees.

Museum Staff Interaction: For AAHoM staff, additional controls will be accessible to provide further functionality of the device if desired for presentations and calibration. This will include, depending on the method of feedback control, gain and coefficient adjustments. If time permits, choice of control method

(PID, State-Space, Fuzzy, Etc.) may be included. General replacement of a standard light bulb in the case of the exhibit may also be required for powering the automatic system.

Power On/Resume: Upon initial power-up, or on resume from a power-outage or brown-out, the system will enter the default balancing mode. If time permits, a self-test procedure may be implemented.

Electrical

The electrical system specifications are generally in regard to safety. The request to remove the wires that hang to the pendulum angle sensor will likely be one of the most challenging to accommodate. Further electrical specifications are inherent from the aesthetics and interaction of the system or benchmarked from the prototypes provided. Generally, specifications are applicable to only the automatic system. The electrical specifications are listed below.

Wiring: The system wiring must use a minimum of 22GA wiring as specified by the AAHoM. Larger gauge wiring should be used where required based on the power requirements of the systems they are connecting with reasonable factors of safety. Wiring should also be visible where possible to emphasize the electrical functions of the system.

A rotary contact or other form of reliable communication should be utilized to remove the wire currently hanging from above the automatic system. If sliding contacts are used, gold-plated contacts are preferred to reduce the effects of corrosion. These parts would be considered “Wear-Parts” and should be easily replaceable with a life expectancy of one year.

For the optical solution, phototransistors with appropriate half-power viewing angles will be required. For four receiving phototransistors, with a 6” diameter of rotation for the emitter, this would require a minimum of 50 degree viewing angle to minimize signal degradation.

Complete wiring diagrams must also be provided with the exhibit for the purpose of replacement and repair, including parts lists and vendors where applicable.

Interaction: The single drop button on the exhibit must be able to handle more than 120,000 cycles. This is from an assumption of 15 cycles per hour on average over an 8-hour day for three years and six-day weeks.

Preferred Vendors: At the request of the AAHoM, Pitman Motors, McMaster-Carr, and Small Parts, Inc. will have priority for available parts and/or be cross-referenced for replacement parts when possible. Moog Inc has also been suggested by the sponsor for rotary electrical contacts, but was not specifically requested. For buttons, a large variety will be provided by the AAHoM. These vendors will also be preferred for mechanical parts, and will not be repeated in that section.

Surge Protection and General Safety: Surge protectors and generally electrical safety devices will be provided by the AAHoM, however internal safety considerations such as fuses and properly insulated wires are the responsibility of the Design Team.

Mechanical

The general assembly of the automatic and smaller manual system will be benchmarked from the given prototype. While the pendulum arm length will be benchmarked from the prototype provide by the AAHoM, the Design Team will design the majority of the larger manual system. Further specification is described below.

Robust Design: The Inverted Pendulum Exhibit should have a 3-7 year life expectancy on mechanical parts. Any failures should be non-catastrophic and easily repaired. The design should accommodate this with simple assembly and maintenance instructions provided with the exhibit. In addition, any coatings or finishes should be evaluated in a similar manner and selected to last for the lifetime of the part where possible.

To help facilitate this, the pendulums will each be comprised of multiple (approximately five) individual components. Based on the concept of their design, this should allow for two rods that are simply threaded and three parts that have more involved machining required. The simple rods, however, are the most likely to be damaged.

Dimensions: The dimensions of the individual exhibits will be approximated from the prototypes. All dimensions for components and component features that are not purchased must be detailed in mechanical drawing provided with the exhibit. Manufacturer's drawing should be included when available for any purchased components.

For the larger, manual system, the outer dimensions will be approximately 16x16x30 inches. This will consist of a 16" diameter control wheel and a 30" long pendulum arm.

Both the smaller manual system and the automatic system will have dimensions on the order of 6" wide, 6"deep and 16" tall with an 8" pendulum as benchmarked from the prototype provided to the Design Team.

Materials: Materials should be selected to maintain the life expectancy of the device mechanically while satisfying the aesthetic requirements of the project. Standard materials, such as 6061 Aluminum, Mild steels, Polycarbonates, etc. should be used unless more exotic materials are specifically required. Bearings, nuts, bolts, shafts, bushings, keys, and other hardware should be purchased from the preferred vendors listed in the Electrical section when possible.

Safety

Considerations for safety with this project are critical as with any engineering design. While experiencing small loads and relatively moderate operating speeds, the device will be in the presence of unfamiliar museum patrons and the public in general. Safety for children is of key importance to this project, so special care must be taken to accommodate children that may be unaware of even the most basic dangerous situations. Below is a simple list of the safety considerations identified by the Design Team:

1. Eliminate pinch-points.
2. Chamfer any sharp edges.
3. Careful electrical work that can withstand electrical surges and brownouts without catastrophic failure.

CONCEPT GENERATION

The development process for our designs included a mixture of textbook engineering design procedures, input from our sponsors and brainstorming sessions. Many of the specifications have been benchmarked from the prototype that this project is based on. Additionally, the Museum provided specific guidelines for safety, robustness, aesthetics, and preferred vendors. Further refinement came through feedback from our peers and sponsors over the past several weeks. Throughout the whole process, a sub-systems thinking approach was used to ensure that each element both met specifications in detail, but also fulfilled the overall goal of production of exhibit-grade devices that fit within the overall museum environment.

Design Methods

For this project, many of the specifications were given at the outset and a significant number of visual specifications remained for us to develop. To meet our goals, we employed some of the standard engineering design methods along with some more unorthodox techniques. A QFD analysis was performed, which reinforced what we already knew to be our design requirements. Most of the rest of the process involved successive rounds of brainstorming and review.

We began by looking at what each subsystem of these models contributed to the overall function and identified where each was lacking in reference to the project goals. We decided early on that a systems approach would be more appropriate than an analytical approach to the problem in order to be able to develop three stand-alone devices that together form the heart of the exhibit. Each individual device plays a role in the function of the system as a whole, which itself needs to interact appropriately with the museum environment.

The vast majority of the input to the overall design process came from brainstorming and feedback from various sources. Most of the developments came through iterations of brainstorming ideas to meet specific goals and gathering feedback from our peers and sponsors as well as from several elementary educators and their students, representative of the primary group of end users. In these iterations, three areas that received our primary focus were safety, aesthetics and robustness. Each of these is described below.

Safety

The safety requirements focused primarily on issues relating to the visitors to the museum. The end users of these devices will be from all ages and walks of life. Some of the safety concerns are common across the three devices while some are case specific. While these issues must be addressed with due diligence, there will always exist some potential for injury from even the best exhibit. The potential for severe injury, however, must be minimized.

Most of the safety issues pertaining to the smaller devices are to be resolved by placing them inside an enclosure. This is a slight departure from the original specifications which called for the manual device to be completely exposed. There is to be a single user interface for each of these devices. The automatic device will have a single button which will break the control algorithm and allow the pendulum to fall. This button will be in a low voltage and/or fused circuit in order to be inherently safe. The manually operated device will also be enclosed. The interface is to be a disc-shaped handle mounted approximately four inches below the bottom of the table top to reduce potential hazards such as pinch points.

The large manual device has been redesigned to be free standing and the six-spoke wheel the pendulum is mounted on can rotate 360°. This creates a safety issue as it is desirable to have a low-friction hub in order to not interfere with the operational dynamics of the system. At the same time the temptation exists for someone to try to see how fast they can spin the wheel. To alleviate this, the hub has been designed to allow free movement within a 90° range. Beyond this range, a torque limiter allows the wheel to turn but with an applied resistance to prevent freewheeling. This assembly is described in detail in the Alpha Design section on page xx. The wheel is also to be mounted approximately four inches above the top of the table to reduce the possibility of pinching and entanglement.

Aesthetics

The overall appearance of the devices is critical in that they need to be an attractive component of the museum. They are to have a very technical look that invites museum visitors to take interest in the exhibit. In addition, the look needs to directly imply the function of the devices and help to convey the overriding message of the exhibit as intuitively as possible. The fit and finish of these devices is required to be of a professional level.

One of the major challenges we faced in the design processes was to find a way to make the three devices look like they belonged together. The original prototypes shared a common theme but were different in their functionality and appearance. The small devices were to be table-mounted while the large pendulum device was to be affixed to a wall. These differences made it very difficult to tie them together visually.

The real breakthrough came when it was decided to make the larger device free standing and to use a six spoke wheel. It is this wheel that completes the package and gives the appearance that they are common to the same exhibit. The wheel design can easily be utilized on all three devices and creates a truly cohesive appearance. Along these lines, the design team decided that it would make sense for the three pendulums to be similar in appearance to further tie them together visually.

Robustness

In order for these devices to be a functional part of the museum, they will need to be able to withstand the daily use and abuse that comes along with any interactive exhibit while requiring minimal maintenance. Further, they will need to stand up to the occasional attempt that will be made to damage them without yielding. It has been expressed that it is desirable for these devices to require no more than minor annual maintenance. Major maintenance and repair shouldn't be required for at least three years.

To meet these goals, one or more ball bearings will be installed at each rotary joint. Each component will be designed to withstand any applied loading with an appropriate factor of safety built in. Those components that will have direct interaction with the public will be substantially over-engineered to be able to take any foreseeable amount of abuse without failing.

Another requirement is that wear items must be easy to replace without having the exhibit out of service for any significant period of time. Therefore, it is our intention to utilize hardware that can be easily sourced and keep the number and complexity of any custom parts to a minimum. CAD files will accompany each of these in the event that a replacement part is required.

One component that was of concern to us was the data transmission device between the optical encoder and the motor controller. In many respects, slip ring contacts served this purpose well, but because the active device was to have a 100% duty cycle, wear would eventually necessitate its replacement. We felt that the slip rings and the motor would be the parts that would be most likely to require periodic replacement. For this reason, we are pursuing a solid state solution that will use optical data transmission to eliminate at least one of these wear components.

DESIGN SELECTION

As time passed, the design ideas developed progressively in increments. At each stage, elements of the overall package grew out of previous ideas and were carried onto the next iteration. This section will serve to document some of the progression from preliminary prototypes to our "Alpha" designs.

Early Concepts

In the beginning of the project, the design team was given access to an existing active prototype. Its accompanying documentation modeled the system dynamics and included a list of components and motor control algorithms. The prototype was fully functional but was lacking in a number of aspects. Overall, this model lacked visual appeal and had some inherent design flaws. One major concern was the overhead wiring that was used to relay the signals from the optical encoder to the motor controller. Nonetheless, the device is functional and we plan to make use of the same servo motor and optical encoder, along with some of the structural features.

During the preliminary stages of the design process, the team was planning to design out certain safety issues in the small models. Both the active and passive versions were to be nearly identical in design and the passive system was to be fully open and exposed. The design team began by developing ideas that would improve the overall appearance while eliminating what could be pinch points. The result of this is shown below in Figure 6.

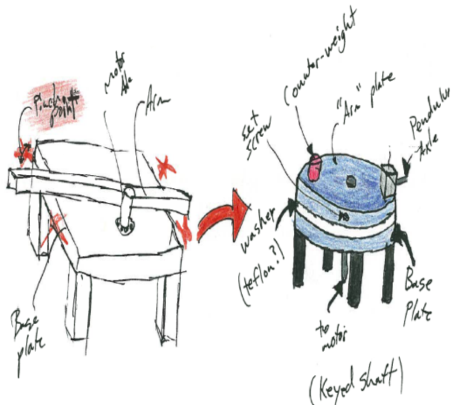


Figure 6: Initial Design Concept Addresses Aesthetics and Pinch Points

It was subsequently decided that both of the smaller models would be enclosed in order to avoid any of these safety concerns as well as to protect them from damage. Designing them to be strong enough to withstand someone trying to pull on the pendulum arm and still retain the desired system dynamics would be highly impractical. Even so, the design team liked the round look and opted to carry this feature on to the next iteration.

While the design team worked on the smaller units, they also had to give a great deal of thought to the larger device. The original prototype given to us was a very simple pivot that would be wall-mounted. Among the issues we set out to address were how to give it an interesting mechanical look that would be somehow similar to the smaller units as well as how to eliminate pinch points and make it safe overall. The original device and our initial design ideas are shown below in Figure7.

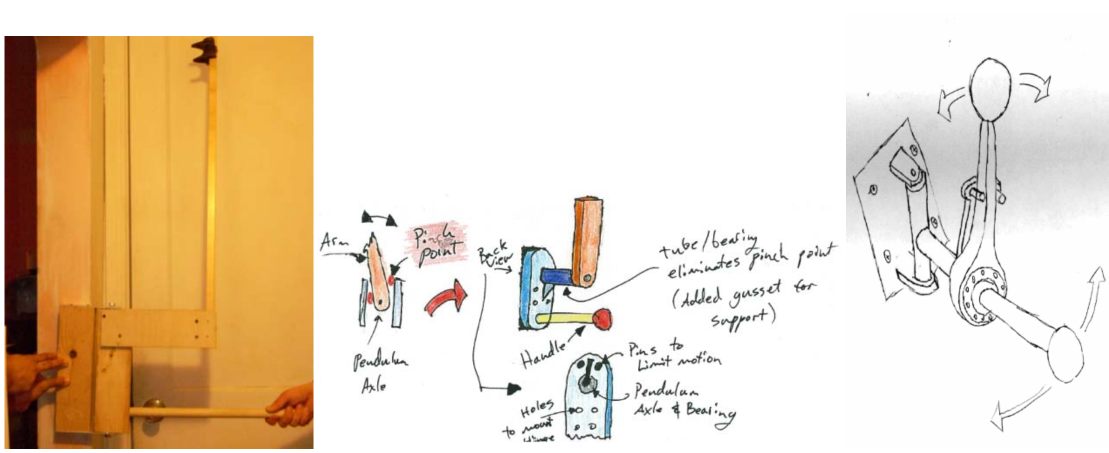


Figure 7: Original Prototype of the Large Passive Device and Design Improvements

The Turning Point

On the 6th of February, the design team met with our project sponsor at the Museum to go over the concept designs and some of the technical details. Earlier in the day, an idea had been suggested that the handle should be more of a partial disk shape rather than a post that stuck straight out. This idea was taken a step further by making the disk into a full circle and having the device be free-standing rather than wall mounted. A spoked wheel design was developed, with the pendulum arm mounted to one of the spokes.

This revelation addressed a number of issues. It allows the exhibit to be placed more or less anywhere in the museum rather than being limited to a location where the large device could be wall mounted. Several of the safety issues were eliminated as well. Most importantly, it ties the three devices together visually and functionally and enhances the appeal of the exhibit as a whole. The free-standing design has an elegant look and will no longer look like a wholly separate piece. Shown side-by-side on the below in Figure 8, one can truly see the cohesive look.

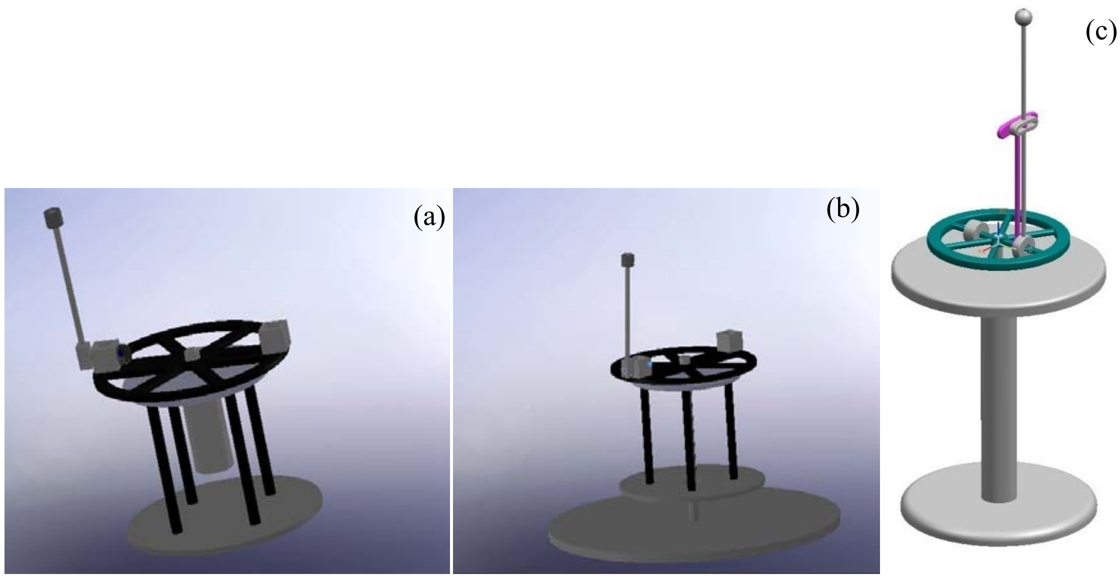


Figure 8: Three "Alpha" Designs Share a Common Look and Appeal; Automatic (a), Small Manual (b), and the Large Manual (c) are Each Pictured Above

ALPHA DESIGN

Presently, CAD models have been created for each of the passive systems as well as the active system of the exhibit. The follow sections provide further details of each Alpha Design that has been developed.

Active System Design

The active system utilizes feedback control to hold a pendulum arm in the inverted position. The feedback control monitors the motor and pendulum arm velocity and position. This data is then used to determine the proper adjustments to be made by the motor. This motor then swings the rotating wheel, shown in Figure 9 on the next page. The rotating arm employs circular six spoke design to help satisfy the requirement that all three systems look similar. The round theme also helps to satisfy the safety requirement. The bearing block and counterweight are mounted to the rotating wheel. As the rotating wheel swings energy is transferred to the pendulum arm mounted on the bearing block, show in Figure 10 on the following page. Two optical encoders record the movements of the motor and pendulum arm. There are two options currently being researched for the transmission of data from the optical encoder to the motor controller. One system utilizes Light Emitting Diodes (LEDs) on the rotating wheel with sensors on the base of the system to receive the signals. The power for the LEDs and optical encoders would be provided by a solar panel placed on the rotating wheel. The alternative to this would be using slip ring to directly transmit the data to the motor controller. The slip rings would transmit both the data from the optical encoder and the power needed to operate the system. The electrical systems, such as the motor, motor controller, and data acquisition systems, will be benchmarked from the previously created prototype.

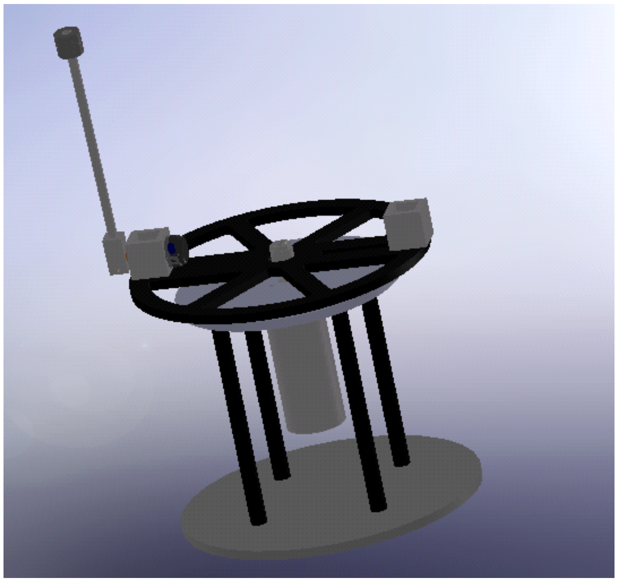


Figure 9: Alpha Design for the Active System

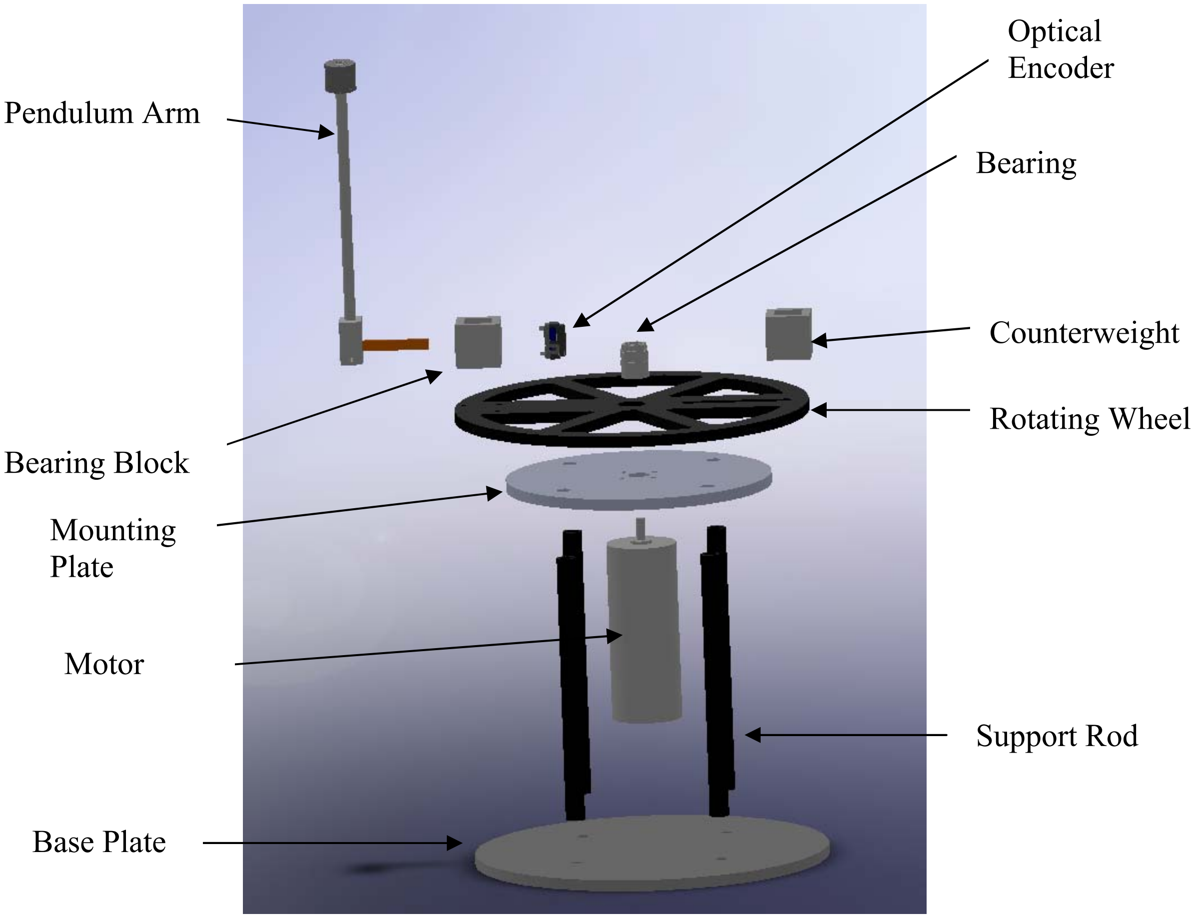


Figure 10: Active System Design Layout

Small Passive System Design

The small active system uses the same components as the passive system. This will ensure that the small passive system resembles the small active system, an important requirement set by the project sponsors. The only change is the motor and electronic control are replaced by a wheel that is manually turned and directly controls the rotating wheel, as shown below in Figure 11 and 12. This wheel will be under the table that the exhibit is displaced upon. The users will be able to turn this wheel to control the pendulum arm movement. The pendulum arm movement will be restricted with 10 degrees within the inverted position. This system will be fully enclosed to protect the users and to prevent damage to the exhibit.

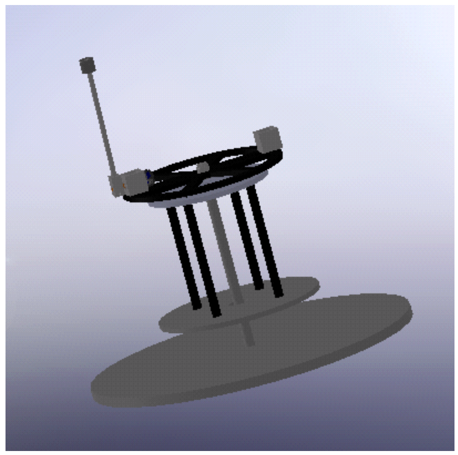


Figure 11: Alpha Design for the Small Passive System

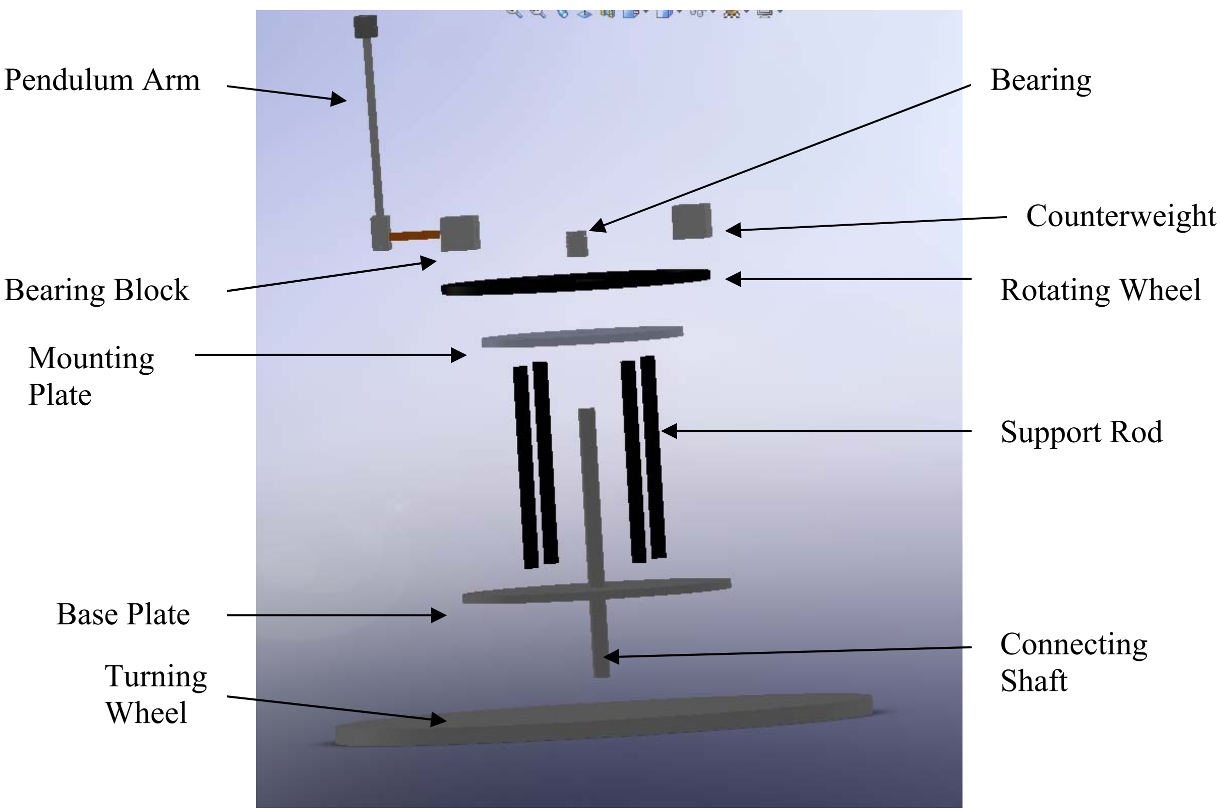


Figure 12: Motor Replacement for the Small Passive System

Large Passive System Design

The large manual system demonstrates the effect of pendulum size and mass on the controllability of the system. While the small manual system will be difficult to control manually, the large system is designed so that with some effort, normal people can hold pendulum in the inverted position for a certain time. As shown in Figure 13, the big manual system consists of a long pendulum (about 3 feet long) sitting on a wheel (16 inch diameter). In order to limit the swing angle of the pendulum (for safety concern), a slot stopper mechanism was designed. As shown in Figure 14 on the following page, an arc slot will be built at the middle of the pendulum arm. A stopper which will be fixed to the wheel then will limit the swing angle of the pendulum within 10 degrees (±5º). The slot on the pendulum arm will be covered by plastic at the front. The width of the stopper was designed so that it covers the slot at the back at any position the pendulum might be. This helps to ensure people cannot stick their fingers into the slot and get pinched. The current model does not include two bearings needed for the wheel and pendulum. The table that the system sits on will be provided by the AAHoM.

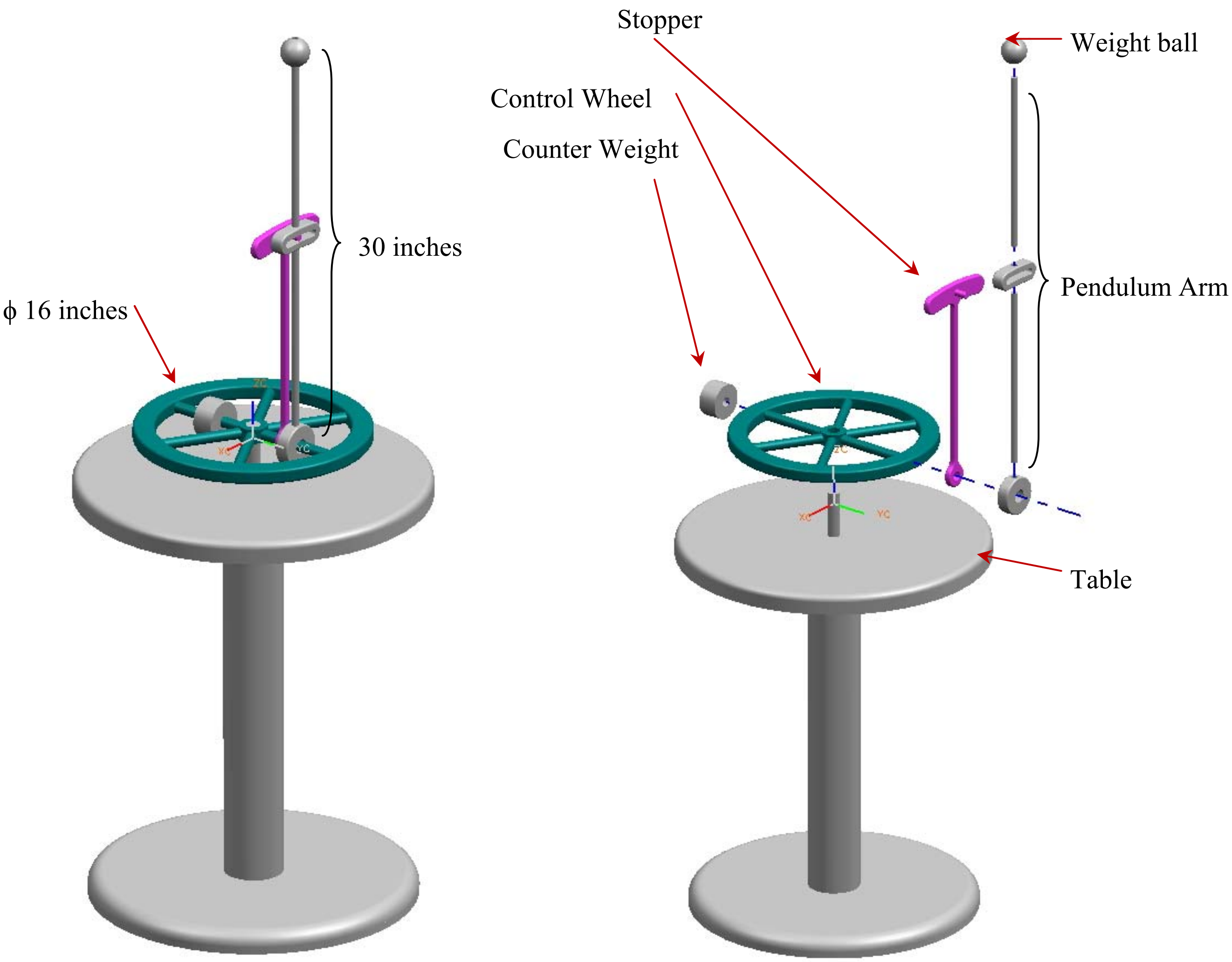


Figure 13: CAD Model of Large Manual System

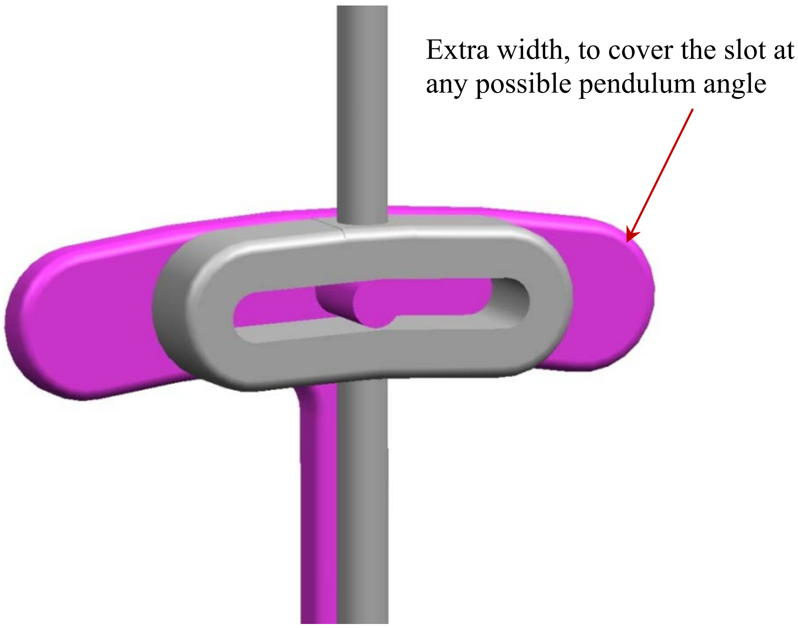


Figure 14: A Close Look at the Slot-Stopper Design.

ENGINEERING ANALYSIS

A mathematical model of the inverted pendulum is needed to develop the control units and transfer functions in the feedback control system. The system model varies according to the purpose of control. In this report, the equations are derived for the force and torque balance of the pendulum arm.

In the following, qualitative analysis, the pendulum and arm are assumed to have centers of mass at their geometric centers. As the design team has yet to finalize the several options for the wiring/data transfer system, some of the parameters of this model are undetermined at this point.

From a modeling point of view, the simplified inverted pendulum system (shown in Figure 15 below) consists of three parts: arm/disk (Link 1), pendulum (Link 2) and the weight (M) at the end of Link 2. There is an encoder holder at the end of Link 1.

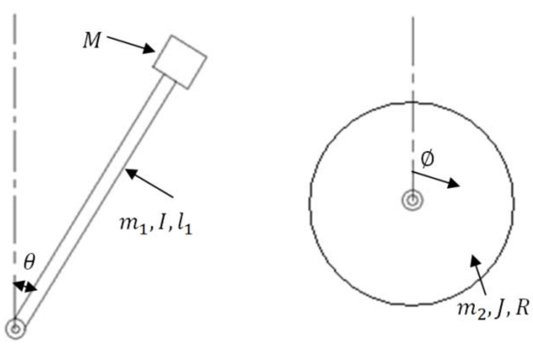


Figure 15: Simplified Inverted Pendulum System

In this modeling, for simplicity, we assume that all the mass of weight (M) to be on the end point of Link 2. The system model can be derived differently depending on the assumptions made. The following equations (shown in Equations 3 and 4 below) are the mathematical model of the system linearized based on the assumption that angle θ is small.

$$(m_1 R^2 + 2J)\ddot{\varphi} - \left(\frac{m_1}{2} + M\right) l_1 R \ddot{\theta} = 2T \qquad \text{Eq. 3}$$

$$[\left(M + \frac{m_1}{4}\right) l_1 + I/l_1]\ddot{\theta} + \left(M + \frac{m_1}{2}\right) g\theta - \frac{m_1 R}{2}\ddot{\varphi} = 0 \qquad \text{Eq. 4}$$

Here, m_1 and M are respectively the mass of the pendulum arm and the weight at its end respectively, θ is the angle between the pendulum and the inverted/vertical position, φ is the angle between the arm and its initial position, l_1 and R are respectively the length of the pendulum and the radius of the turning disk, and I and J are respectively the rotational inertia of the pendulum and arm about their center of mass.

PREVIOUS CHALLENGES

While some elements of this design are straightforward, several challenges need to be addressed, including the data transfer system, stand-alone exhibit and safety hazards. Currently, the most significant challenge is the wireless data transfer system.

Data Transfer System

The angle θ of the pendulum arm on the active device is measured using an optical encoder. On the current prototype, the data transfer cable connecting this encoder and the control system is overhead and unsightly. To address this issue both in terms of aesthetics as well as overall functionality, several concepts have been generated in the Design Review 1, including the sliding contact concept, multiple bearing concept and the wireless concepts. Due to the low cost, easy implementation and maintenance, the design team chose the optical wireless concepts. However, several challenges are also introduced.

1. The encoder has two channels.
   The encoder used to measure angle θ has two output channels, meaning at least two sets of optical emitter-receiver devices are needed. The problem lies in avoiding interference or noise between the two sets of devices. A potential solution will be implementing two sets of LED devices with different wavelengths that don't overlap in the spectrum. Each receiver is only sensitive to the corresponding LED wavelength and will not record signals from the other LED.

2. Power
   Although the output signals can be transferred by the optical data transfer system, the encoder still needs 5V electrical power source to operate. The plan is to implement solar cells on the system. A powerful light source above the device is needed to meet this need. Most solar cells currently available from vendors were specified as 0.5V voltage sources. Therefore, at least 10 such solar cells will be placed on the upper surface of the active system's turning disk, which has a very limited area for such implementation.

3. Noise
   Ambient light, such as the sun light might be a source of noise, especially for infrared devices. To avoid this problem, the device can be enclosed in a tube that turns with the motor shaft. LED devices may be free from this problem considering their narrow bandwidth and low intensity of the ambient sources.

Stand-alone design
Another challenge lies in creating an interface that can utilize the system controls that have already been produced. The existing prototype requires the use of a computer running LabView software to control the motor. Several options will be examined to integrate the control functions into the device itself, including microcontrollers and PLC devices.

Safety Hazards
For both manual systems, pinch points may exist between the spokes of the wheel/disk and base unit. One potential solution is to implement a modified spider coupler and a torque-limiting clutch on the main shaft. When the viewer turns the wheel, the spider couplers will provide approximately 90 degrees of free travel. After this range, the spider couplers will engage, transferring torque to the limiting clutch which provides frictional resistance and tries to stop the turning. This setup can prevent viewers from turning the wheels too fast, and therefore avoid a serious of safety issues. Figure 16 below shows the anticipated assembly of this device.

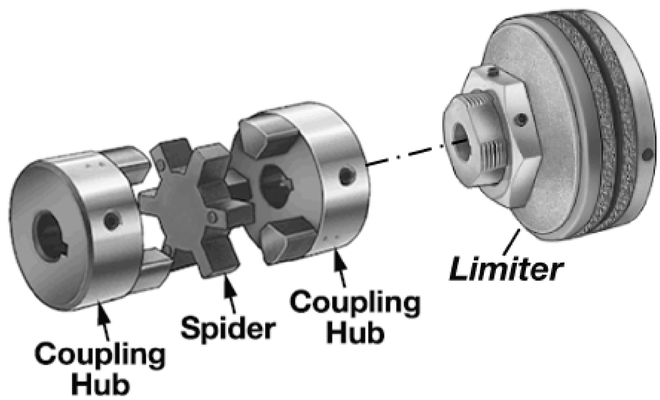


Figure 16: Coupling Assembly Applies Resistance Beyond 90^o

PROJECT PLAN
As of the date of this report, we are slightly behind the original schedule we had established. This is primarily due to the technical challenges presented by data transmission. We had budgeted roughly two extra weeks into the overall project, and at this point, we estimate that we have used roughly two days of that extra time. Overall, we remain in good shape in terms of time to successfully complete the project.

Design
The majority of the gross design work has been completed. What remains is some of the finer details that will come with the final selection of a data transmission method and a small number of key hardware components. These final selections are to be made during the week of February 23rd and procurement activity will begin by the end of that week. Once we have these details in order, we can finalize our CAD models and begin machining the custom components.

Production
We plan to begin the prototyping stage of the project during the week of March 2nd. By that time, the majority of our hardware should be in hand or on its way, with the vast majority comprised of off-the-shelf components. Raw materials for the machined parts will be sourced locally from stock sizes to insure future availability in the event any of the parts requires repair or remanufacturing.

Lab testing of subsystems is scheduled to begin the week of March 9th with full assemblies ready for evaluation in the week to follow. We intend to have functional devices prior to the third design review so that we can schedule times to give demonstrations at the elementary schools in the third or fourth week of

March. This is a lofty goal, but again some extra time is built into the schedule. This would allow adequate time to apply the finishing touches to each of the devices and compose a useful and well put together use and care manual. We have also been asked to design the backdrop for the large manual pendulum, which will itself present many challenges.

Team Responsibilities

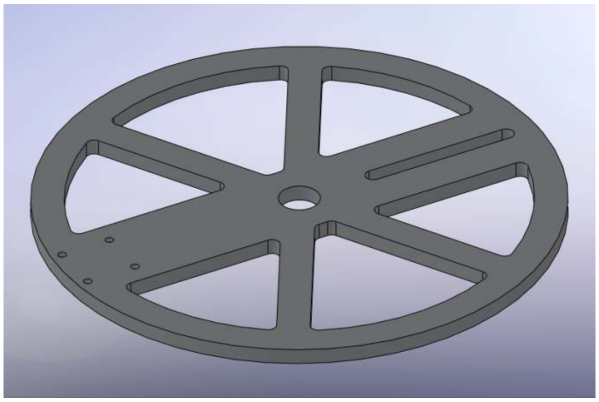
The majority of the remaining work will be shared equally among the team members, with lead roles given to those best suited. Josh has extensive machine shop experience and will be taking the lead on the production of the custom components. He will also play a critical role in the design of the motor controller, making use of his additional experience with robotics and programming. Hechen and Yiqi will share the lead in the design and analysis of the system dynamics involved in the project. Max will be tracking the budget and overall progress of the project to keep things on track. Mike will share lead roles in project management and composition of reports and documentation.

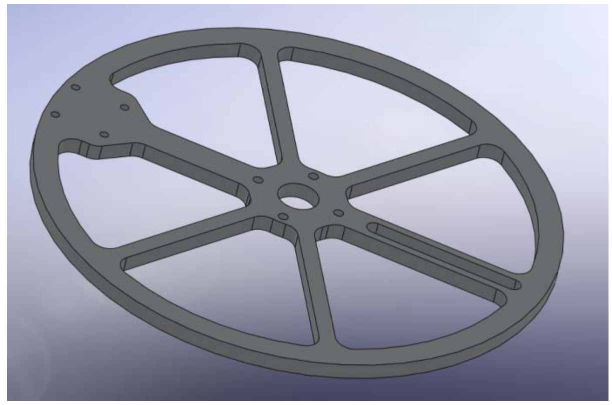
PARAMETER DETERMINATION AND DESIGN CHANGES

The team determined that most of the parameters for the two small systems can be drawn from the given prototype. Those include most of the shapes and sizes of the parts and control methods. The few changes of parameters between the given prototype and the alpha design include changing the rotating arm to a wheel, rounding the motor mount and base plates, and replacing the overhead wiring with a solar-powered infrared data transmission system mounted on the rotating wheel. In addition, two major changes were made to the alpha design of the small systems since Design Review 3:

- The width of the spokes in the rotating wheel was reduced in order to reduce the rotational inertia and improve system response. As shown in Figure 17, the spokes were initially ½" wide in the alpha design, which made the mass of the wheel significantly larger than the rotating arm used in the original prototype. To make sure the motor is still able to drive the system quickly enough, the rotational inertia of the wheel needed to be minimized. This was accomplished by reducing the spoke width to ¼" as well as reducing the dimensions of other non-critical areas. The resulting dimensions retain the necessary strength and have the side benefit of more closely resembling the wheel on the large device. Similar dimensional changes were made on the small passive device.
- A stabilizing hub was added under the wheel of the small passive system. In the alpha design, the wheel of the passive system sits on a shaft with a diameter of 1". It was determined that this design wouldn't keep the wheel true to the shaft adequately, and that a stabilizing hub with a flag diameter of 2 inches, as shown in Figure 18, would address this issue well.

Significant progress has also been made to the infrared data transmission system since DR2. Validation testing was done using an evaluation setup to transmit the encoder signal to the motor controller on the existing prototype. The test results showed that the experimental system now is able to balance the pendulum when the pendulum was initially in the inverted position. The system isn't currently able to transmit fast enough to be fully functional, but an improvement to the signal processing is in progress and should solve this problem.





Alpha design Final design

Figure 17: The Spoke Width of the Rotating Wheel was Narrowed From ½” to ¼” in Order to Reduce the Rotational Inertia of the Wheel

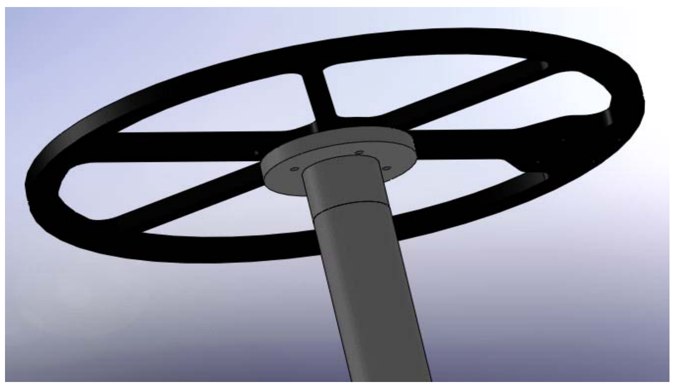


Figure 18: A Stabilizing Hub was added to the Small Passive System to Keep the Wheel True

Large Manual System

The general look and size of the large system design has not changed significantly since the alpha design. The pendulum arm length was suggested to be 36 inches by the sponsor. The control wheel diameter was determined to be 16 inches, given that the diameter of the table on which the system will sit is about 24 inches. It was agreed within the team and sponsor that the wheel diameter should be a little smaller than that of the table so as to avoid some safety issues, such as to prevent children from hanging on the wheel.

Changes from Alpha Design

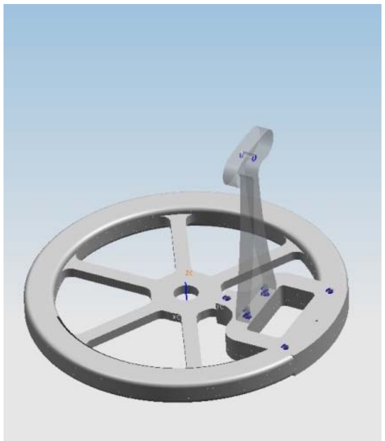
While the main theme of the design remains the same, the team did some adjustment to the alpha design due to some safety and manufacturing considerations.

Changed the shapes of the control wheel and stopper As shown in Figure 19, the base of the stopper was changed to increase its strength. It was also decided that it would be best to attach the stopper to a flat plain on the redesigned wheel. The 3” distance between the mounting screws will give the stopper adequate resistance to torque loading caused by contact between the pin and the pendulum arm. The stopper was also shortened from 15” to 10” to further reduce the moment at the base produced by the strike force, and thus reduce the force on the screws.

Add the angle and torque limiter As shown in Figure 20, the angle limiter for the wheel has been redesigned since DR2. Two rubber bumpers will stop the shaft from rotating once the key on the shaft hits them, giving the shaft 90° of freedom. To prevent possible damage to the angle limiter, a torque limiter mounted to the wheel which allows rotation beyond 90° with an added frictional force. The amount of resistance generated by the torque limiter is adjustable up to 35 lb-ft.

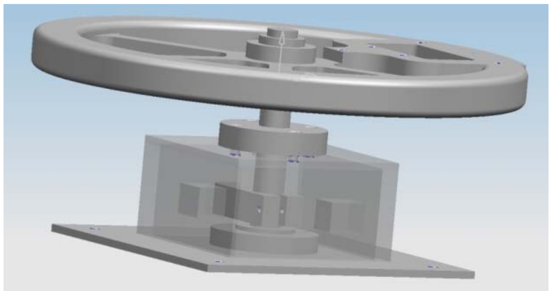
Combined three parts of the pendulum arm into one As shown in Figure 21, the lower three parts of the pendulum arm in the alpha design are combined into one piece in order to avoid the alignment problem between the bearing and slot block. The pendulum arm is also strengthened compared to the alpha design. The size of the bottom part is 1.25"x1.5" in the final design. The upper part is an aluminum tube with an OD of 1" and ID of 0.5".

Alpha design for wheel and stopper

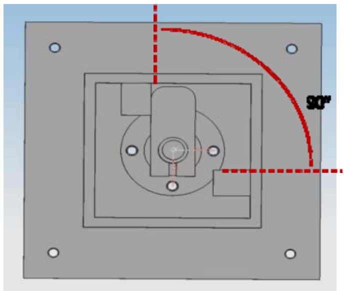


Final design for wheel and stopper

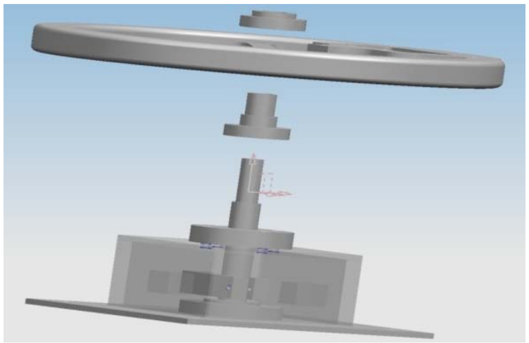
Figure 19: Design Changes of Control Wheel and Stopper



Over view of the angle and torque limiter design



Top view of the angle limiter



Exploded view showing torque limiter attachment to wheel

Figure 20: The Angle and Torque Limiter Design

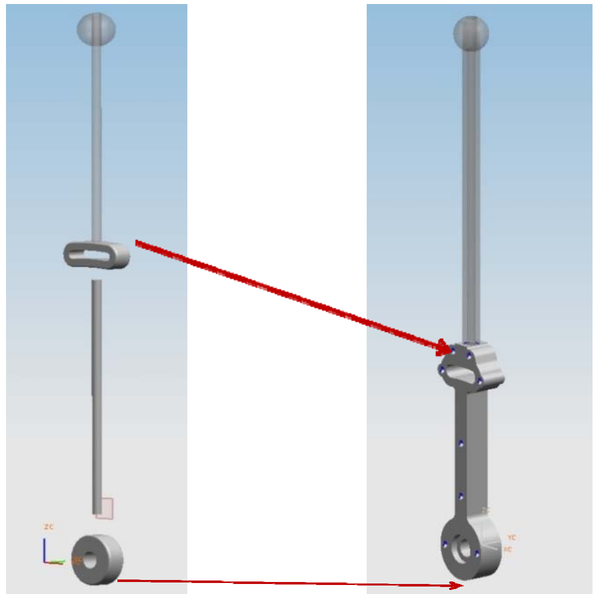


Figure 21: Three Parts of Pendulum Arm Combined Into One

FINAL DESIGN

This section describes the three devices designed for the Inverted Pendulum Exhibit. Each device is present individually; however there are many similarities, especially among the smaller devices. Due to the large number of individual components, many of the dimensioned drawings will be placed in Appendix J. The description of the electrical system for the automated device will be described here although some of the details are still being tested. Below are the CAD assemblies of each exhibit.

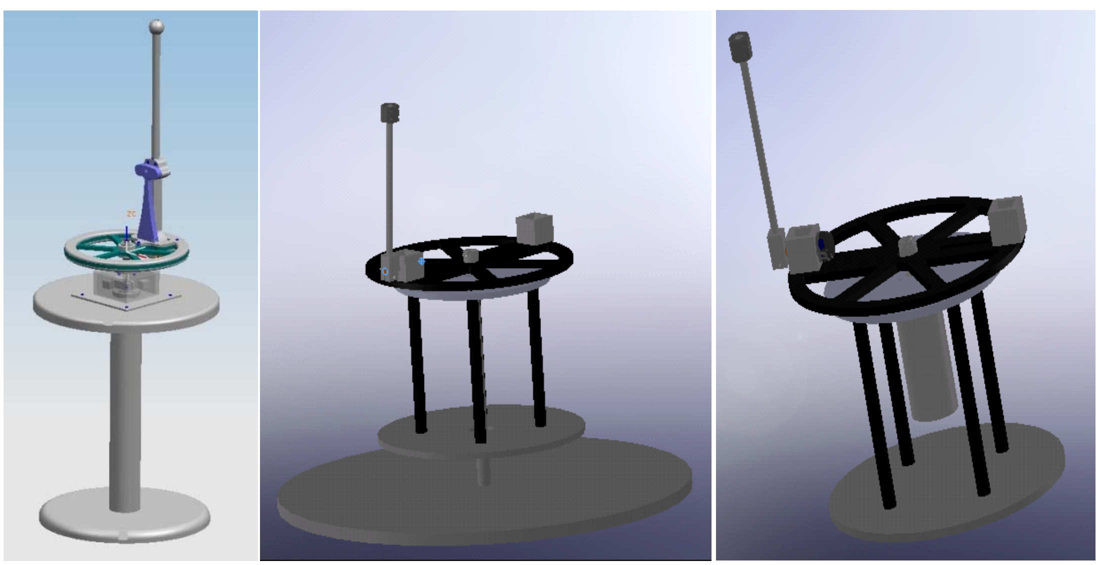


Figure 22: Large Manual Exhibit, Small Manual Exhibit, and Small Automatic Exhibit

Large Manual Exhibit

The large manual system allows museum patrons to attempt to balance an inverted pendulum with a long heavy pendulum arm. Through dynamic analysis the length and weight of the pendulum was optimized to have a natural frequency that would give a period larger than the average human reaction time. This helps to ensure that the museum patrons can successfully balance the pendulum. Also, the pendulum motion is limited to 10 degrees to further help the patrons. This motion is controlled by stationary pin that is inserted into a slot in the pendulum arm, as shown in Figure 23.

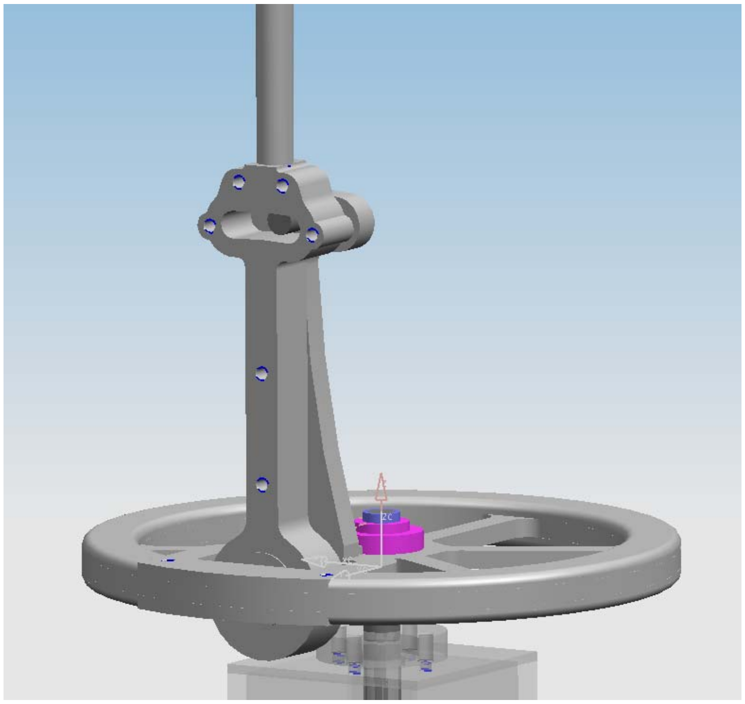


Figure 23: Angle Limiter Constrains the Pendulum Arm to 10 Degrees of Motion.

The pendulum arm is an assembly made of four pieces. The lower assembly, shown in Figure 24, is made of two ¾" pieces of aluminum that will be bolted together, shown in Figure 25. This helps to increase the strength and durability of the pendulum arm. The upper assembly is comprised of a 1" aluminum tube with ¼" wall thickness with a 2" spherical steel weight attached to the top. This assembly is clamped into the cavity in the top of the lower assembly. Supporting the pendulum arm will be two ball bearings placed in the bottom cavity of the lower assembly.

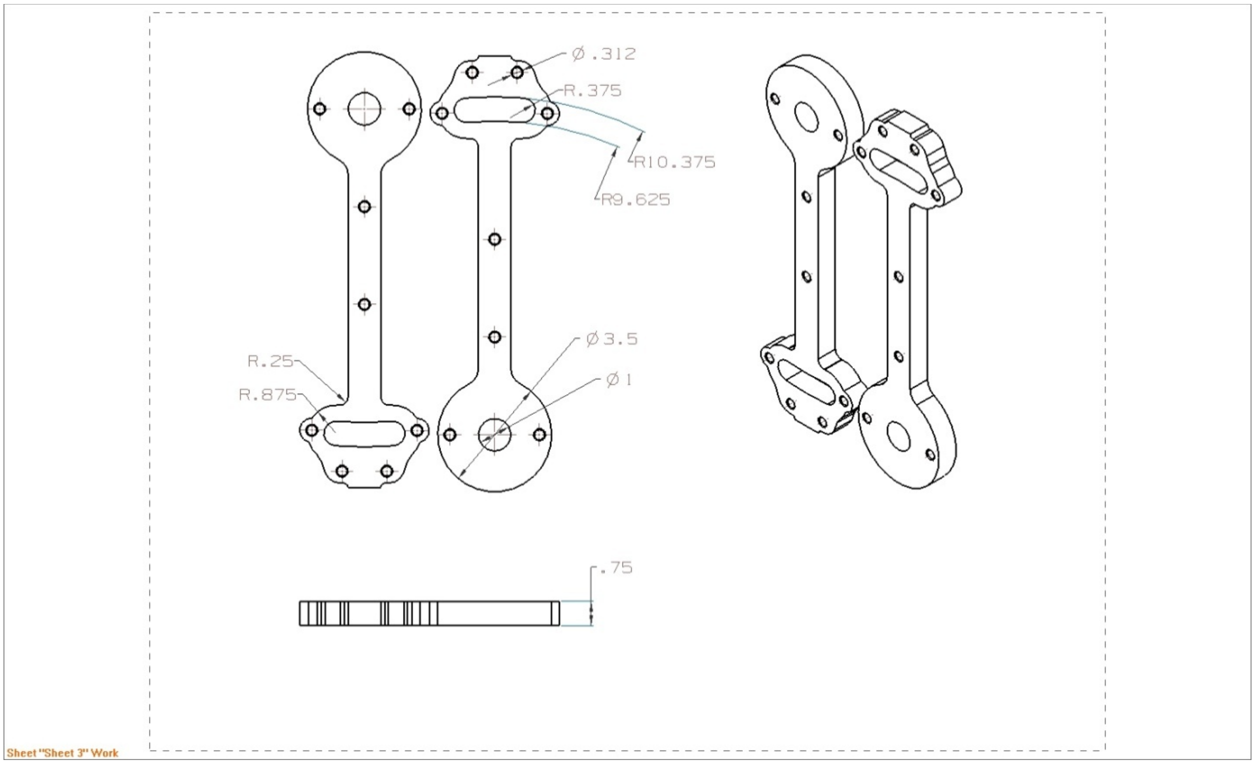


Figure 24: Dimensioned Drawings for the Two ¾" Halfs of the Lower Pendulum Arm Assembly

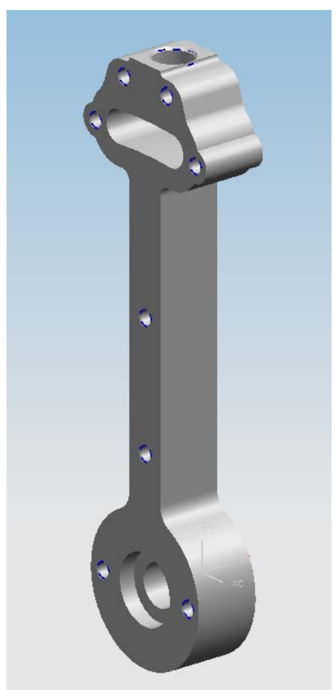


Figure 25: Lower Pendulum Arm Assembly

Another important feature of the large manual system is the angle limiting design, shown in Figure 26. This design limits the motion of the control wheel to 90 degrees. After the wheel reaches the 90 degree limit a torque clutch, shown in Figure 27, is activated. This clutch allows the wheel to continue to spin with up to 35 lb-ft of resistance. This will prevent abuse of the exhibit through free-wheeling and also prevents the damage that would occur if wheel was to only have the 90 degree hard stop.

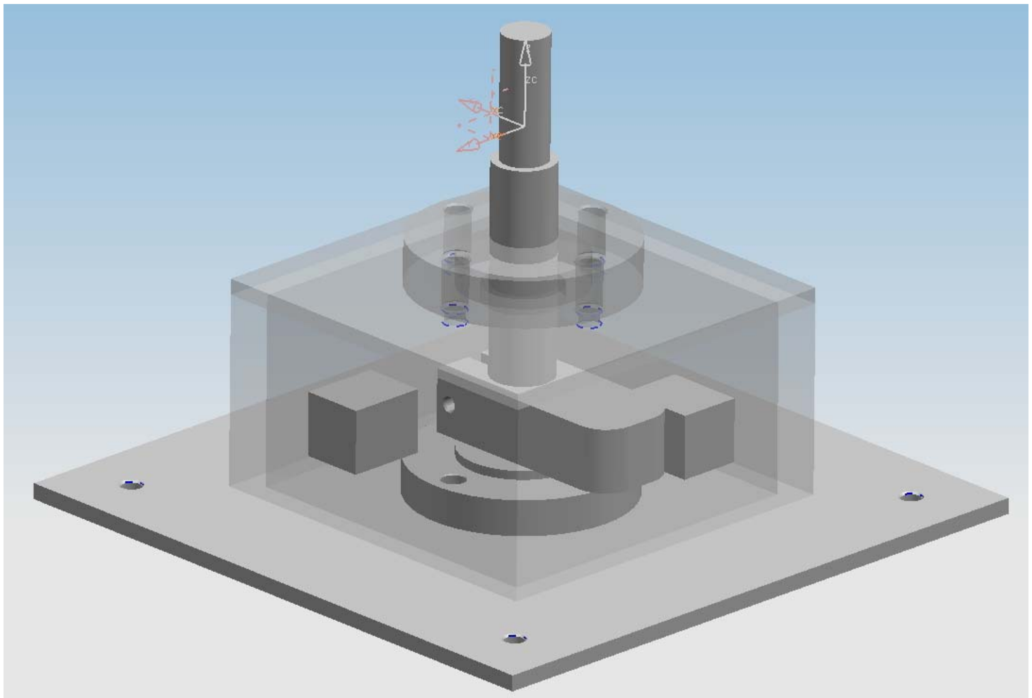


Figure 26: Angle Limiting Design

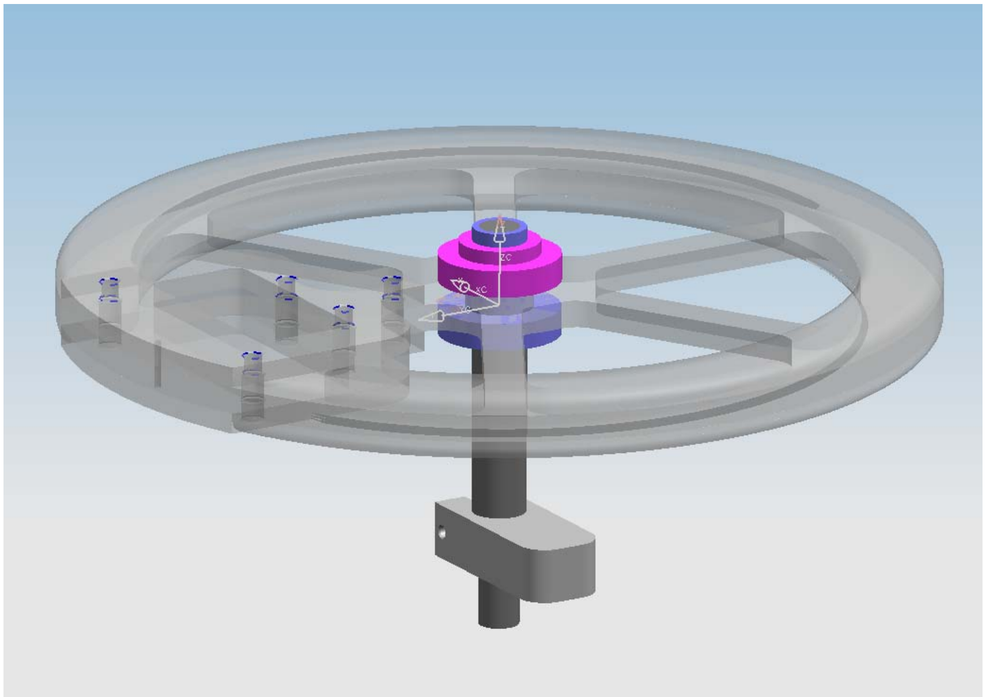


Figure 27: Torque Clutch

This exhibit, shown in Figure 28, has been designed to look similar to the smaller exhibit to help the patrons understand the concepts behind the feedback controls.

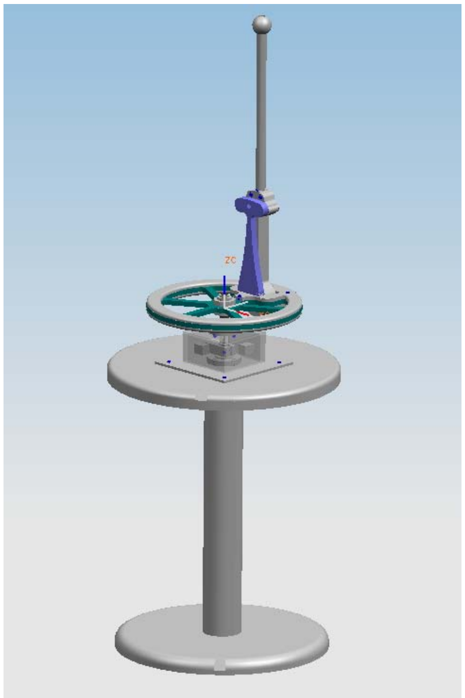


Figure 28: Overview of Large Manual Inverted Pendulum System

Small Manual Exhibit

The purpose of the small manual system is to allow a museum patron to attempt balancing a short pendulum. The pendulum has been sized such that this should prove very difficult to do, emphasizing the capabilities of computer-controlled systems. . This exhibit has been designed in conjunction with the smaller automated system to reinforce the concepts of Mechatronics and expedite the manufacturing process by having many identical components.

While the exhibit should prove difficult to balance for most people, a limit has been attached to make it more simple. Rather than trying to swing the pendulum up from a hanging position, the pendulum will be held within at 10^{o} range of vertical. This will not only make the exhibit less frustrating, but will also eliminate the need to rotate the device vigorously, reducing the risk of damage to the exhibit. This angle limiter can be seen below in figure 30. Also, figure 29 shows a hub designed to make the rotating wheel more stable.

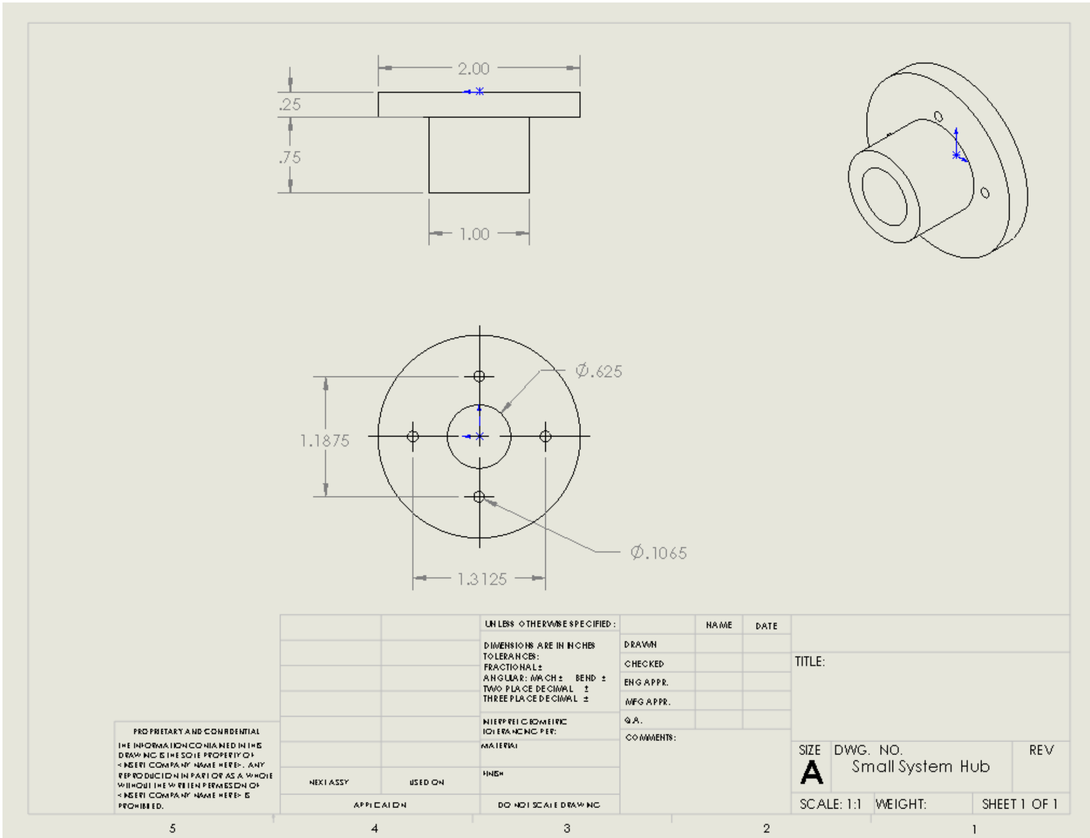


Fig 29: Hub Attaching Control Shaft to the Pendulum Wheel

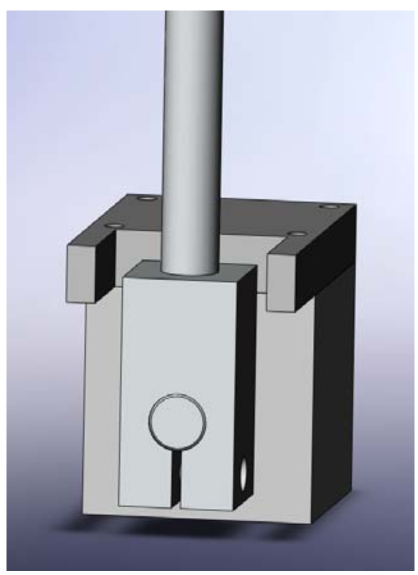


Fig 30: Stopper Allowing 10^o Range of Motion

Automated Exhibit

The automated exhibit is physically very similar to the smaller manual device. The dimensions were kept as similar as possible to tie the exhibits together aesthetically. Also, having a short pendulum, the exhibit demonstrates the ability of computer-control to tackle difficult problems. The following are some of the key features of the automated device, including the control wheel (Figure 31), the pendulum attachment (Figure 32), and the motor attachment (Figure 33).

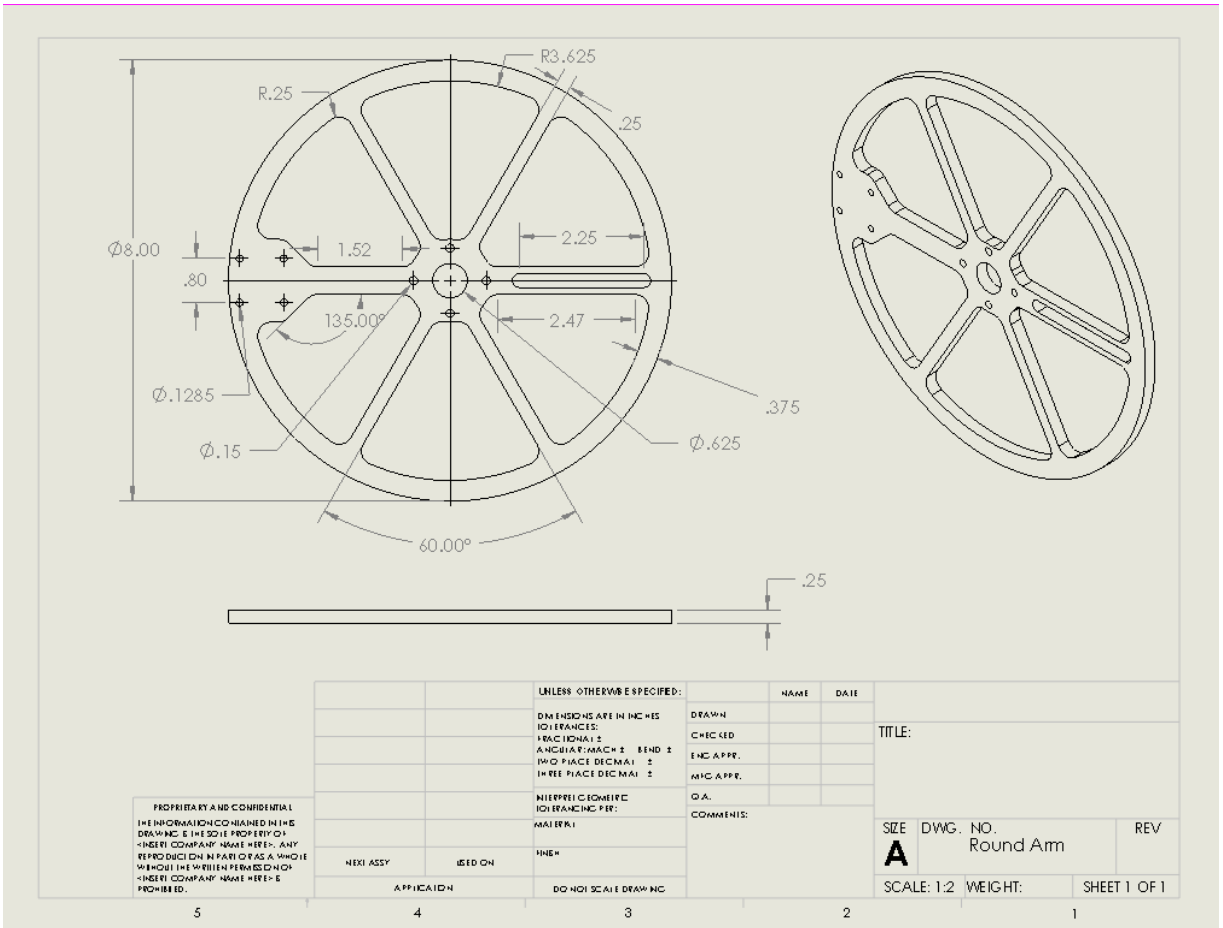


Fig 31: Dimensioned Drawing of Control Wheel

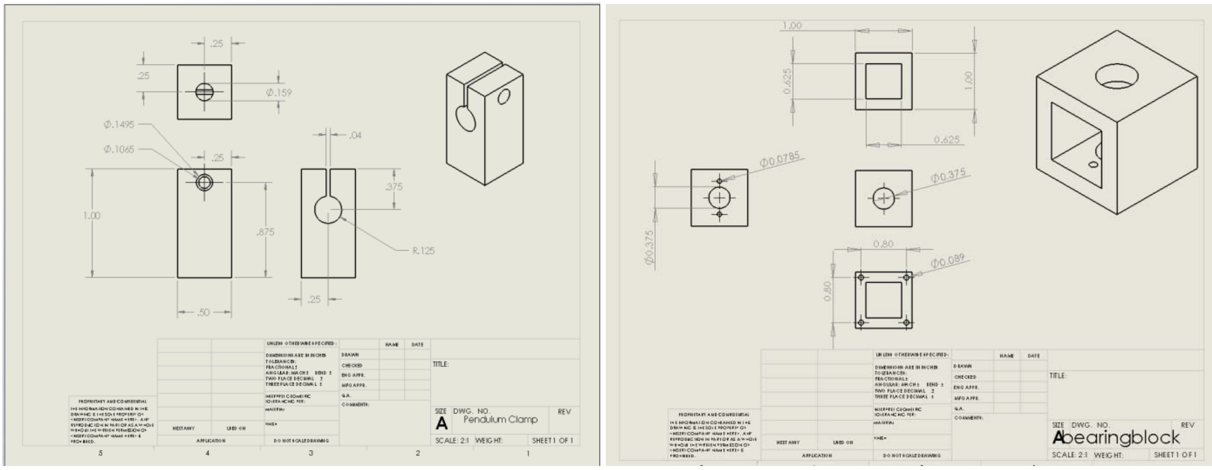


Fig 32: Dimensioned Drawing of Pendulum Attachment Clamp/Bearing Block

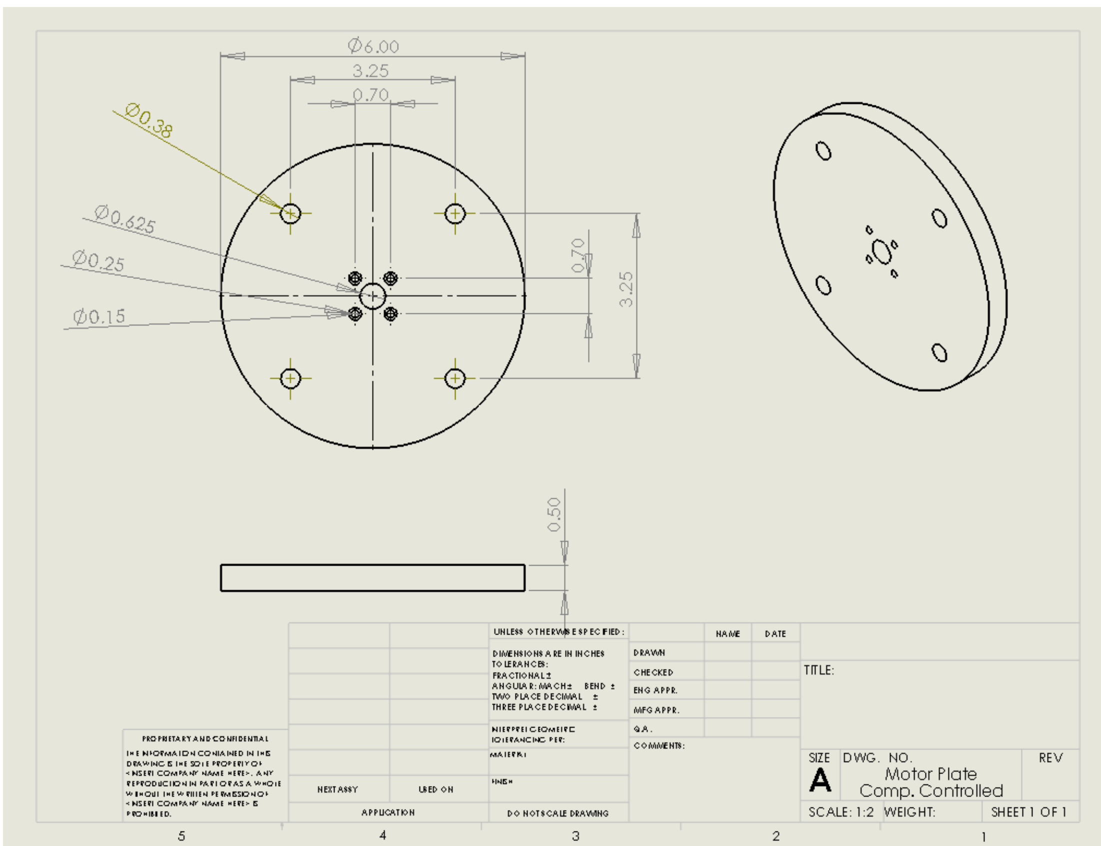


Fig 33: Top Plate with Motor Attachment Holes

The electrical features of the automated exhibit can be separated into four major tasks: the pendulum position decoding/transmitter, the pendulum position receiver, the motor position decoding, and the motor control. These have been combined into a “Transmitter” circuit, which will be placed on the moving wheel of the exhibit, and the “Receiver/Controller” circuit, which will be on the table of the exhibit. Specific component part numbers and descriptions can be found in Appendix H in the electrical bill of materials.

The transmitter side of the automated system begins with two 6-Volt solar panels providing approximately 100mA of current. These two panels will be placed in parallel to increase the total current output to around 200mA, which should be far more than is required by this circuit. This power will then be regulated to 5VDC and distributed to an optical angle encoder, a quadrature decoder, an 8-bit microcontroller, and an infrared LED. The optical encoder can provide up to 1440 pulse/rev accuracy, which will be decoded into a series of pulses with direction that will be sent to an 8-bit HCS08 family microcontroller. This microcontroller will use the decoded signal to calculate the position and angular velocity of the pendulum, transmitting it to the receiver via an infrared LED modulated to 455kHz. This signal will use 3 bytes of information which will be transmitted at 20kBits/second. A schematic for this can be seen in Figure 34 with the math to determine the encoder resolution and expected error in Appendix G. From this

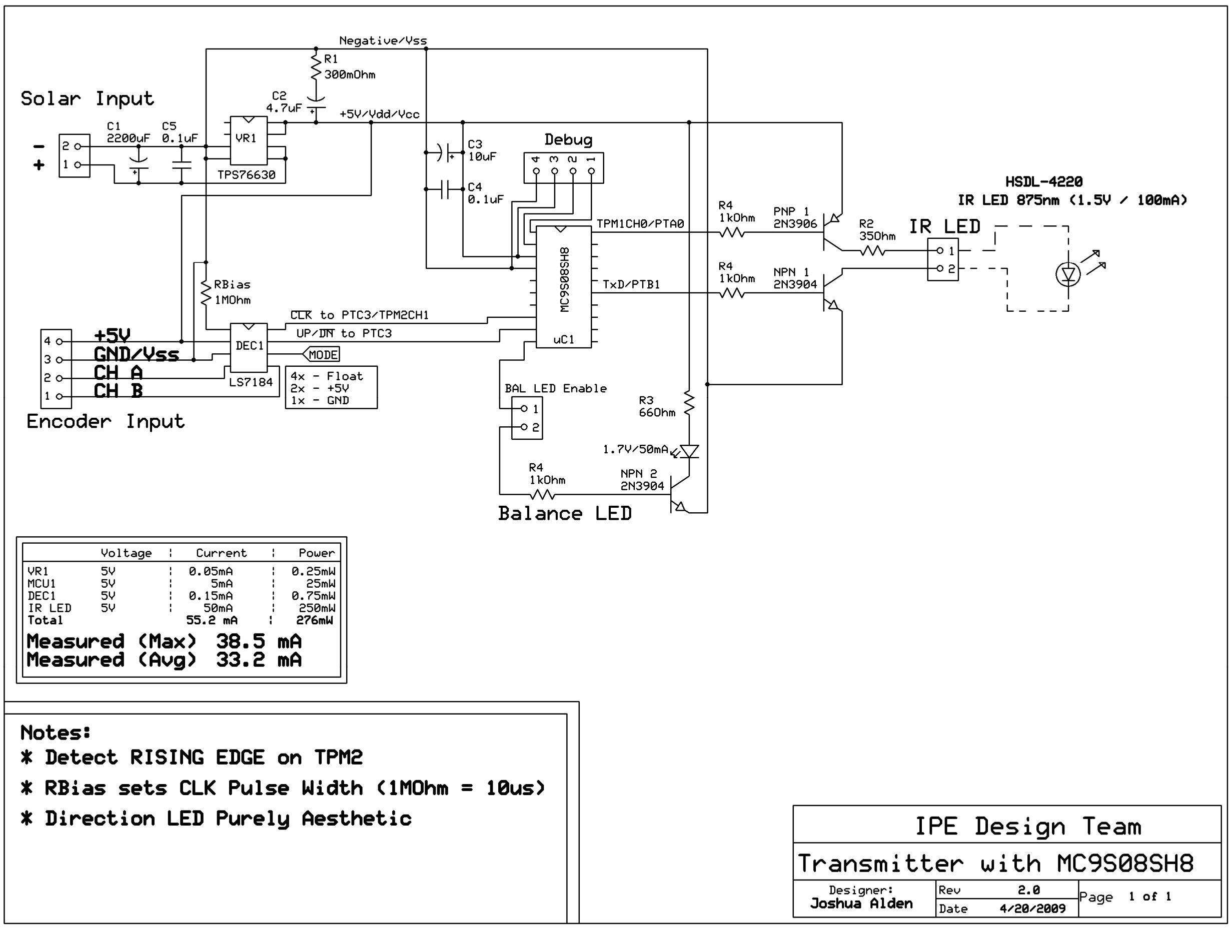


Fig 34: Schematic for the Solar-Powered Angle/Velocity Transmitter Circuit

The receiving end of the system will begin with the TSOP7000 IR Receiver from Vishay Semiconductors, and the schematic follows in figure 35. This device amplifies, filters, and demodulates the infrared signal resulting in a serial data output that can be input directly to the serial input of the 8-bit microcontroller. In a manner similar to the transmitter circuit, the motor's optical encoder will be processed into a position and velocity. This value will be transmitted to the same 8-bit microcontroller that is receiving the pendulum data via the Inter-Integrated Circuit bus.

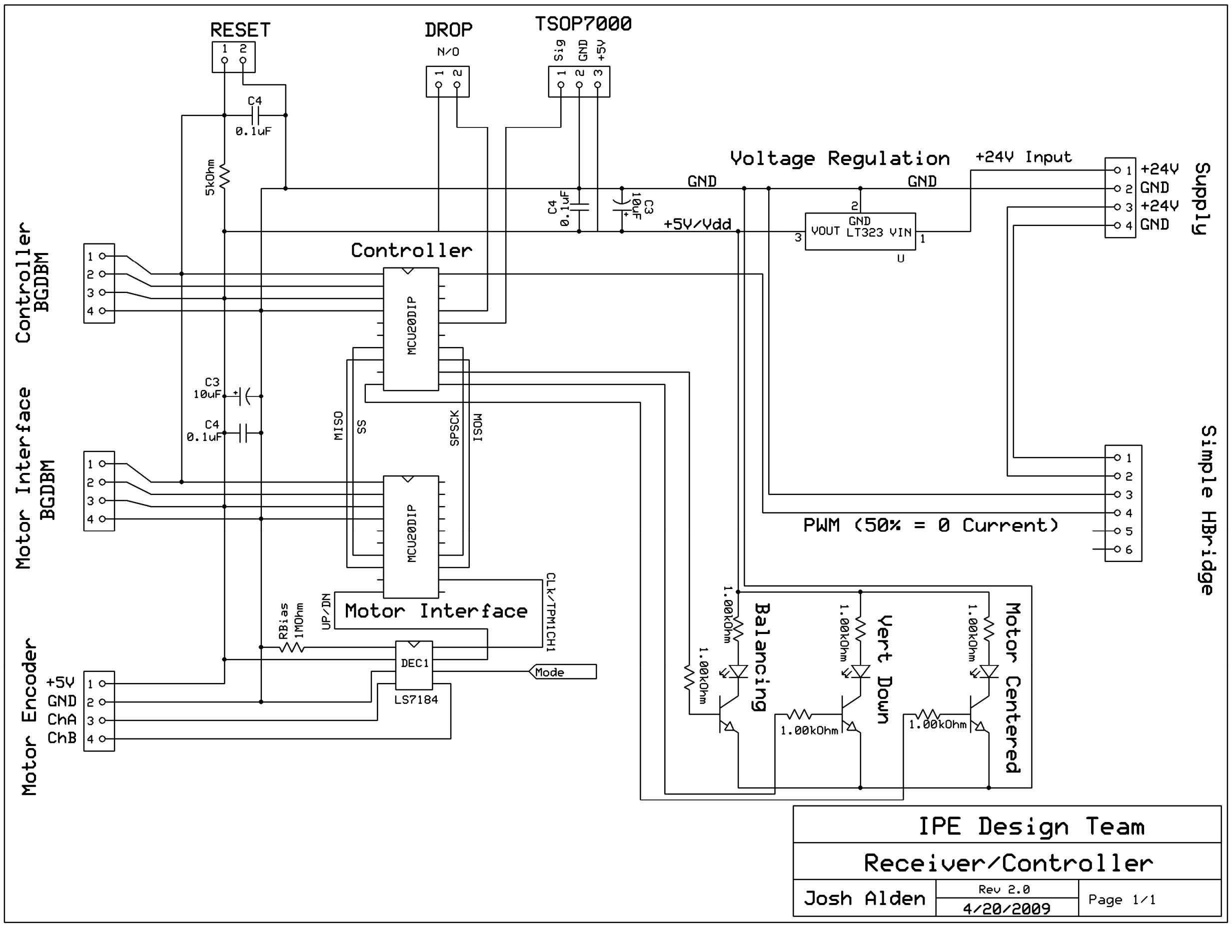


Fig 35: Schematic of Receiver/Motor Control Circuit

The microcontroller that is receiving the velocity and position data for the pendulum and motor will then process this data in a manner similar to that of the prototype's LabView controller. It will then output a Pulse-Width Modulated (PWM) signal corresponding to the desired motor velocity. This PWM signal will then travel to the Simple-H motor controller, which is a full-bridge motor controller shown in figure 36.

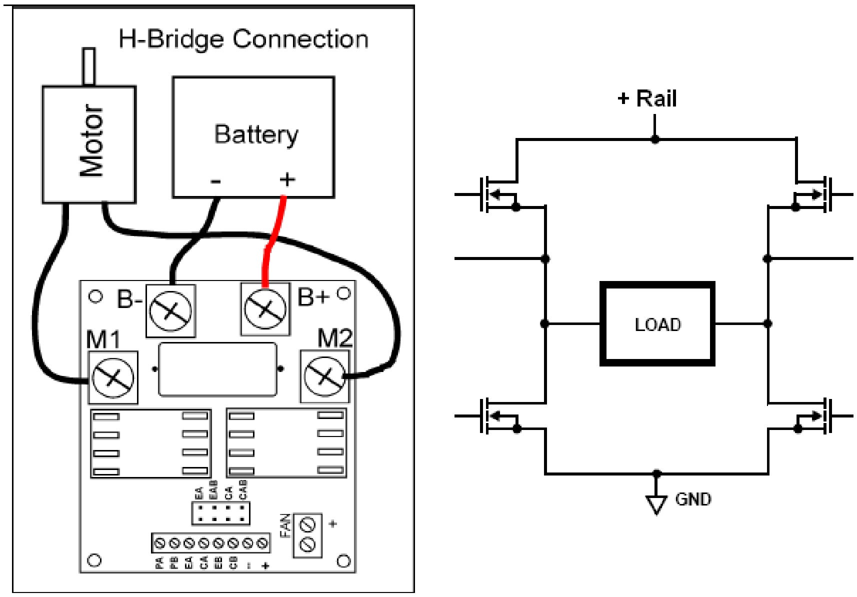


Fig 36: Simple-H Motor Controller Connections and Basic Electrical Schematic

This full-bridge controller can run the motor from full forward to full reverse using four power MOSFETS. It is rated above the maximum power rating of our motor and also includes internal thermal and inductive-kick protection.

PROTOTYPE DESCRIPTION AND CHALLENGES

The final prototype produced will be delivered to the Ann Arbor Hands-on Museum where it will be a functional exhibit for years. For this reason, the final prototype must be a complete to scale system that will closely follow the final design. There are, however, areas of the design that present challenges. The items are listed below:

1) The infrared data transmission system does not transmit data at a fast enough rate to be fully effective. It can balance the pendulum but when the pendulum is swinging at high velocities the infrared data transmission system fails. This problem will be addressed by using a different data transmission method that should eliminate accumulating error that is currently preventing the system from operating.
2) Another issue to be dealt with is the controller programming. The controller will be converted from its current LabView format to C++ code that will be programmed on a microprocessor. The intricacies and component options for this system are currently being explored.
3) The current motor controller is more powerful than required by the system. Therefore, this controller will be replaced by an H-bridge controller that will fit the systems needs.
4) Currently the electronic systems are utilizing a prototyping circuit board. These boards will be replaced by etched circuit boards. The new boards will be smaller and allow for more condensed packaging.
5) The counterweight employed on the manual systems is bulky and unattractive. This counterweight will be replaced by a slotted weight that will be concealed within the rotating wheel.

6) The pendulum on the large manual system is held in place by a shaft fastened by taper pin. This set-up makes it difficult to remove the shaft and perform maintenance on the pendulum arm. This problem can easily be remedied by replacing the pinned shaft with a shoulder bolt.
7) There is also a potential fatigue issue with the angle limiter on the large manual pendulum system. Every time the pendulum arm is stopped by the limiter the majority of the load is applied to a shoulder bolt. The concern is that this bolt will become fatigued and fail after many cycles. This potential failure is currently being researched and tested.

FABRICATION OF COMPONENTS

One of the goals of this project is to use parts and components that are either readily available or easy to reproduce. For this reason, the majority of the parts we designed are primarily two-dimensional with a small number of additional machined features. The number of critical dimensions was kept to a minimum so that machine shop time would be kept to a minimum. The overall design is intended to be robust enough to withstand years of service without failure, but it is impossible to design for every possible scenario. The following sections will describe the parts and the production processes involved.

Materials

The materials used in this project have been selected based on factors such as cost, appearance, strength, and ease of machining and finishing. For the most part, the specific materials were predetermined and/or dictated by our sponsors. We did perform failure analysis and made use of the Cambridge Engineering Selector software to verify the materials based on specific applications.

The majority of the components that we will be fabricating will be made of 6061 Aluminum. This material was chosen because it is relatively available and affordable. It is also very easy to machine and provides a variety of finishing options ranging from hand polishing to anodizing. Aluminum also has a relatively low density, which makes it a good choice for the rotating components as it minimizes rotational inertia.

Nearly all of the hardware components are made of various steel alloys. The screws used are either carbon steel with a black oxide layer or stainless steel depending on location. This provides different visual contrast where appropriate. All of the rotating components are supported by ball and/or tapered roller bearings to reduce frictional damping and extend component life cycles.

Other materials were used for certain specific components. The base of the table consists of a 2” diameter schedule 40 stainless steel pipe attached to a cast iron base. Black ABS plastic will be used on the gripping surfaces on the large wheel, providing a comfortable contact surface with an interesting color contrast to the aluminum wheel and pendulum. A 1” diameter schedule 40 aluminum pipe will support a 2” diameter stainless steel ball at the top of the large pendulum. Rubber blocks will be used as stoppers in the base of the large wheel to absorb impact in the 90° rotational limiter.

Pendulum Wheels

The wheels for all three devices are designed with certain features intended to tie the exhibit together as a whole. For the smaller devices, rotational inertia in the top wheel is a concern, so they were designed to minimize mass while retaining an adequate level of strength. The wheel on the large device is the primary point of contact for the user, and thus requires a substantially higher level of strength. As shown in Figure 36 below, certain visual cues in the wheel design help to carry over a similar appearance from one device to another.

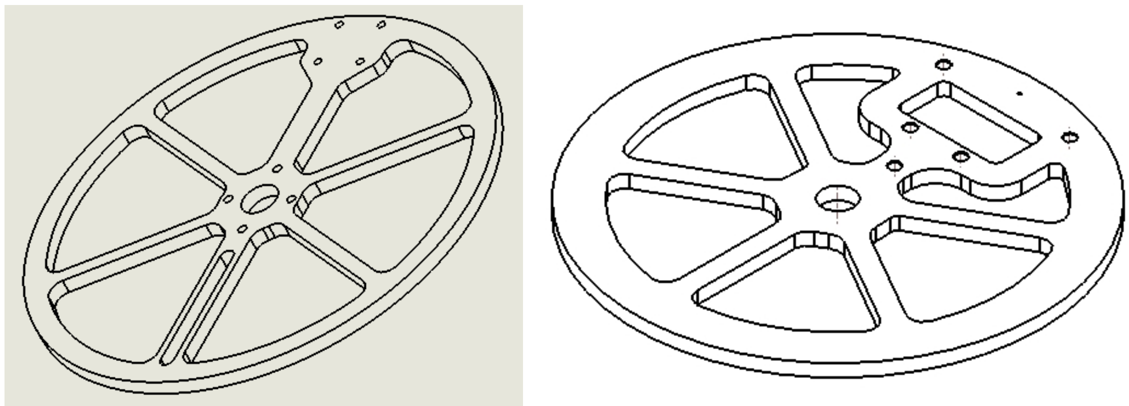


Figure 37: Wheel Design for Small and Large Devices Share Key Visual Features

The large wheel is a laminated design. The main component is made of ¾” thick aluminum plate and includes all of the features of the wheel as a whole. A recess will be machined in the center to accommodate the torque limiting clutch. The mounting location for the pendulum was designed to accommodate the torque loading that will result from the contact between the pendulum and the stopper plate. This section of the wheel will be further supported by 3/8” thick support plates, shown in Figure 38 below, which will add strength and contribute to the visual appeal of the device. The remainder of the hand rim area will be covered top and bottom by black ABS plastic that will be contoured for comfort. This will also contribute to the visual appeal of the wheel by adding an interesting contrast.

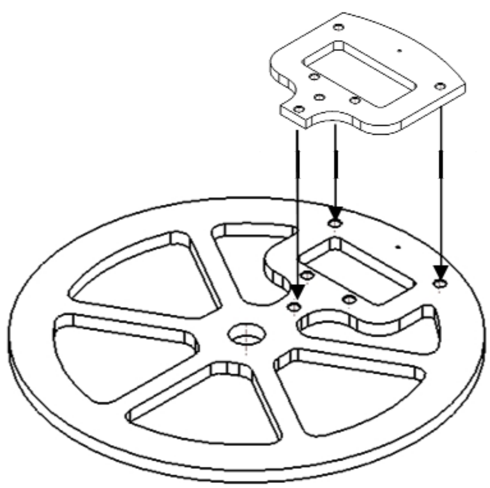


Figure 38: Support Plates Will Reinforce the Pendulum Mounting Location on the Wheel

Large Pendulum

The large pendulum needs to be highly durable. It will be supported in the opening on the large wheel by a ¾” shaft and flanged ball bearings front and back. The lower section of the pendulum will be made of two ¾” thick aluminum pieces sandwiched together. The upper part will consist of a 2” stainless steel ball filled with steel shot for ballast. This will sit atop a 1” OD schedule 40 aluminum pipe. The bottom of this pipe will contain a plug and an interference fit will keep it in place on the lower portion. A roll pin will be installed from the back side to insure that it will remain in place.

Mounted to the wheel directly behind the pendulum will be the stopper plate. This plate is designed to limit the motion of the pendulum to 10° on either side of vertical. Its shape, in conjunction with an acrylic plate covering the front side of the opening in the pendulum, eliminate the pinch points that would otherwise exist. Figure 39 below shows how the pendulum and stopper plate interact via the pin located in the slot.

Figure 39: Pendulum and Stopper Plate on Large Device Eliminate Pinch Points and Limit Travel to 10° on Either Side of Vertical

Other Components
The remaining components of the design consist of purchased parts and simple two-dimensional components. These consist of the top and bottom plates on the smaller devices and the case for the large wheel base.

MANUFACTURING PROCESSES

As stated earlier, our design is intended to be relatively simple to manufacture, requiring fairly simple processes to minimize expensive shop time. To accomplish this, we kept tolerance requirements to a minimum wherever possible to allow the use of less time-intensive procedures.

Water Jet
We will be making extensive use of the OMAX 2626 Jetmachining Center in the ERC, as the number of parts that need to be machined would otherwise require more time than allotted for the project. While the water jet cutter has drawbacks in the sense that it can only produce two-dimensional parts and has somewhat limited tolerance capabilities, it more than makes up for its shortcomings in production rate.

Among the main advantages to using a water jet is that setup and production time are far shorter than for most other processes. To make many of our parts on a mill would require numerous tool changes, long setup times and extensive amounts of cleanup. To use the water jet in the ERC, one only needs to produce two-dimensional CAD drawings in .dxf format. The software in the lab will take the drawings and automatically develop the appropriate tool paths and rates based on the type and thickness of the material. Machine setup requires nothing more than simple clamping of the material and setting the coordinate axis. The part is then submerged and is cut under a layer of water to eliminate any mess. The only cleanup required after the part is made is a simple rinsing with a water hose to remove any leftover abrasive or debris.

Lathe
Hubs will be produced to reinforce the mounts on the small manual device at the top and bottom of the rotating shaft. These hubs, as seen in Figure 40 below, will insure that the top wheel and the control wheel will remain true in reference to the shaft itself. These hubs will be machined on the lathe from 6061 aluminum and will attach to the shaft with an interference fit and a roll pin.

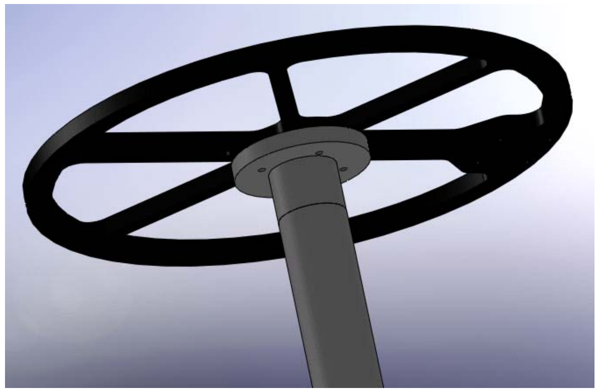


Figure 40: Hub Adds Support to Wheel and Keeps it True to Shaft

Mill
In general, our design requires relatively low precision in the dimensions of holes in parts. This was done to allow as much production work as possible to be done using the water jet, as it is much faster than milling operations. However, certain features will require the use of a mill. These include a small number of holes that will be threaded and/or require precise location for a proper fit between components.

A recess will be added to the center of the large wheel to accommodate the installation of the torque limiter, as it can accommodate a maximum thickness of ½”, including the steel wearing surfaces that we will be adding. The thickness of this center section needs to be maximized and the edges will need to be radiused to retain the overall strength of the part.

The mill will also be used to apply edge treatments where required for aesthetics and safety requirements. The edges of the parts produced on the water jet are generally sharp and need to be deburred at the least. Rounded edges are generally less susceptible to fatigue failure and are required on any part that will be accessible to the user.

Electronics
The circuit boards for the transmitter side of the control circuit will be custom made and etched and will mount within two of the cutouts on the wheel of the small automated unit. These boards will contain the onboard processors that will convert the output from the optical encoder on the pendulum shaft to a signal containing angle and direction in a digital modulated signal. The solar cells will be mounted overhead and will protect the circuit boards from the intense direct lighting that will be provided overhead from a 20W MR16 quartz halogen bulb.

Assembly
All three devices were designed for assembly utilizing simple hand tools. Most of the assembly requires nothing more than a screwdriver and a set of hex wrenches. The electronics are comprised of off -the-shelf electronics that consist of plug in modules, with the exception of the basic resistors and transistors that are soldered to the circuit boards. Most of the mechanical components are assembled with bolts threaded into holes in the components. This was done to allow for ease of repair and maintenance while in service.

DESIGN VALIDATION

Requirements for aesthetics, interaction, electronics and mechanical behavior were established by the Ann Arbor Hands-On Museum. The testing and simulations discussed in this section are designed to validate the final designs and ensure all the electrical and mechanical specifications are properly met. This testing is ongoing and will be conducted though the month of April when the three systems are fully assembled.

Testing to be Performed

1) Stand-Alone Control Circuitry (in progress)

This testing involves detailed verification of each component of the control circuitry from decoding the quadrature signals and counting them properly to basic infrared and serial communications between microcontrollers. Each test is specific to the program algorithm used and will be described further in the Validation Results section on the following page.

2) System response to increased inertia (done)

In the latest design, the pendulum is attached to a wheel instead of a rotating bar. The wheel will result in a significant increase of rotational inertia at the end of the motor shaft which dramatically changes the system dynamics. The test results show that the current Labview program provided by the sponsor can balance the pendulum when it is initially in the inverted position. However, the complete set of parameters for the new setup will need to be determined through further experimentation.

3) Research gain values in the Labview program

Some modifications must be made to account for the increased rotational inertia incumbent in the new design. Theoretically, the change in the rotational inertia will result in a change of the gain values in the control system. Specifically, motor and pendulum speed and position gains will be changed. They can be calculated from the dynamic model developed in DR1. However, theoretical calculation maybe inaccurate because there are other accessories on the wheel that are difficult to model, such as the solar panels and the microcontrollers. A more practical approach may be to use a trial and error method to determine the correct gain values once final assembly of the device is completed.

4) Stability of the large system

After the large system is assembled, testing will be done to simulate the type of use and abuse the device will be exposed to when it is in service. The goal of this testing will be to prove that it functions as intended and that the overall design is safe and durable.

5) Ease of operation of the manual systems

As required, the small system will be difficult to balance while the large system is easier. Therefore, when the two manual systems are built, the team will test how easy it is to operate them and tune the devices to meet this requirement.

6) Simulations and Calculations

Stress analysis: In the exhibit application, the stresses in the systems are relatively low compared to the yield stress of the 6061 aluminum alloy. However, due to the heavy daily use in the museum, fatigue failures must also be taken into account. Identified weak points will be further analyzed; fatigue load cycles will either be calculated by hand or though finite element analysis programs. An estimation of the life time/total number of load cycles will be the final deliverable.

Simulation of rotational inertia: This simulation will be done in the CAD program to help access the sizing of the motor relative to overall design. This information can also help provide a rough estimation of how to modify the gain values in the Labview program by completing the dynamic model.

Validation Results

To gauge the success in meeting customer and engineering specifications, many tests have been conducted. For the manual systems, these tests have generally been simple and qualitative. The automatic system, however, has required far more complex testing and results in a more qualitative "functioning" or "not functioning." These tests, both for the manual and automatic systems, have verified that many of the project tasks have been completed, or will be easily met with future work. The following sections break down the testing conducted on each system.

Large Manual System

The test results for the larger manual system are very promising for a successful museum exhibit. Testing of the device is largely completed by simply by using the device. The project had five main goals for the large manual system listed below.

Goals:
- Easily Balanced
- Robust
- Intuitive Use
- Safety
- Aesthetics

Aesthetics, Safety, and Intuitive Use were all verified during the Design Expo when patrons of the expo were attracted to the device and able to use it without explanation or injury. In asking many people that used the device, many agreed it was easy to use and simple to understand how key components worked. While specific aspects of safety were not tested, the safety devices implemented were proven to work as designed. These include the pendulum stop preventing motion beyond 10 degrees and the wheel stops preventing motion beyond 90 degrees. The friction clutch which allows for resisted motion beyond 90 degrees also appeared to be functioning properly.

From observations during use, two key components were identified for improvement. The aesthetics of the device had not been completed, and questions on material finish were brought up by Design Expo patrons. This system also appeared more difficult to balance than was initially intended. Each of these issues will be easily addressed by completing the finishing process and adding weight to the pendulums capping ball.

Require Future Work:
- Easily Balanced: Add weight to pendulum ball.
- Aesthetics: Complete finishing of material (polishing, masking, sandblasting).

Small Manual System

This system was tested similarly to the larger manual system. Many of the results are again qualitative and derived from public use during the Design Expo. The results generally met or exceeded the team's expectations. During use, patrons were able to use the device without explanation and appeared to find the pendulum extremely difficult to balance. Again, no one was injured using the device, nor was it broken. The aesthetics did again come into question, however not as frequently as with the larger device. Upon completing the finishing work planned for the device, it is believed that the aesthetics of the device will also meet the Ann Arbor Hands-On Museum's expectations. This is summarized below.

Goals:
- Difficult to Balance
- Robust
- Intuitive Use
- Safety
- Aesthetics

Require Future Work:
- Aesthetics: Complete finishing of material (polishing, masking, sandblasting).

Small Automatic System
Mechanically, this system has also met all but the aesthetic requirement of the project, which must simply be completed as planned. The electronics have not fared so well and require more work and development. Many of these issues have arisen from excess noise and programming errors which must addressed individually. Due to the complexity of the electronics, this section has been divided into the general goals followed by specific electronic goals.

Besides the electrical system and some finishing, the general goals of the automatic system have been met. The system is very similar to the prototype developed in a previous project, which proved the mechanical setup of the pendulum, motor, counterweight, and base setup. Minor changes to accommodate electronics seem to have affected the setup minimally after having the new top wheel balanced with the prototype setup which originally used a straight flat bar. The single “Drop” button seemed intuitive to use, as many patrons of the Design Expo pressed it, often repeatedly, even without having any affect on the device since it was not functional. Safety beyond the electrical fusing and proper wiring will be provided by encasement. This has not yet been produced by the Ann Arbor Hands-On Museum, and thus cannot be tested. Reasonable encasement, utilizing something such as 1/4” thick Polycarbonate plastic should provide ample protection in the event of pendulum arm detachment. The final finish has not been completed either, but upon asking Design Expo visitors, the relationship between the automatic and manual systems did appear to be obvious.

General Goals:
- Robust
- Intuitive Use
- Safety
- Aesthetics

Require Future Work:
- Aesthetics: Complete finishing of material.

Testing of the electrical system has been far more complex and detailed. This intends to give an overview of the key components tested, however further testing is still required. The testing of the system has been done utilizing the microcontroller's Background Debug Mode (BDM), a basic multimeter, and an OWON Digital Oscilloscope (Model#PDS5022S). The following list describes each of the key aspects of the electrical system and the testing for it. Balancing the system with the stand-alone circuitry has not been tested due to the present servo amplifier controlling voltage rather than current. This must be corrected to utilize the control algorithm developed for this system.

Pendulum Angle and Velocity Decoding: The data coming from the E4P optical rotary shaft encoder is a quadrature signal that is simply tested by attaching channels A and B of the encoder to channels 1 and 2, respectively. This was done, which verified that Ch A of the encoder leads Ch B and vise versa properly. The data is then decoded using an LFLS7184 which triggers a clock on the Transmitter microcontroller. Verification of motion count/velocity was verified using the processor's BDM interface.

Infrared Communication: Communication is done over a 455kHz carrier frequency modulated with the pendulum's angle/velocity information. Testing of this system includes checking the carrier frequency, which was measured at 456.8kHz (well within tolerance), and the received data. Channel 1 of the oscilloscope was then attached to the transmitter and channel 2 to the receiver (TSOP7000) signal pin. Upon running the system, after some debugging, the received signal is matching transmitted signal within a very short (apprx. 5uS) delay. It should be noted however, that if the signal is lost gradually, the receiver must be power cycled to reset the automatic gain control (AGC). The AGC can be reviewed in more in the manufacturer (Vishay) data sheet. The final test of the infrared communication was to send a series of data from the transmitter to the receiving microcontroller and verify through the BDM interface that the information was received correctly. This was not working properly for many potential reasons, however after re-writing the entire receive algorithm in a more robust, however slower, manner it is now working properly. There is still some noise encountered, and further error checking may be implemented to make the system more reliable.

Motor Communication: The angle and velocity of the motor are obtained in manner similar to that of the pendulum. A quadrature signal was verified to be working properly, as was another LFLS7184 decoder. The angle/velocity counts were also verified in the Motor Interface chip as to be working properly. Communication with the receiving microcontroller was also verified using the BDM interface. Again, what is presently assumed to be noise from using a breadboard, should be investigated. Reducing noise or providing further error checking may again make the system more reliable however it is presently working reasonably well.

Solar Power: To begin testing the feasibility of solar powering the transmission circuit, the voltage and current draw of the system were measured using a basic multimeter. With a 5V supply drawing 35 to 40mA, the system is only drawing up to 200mW of power. The solar cells purchased should be sufficient to provide this power (300mW total expected), however must be tested with the lighting provided by the Ann Arbor Hands-On Museum to verify this.

Electrical Goals:

- Pendulum Communication
- Infrared Communication
- Motor Communication
- Solar Power
- Balanced Automatically by Stand-Alone System

Require Future Work:

- Infrared and Motor Communication: Reduce noise and add further error checking.
- Motor Control: Order servo amplifier that utilizes current control.
- Solar Power: Test ability of actual casement lighting to provide sufficient power.

CRITIQUE AND FUTURE WORK

Given the scope of the work involved in this project, our sponsors have directed us to take the time necessary to properly complete fabrication and finishing. To this end, we have re-evaluated our schedule to allow for additional shop time. The following describes the scope of the work remaining for each of the deliverables prior to delivery to the Museum.

Use and Care Manual

A complete manual is to be assembled, which is intended to provide any information that might be needed by the Museum over the life of the exhibit. Completion of this manual requires that the devices are finished so that the full set of specifications can be finalized. For example, we are considering some minor rework that will change some dimensions on a number of components.

The manual will be comprised of a set of engineering drawings, a CD ROM of CAD files, as well as assembly and maintenance instructions for each of the devices. The drawings will be dimensioned to allow someone to machine each of the components from scratch, should that become necessary. The CAD files will allow export into an appropriate format for CNC machining, and the assembly instructions will detail the order of operations for disassembly and reassembly of the primary components.

Active Device

The active device is nearly complete mechanically, but requires further development of its electronics. The vendor that we purchased the motor from sent us a motor that has the wrong shaft size, so we are awaiting delivery of the correct model. There are currently a number of signal transmission and processing issues to work out. Once the signal transmission issues have been rectified, a custom printed circuit board (PCB) will be produced to house the electronic components mounted on the wheel. This PCB will mount to the slot on the wheel opposite the pendulum and double as an adjustable counterweight. Once the hardware problems have been addressed, the operating parameters can be determined and the software will be hard-coded onto the motor controller. Another minor issue that may need to be addressed is that the solar array might need to be expanded, as it has not been tested under the lighting that will be provided by the Museum.

Additionally, the bearings purchased for the pendulum shafts on both of the smaller devices should be replaced with sealed bearings in the interest of longevity.

Small Manually-Operated Device

A number of components are in need of finish work on this device. For the most part, this work is relatively minor in scale. The ball bearing in the top plate was intended to be a press fit, but the opening was mistakenly made ~0.005 in too large. This could be corrected by knurling the surface in the opening, but it would be preferable to reproduce the part to the proper dimensions.

In the interest of having a functional prototype for the Design Expo, a couple of the components were fabricated with an emphasis on function over form. The control wheel was made to scale out of a sheet of plywood and mounted to the lower hub. This served the purpose well and provided proof of concept. The angle limiter on the pendulum arm, while functional, leaves a great deal to be desired in aesthetics. We would like to produce a part that resembles the backstop on the large manual device to further tie the devices together.

Large Manually-Operated Device

A number of repairs and finishing operations remain on the largest of the three devices. Some are aesthetic in nature, while others are mechanical and affect the overall function of the device.

Due to an oversight, the bearings are a loose fit on the pendulum axle. We failed to realize that the shoulder bolt used for the axle is 0.004 in under 0.75 in. This results in an unacceptable amount to longitudinal travel at the top of the pendulum. We are currently weighing our options on this issue to ensure that the solution is sensible.

The stainless steel ball at the top of the pendulum is currently mounted using #8-32 threaded rod. While we feel it is sufficient in the short term, it wouldn't be appropriate should additional ballast need to be added to improve the system dynamics. The ball is currently filled with silica sand, but it may be beneficial to use a ballast material with a higher density.

The remaining operations are finishing details and wrapping up of loose ends. The plastic covers on the top and bottom of the wheel need to have their edges rounded over and be buffed. The fiber washers in the torque limiter need to be adhered to the wheel. The enclosure for the base of the device has a 1/4x20 tap broken off in one of the holes. If it proves impossible to remove the tap, a new enclosure will need to be made. The aluminum tread plate has been machined and is ready to be attached to the cast iron base for the table.

Finishing Work

In addition to the mechanical work to be done, surface treatments need to be applied. For the most part, we plan on applying surface finishes that highlight key features and/or lend an interesting contrast. We would like to apply logos to certain components pending final sponsor approval. These surfaces will be polished with a Scotchbrite® pad, have vinyl logos applied and sandblasted. This results in lettering that stands out in a very eye-catching manner against a dull background. The remaining surfaces will be polished. All of the aluminum surfaces will then have a paste wax applied to prevent oxidation.

We were also asked to provide our interpretation of the display literature and graphics. This work is near completion and will be ready for review within the week.

CONCLUSIONS

The Ann Arbor Hands-On Museum has requested that an exhibit focused on new technologies be created. The project sponsors, Professor Shorya Awtar and the Ann Arbor Hands-On Museum, require that the exhibit focus primarily on mechantronic systems and feedback control. Three inverted pendulum systems will be used to realize this objective. The first inverted pendulum will be an active system that utilizes feedback controllers and various mechantronic components to balance a pendulum arm in the inverted position. The remaining two systems will be passive systems that will be controlled by the museum visitors. One of the passive systems will closely resemble the active system, both in scale and appearance. This will make it difficult to balance in the inverted position. The final passive system will be larger with more mass and pendulum arm length, making the system easier to balance. The physical motion in the passive system will mimic the motion in the active system, allowing the museum visitors to further understand the fundamentals of feedback control.

The project sponsors coupled with the design team created engineering specifications to ensure that the desired outcome is attained. Literature research, benchmarking, analysis of the relevant engineering fundamentals, and the designing of concepts were also completed. Through this analysis the relevant design issues, challenges, and future assignments were identified. All of the aforementioned planning and analysis allowed the design team to select the design ideas that best fit the requirements and specifications of the project. These design idea were then complied and the alpha designs were modeled for the three inverted pendulum systems.

In order to finalize the design the group refined the alpha design to closely conform to the safety and manufacturing considerations. The design group was able to complete the design and manufacturing on the project prior to the deadline. However, the electronics and aesthetics work still needs to be completed. The project sponsor has granted the team a deadline extension to ensure that all work is finished at the required level of quality.

REFERENCES

[1] Stuart Bennett, *A Brief History on Automatic Control*, July 1996, IEEE

[2] Craig K.C., Awtar S. et al., *Inverted Pendulum Systems: Rotary and Arm-driven, A Mechatronics System Design Case Study*, Mechatronics, Vol.12, No.2, Feb 2002, 357-370

[3] Jeffrey W. Muttart, *Quantifying Driver Response Times Based upon Research and Real Life Data*

[4] S. Suherman and R. H. Plaut, *Effect of Human Response Time on Rocking Instability of A Two-Wheeled Suitcase*, Journal of Sound and Vibration (1997) 207(5), pg.617-625

[5] http://industrial.panasonic.com/wwwcgi/jvcr13pz.cgi?E+SC+4+ATA7004+LNA2603F+8+WW, Data sheet for LNA2603F GaAs Infrared Light Emitting Diode, Panasonic

TABLE OF APPENDICIES

APPENDIX A: BIOGRAPHIES OF THE INVERTED PENDULUM TEAM MEMBERS

Hechen Yu

I was born on June 11, 1987 in Shanghai China. I lived in Shanghai for the first 20 years of my life. Then in the year of 2007, I was transferred to Michigan and continue my undergraduate study here.

Interesting Facts

I am interested in Dynamics and Controls, and Manufacturing, and have quite a lot of experience on that field. I am planning to pursue a PhD's degree after graduation and will concentrate on either Dynamics or Manufacturing System if accepted.

Joshua Alden

I was born in December of 1986 and am now a senior at the University of Michigan in the Mechanical Engineering BSE program. I have lived in Michigan my whole life, most of which I have spent tinkering, re-engineering, and building in my garage. During my High school career I participated on a F.I.R.S.T. robotics team as the head machinist, and later as the team leader. Presently, I work for Alro Steel Corporation as a sales representative and fabricator. I also mentor students that are on the robotics team I was once a member of, teaching machining basics on a Lathe and CNC Mill as well as design and concept generation skills.

Interesting Facts

I enjoy being with my friends on the weekends and riding my bicycle. I am currently working with a friend of mine on the design and build of a few custom bike frames as well as getting my 'garage-shop' in better condition. I have a small manual mill, two MIG welders, an Oxy-Acetylene setup, and a small sand-blasting box as well. I enjoy programming to relax, having written some of my own encryption and image processing software in my spare time.

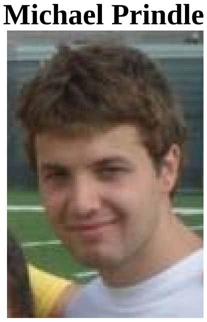
Max Bajcz

I was born on July 14, 1974 in Pontiac, Michigan and grew up in Milford, where I met my wife of eight years. I've always had an interest in science and engineering and spent a considerable portion of my childhood working on one project or another. I will graduate with my BSE in Mechanical Engineering with a Manufacturing Systems Concentration this semester and plan to pursue a career in engineering and/or management.

Interesting Facts

I am the proud father of three, ages two, four and six. My two oldest are competitive swimmers and are dying to work on this project. My youngest doesn't seem to have the same affinity for the water and seems to be mostly interested in breaking things. I am a transit supervisor on campus and also work for a local construction company. I enjoy home remodeling and various other forms of tinkering that help feed my addiction to collecting tools.

Michael Prindle



I was born on February 5, 1987 in Kalamazoo Michigan. I lived in Lawton Michigan for the first 18 years of my life. I became interested in Mechanical Engineering in early high school. I had been restoring a 1969 Chevrolet Chevelle for the past couple of years and really enjoyed myself during this project. This lead to some research into what type of careers would involve similar work. I then discovered that many of the interesting jobs in the automotive industry require a Mechanical Engineering background. I will be graduating in May with my BSE in Mechanical Engineer. Upon gradation I hope to have secured a full time position in the engineering industry. While I am still interested in being employed in the automotive industry, I realize that the odds of landing a job in the automotive industry have dropped significantly in the past few years.

Interesting Facts

I currently work for the University of Michigan's Mobile Robotics Laboratory. I like to golf. I am a huge Detroit Lions and University of Michigan fan. I have season tickets for University of Michigan football and hockey. I have a brother who is currently pursuing his Master's in Electrical Engineering at Michigan Technological University. My mother works for Perrigo and my father runs his own construction business. I also have a girlfriend of two years who is currently pursuing her Bachelors' degrees in Political Science and Environmental studies here at the University of Michigan.

Yiqi Gao

I was born in Suzhou, China, a city with many old style gardens. I spent my first 18 years in Suzhou and then went to Shanghai for college study in Shanghai Jiaotong University. I studied 2 years in SJTU and then transferred to University of Michigan.

Interesting Facts

I'm now working in Human's Biomechanical and Controls lab in UM. I'm planning to continue my study in graduate school in the field of controls & dynamics after getting my BSE degree here in May.

APPENDIX B: CONCEPT SKETCHES

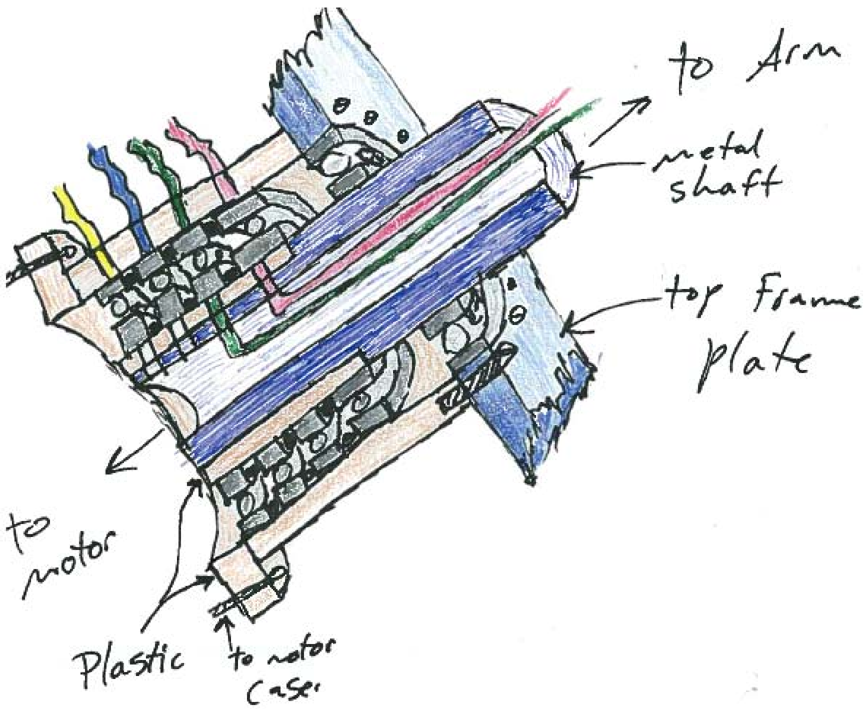


Figure B1: Ball Bearing Slip Ring Design

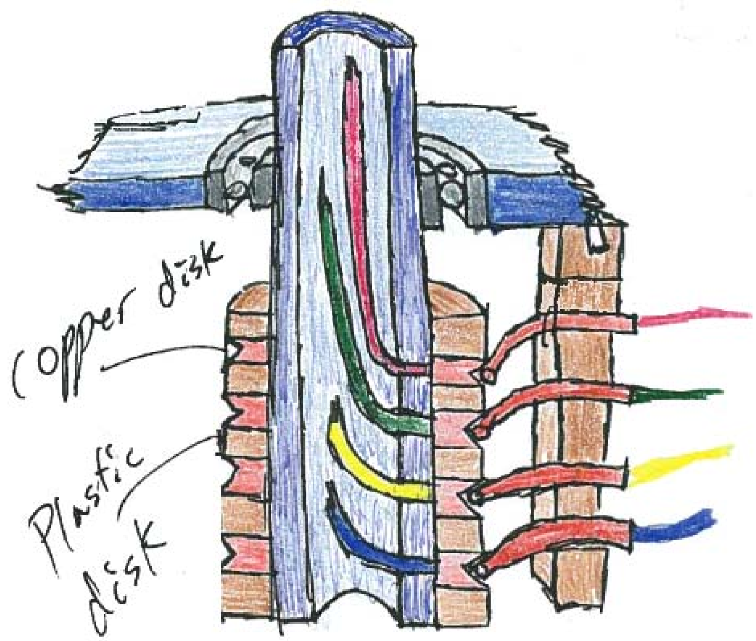


Figure B2: Sliding Contact Slip Ring Design

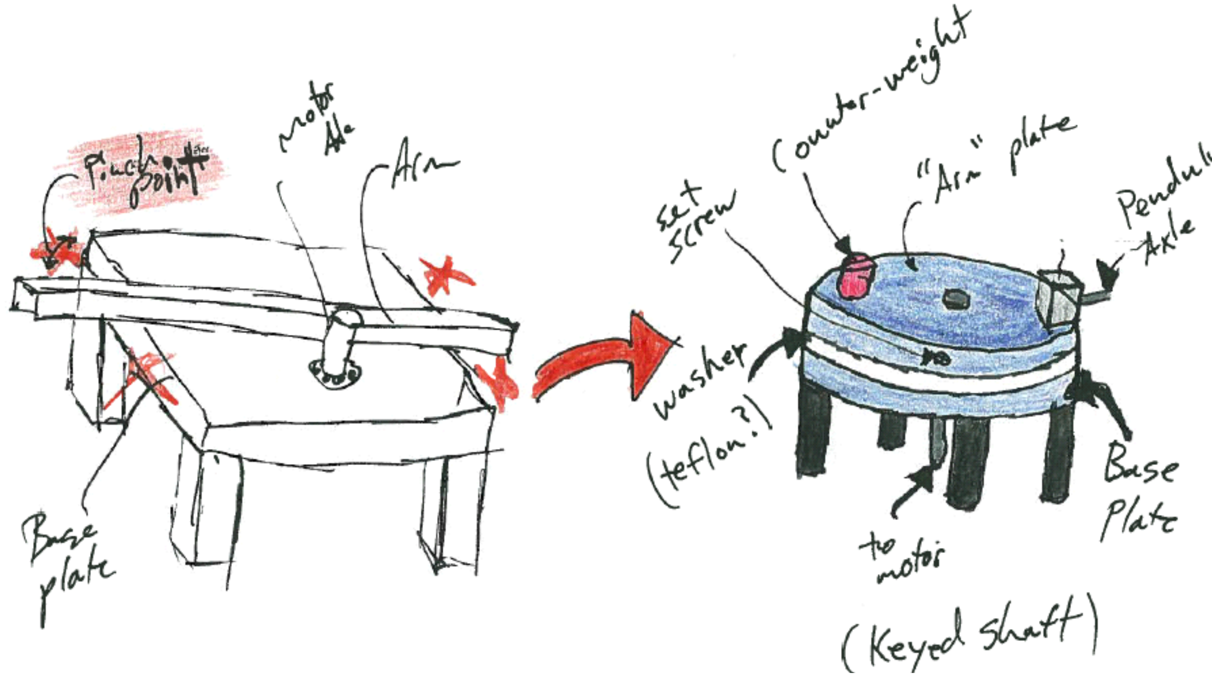


Figure B3: Rotating Disc Eliminates the Pinch Points Created by a Rotating Bar

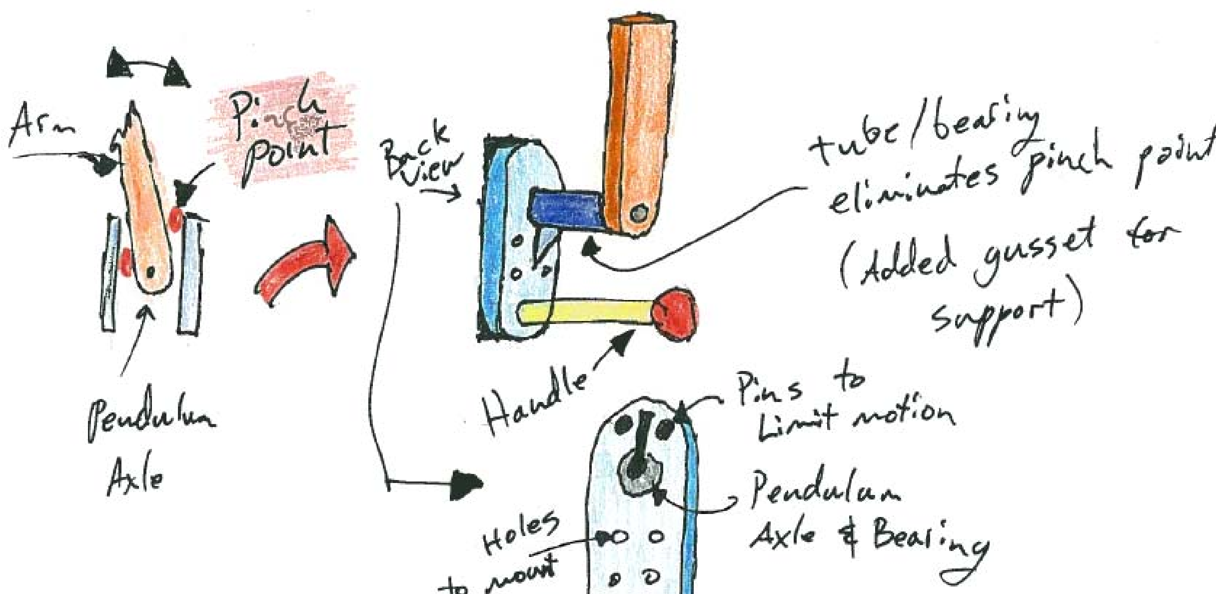


Figure B4: Several Pinch Point Elimination Concepts

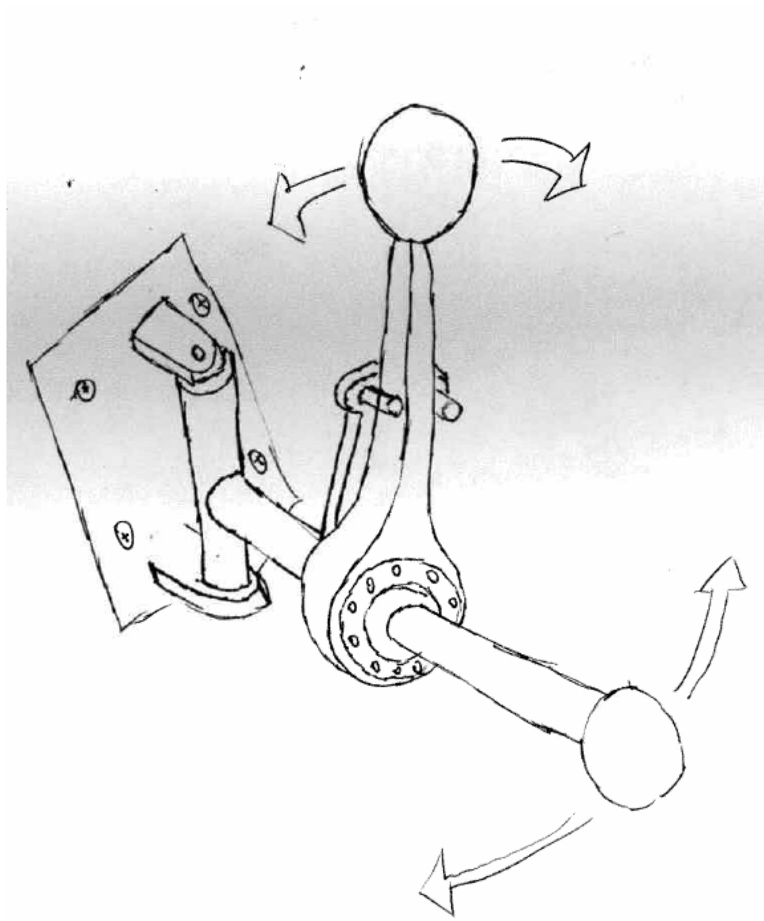


Figure B5: Large Passive Inverted Pendulum Design

APPENDIX C: QUALITY FUNCTION DEPLOYMENT (QFD) DIAGRAM

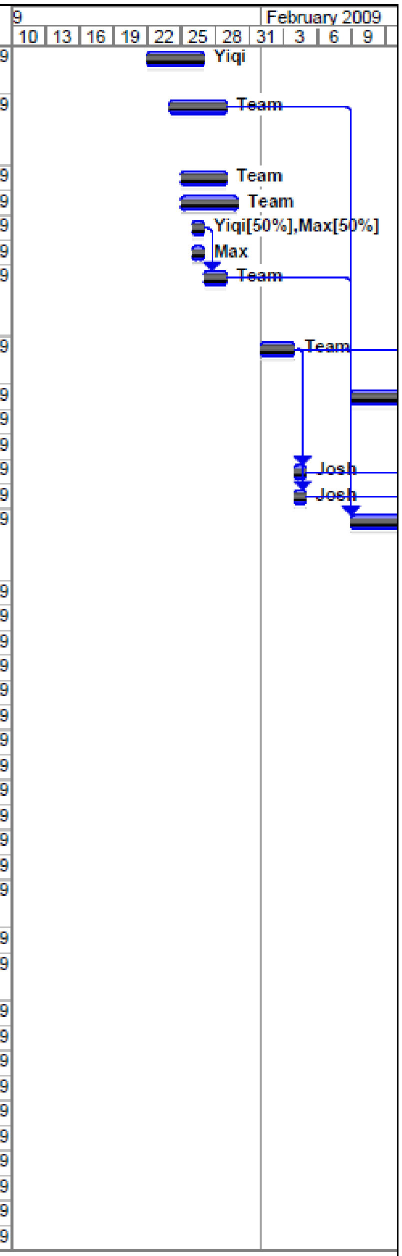
	Coatings	Matrials	Casement	Rotating Electrical Contact	Wire Gauge	Motor	Motor Controller	Power Supply	Optical Angle Encoder	Base Bearing Life	Pendulum Bearing Life	LMIPE	SMIPE	AIPE	Base Size	Casement Size	Mounting	Feedback Method	Microcontroller	Button(s)
Coatings	X	5	0	0	0	0	0	0	0	0	0	3	3	3	0	0	0	0	0	0
Matrials (Clear Plastics, Aluminum,		X	5	3	0	3	3	0	0	5	3	5	5	5	3	3	5	0	3	0
Casement (AAHoM)			X	0	0	0	0	0	0	0	0	0	0	0	3	5	3	0	3	3
Rotating Electrical Contact (Min. 1				X	5	3	0	5	5	3	0	0	0	0	0	0	0	3	3	0
Wire Gauge					X	5	5	5	3	0	0	0	0	0	0	0	0	0	0	3
Motor						X	5	5	0	3	0	0	3	5	0	0	0	3	3	0
Motor Controller							X	5	0	0	0	0	3	5	0	0	0	3	5	0
Power Supply (120VAC to 5/12/24								X	0	0	0	0	3	5	0	0	0	0	5	3
Optical Angle Encoder									X	0	0	0	3	5	0	0	0	3	3	0
Base Bearing Life (3-7 Years)										X	0	5	3	3	0	0	0	0	0	0
Pendulum Bearing Life (3-7 years)											X	5	5	5	0	0	0	0	0	0
Large Manual System (LMIPE)												X	0	0	5	0	5	0	0	0
Small Manual System (SMIPE)													X	5	5	3	3	0	0	0
Small Automatic System (AIPE)														X	5	5	3	0	0	0
Base Size															X	5	5	0	3	0
Casement Size																X	5	0	3	0
Mounting																	X	0	3	3
Feedback Method (PID, Fuzzy,																		X	5	3
Microcontroller (PIC, BasciStamp,																			X	3
Button(s) (Type, Number of)																				X

			Aesthetics			Electrical						Bearing Life		Pendulum Size			"Connection" to Museum			Control		
	Customer Needs	Weighting (1-10	Coatings / Finish	Matrials (Clear Plastics, Aluminum, Steel, Etc.)	Casement (AAHoM)	Rotating Electrical Contact (Min. 1 yr)	Wire Gauge (Min 22GA)	Motor (Min 3 yr)	Motor Controller (Min 7 yr)	Supply (120VAC to 5/12/24 VDC) (Min 7	Optical Angle Encoder (Min 7 yr)	Base Bearing (3-7 Years)	Pendulum Bearing (3-7 years)	Large Manual System (LMIPE)	Small Manual System (SMIPE)	Small Automatic System (AIPE)	Base Size	Casement Size	Mounting	Feedback Method (PID, Fuzzy, State-Space)	Microcontroller (PIC, BasciStamp, Discrete Components)	Button(s) (Type, Number Of)
Aesthetics:	Technical Look	9	10	10	10	5	0	3	1	1	5	2	2	7	7	7	3	1	2	4	2	3
	Emphasize Working Components	7	10	10	5	5	5	3	2	2	5	2	2	7	7	7	6	4	1	0	1	3
	"Feedback-Control" Theme	7	1	1	5	1	1	1	2	2	7	0	0	10	10	10	3	2	0	10	4	5
	"How Things Work" Theme	8	1	1	5	1	5	2	1	1	5	4	4	2	2	2	3	2	0	6	2	5
Interaction:	Simple	7	1	5	1	0	0	0	0	0	0	0	0	7	7	1	0	2	4	1	1	10
	Intuitive	6	1	5	5	0	0	0	0	0	0	0	0	6	7	1	0	2	4	1	1	10
	Normally Balancing	5	0	1	0	0	0	0	0	0	0	0	0	0	0	5	0	0	0	5	0	2
	More Controll for AAHoM Staff	5	0	0	1	0	0	0	0	0	0	0	0	0	0	5	0	5	0	10	3	8
	No Manual Initiation	8	0	1	0	0	0	2	0	0	0	0	0	0	0	2	0	0	0	3	1	0
Electrical:	Safe Wiring	9	0	1	5	10	10	3	6	10	2	0	0	0	0	2	2	1	3	0	6	7
	Pitman Motors Preferred	3	0	0	0	0	1	8	5	2	0	2	0	0	0	0	2	0	0	2	5	0
	Robust	8	0	0	0	10	5	10	10	10	7	2	6	0	0	2	3	0	2	5	8	10
	Use "Off-The-Shelf" Components	5	0	0	0	5	5	5	6	6	6	7	7	0	0	0	1	0	0	3	5	3
Mechanical:	Simple Disassembly	6	0	5	1	5	1	1	0	0	2	7	7	6	6	6	8	6	8	0	0	2
	Robust	8	5	10	5	1	2	10	1	1	5	10	10	10	10	10	6	4	10	3	3	0
	Size Similar to Prototypes	6	0	5	5	0	2	5	0	0	2	5	5	10	10	10	10	10	10	0	0	2
General	Less than $1500	10	7	5	0	5	1	5	5	5	5	2	2	1	1	1	1	0	1	5	5	1
	Raw Score		298	452	363	378	284	409	282	309	387	293	319	469	475	497	333	255	318	401	337	495
	Relative Weight		4.1%	6.1%	4.9%	5.1%	3.9%	5.6%	3.8%	4.2%	5.3%	4.0%	4.3%	6.4%	6.5%	6.8%	4.5%	3.5%	4.3%	5.5%	4.6%	6.7%

Figure 1: QFD Diagram

APPENDIX D: PROJECT SCHEDULE AND PLAN

ID		Task Name	Duration	Start
16	✓	Benchmarking (similar projects and lateral designs)	5 days	Thu 1/22/09
5	✓	Generate list of data transmission options	5 days	Sat 1/24/09
10	✓	Compose oral report for Design Review #1	4 days	Sun 1/25/09
11	✓	Compose written report for Design Review #1	5 days	Sun 1/25/09
17	✓	QFD (basic – not too much detail, per Prof. Im)	1 day	Mon 1/26/09
18	✓	Spreadsheet to track expenses	1 day	Mon 1/26/09
6	✓	Compose spec sheet with all requirements	2 days	Tue 1/27/09
1	✓	Generate list of component options	3 days	Sun 2/1/09
14		CAD drawings of fabricated components	11 days	Mon 2/9/09
20		Visit MITC exhibit	1 day	Mon 2/23/09
2		Select motor controller	3 days	Mon 2/23/09
3	✓	Select power supply	1 day	Wed 2/4/09
4	✓	Select optical sensor	1 day	Wed 2/4/09
7		Select data transmission option	10 days	Mon 2/9/09
19		Write code for motor controller	5 days	Thu 2/26/09
30		Order parts and materials	2 days	Thu 2/26/09
29		Fabricate components	5 days	Mon 3/2/09
39		Send parts out for machining	5 days	Sat 2/21/09
15		Adams simulation (if necessary)	5 days	Mon 3/23/09
31		Assemble and fine tune active prototype	3 days	Mon 3/9/09
32		Assemble small passive prototype	1 day	Mon 3/9/09
33		Assemble large passive prototype	1 day	Mon 3/9/09
23		Compose oral report for Design Review #2	5 days	Sun 2/15/09
26		Compose written report for Design Review #2	6 days	Sun 2/15/09
22		Prototype testing	2 days	Thu 3/12/09
38		Send parts out for coating	5 days	Thu 3/12/09
8		Assemble and program motor controller	2 days	Thu 3/5/09
12		Spring Break	9 days	Sat 2/21/09
13		Elementary school demonstrations	2 days	Mon 3/23/09
34		Safety Review (Date TBD)	3 days	Thu 2/19/09
24		Compose oral report for Design Review #3	4 days	Sun 3/22/09
27		Compose written report for Design Review #3	5 days	Sun 3/22/09
35		Final prep for Design Expo	21 days	Sun 3/22/09
21		Write "our version" of poster presentation	4 days	Mon 3/23/09
36		Write final report	14 days	Fri 4/3/09
25		Compose oral report for Design Review #4	4 days	Sun 4/5/09
28		Compose written report for Design Review #4	5 days	Sun 4/5/09
9		Compose use and care manual	21 days	Mon 4/6/09
37		Deliver exhibit to AAHoM	3 days	Tue 4/28/09



Project: ME450Gantt 2-16-09
Date: Tue 2/17/09

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

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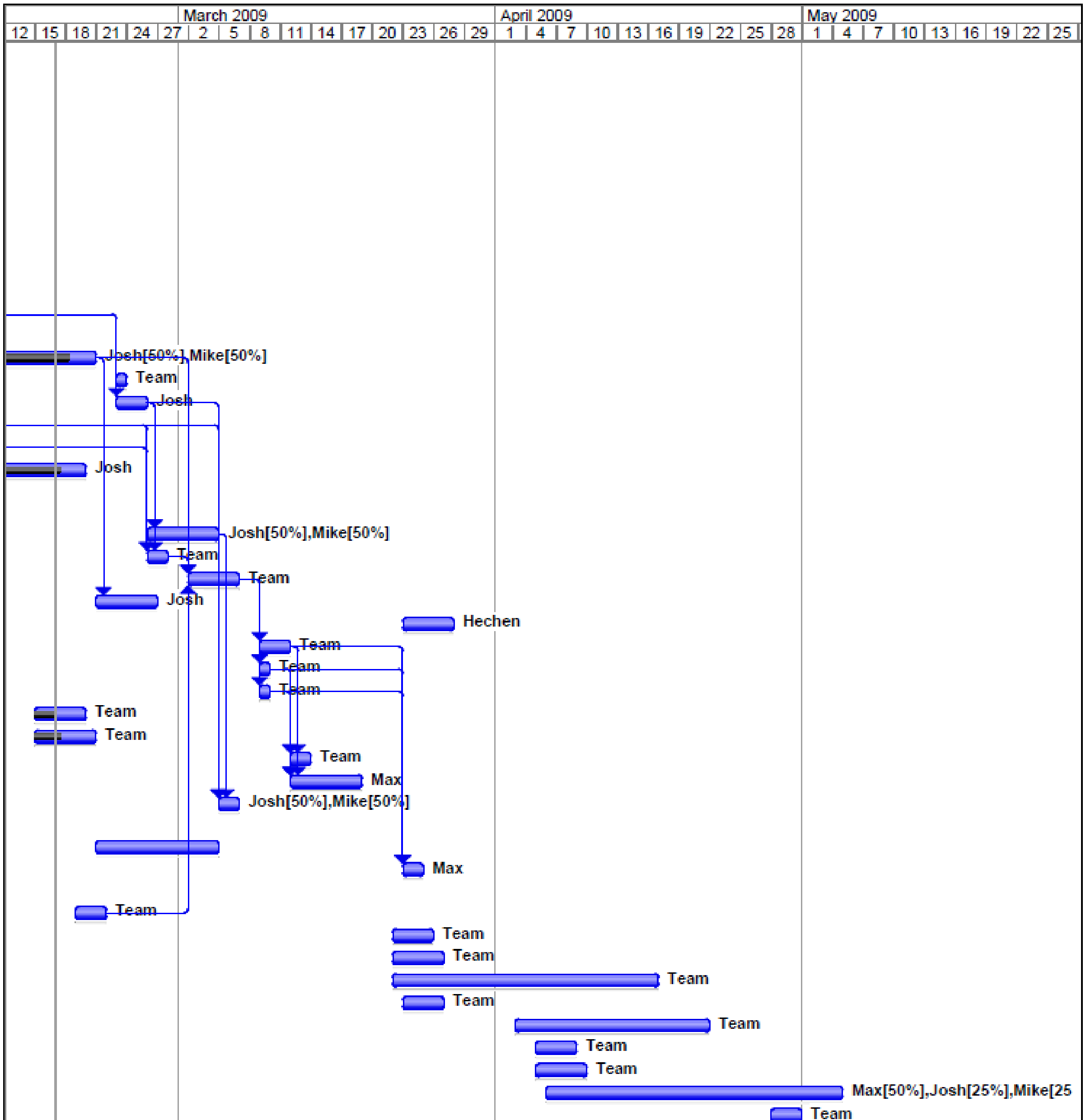

Project: ME450Gantt 2-16-09
Date: Tue 2/17/09

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

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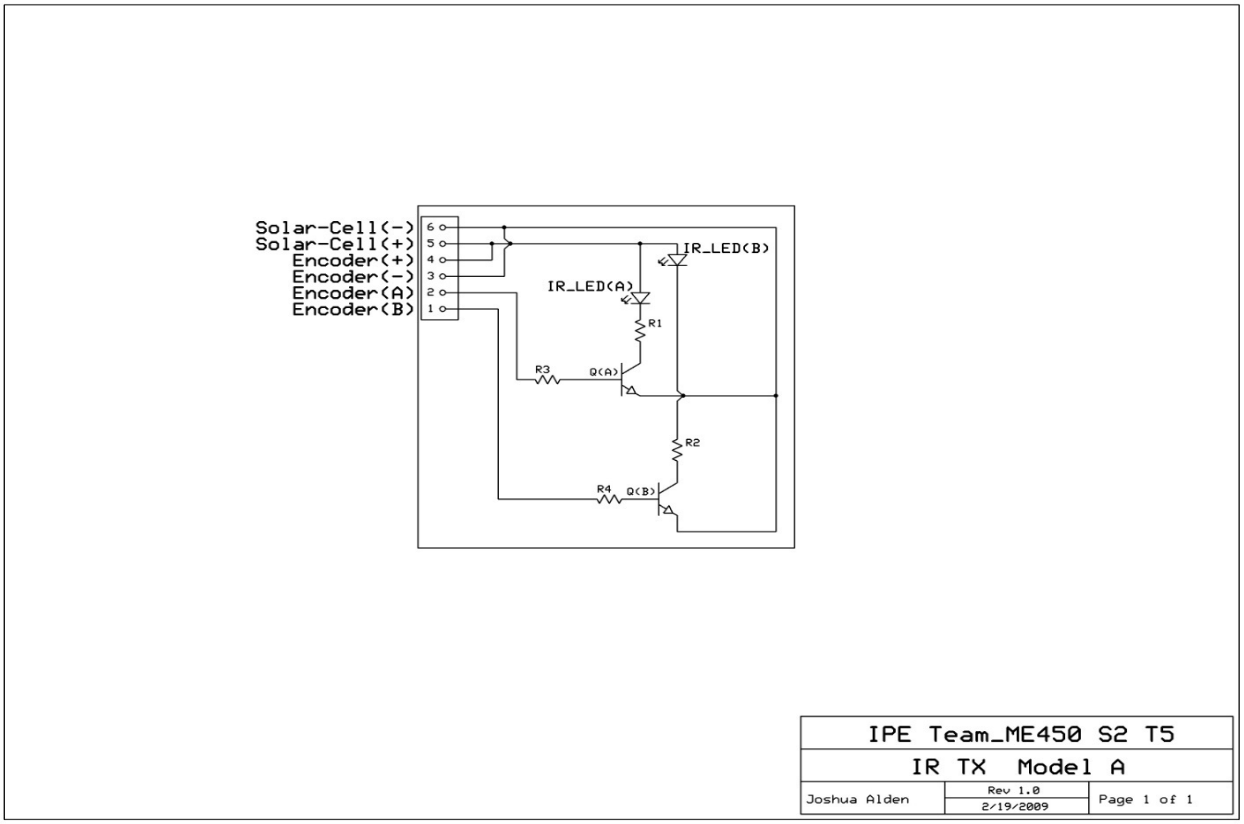
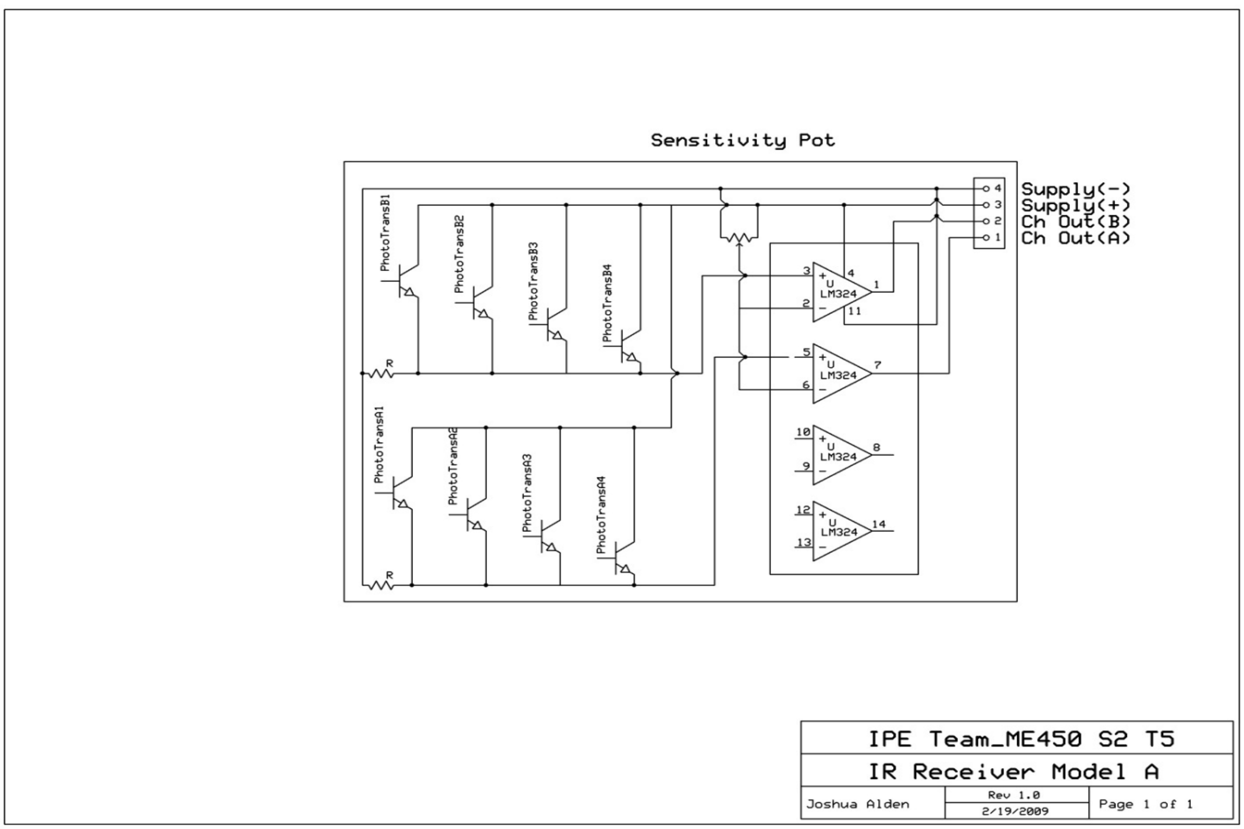
APPENDIX E: PRELIMINARY ELECTRICAL SCHEMATICS





APPENDIX F: SPECIFICATIONS SHEET

	Component	Description	Specification
Entire Exhibit			
General	Any Non-Wear	Minimum useful life of any component not designed for replacement or expected to fail by general use.	3 Years
	Expected Wear	Minimum useful life of any component designed for replacement and expected to fail by normal usage (i.e. sliding electrical contacts, bearing, fuses, buttons, however light-bulbs are not included).	1 Year
Electrical	Wiring	Minimum wire gauge to be used on low-voltage (5~24VDC) circuitry.	22 GA
	Fuse/Circuit Breaker	Fuses or circuit breakers should be used where appropriate. Surge protection to be supplied by AAHoM.	TBD per Power Required
Automated Exhibit			
Electrical	Power Supply	Input/Output Voltage	120VAC/24VDC/5VDC
		Power Rating	60W
		Surge Protection	Supplied by AAHoM
	Buttons	Power Rating, Minimum	12VDC/1A
		Size	As Provided by AAHoM
		Color	As Provided by AAHoM
		Life, Minimum Cycles (15cyc/hr x 8hr/day x 6 days/wk x 52wks/yr x 3yrs = 112,320)	120,000 Cycles
	Motor	Type	DC Servo Motor
		Presently benchmarked from prefered vendor and previous prototype.	Pittman Express MFG#9237S011
	Tachometer	Single unit with benchmarked servo motor	N/A
	Motor Controller	Type	DC Servo Motor Controller
		Presently benchmarked from previous prototype	Advanced Motion Controls, 25A series
	Angle Sensor	Type	Optical Encoder
		Presently benchmarked from previous prototype	US Digital MFG#E4P
		Detection Range	360 Deg
		Shaft Diameter	0.25 inch
		Power Requirements (MAX)	5.5VDC/18mA
	Programmable IC	Type (BASIC Stamp, OOPIC, Motorola, etc)	TBD
		Prototype: LabView software with attached DAQ	N/A
	IR LED	Wavelength	950 nm
		Package	T1-3/4 (5mm)

		Emitters per Channel	1 IR LED
	IR Transistor	Type	Optical PNP
		Minimum viewing angle (Half-Power)	50 Deg
		Package	T1-3/4 (5mm)
		Peak Detection Wavelength	950 nm
		Receivers per Channel (As per Alpha Design)	8 IR Phototransistors
	Discrete Components	TBD (Resistors, Switches, Fuses, Capacitors, Gates, Amplifiers, Standard BJT/MOSFET Transistors, etc)	TBD
Mechanical	Control Wheel (CW)	Diameter	6 inch
		Material	Aluminum
		Shaft Diameter	TBD
	Pendulum Arm (PA)	Length	8 Inches
		Number of Components	5 pcs
		Motion Range	360 deg
		Bar Diameter	0.5"
		Ball Diameter	TBD
		Ball Mass	TBD
	Case	Yes	Supplied by AAHoM
Small Manual Exhibit			
Mechanical	Control Wheel (CW)	Diameter	TBD
		Material	TBD
		Shaft Diameter	TBD
	Overload Clutch (OC)	Type	Adjustable Friction
		Overload torque	10-50 ft-lb
		Shaft Diameter	TBD (Match CW)
	Motion-Limiting Coupling	Type	Possibly Modified Spider Coupling
		Free Motion Range	Appx 90 Deg
	Pendulum Arm (PA)	Length	8 Inches
		Number of Components	5 pcs
		Motion Range	10 deg
		Bar Diameter	0.5"
		Ball Diameter	TBD
		Ball Mass	TBD
Large Manual Exhibit			
Mechanical	Control Wheel (CW)	Diameter	16 inch
		Material	Aluminum or 304SS
		Shaft Diameter	TBD
	Overload Clutch (OC)	Type	Adjustable Friction
		Overload torque	10-50 ft-lb
		Shaft Diameter	TBD (Match CW)
	Motion-Limiting Coupling	Type	Possibly Modified Spider Coupling
		Free Motion Range	Appx 90 Deg

	Pendulum Arm (PA)	Length	30 Inches
		Number of Components	5 pcs
		Motion Range	10 deg
		Bar Diameter	0.5"
		Ball Diameter	TBD
		Ball Mass	TBD

APPENDIX G: CONTROLLER TIMING CALCULATIONS

Velocity resolution and expected error. “x2” mode is likely to be used.

Measured System	Rad/s	Rev/Rad	Rev/s	Deg/s	Rev/min
Velocity (max)	30	0.159154943	4.774648293	1718.87339	286.4788976

Quad Encoder Properties:

Cycles/Rev	Pulses/Cycle (Resolution Mode)	Pulses/Rev	Pulse/Deg	Deg/Pulse	Pulse/Rad	Rad/Pulse
	4	1200	3.333333333	0.3	190.98593	0.00524
	2	600	1.666666667	0.6	95.49297	0.01047
300	1	300	0.833333333	1.2	47.74648	0.02094
	4	1440	4	0.25	229.18312	0.00436
	2	720	2	0.5	114.59156	0.00873
360	1	360	1	1	57.29578	0.01745

Timing

Cycles/Rev	Pulses/Cycle (mode)	Pulse/s (max) = Rev/s * Pulse/Rev	Micro-sec/Pulse (min)	RTCC @ max velocity	Bits Required for pulse/s	Max Velocity for this number of bits (Pulse/s)	Max Velocity for this number of bits (Rad/s)
	4	5729.577951	174.5329252	5.58505361	13	8192	42.8932117
	2	2864.788976	349.0658504	11.1701072	12	4096	42.8932117
300	1	1432.394488	698.1317008	22.3402144	11	2048	42.8932117
	4	6875.493542	145.4441043	4.65421134	13	8192	35.74434308
	2	3437.746771	290.8882087	9.30842268	12	4096	35.74434308
360	1	1718.873385	581.7764173	18.6168454	11	2048	35.74434308

Miniumum Real Time Clock Counter Interval (31.25us)		3.13E-005			
Resolution:			Range of Actual Velocity		
Cycles/Rev	Pulses/Cycle (mode)	Expected min RTCC	Velocity(rad/s) Min (Rad/Pulse)/(RTCC Int*RTCValue)	Velocity Max	Worst-Case (Max Vel) Resolution (+/-rad/s)
	4	5	27.92527	33.51032	2.792526803
	2	11	27.92527	30.46393	1.269330365
300	1	22	29.13941	30.46393	0.662259321
	4	4	27.92527	34.90659	3.490658504
	2	9	27.92527	31.02808	1.55140378
360	1	18	29.39502	31.02808	0.816528305

APPENDIX H: ELECTRICAL BILL OF MATERIALS

Component	Description	Vendor	Vendor Number	MFG#	Quanty	Cost	Total
Voltage Regulator	5VDC 8-pin DIP	Digikey	296-2730-5-ND	TPS76650D	2	1.2	2.4
PNP Transistors	TRANS PNP GP SS 200MA 40V TO92	Digikey	2N3906RLRAGOSCT-N	2N3906RLRAG	10	0.194	1.94
NPN Transistors	TRANS NPN GP 200MA 40V TO92	Digikey	2N3904RLRAGOSCT-N	2N3904RLRAG	10	0.197	1.97
Surface-Mount Controller	IC MCU 8BIT 8K FLASH 20-TSSOP	Digikey	MC9S08SH8CTJ-ND	MC9S08SH8CTJ	4	2.13	8.52
DIP-Mount Controller	IC MCU 8BIT 8K FLASH 20-DIP	Digikey	MC9S08SH8MPJ-ND	MC9S08SH8MPJ	4	2.38	9.52
.33 Ohm Resistor	RES .33 OHM .33W 5% MF FUSIBLE	Digikey	PPC.33ACT-ND	NFR2500003307JR500	5	0.682	3.41
IR LED	EMITTER IR 5MM 875NM	Digikey	516-1261-ND	HSDL-4220	5	0.75	3.75
Dip Socket - 20Pin	IC SOCKET 20POS DIP TIN	Digikey	A24810-ND	2-641612-1	10	0.528	5.28
Dip Socket - 16Pin	IC SOCKET 16POS DIP TIN	Digikey	A24809-ND	2-641610-1	10	0.528	5.28
Dip Socket - 8Pin	IC SOCKET 8POS DIP TIN	Digikey	A24807-ND	2-641260-1	10	0.264	2.64
1kOhm Resistor	RES 1.00K OHM 1/4W 1% METAL FIL	Digikey	1.00KXBK-ND	MFR-25FBF-1K00	20	0.098	1.96
360 Ohm Resistor	RES METAL FILM 360 OHM 1/4W 1%	Digikey	P360CACT-ND	ERO-S2PHF3600	20	0.171	3.42
.68 Ohm Resistor	RES .68 OHM 2W 5% METAL FILM	Digikey	P0.68W-2BK-ND	ERX-2SJR68	5	0.206	1.03
1MOhm Resistor	RES 1.00M OHM 1/4W 1% METAL FIL	Digikey	1.00MXBK-ND	MFR-25FBF-1M00	20	0.106	2.12
4.7uF Capacitor	4.7UF 25V MINI ALUM ELECT (KA)	Digikey	P812-ND	ECE-A1EKA4R7	20	0.091	1.82
10uF Capacitor	10UF 16V MINI ALUM ELECT (KA)	Digikey	P807-ND	ECE-A1CKA100	20	0.091	1.82
.1uF Capacitor	CAP .1UF 50V 20% CER RADIAL	Digikey	399-4209-ND	C317C104M5U5TA	20	0.121	2.42
Vendor Total		Digikey					**59.3**
Terminal Block	PCB 3 Position Screw Terminal Block	Electronic Goldmine	G16513		4	1	4
Terminal Block	4 Position Quick Connect Wire Block	Electronic Goldmine	G16830		4	0.79	3.16
Solar Cell	6VDC, 100mA, 5x2" Solar Cell	Electronic Goldmine	G15555		2	8.95	17.9
Vendor Total		Electronic Goldmine					**25.06**
H Bridge Motor Driver	28V, 20A, full-Bridge, PWM	RobotPower	Simple-H		1	79.99	79.99
Vendor Total		RobotPower					**79.99**
Optical Encoder	300Cyc/Rev, 5VDC	US Digital	E4P-100-059-D-D-D-B		1	22.95	22.95
Quadrature Decoder	x1,x2,x4 Resolutions, 5VDC, 8-Pin DIP	US Digital	LFLS7184		4	3.2	12.8
Vendor Total		US Digital					**35.75**
Estimated Total:							**200.1**

APPENDIX I: MECHANICAL BILL OF MATERIALS

Item description	Item #	Vendor	Quantity	Price	S&H	Total
Invoice # 4483642-01						
Steel tapered roller bearing - 3/4" shaft	5709K14	McMaster-Carr	1	$16.20		$16.20
Outer ring for above	5709K54	McMaster-Carr	1	$7.62		$7.62
Miniture precision SS ball bearing	57155K355	McMaster-Carr	4	$7.62		$30.48
316 SS cup point socket set screw 10-32, 5/8" (25 pk)	92313A831	McMaster-Carr	1	$6.17		$6.17
Alloy flat head socket head cap screw 3/8x24 thread 1.25" (10 pk)	91266A654	McMaster-Carr	2	$5.39		$10.78
300 series SS socket cap screw 6-32x 3/8" (10 pk)	92200A146	McMaster-Carr	1	$3.71		$3.71
18-8 SS socket head cap screw 4-40 x 5/8" (100 pk)	92196A112	McMaster-Carr	1	$4.49		$4.49
18-8 SS socket head cap screw 6-32x 1/2" (100 pk)	92196A148	McMaster-Carr	1	$5.15		$5.15
1-piece clamp-on shaft collar; 1/4" bore; 11/16" OD; 5/16" W	6435K12	McMaster-Carr	6	$1.98		$11.88
Connecting rod; 6"; 3/8"x24 female threaded	6516K61	McMaster-Carr	8	$8.53		$68.24
6" connecting rods (pendulum arms	6516K51	McMaster-Carr	2	$7.72		$15.44
Torque limiter 3/4"bore; 3/16"x3/64" keyway; 35ft-lb	6524K11	McMaster-Carr	1	$67.78		$67.78
Low carbon steel shim disks, 3" dia, 0.002" thick (5 pk)	2904T24	McMaster-Carr	1	$13.98		$13.98
Invoice Total					**$9.50**	**$271.42**
Invoice # 4521643-01						
Steel tapered roller bearing - 3/4" shaft - #09067	5709K14	McMaster-Carr	1	$16.20		$16.20
Outer ring for above	5709K54	McMaster-Carr	1	$7.62		$7.62
Steel ball bearing-ABEC-1, Double shielded; 1"shaft, 2"OD	60355K32	McMaster-Carr	1	$9.69		$9.69
Steel ball bearing, flanged double-sealed; 3/4" shaft, 1-5/8"OD	6384K367	McMaster-Carr	2	$8.88		$17.76
Invoice Total					**$4.75**	**$56.02**
Invoice # 4309						
Keyless bushing	6202103	Fenner Drives	1	$32.21		$32.21
Invoice Total			**Tax:**	**$2.28**	**$5.88**	**$40.37**

Total Current Invoices	**$367.81**
Total Pending Orders	**$450.51**
Current total	**$818.32**

Pending Orders

6061 Aluminum square tube;1"x1"; 3/16" wall thickness	6546K341	McMaster-Carr or Alro?	1	$5.95	$5.95
6061 Aluminum round bar shaft 1"dia		Alro	1		$0.00
6061 Aluminum Flat stock 1/4" thick		Alro	1		$0.00
6061 Aluminum Flat stock 3/8" thick		Alro	1		$0.00
6061 Aluminum Flat stock 1/2" thick		Alro	1		$0.00
6061 Aluminum Flat stock 3/4" thick		Alro	1		$0.00
Steel round bar; 1" dia		Alro	1		$0.00
Steel plate; 1/4" thick		Alro			
Optical encoder US Digital E4P		AndyMark	1	$23.00	$23.00
Pitman servomotor 9237S011		Click Automation	1	$221.56	$221.56
Electronics (approx)					$200.00

APPENDIX J: DIMENSIONED DRAWINGS

Appendix J.1 Large Manual System

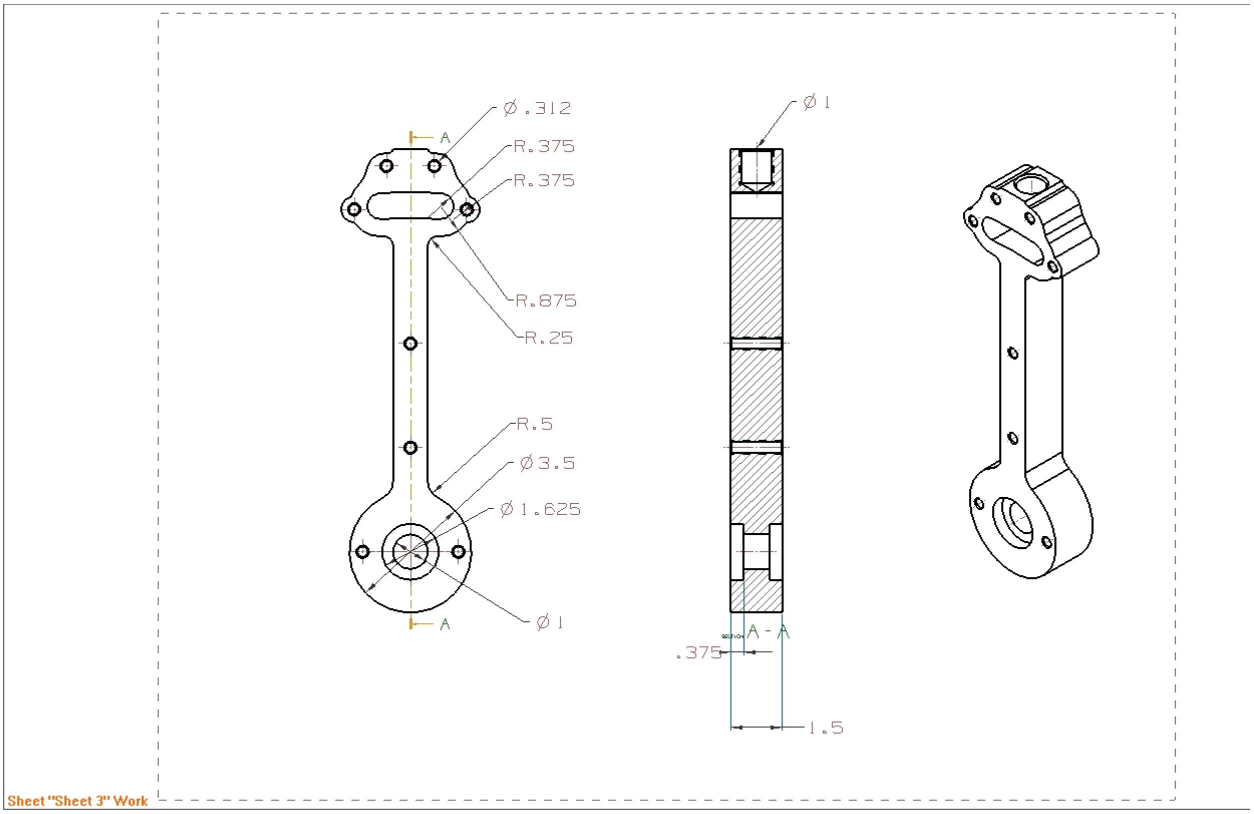


Figure J.1.1: Lower Pendulum Arm Assembly

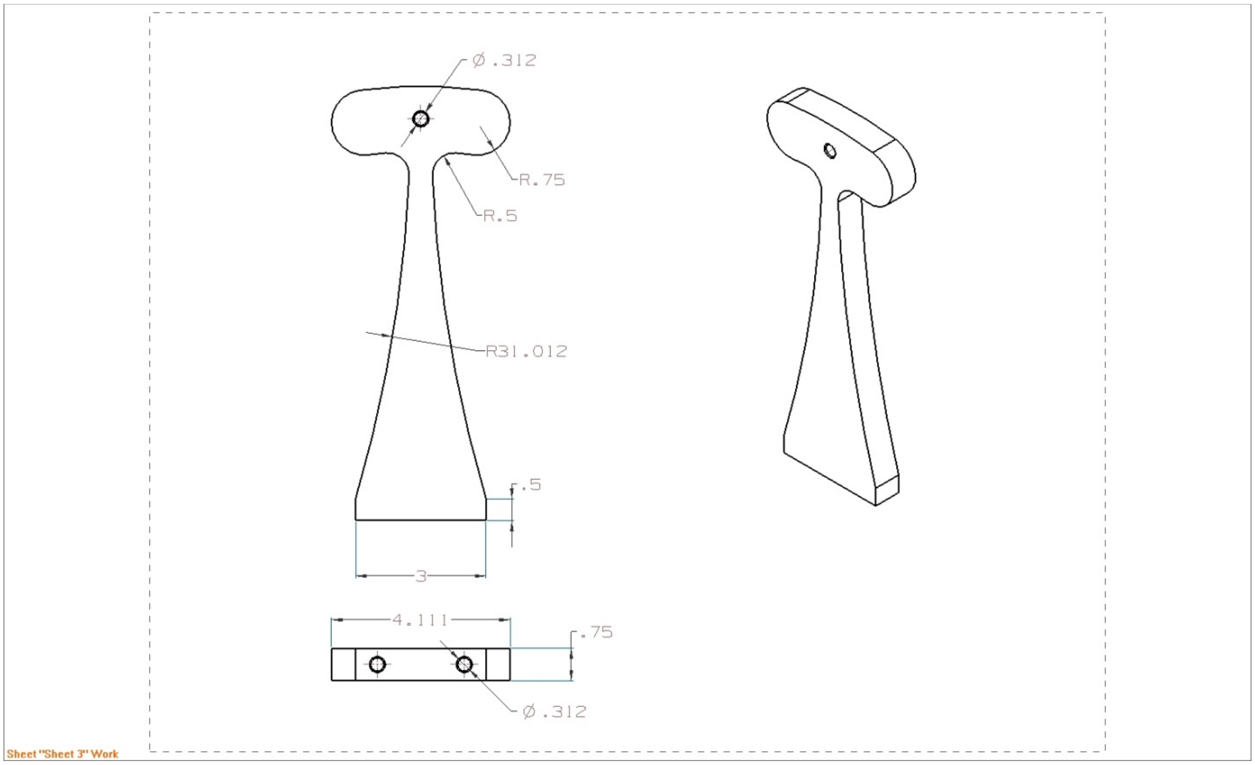


Figure J.1.2: Pendulum Angle Limiter

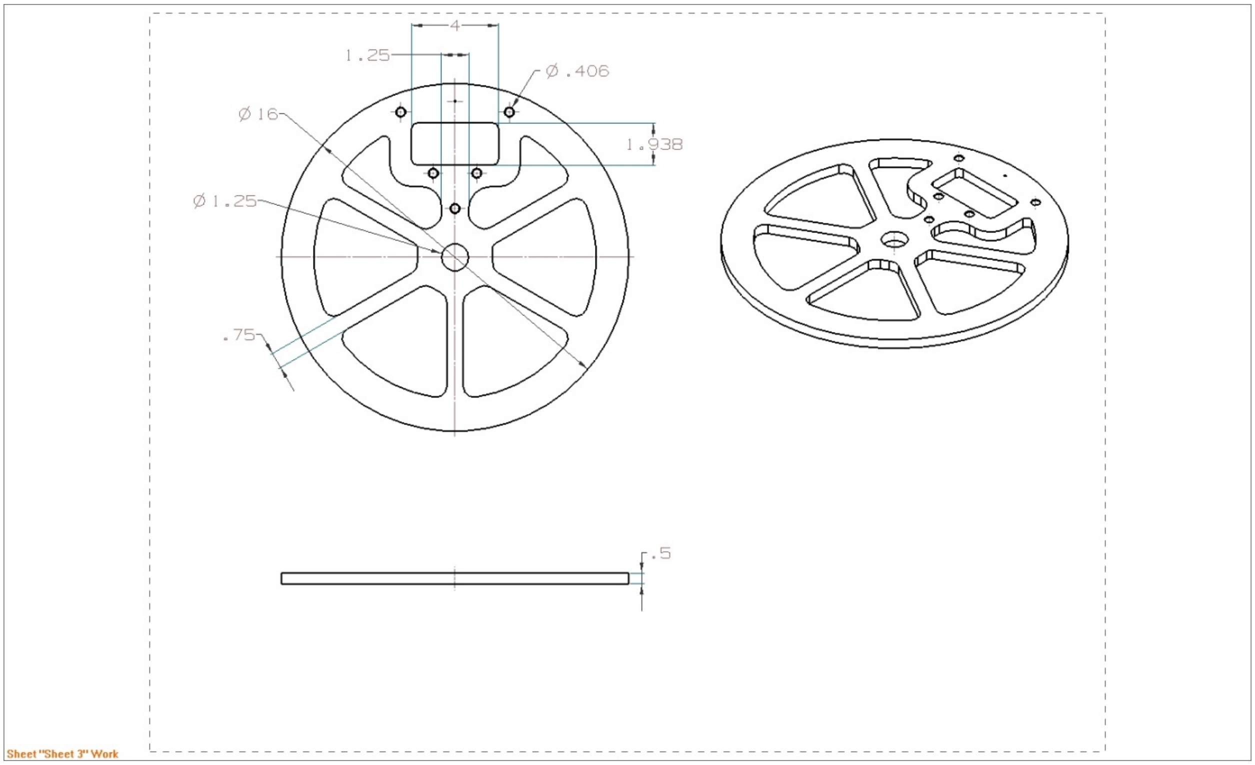


Figure J.1.3: Pendulum Control Wheel

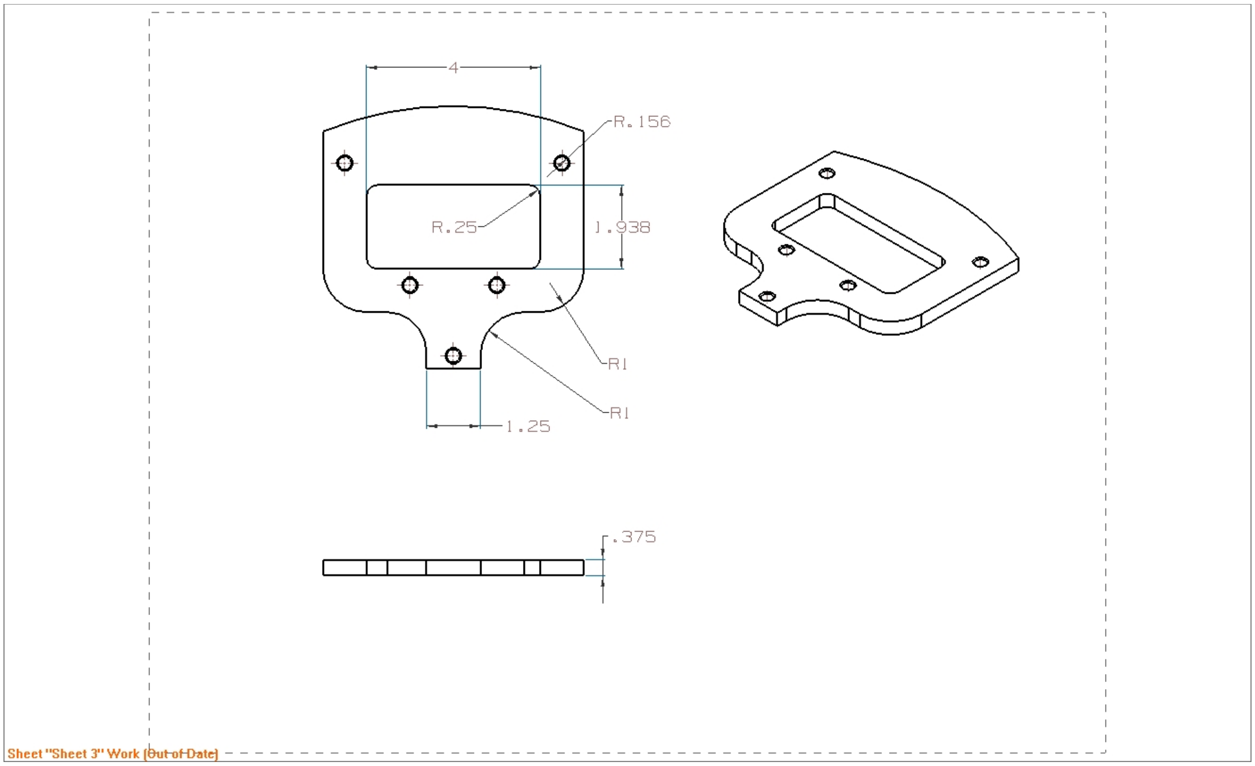


Figure J.1.4: Pendulum Control Wheel Support

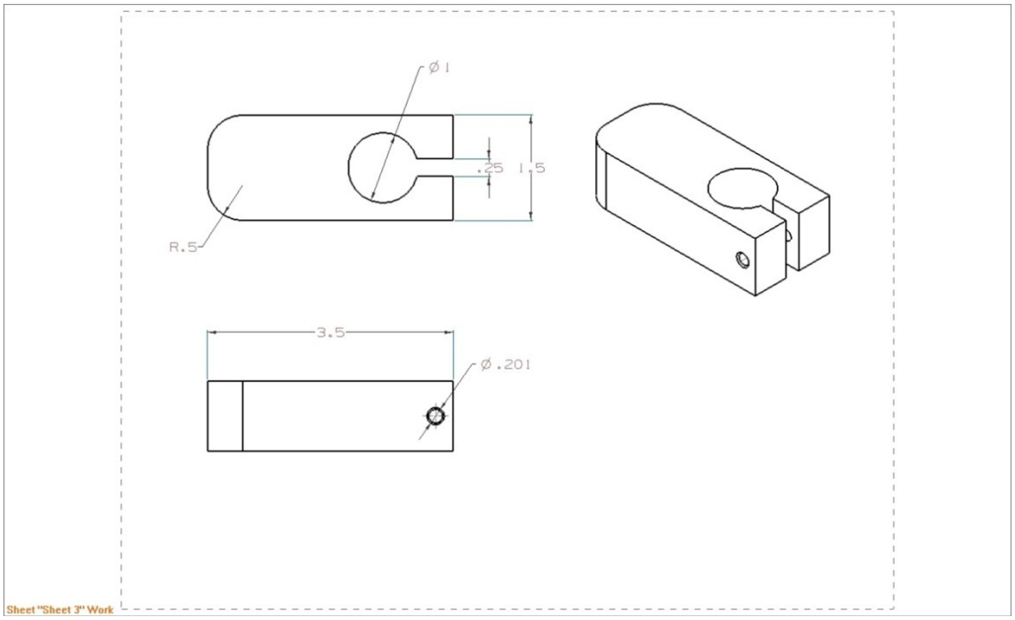


Figure J.1.5: Angle Limiter Pin

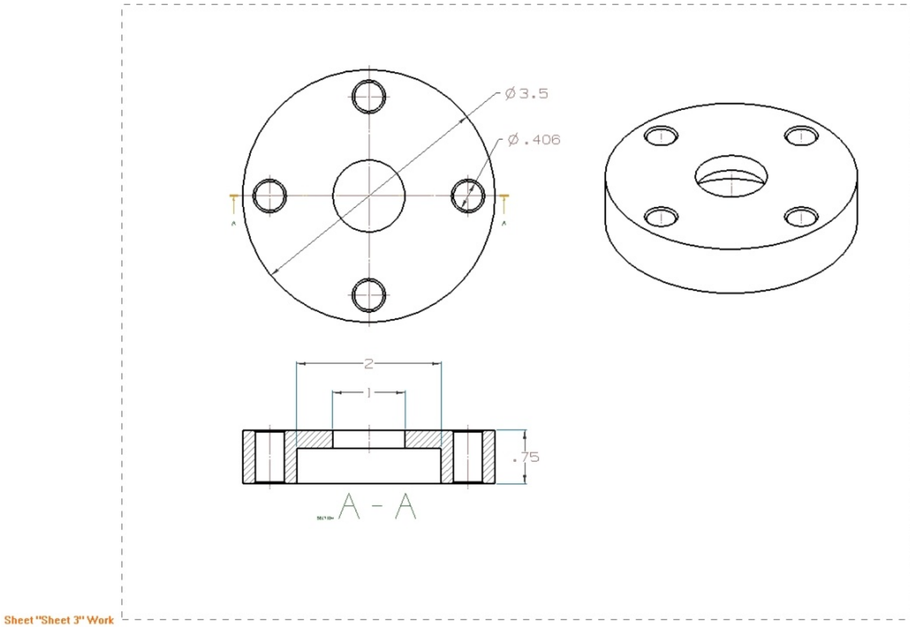


Figure J.1.6: Angle Limiter Box Top Bearing Cover

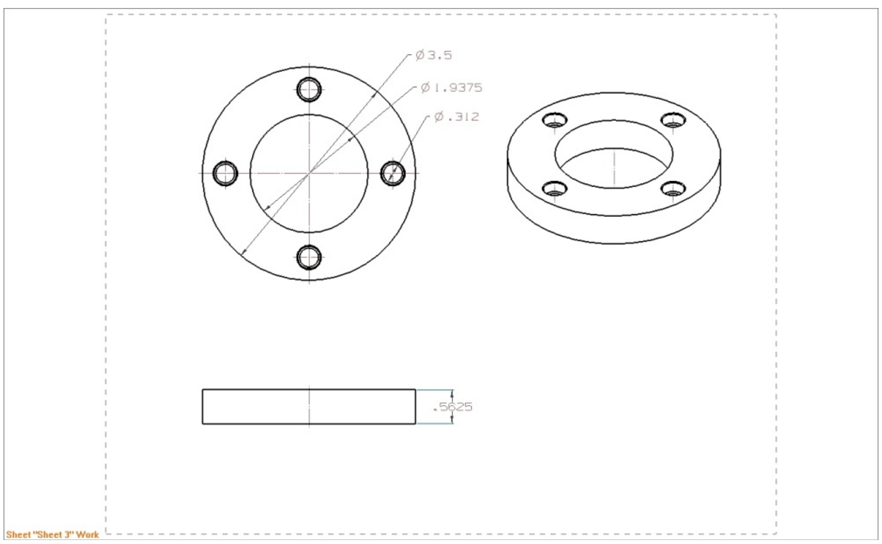


Figure J.1.7: Angle Limiter Bearing Holder

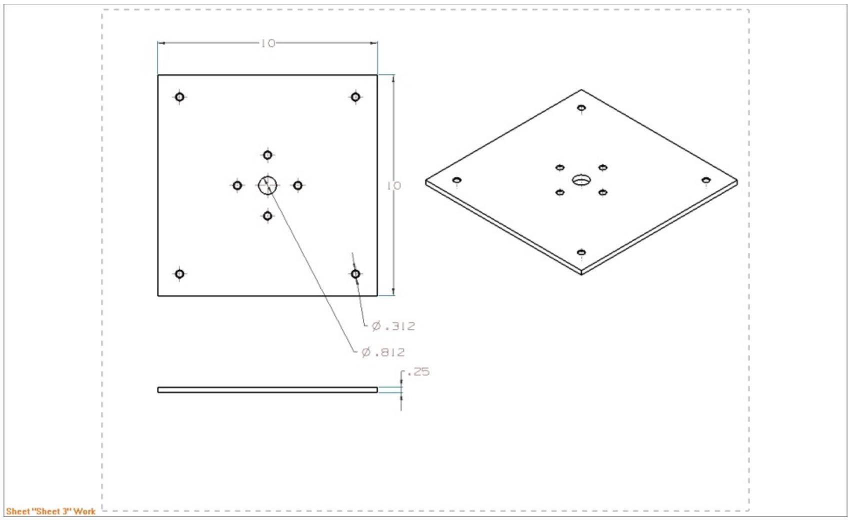


Figure J.1.8: Angle Limiter Box Base

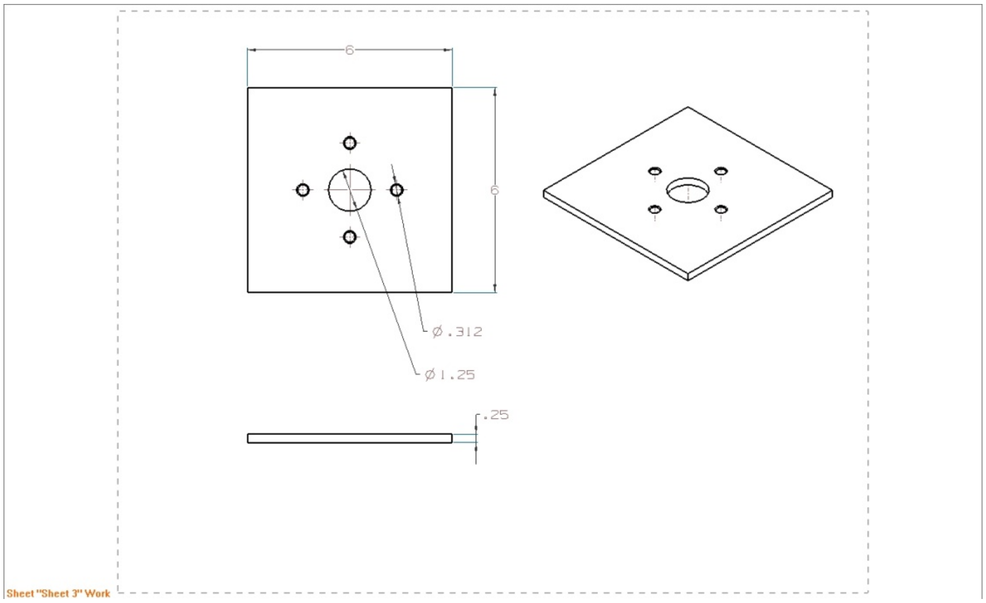


Figure J.1.9: Angle Limiter Box Cover

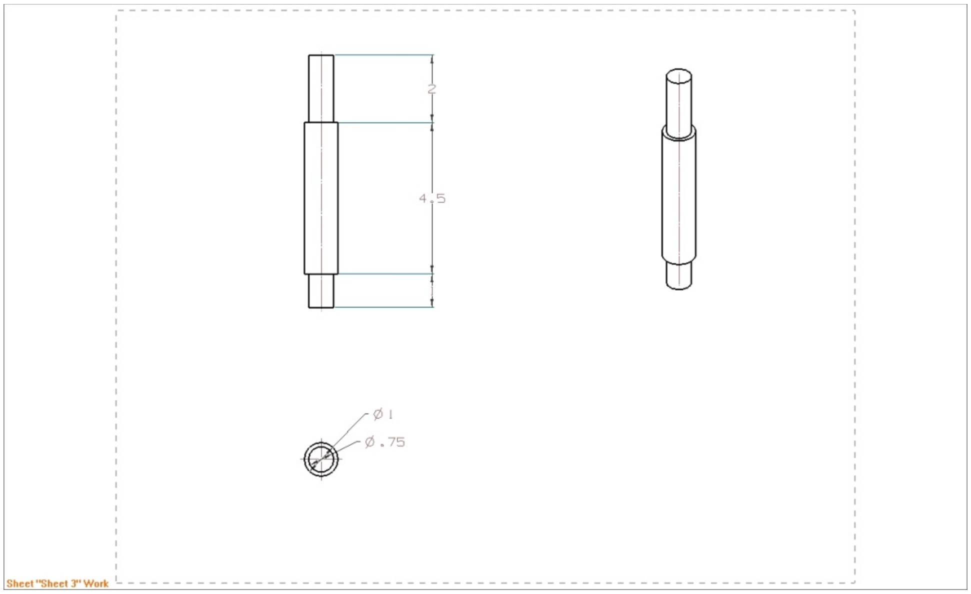


Figure J.1.10: Pendulum Control Wheel Vertical Mounting Shaft

Appendix J.2 Small Systems

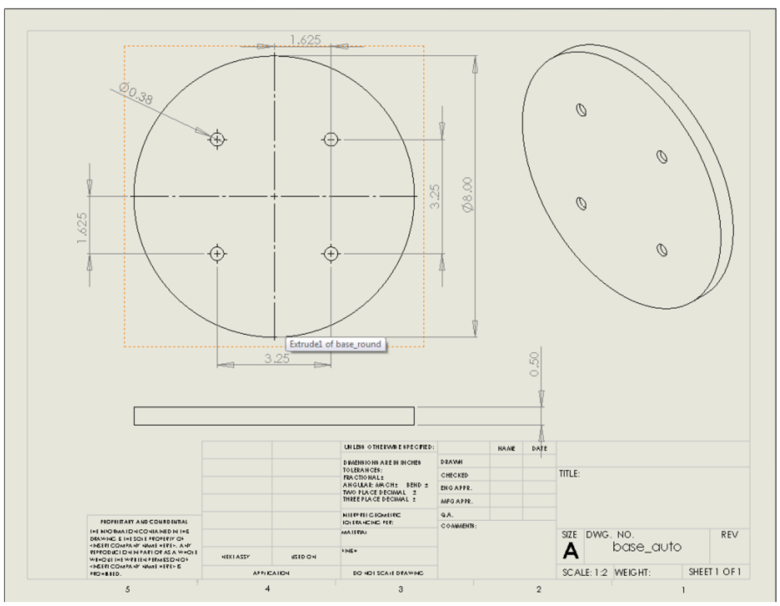


Figure J.2.1: Automatic System Base Plate

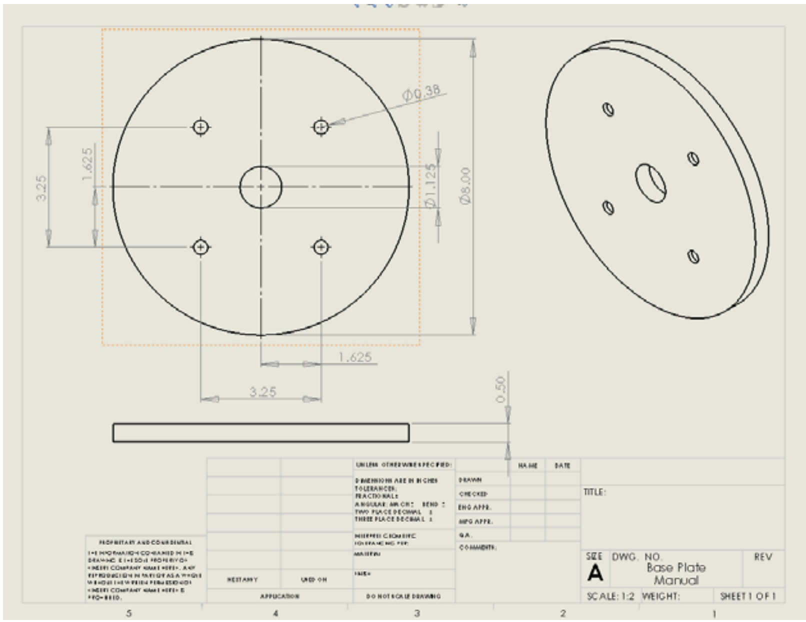


Figure J.2.2: Manual System Base Plate

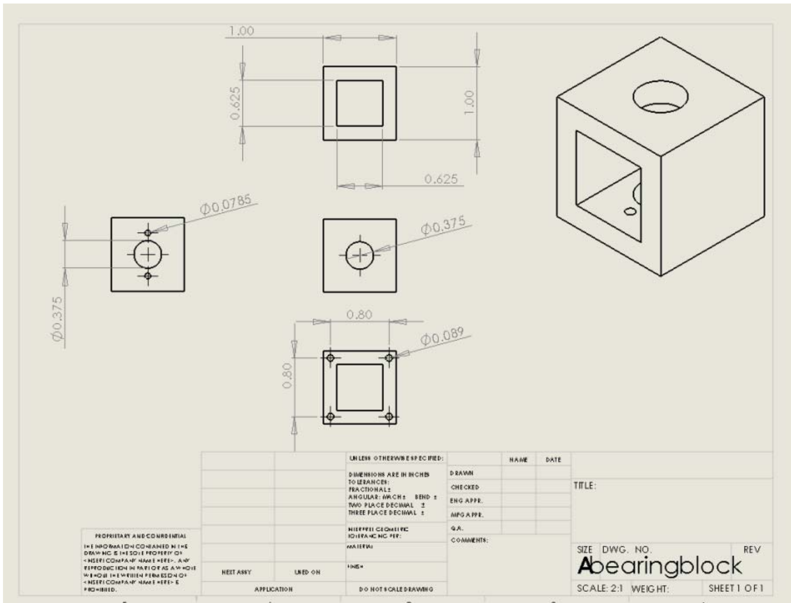


Figure J.2.3: Bearing Block

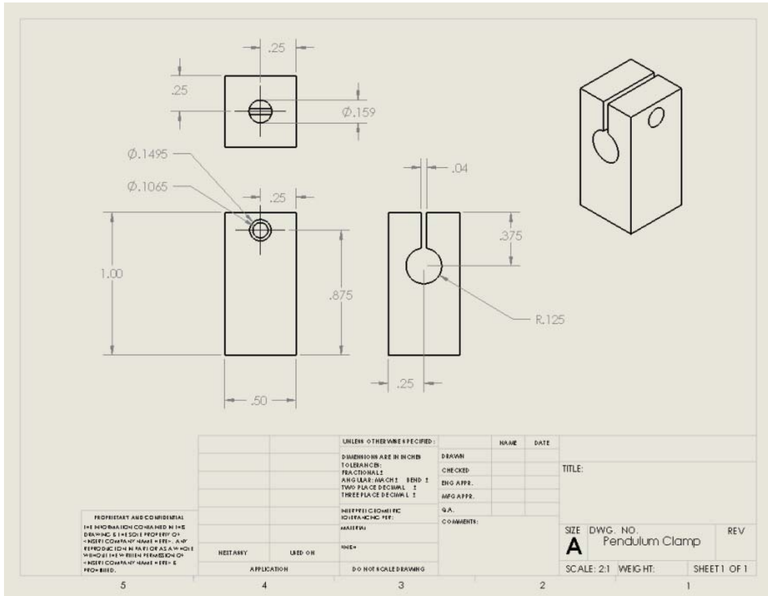


Figure J.2.4: Pendulum Clamp

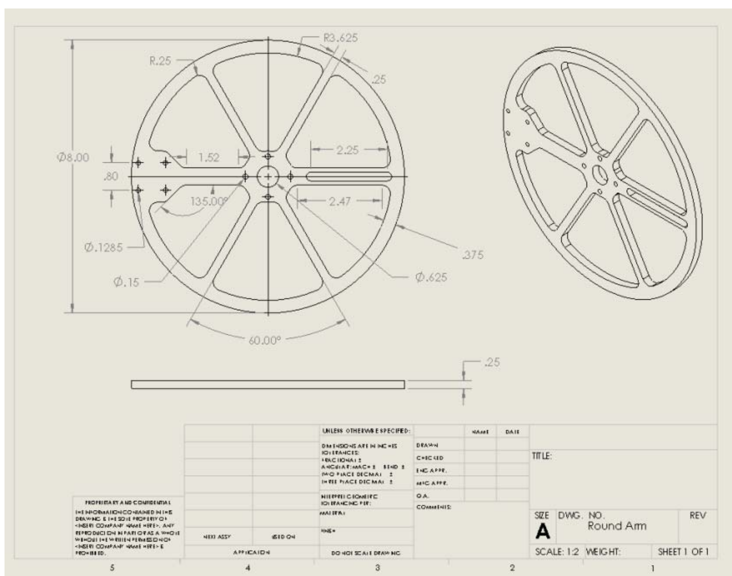


Figure J.2.5: Small System Control Wheel

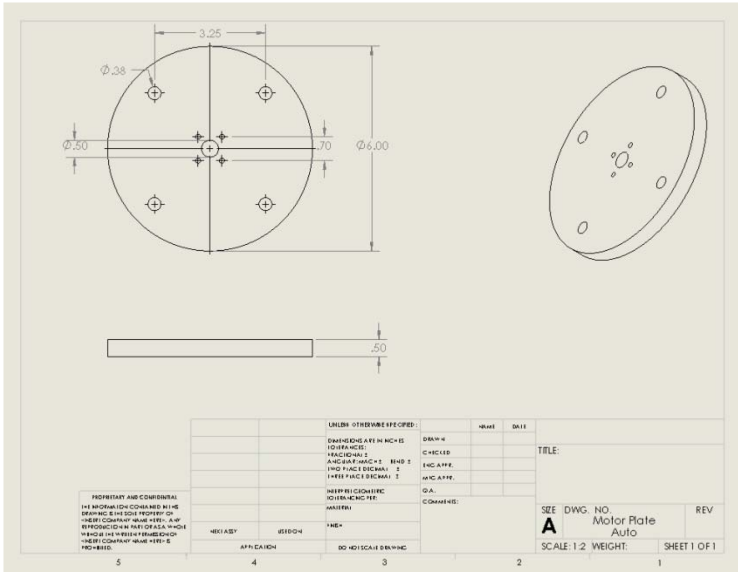


Figure J.2.6: Automatic System Motor Mount Plate

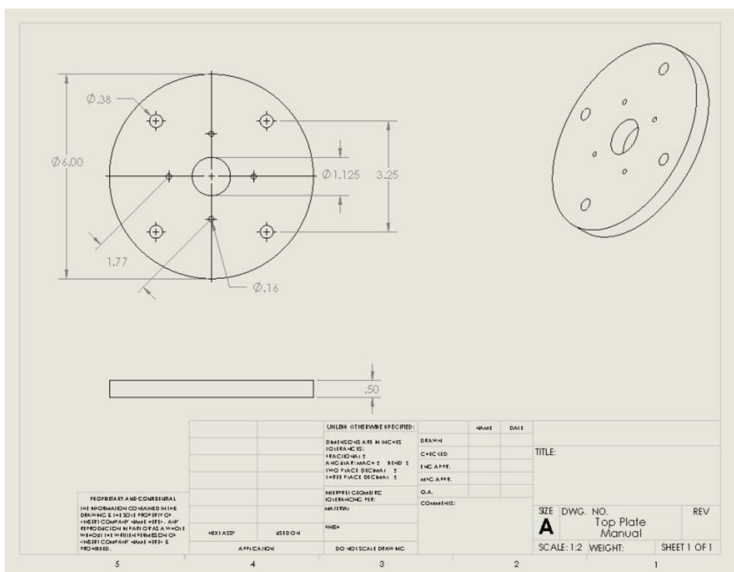
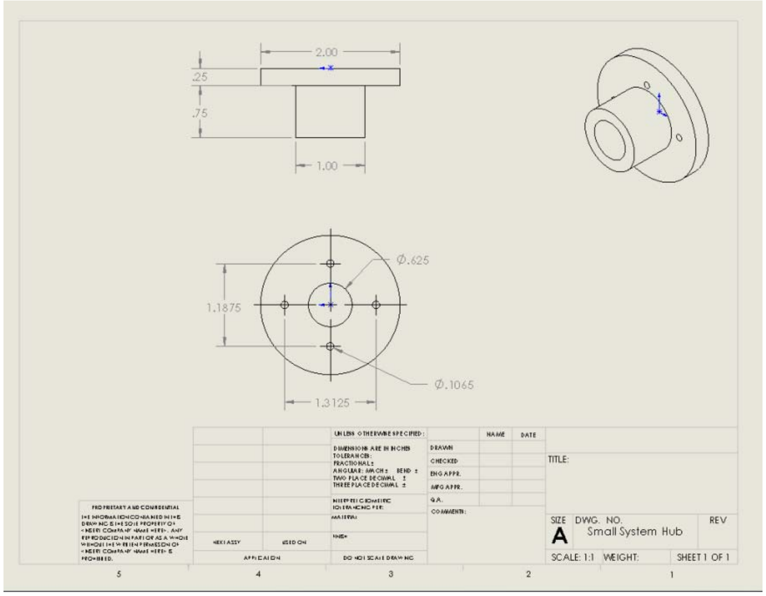


Figure J.2.7: Manual System Motor Mount Plate


2.00
.25
.75
1.00
Ø.625
1.1875
Ø.1065
1.3125
UNLESS OTHERWISE SPECIFIED:
NAME
DATE
DIMENSIONS ARE IN INCHES
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±
DRAWN
CHECKED
ENG APPR.
MFG APPR.
Q.A.
COMMENTS:
TITLE:
PROPRIETARY AND CONFIDENTIAL
NEXT ASSY
USED ON
APPLICATION
DO NOT SCALE DRAWING
SIZE
A
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Small System Hub
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1

APPENDIX K: MATERIAL SELECTION BASED ON FUNCTIONAL PERFORMANCE

The project sponsor requested that active system, small manual system, and some components of the large manual system be made of aluminum. This was chosen because Aluminum has a high strength to weight ratio and it can easily be machined and polished. This helps to improve the functionality and the aesthetics. However, it was necessary to determine an appropriate material for pendulum arm and angle limiter enclosure box for the large manual system.

Large Manual System Pendulum Arm

The function of the large pendulum arm is to swing freely so the exhibit operator can attempt to balance the arm using the control wheel. The objective was to design the pendulum arm so that the operator can easily balance the system after a few attempts. Through dynamic analysis it was determined that a long heavy pendulum arm will be easiest to balance. The sponsor requested that the pendulum arm be approximately 3 feet long, thus it became important to choose a material that would give an appropriate mass to optimized balancing difficulty. It was also important that the material be strong enough to endure the possible forces from exhibit abuse.

Aluminum alloys, stainless steel, steel alloys, plywood and titanium alloys will be explored as options using CSE software.

Figure K.1: Aluminum Alloys have the Highest Machinability of Available Materials

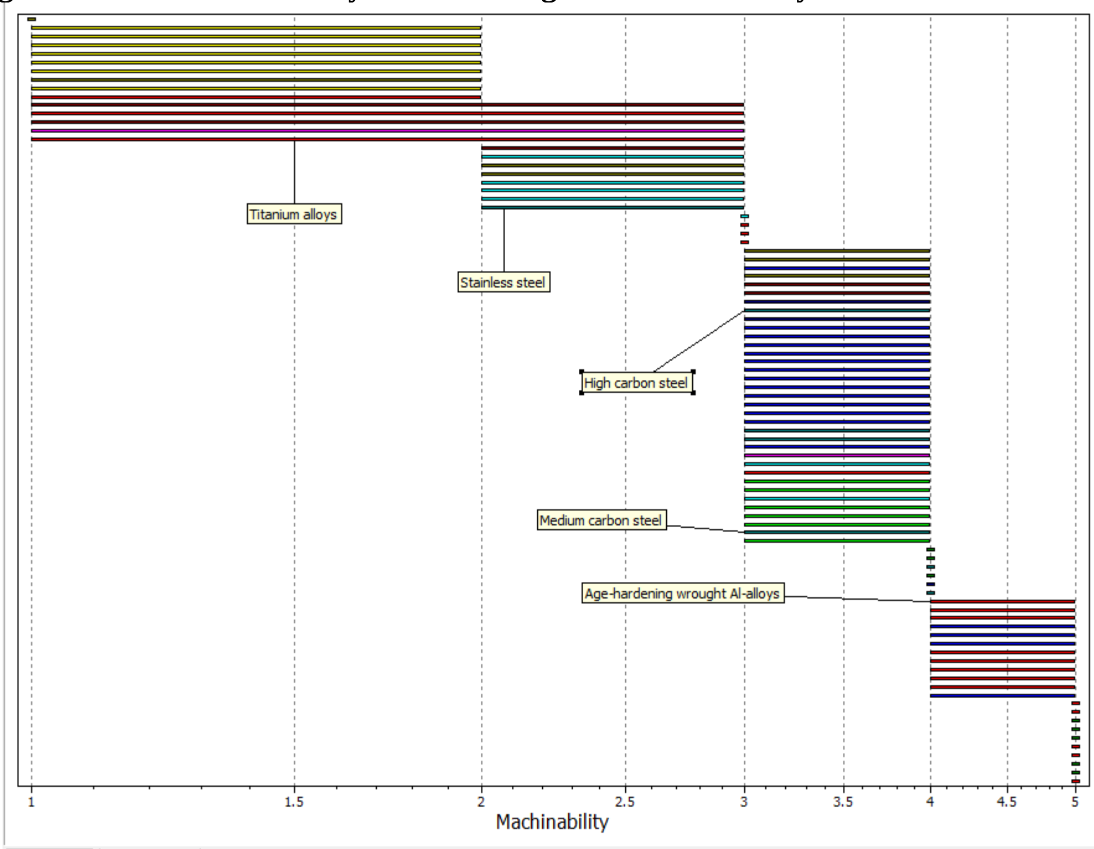


Figure K.2: Aluminum Alloys have a Slightly Higher Price than Steel Alloys

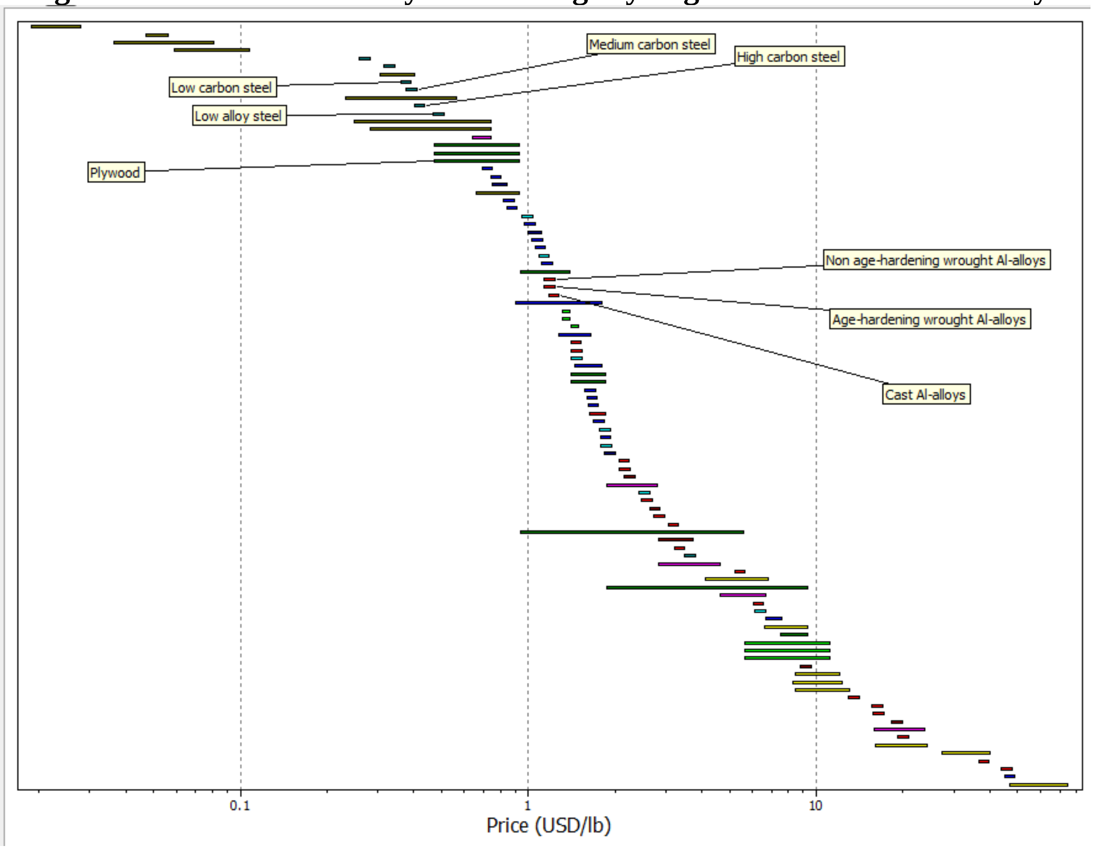


Figure K.3: Aluminum Will Provide a High Enough Tensile Strength

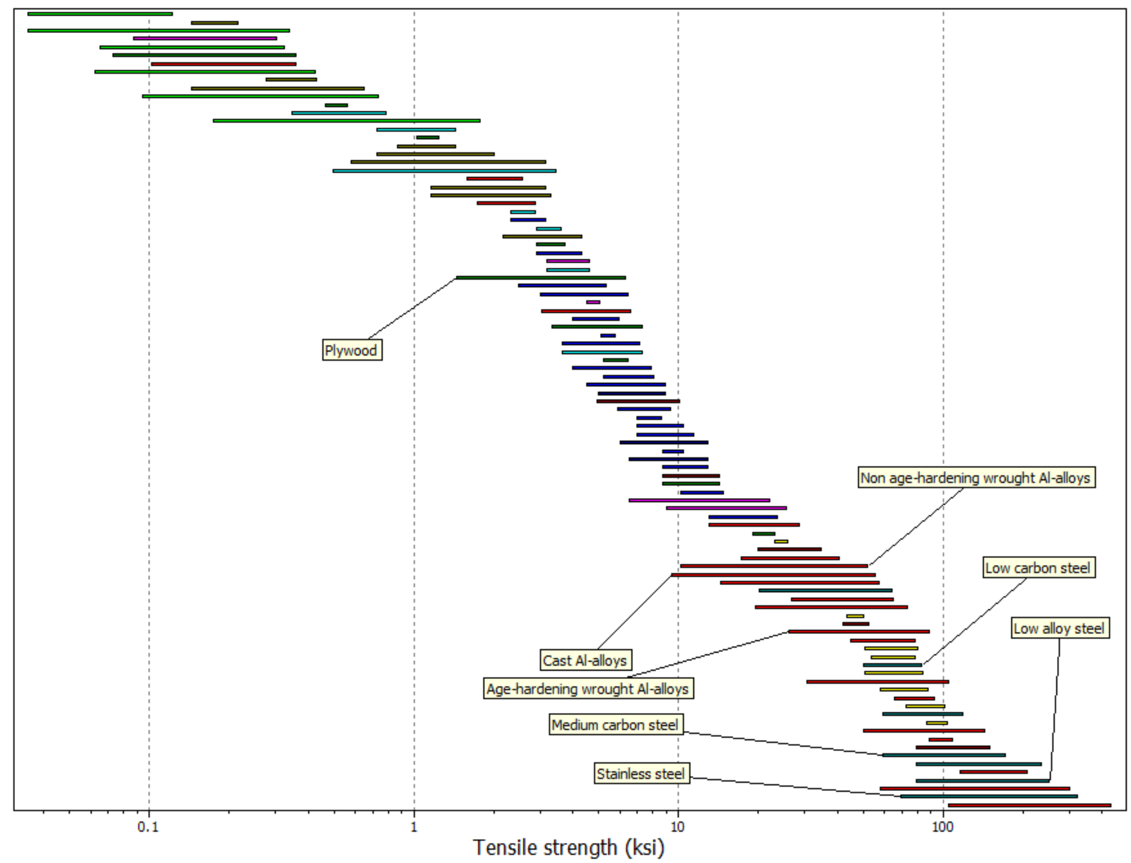
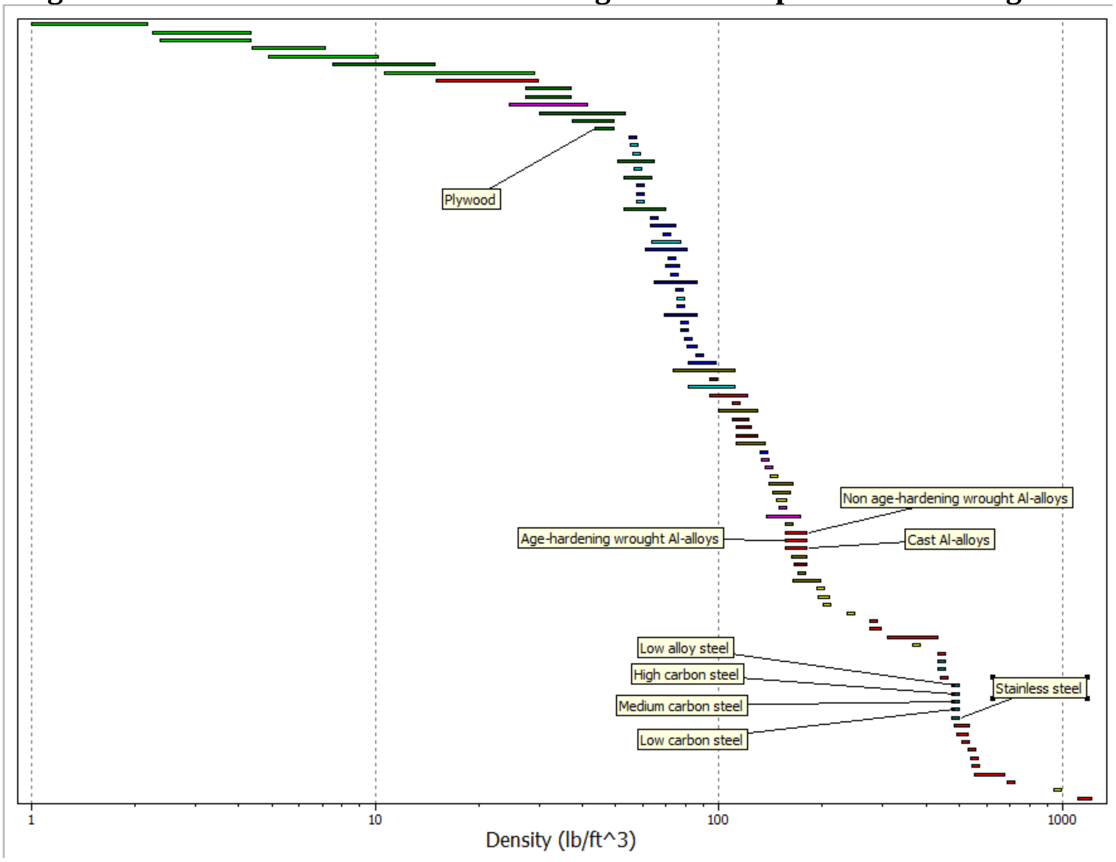


Figure K.4: Aluminum Will Provide Enough Mass to Optimize Balancing Ease



7075 aluminum was the material selected for this component. Plywood was not selected because it does not meet the necessary weight or strength requirements. While all other metal options have a higher strength and mass, shown in Figures K.3 and K.4, aluminum will meet the necessary requirements and is also has the highest machinibility, as shown in Figure K.1. Machinibility was an important factor in producing an aesthetically pleasing project. As shown in Figure K.2, aluminum has a higher cost than steel alloys. However, the higher cost of aluminum can be ignored as all of the materials were donated by Alro Steel. While 6061 aluminum fulfills all of the requirements for this component and is more easily machined, a large piece of 7075 aluminum was donated to the project. A comparable piece of 6061 aluminum would have cost approximately $120.00.

Large Manual System Angle Limiter Enclosure Box

The angle limiter enclosure box functions to conceal the angle limiter and to support the weight of the inverted pendulum system. Strength was the main concern when designing this component due to the large weight of the system and the possibility of large reaction forces during operation. The only constraint on this component was the availability of the material.

Steel was the material selected for this project. Steel alloys provide a high tensile strength, shown in Figure K.3, while maintaining reasonable machinability, shown in Figure K.1. Also, the necessary steel was readily available and donated from Alro Steel.

APPENDIX L: MATERIAL SELECTION BASED ON ENVIRONMENTAL IMPACT

It is estimated that around 10 kilograms of Aluminum will be needed for all three systems. Most parts are designed for safety and aesthetic reason; therefore same volume of material will be used if we switch to another material, such as steel, regardless of its stronger mechanical properties. Considering the limited materials we have in “SimaPro” and the results from “CES”, we will compare the eco effects of 10 kilograms of 6061 Aluminum (SimaPro does not have 6061 type, so 6060 type is chosen asan approximation), 10 kilograms of 7075 Aluminum and 28.7 kilograms of a common stainless steel, by using the EcoIndicator 99 (EI 99)standards.
The results are shown in Figure HC1, Figure HC2, Figure HC3 and Figure HC4. Figure HC1 shows Stainless steel will have the least amount of total emission. Figure HC2 and Figure HC3 show that among the category Human Health, Ecosystem Quality and Resources, Resources is the most important and Human Health is the second by far less significant; they also show that the 6061 aluminum (6060 in SimaPro) and Stainless steel are better rated by EI99 in the Resource category while stainless steel will do the lest damage to human health. Figure HC4 shows relative impacts in disaggregated damage categories for reference.
Direct safety issues and performance must be considered before taking the environmental effect into account. First, an exhibit that will be frequently exposed to children should not be heavy in case that the moving parts with great inertia and kinetic energy will accidentally injure the little viewers. Second, either for the active or passive system, a higher rotational inertia and will more likely to result in excessive load to the motor and excessive difficulty of operation, respectively. Therefore, considering these two points, aluminum is superior because of its light weight. Therefore, although the EI99 rated steel to be the most eco-friendly material among the three metals, a selection will be made between the 6061 aluminum and 7075 aluminum. From Figure HC3, it is obvious that 6061 aluminum has a better EI 99 rating than 7075 aluminum and it is thus chosen by the team.

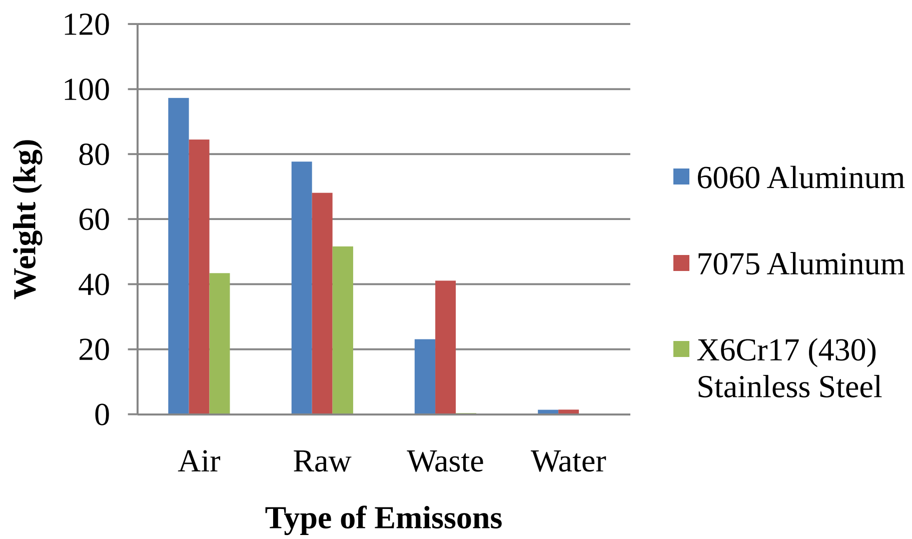


Figure L.1: Total Emissions of Different Materials

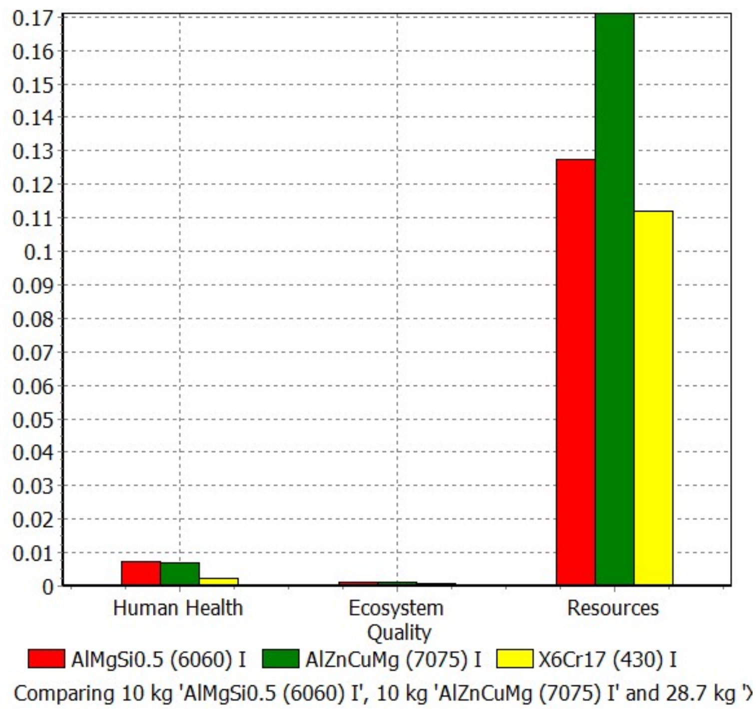


Figure L.2: Normalized Score in Human Health, Eco-Toxicity, and Resource Categories

APPENDIX M: MACHINING PROCESS SELECTION

This project is a museum exhibit for the Ann Arbor Hands On Museum so there will likely only be one exhibit ever produced. Occasionally worn or broken parts may have to be replaced. These conditions allowed for the use of manufacturing processes that were appropriate for rapid prototyping but may not be as appropriate for mass production.

Large Manual System Pendulum Arm

The large manual system's pendulum arm was made of two ¾" halves of 7075 Aluminum. The design contains many small holes and curved features but no 3 dimensional features. This design coupled with a production volume of one made the water-jet cutter a logical choice for manufacturing. The water-jet cutting machine's cutting speed is only surpassed by that of the laser cutting machines, shown in Figure M.1. However, the laser cutter was not selected because the machine available through the University could not cut through thick enough pieces of aluminum. Water-jet cutting also produces a high tolerance similar to that of a milling machine, shown in Figure M.2. The University's water-jet cutting machine can also cut through up to 1¼" Aluminum in one pass where it would take several passes on a lathe or mill, as shown in Figure M.3. It also requires minimal preparation, setup, and clean up. The University's CNC's machines had a large lead time and also require significantly more preparation, machining time, setup time, and clean up time.

Figure M.1: Water-Jet Cutting has a High Cutting Speed

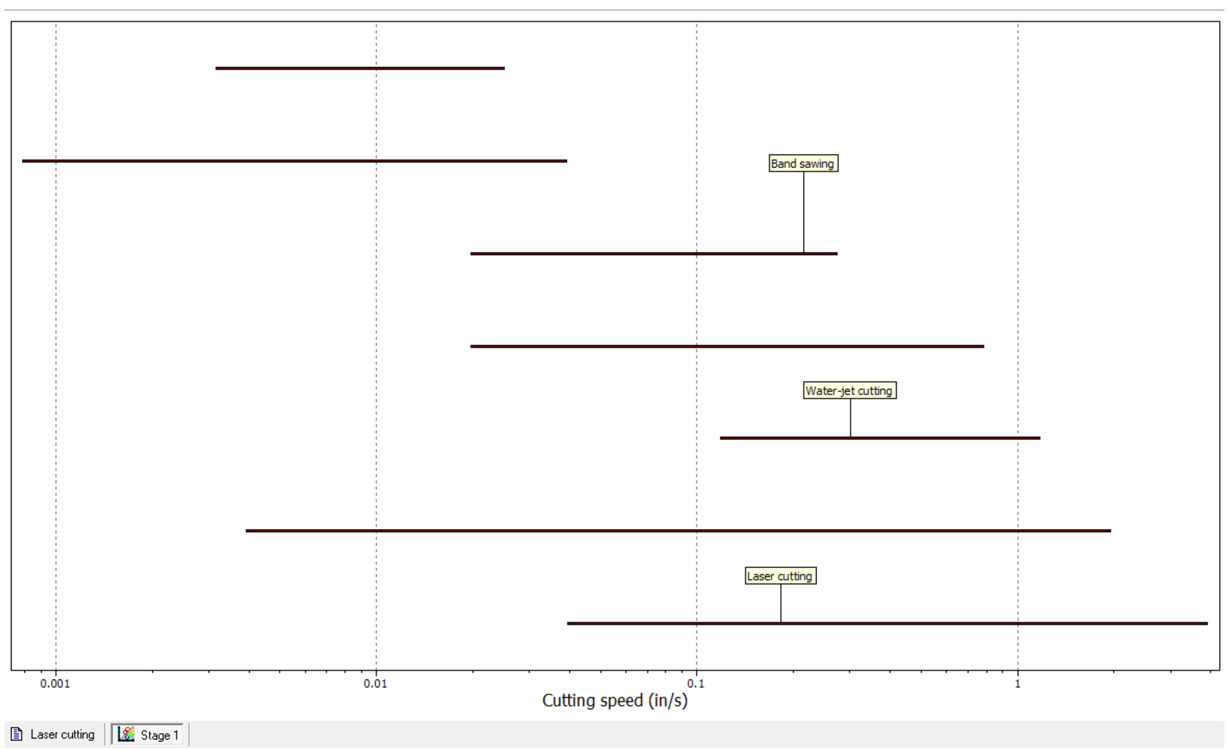


Figure M.2: Water-Jet Cutting Has Tolerances Equivalent To That Of Other Available Machining Processes

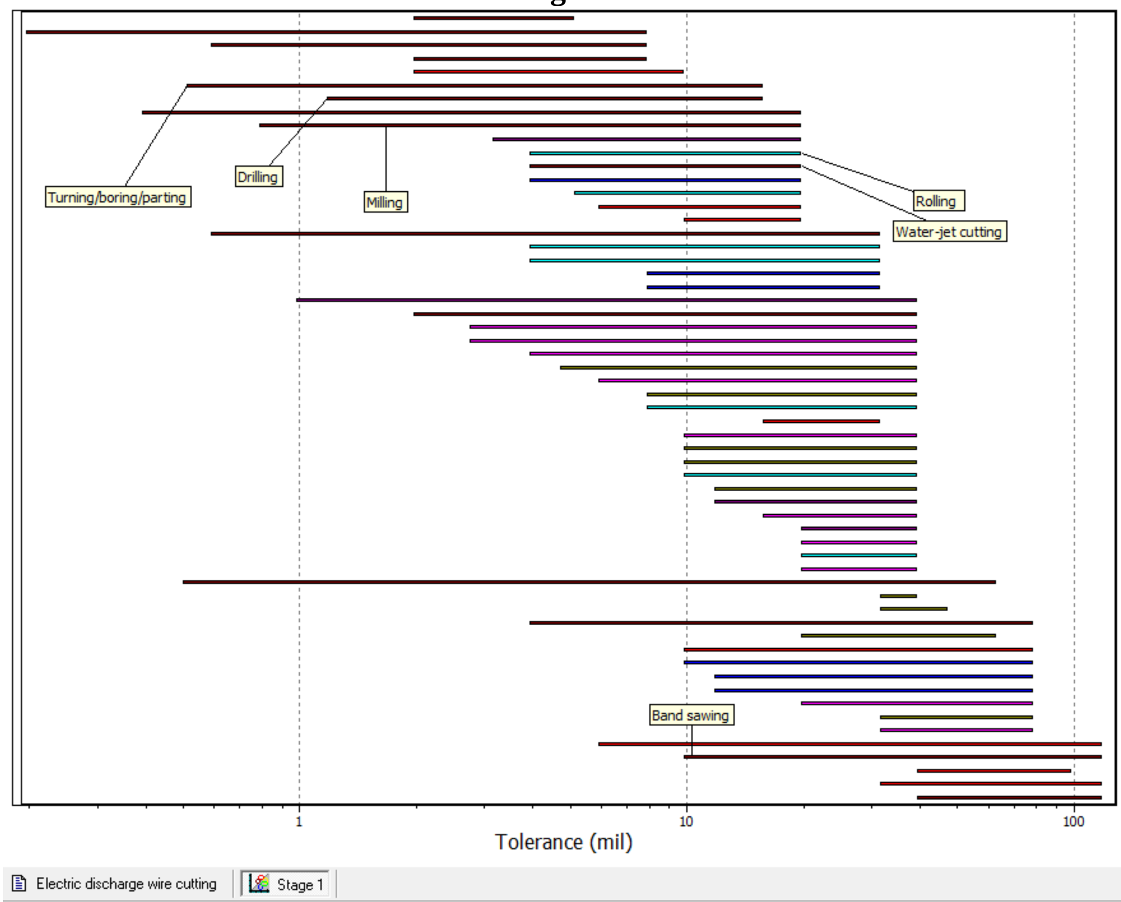
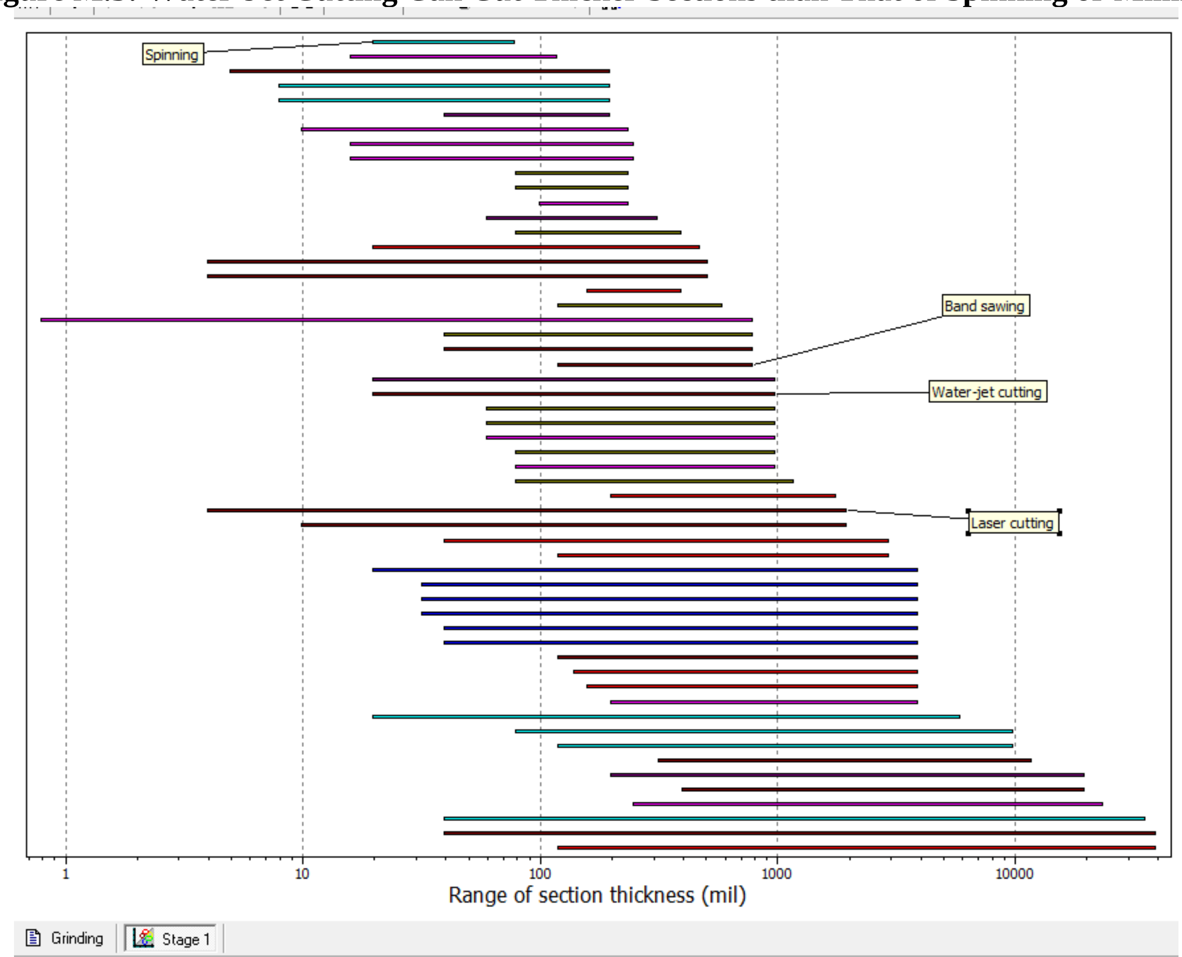


Figure M.3: Water-Jet Cutting Can Cut Thicker Sections than That of Spinning or Milling



Large Manual System Angle Limiter Enclosure Box

The large manual system's angle limiter enclosure box was to be constructed out of ¼" steel plates. The design of these plates was simple and did not contain any 3 dimensional features. Therefore, the water-jet cutter was selected for this component for the same reasons listed above. The water-jet cutter was used extensively for this project due largely to it availability, ease of use, speed of operation, and precision.

The water-jet cutting machine uses a pressurized stream of water and sand to cut through materials. This leaves the edges of the parts rough and not square. Therefore some post-machining was required; however, the addition time spent on the post machining was more than accounted for by the time saved through the use of the water-jet cutting machine.

APPENDIX N: FATIGUE ANALYSIS

As a museum exhibit, the three systems will be under heavy daily operations, which raise the issue of fatigue failure. Therefore, the team was requested by the sponsors to conduct fatigue analysis to the dangerous points.

All moving components under stress were made of 6061 Aluminum, which has fatigue strength of 96.5 MPa for 10,000,000 cycles of fully reversed load [1]. Most components will have stresses lower than this fatigue stress by order of magnitude, meaning those components will not be concerned for fatigue failure. (Figure N.4).

However, the team has identified that the stopper of the large passive device will be a dangerous component for fatigue failure, because of the relatively large loads and small cross sectional areas on that part. Most dangerous points were assumed to be at the neck of the stopper and the stopper pin, which are under significant shear (Figure N.1). To research the fatigue life of this part, the stress must be found at the dangerous points. Therefore, a finite element analysis (FEA) was conducted.

Figure N.2 shows the loads and boundary conditions: the base of the stopper is constrained for displacement in all degrees of freedom, and a concentrated force of 500 N is applied (with a safety factor around 10) at the end of the stopper pin to mimic the impact caused by the collision of the pendulum arm and the stopper pin. The stopper was automeshed since this is applicable to static simple geometry analysis. Figure N.3 (Stresses were in “Pa” in Figure H3) shows the results of the FEA: 29.7 MPa stress at the neck and 104 MPa stress at the stopper pin with stress concerntration.

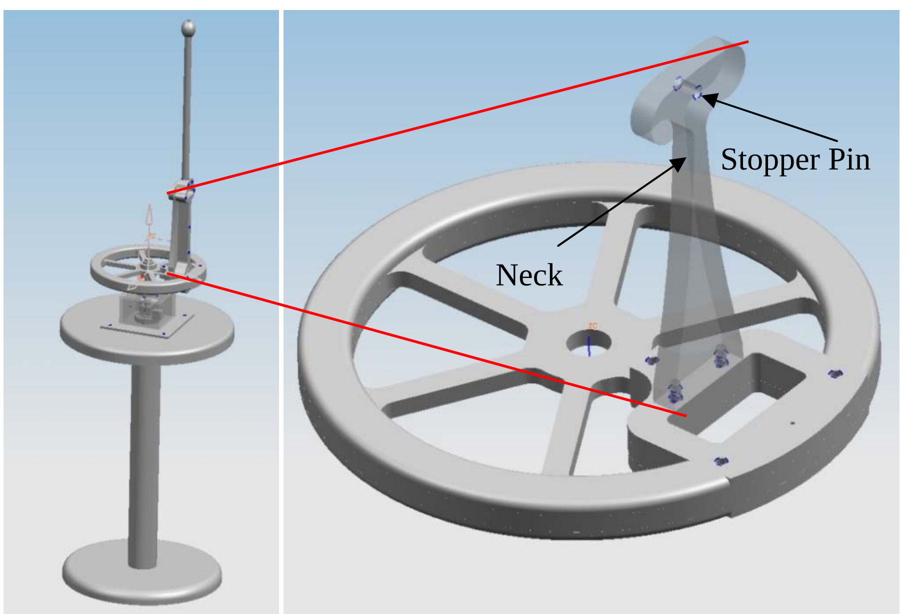


Figure N.1: Dangerous Fatigue Points on the Large Passive System’s Stopper

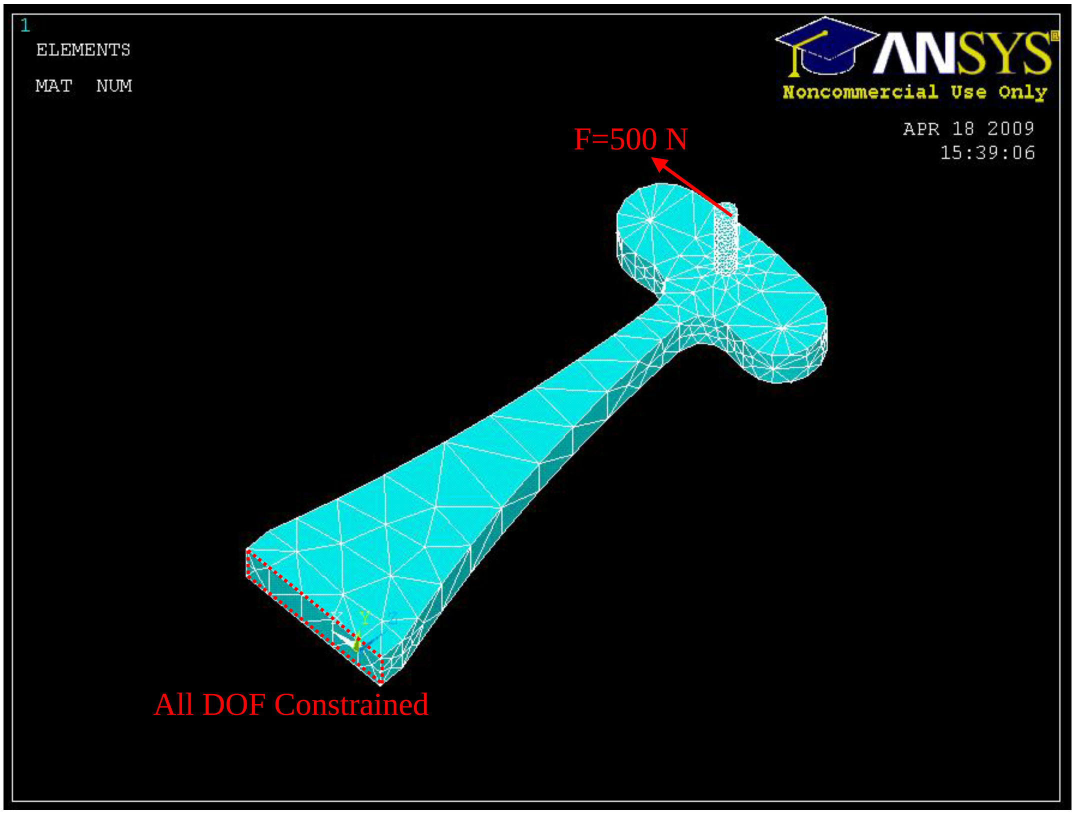


Figure N.2: Loads and Boundary Conditions with the Meshed Component

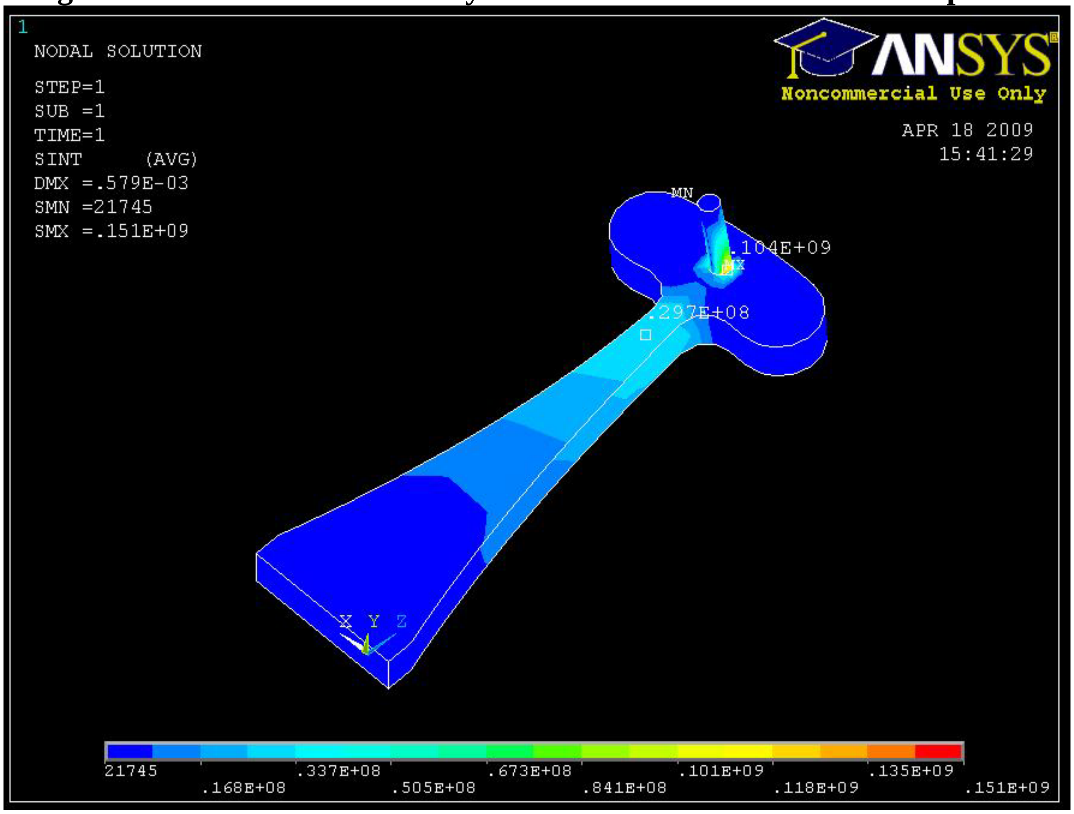


Figure N.3: Stress Distribution with the Stresses at Dangerous Points

The fatigue life is predicted by the following empirical equation [2]:

$$\sigma \quad = \frac{14{,}479}{\sqrt{N}} + \ 96.5\ MPa \qquad \text{Equation N.1}$$

With the stresses known: 29.7 MPa stress at the neck and 104 MPa stress at the stopper pin, Equation H1 predicts that the neck is free from fatigue failure while the pin has a fatigue life of 3,700,000 fully reversed cycles.

In conclusion, assuming the museum opens 8 hours every day in every year, 500 load cycles for each hour, and with the excessive operation taken into account (a safety factor around 10), the stopper pin as the most dangerous component can survive at least 2 and a half years while all other components will be safe from fatigue failure for the whole life time of the devices. Although this doesn't strictly meet the requirement of 7-year life time, the stopper pin is designed to be replaceable and is an easy-to-purchase part. It will need a replace every 2 to 3 years. In order to avoid replacing the stopper pin this often it has been replaced with a 304 stainless steel stopper pin. This will greatly improve life time of the pin.

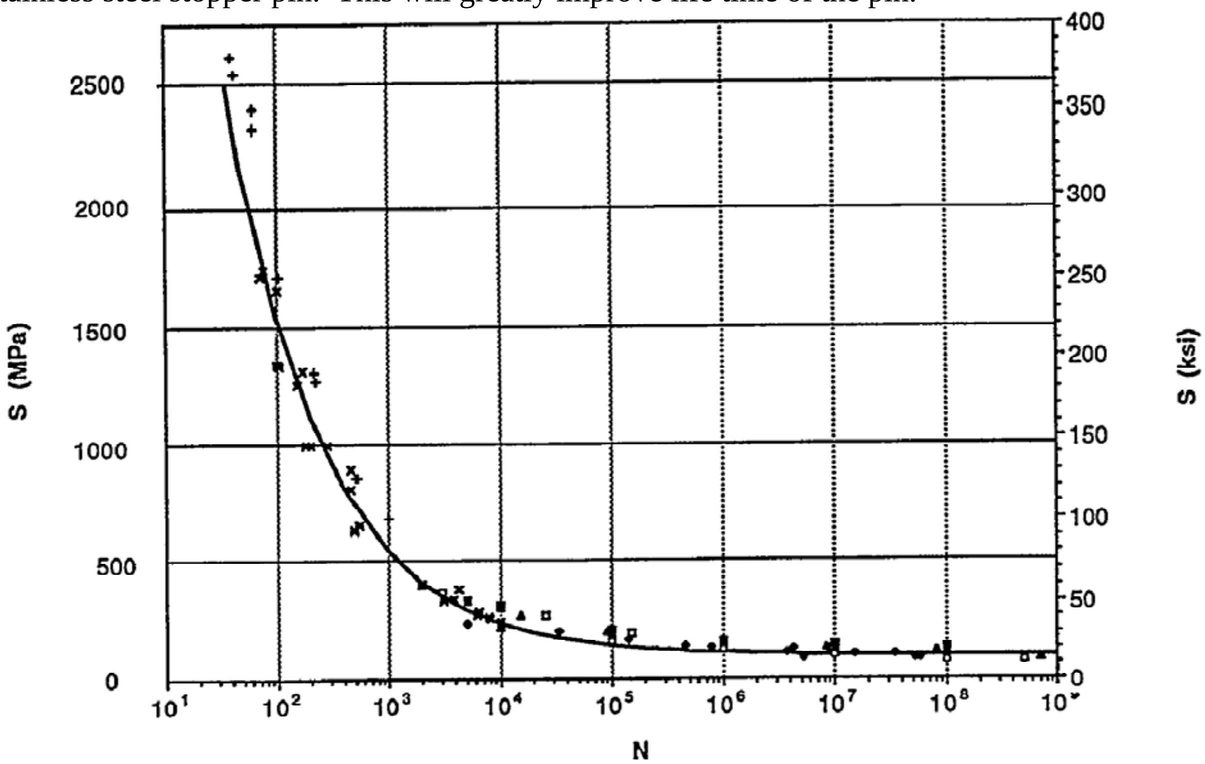


Figure N.4: Fit to Fully Reversed 6061 Data [3]

REFERENCE

[1] "6061 Aluminum", *Structural Alloys Handbook*, Volume 3, Battelle, Columbus, Ohio, 1989

[2] G. T. Yahr, Fatigue Design Curves for 6061-T6 Aluminum, Office of Scientific & Technical Information, 1993, p. 4

[3] G. T. Yahr, Fatigue Design Curves for 6061-T6 Aluminum, Office of Scientific & Technical Information, 1993, p. 12

APPENDIX O: SAFETY REPORT

Safety Reporting Directions: Please address the following points and questions.

1. **Executive Summary**. Answer the following questions: What activities or designs are covered by this report? What hazards have you identified and eliminated? What analysis have you performed and why do you conclude that the activities/designs are low risk? Be sure you consider all aspects of your project: experimental data collection, component design, system design, manufacturing, assembly, and testing.
2. **Experimentation Plans Prior to Design Completion**. For your experimentation, list what data you will be collecting and why. Are any experiments that might have safety risks unnecessary? Why/Why not?
3. **Purchased Component and Material Inventory**. Provide an inventory of all materials (solid materials such as aluminum/wood/etc.) and purchased components you will be using. Why are these materials and components necessary? a. Complete an FMEA for any purchased components that have safety risks. Provide the FMEA table as an appendix to this Safety Report and summarize the results in your own words for the main report body.

    4. **CAD Drawings and DesignSafe Summary for Designed Parts**. Provide CAD drawings for components you have designed and will manufacture. a. Conduct a risk assessment using Designsafe software (available on CAEN) for each designed component and for the full assembly of components constituting your design. Provide the Designsafe output as an appendix to this safety report and summarize the results in your own words for the main report body.

    5. **Manufacturing**. Provide a list of all fabrication or manufacturing activities you will perform. Where will these activities take place? Why are these processes necessary? a. CAD drawings for parts to be manufactured are required (per #4 above).

    b. For machining or forming processes, list special setup requirements and the operational conditions that will be employed (e.g., speeds, feeds, etc.).

6. **Assembly**. How and where will your components be assembled? On what basis do you conclude that the assembly will not fail before use, during use, or after use?

    7. **Design Testing and Validation**. How and where will your final design be tested? Which design specifications are being validated through the testing? Do you plan to test aspects of your design as you manufacture your prototype, or are you going to be validating a finished prototype after most/all manufacturing has been completed? a. What would you consider to be your first major test of the design?

    b. Have you arranged with your Section Instructor to have a cognizant individual present at your first major test? Who will this be? When do you expect this first test to take place?

    8. **Additional Appendices**: a. For every chemical (powder, liquid, gas – distinguished from a "material" defined in step 2 above as a solid) you propose for use in testing or design, you must supply a complete MSDS as an appendix.

    b. If relevant safety documentation is provided with a purchased component, include it as an appendix.

9. **Submission**. After addressing points 1-8 above, please do the following: a. Submit this report to your Section Instructor for signature. Please check with your Section Instructor to learn if a hard copy or an electronic copy is preferred for signature. Regardless, please create an electronic copy for filing and email to Bob Coury and Dan Johnson (below).

b. After the report is signed, email a copy to Bob Coury (hornet@umich.edu) and our course GSI Dan Johnson (danijohn@umich.edu) i. Both Bob and Dan are expected to raise additional safety concerns that will be shared with the students and the Section Instructor. They have the authority to stop any activity they deem unsafe, regardless of whether a safety report has been signed. If this happens, the safety report will be revised and re-signed by the Section Instructor, then emailed with revisions to Bob Coury and Dan Johnson

1. Executive Summary

Overview

Ann Arbor Hands-on Museum has requested the design team to design an informational exhibit utilizing one active and two passive/manual inverted pendulum systems. All design ideas have been finalized in Design Review 2. The team is planning to move on to the next stage of the design processes, manufacturing and testing. Parts for all three devices were determined to be either made in house or purchased from out sources. Some optical/mechanical tests are also necessary to determine the active system’s data transfer mechanism. Solutions for manufacturing parts and assembling the devices are discussed in this report as well.

Design Elements

A full safety analysis is therefore conducted on the purchased components, designed components, material, the entire device operation, and other relevant processes. In the analysis, FMEA and *designsafe* program were utilized as well as judgments by relevant engineering experience and knowledge. All purchased parts were analyzed by FMEA and designed components were analyzed by *designsafe*. According to these analyses, only a few issues are identified as potential hazards in these systems. Two major problems are the bearing life and disoperation by viewers. Potential solutions such as adding extra bearings and adding warning labels can well solve the above problems respectively.

Manufacturing and Assembly

For the designed components, the manufacturing process includes: CNC milling, drilling, and press fitting. The hazards here are the general machine shop hazards, such as fast moving equipment and flying chips. To avoid these hazards, standard machine shop training was conducted by professional personnel to the team before the team goes into the machine shop. Compared with manufacturing, assembly processes are relatively low-risk. Most of the manufacture and assembly only involves generic fastening components. Only one part need to be welded.

Testing

Testing is also a low-risk process at the current stage. We are planning to test the infrared data transfer system which operates under a very low voltage, and the power level of the implemented infrared device is far below the dangerous levels.

2. Collected Data

<u>Design Testing and Validation</u>

The IPE Design Team plans to test a few key changes being made to the prototype. The change in communication, from direct wiring to a wireless infrared system, is probably the most significant. Also, the powering of this system, via solar cells rather than a 120VAC power supply, must be tested. The last major test will be of the system's response to an increased moment of inertia. Future testing of the control program is expected to take place after these tests have been completed and analyzed. The safety concerns for each of these tests do not go beyond those found with the current prototype's operation and appear worthwhile to conduct.

Infrared Communication Testing: Testing of the infrared communications system will be required to determine if the data transfer rates are adequate and data propagation delays short enough to allow proper operation of the prototype. This testing will be done in three stages, the first will use the current prototype without any physical changes and the last two will use the Motorola series programmable IC's. None of these tests should pose safety threats beyond those present with the current prototype.

For the first test, to determine the required data transfer rates, the sampling rate of the LabView/DAC setup will be reduced until there is a noticeable effect on the system's performance. This should provide a higher approximation to the data transfer rates required as the LabView/DAC setup is handling not only the optical encoder data, but also the motor tachometer data and the outgoing motor control signals.

The second two tests will involve placing the preliminary infrared communications circuitry between the optical encoder and the DAC inputs. This will allow for testing and debugging of the infrared transmitter/receiver hardware and software. The transfer rates of these two devices are at approximately 3800 baud. The first test will simply mimic the A/B channels of the optical encoder while the second test will send an angle and angular velocity. The second is more complex, however far more tolerant to interference in the transmission, and will require modification of the LabView code to take angle/angular velocity as inputs rather than pulses. This tolerance comes from each pulse of the encoder being directly accounted for, then being transmitted as a whole value (say 100 degrees), rather than each pulse being transmitted, in which case "missed pulses" would eventually accumulate in the receiver as error.

System Response to Increased Inertia: The design change from a simple bar connecting the motor and pendulum to a wheel increases the moment of inertia of the controlled system. A simple test, once the pieces are manufactured, will be conducted to ensure that this change in momentum will not adversely affect the performance of the prototype. Also, new control coefficients are expected, and will be confirmed from this test. Proper connection of the motor to the control wheel, as well as the counterweight and pendulum assembly, will be required for safe operation. Connections similar to those used in the prototype will be used. Safety glasses should be worn during the testing and a reasonable distance to the device should be maintained to prevent injury, however no safety concerns beyond those with the current prototype are expected.

3. Prototype Material & Purchased Component Inventory

Material and Part list: Small Active/Manual System

1. Steel Tapered-Roller Bearing Roller Assembly for 3/4" Shaft Diameter – This bearing is necessary to reduce friction in the shaft and controlling wheel assembly for the small manually controlled system.
Vendor: McMaster Carr
Part Number: 5709K14

2. Miniature Precision SS Ball Bearing – This bearing will be used to reduce friction in the rotating pendulum assembly by being placed in “bearing block” that supports the pendulum assembly.
Vendor: McMaster Carr
Part Number: 57155K355

3. Type 316 SS Cup Point Socket Set Screw 10-32 Thread, 5/8" Length – This set screw will be placed in the pendulum arm clamp and will hold the pendulum arm in place.
Vendor: McMaster Carr
Part Number: 92313A831

4. 18-8 Stainless Steel Socket Head Cap Screw 3/8"-24 Thread, 1" Length – 2 packs of these screws will be necessary to fasten the base plates and connecting rods together.
Vendor: McMaster Carr
Part Number: 92196A359

5. Military Specification Socket Head Cap Screw 300 Series SS, 6-32 Thread, 3/8" Length, MS 16995-17 – This screws will be used to mount the motor to the upper base plate.
Vendor: McMaster Carr9
Part Number: 2200A146

6. 18-8 Stainless Steel Socket Head Cap Screw 4-40 Thread, 5/8" Length – These screws will be used to hold the bearing block and pendulum assembly in place.
Vendor: McMaster Carr
Part Number: 92196A112

7. 18-8 Stainless Steel Socket Head Cap Screw 6-32 Thread, 1/2" Length – These screws will be used to secure the shaft from the optical encoder to the pendulum clamp.
Vendor: McMaster Carr
Part Number: 92196A148

8. One-Piece Clamp-on Shaft Collar Black-Oxide Steel, 1/4" Bore, 11/16" OD, 5/16" Width – Six of these shaft collars will be used as pendulum weights
Vendor: McMaster Carr
Part Number: 6435K12

9. Right-Hand Threaded Connecting Rod 6" Overall Length, 3/8"-24 Threaded Female Ends – Eight of these rods will be used as support rods to connect the upper and lower base plates while maintaining six inches of spacing.
Vendor: McMaster Carr
Part Number: 6516K61

10. Multipurpose Aluminum (Alloy 6061) Rectangular Tube 3/16" Wall Thickness, 1" X 1", 1' Length – This rectangular tube will be used for manufacturing the bearing block and the counterweight.
Vendor: McMaster Carr
Part Number: 6546K341

11. Right-Hand Threaded Connecting Rod 6" Overall Length, 10-32 Threaded Female Ends – Two of these rods will be used as pendulum arms.
McMaster Carr - 6516K51

12. 1018 cold rolled Steel rod 1" Diameter, 1' Length – This stock will be used to manufacture the controlling shaft for the small manual system.
Vendor: Alro Steel

13. Keyless Bushing – Two of these keyless bushing will be used to connect the motor shaft to the rotating six spoke wheel.
Vendor: Fenner Drives
Part Number: 6202103

14. 8” Aluminum Disc 5/8” thick – Two of these discs will be used to manufacture the lower base plate for both the small electronically controlled and manually controlled systems.
Vendor: Alro Steel

15. 6” Aluminum Disc 5/8” thick – Two of these discs will be used to manufacture the upper base plate for both the small electronically controlled and manually controlled systems.
Vendor: Alro Steel

16. 8” Aluminum Disc ¼” thick – Two of these discs will be used to manufacture the rotating wheels for both the small electronically controlled and manually controlled systems.
Vendor: Alro Steel

17. ½” square 1” long Aluminum – This piece of aluminum will be used to manufacture the pendulum arm clamps.
Vendor: Alro Steel

Material and Part list: Large Manual System

1. 18”x18” aluminum 6061 plate ¾” thick—this will be used to manufacture the main part of the control wheel.
Vendor: Altro Steel

2. 18”x36” ABS plastic plate 3/8” thick—this will be used to manufacture the top and bottom cover of the control wheel to cover the part where viewer handles the wheel.
Vendor: Altro Steel

3. 15”x8” aluminum 6061 plate 3/8” thick—this will be used to manufacture the top and bottom cover of the control wheel to hold the shaft holding the pendulum.
Vendor: Altro Steel

4. 8”x12” aluminum 6061 plate ¾” thick—this plate will be used to manufacture the pendulum stopper and also the gusset which will support the stopper in its vertical position.
Vendor: Altro Steel

5. Stainless steel shoulder bolt—after cutting the head off, the bolt will be used to made the stopper pin for the pendulum stopper
Vendor: Altro Steel

6. 12”x12” aluminum 6061 plate ¾” thick—this plate will be used to manufacture the lower part of the pendulum arm.
Vendor: Altro Steel

7. 36” long aluminum 6061 structural tube with 1” OD and 0.5” ID—this tube will be used as the upper part of the pendulum arm
Vendor: Altro Steel

8. 2” diameter stainless steel ball—this ball will be used to make the pendulum weight
Vendor: Provided by Ann Arbor Hands-on Museum

9. Friction torque limiter—this device will be needed to make the wheel be able to rotate against the shaft when a large torque is applied to the wheel. This can prevent damage to the angle limiter which limits the wheel within 90 degrees.
Vendor: McMaster-Carr
Part Number: 6524K11

10. 8”x8” cast iron plate ¼” thick—two of these plate will be needed to manufacture the cover and base of the angle limiter under the wheel
Vendor: Altro Steel

11. 3” high 6”x6” cast iron rectangular tube with 3/8” wall thickness—this is used to manufacture the case of the angle limiter
Vendor: Altro Steel

12. 4”x8” aluminum 6061 plate ¾” thick—this plate will be needed to manufacture the two bearing holders placed at the top and bottom of the angle limiter case
Vendor: Altro Steel

13. 2”x 4” aluminum 6061 plate ¾” thick—this will be used to manufacture the stopper pin for the angle limiter
Vendor: Altro Steel

14. 8” long 1” diameter steel rod—this rod will be needed to manufacture the shaft holds the wheel
Vendor: Altro Steel

15. 2”x2”x8” delrin block—this will be used to manufacture the bumpers in angle limiter
Vendor: Altro Steel

16. Flanged double sealed ball bearing—two of these bearings will be needed to hold the pendulum arm
Vendor: McMaster-Carr
Part Number: 6384K367

17. Double sealed ball bearing—this bearing will be holding the wheel shaft at the top of the angle limiter case.
Vendor: McMaster-Carr
Part Number: 60355K32

18. Tapered roller bearing—this bearing will be holding the wheel shaft at the bottom of the angle limiter case
Vendor: McMaster-Carr
Part Number: 5709K14

19. Steel Tapered-Roller Bearing Outer Ring—this part will be needed to assemble the roller bearing in #18
Vendor: McMaster-Carr
Part Number: 5709K54

20. 6”x6” polycarbonate plate—this plate will be used to manufacture the cover of the slot stopper to eliminate pinch points
Vendor: Altro Steel

<u>FMEA Analysis Results of Purchased Components</u>

The majority of the components selected for the Inverted Pendulum Exhibit will either be purchased or machined from 6061-T6 aluminum. Aluminum was selected due to ease of machining, strength, availability, and quality/variety of finish. Bearings, nuts, bolts, and electronics will generally be purchased. A full BOM can be found in Appendix A as well as the FMEA for components with appreciable expected failure.

Safety concerns due to purchased components arise largely from bearing failure. Each bearing has been expected to seize, become loose (“wobble” with more than purely rotational motion), or detach from its mount. Detachment is the most severe, with a potential to cause injury especially in the case of the non-enclosed larger system. However, due to the design of the larger assembly,

this is all but impossible without intentional disassembly. As for the small systems, being enclosed should prevent severe over-loading which might cause detachment. This leaves wear as a primary cause of failure which should be easily detectable during maintenance. Detection by simply trying to “wiggle” each bearing-joint ensuring that only a single, rotational, degree of freedom is experienced should suffice. Seizing is most likely a sign of sever over-loading, however should pose minor, if any, safety concerns. As with becoming loose, detection should occur during basic maintenance, ensuring that each bearing moves purely in rotation and does so with little resistance. Any bearing that seems to allow for more than purely rotational movement, or provides significant resistance to movement, should be replaced with one that meets or exceeds the ratings of the supplied bearings.
Mechanically the failure of other purchased components should be very rare. This would include the failure of nuts/bolts, threaded rods, and keyless bushings to attach various components. Sized appropriately, they should pose little risk of failure as well as being redundant in many locations. With careful inspection of the device during maintenance any loose, cracked, or stripped hardware should be easily identified and replaced. The use of thread-locker during final assembly and during replacement of worn/damaged parts should further prevent these failures.
Failure of electrical components should also be minimal. Basic surge protection and fusing should protect the electronic components from failure. The optical angle encoder and control motor are the only electrical components expected to fail. This is expected to occur due to mechanical wear and should also be non-catastrophic; posing little safety concern however may impair performance. Replacement should be made using similar components.

4. CAD Drawings of Designed Parts
<u>CAD Model: Small Manual/Active System</u>

Figure O.1: Base Plate Manual System

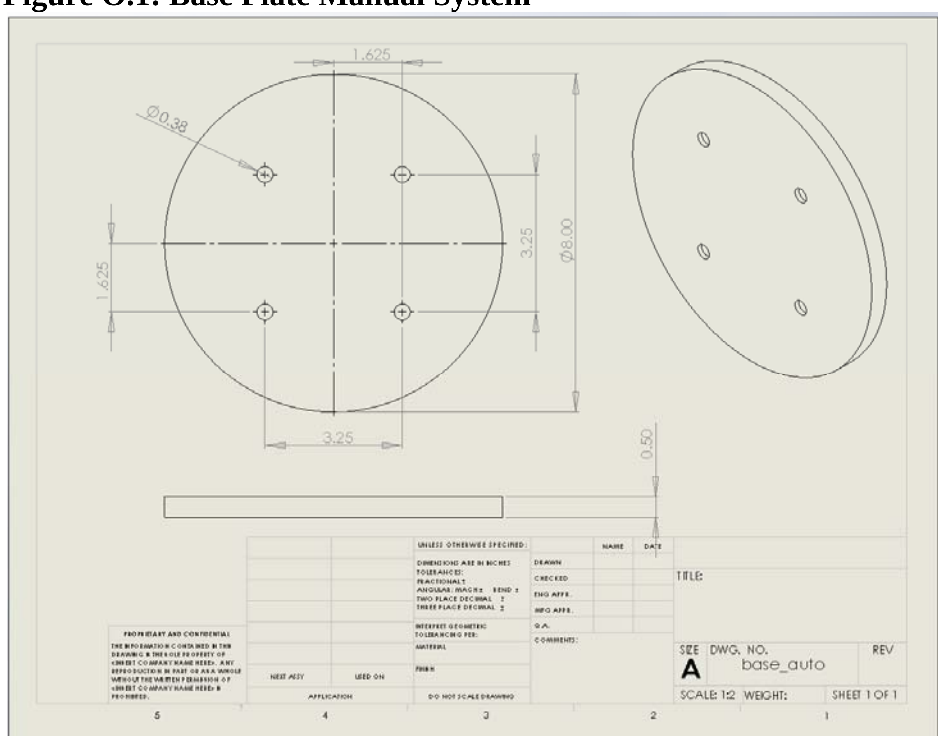


Figure O.2: Base Plate Manual System

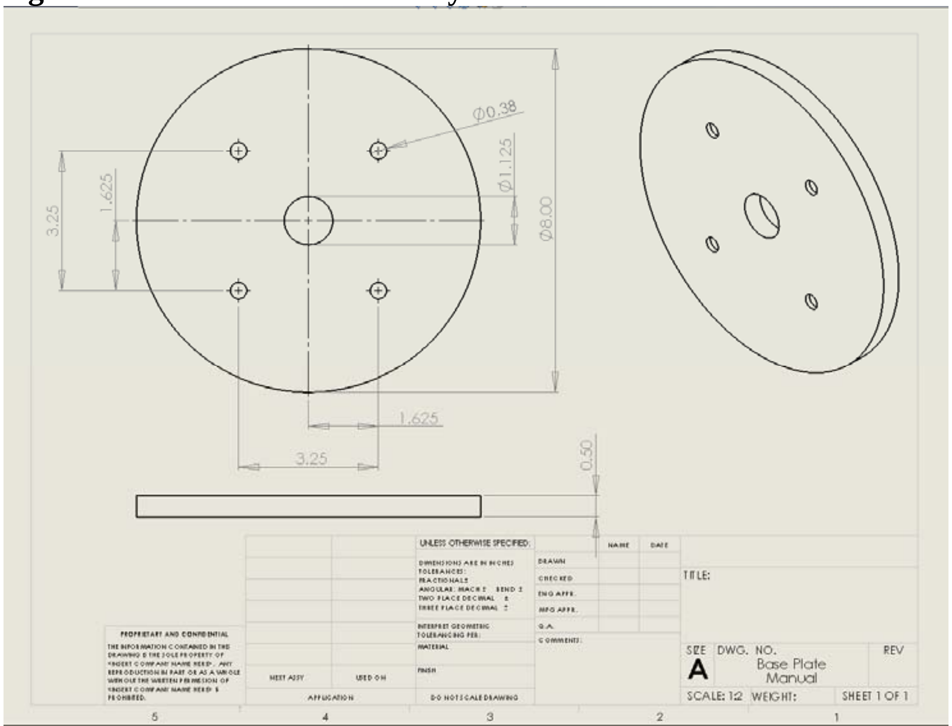


Figure O.3: Bearing Block

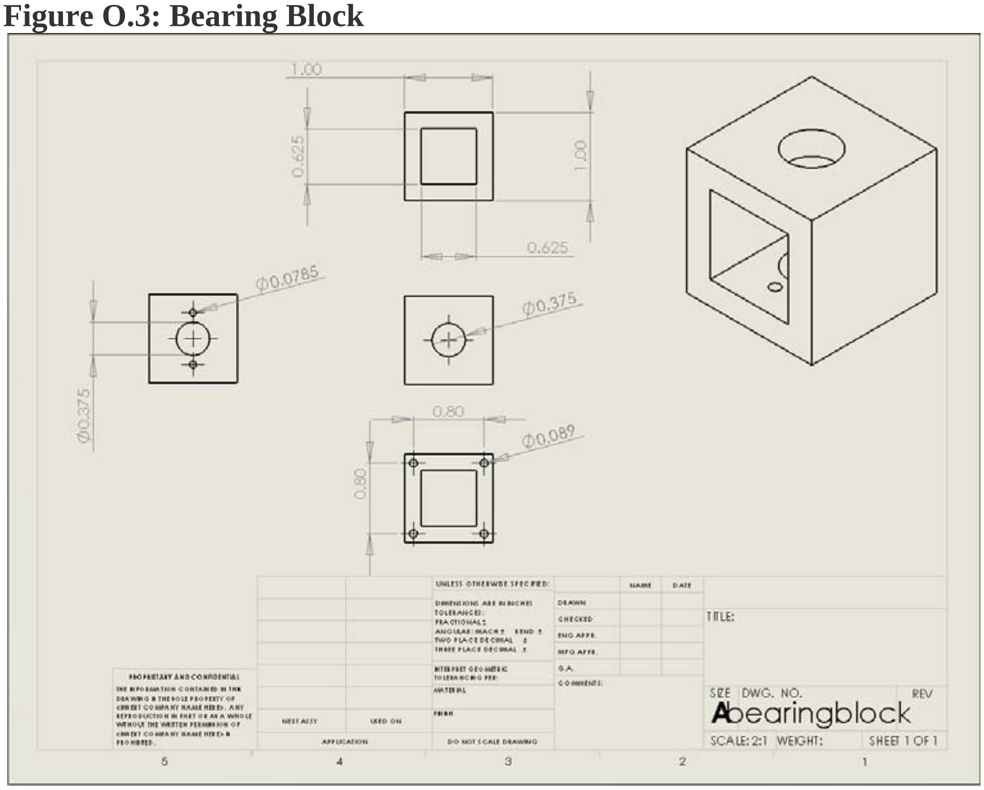


Figure O.4: Pendulum Arm Clamp

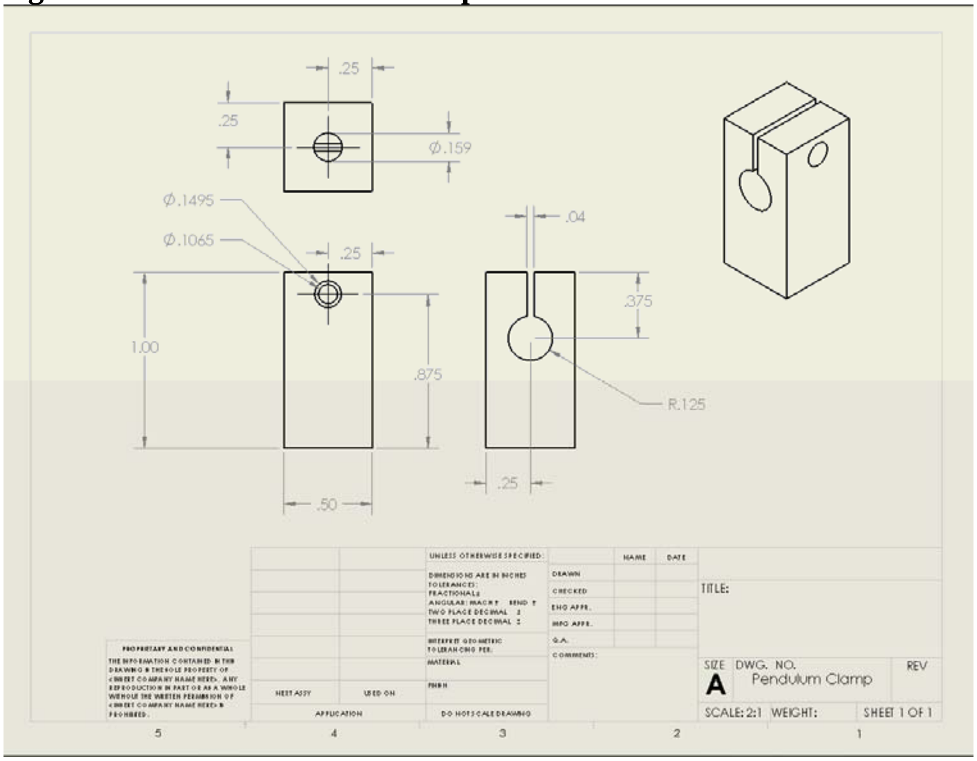


Figure O.5: Controlling Shaft for The Manual System

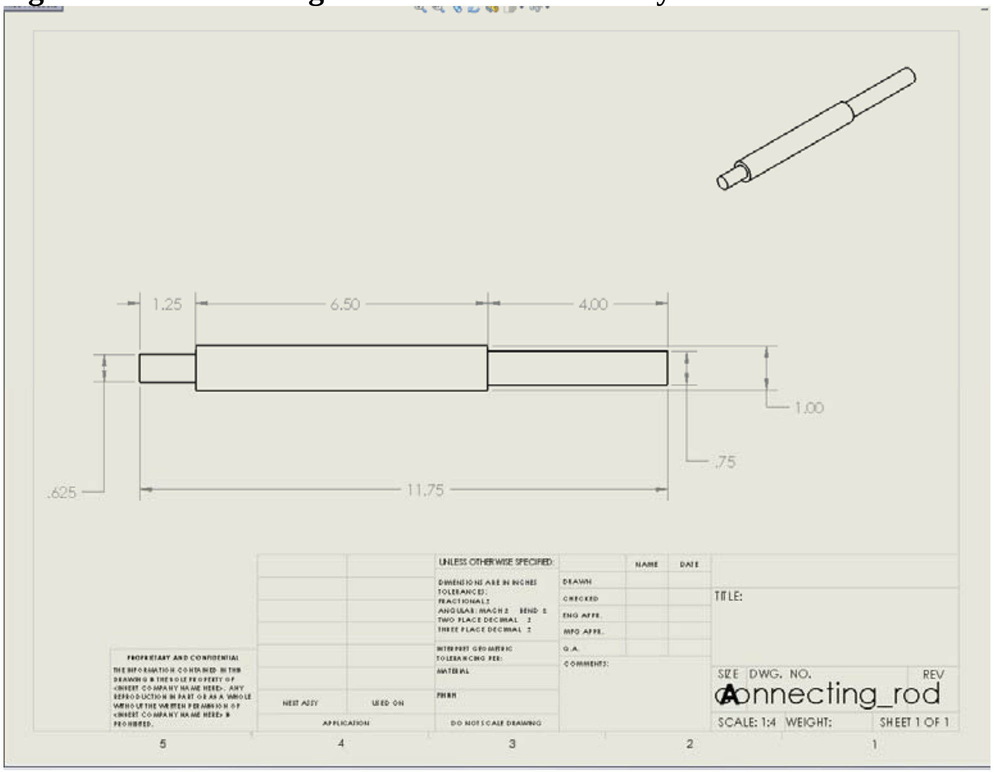


Figure O.6: Rotating Wheel

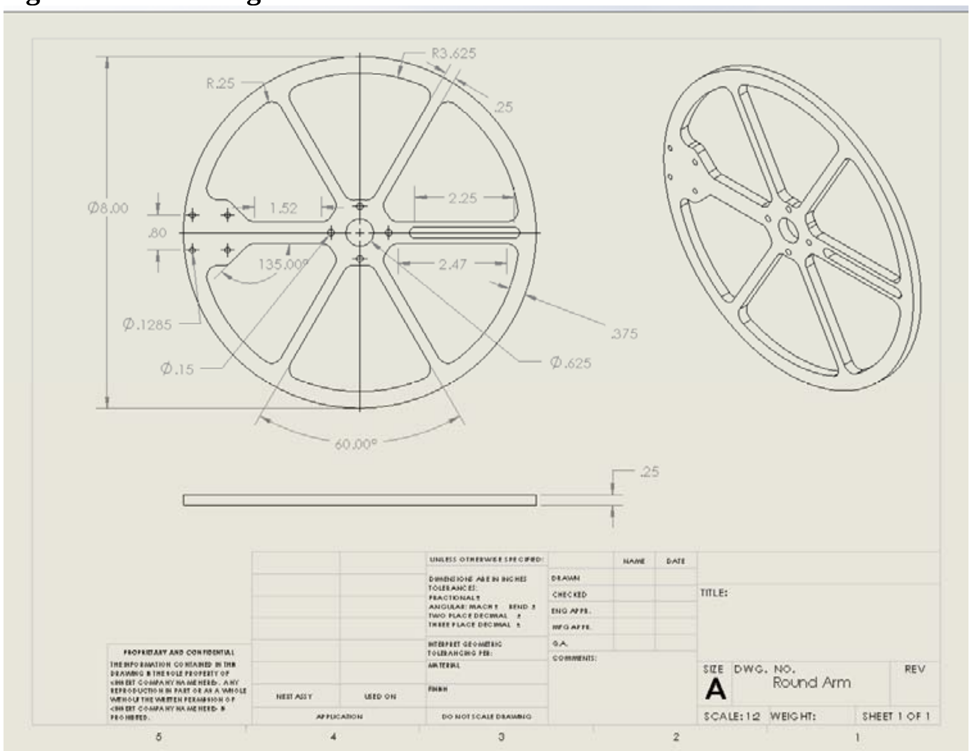


Figure O.7: Top Plate Active System

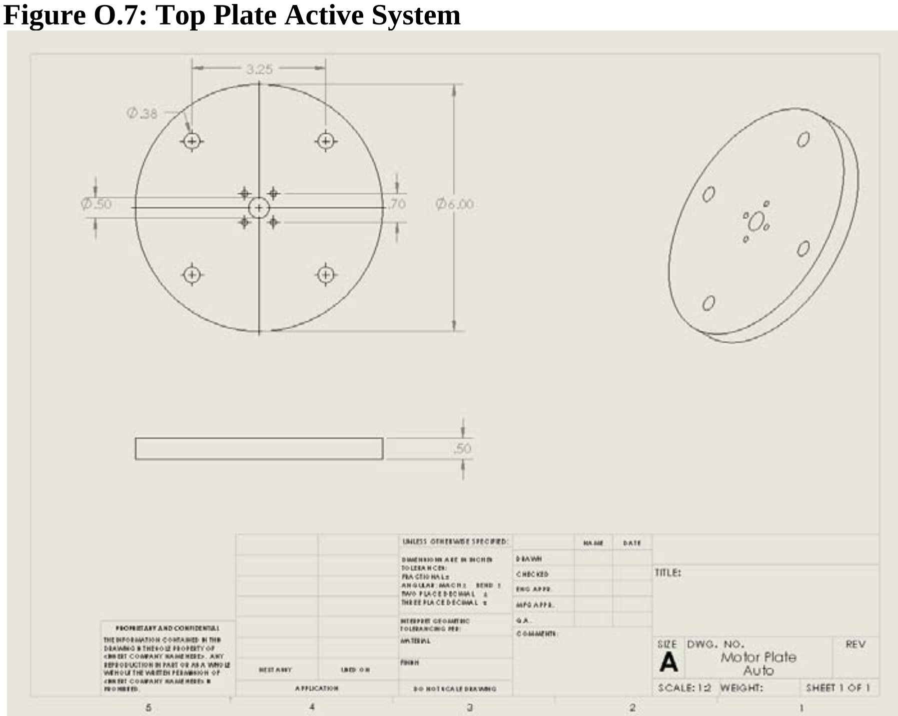


Figure O.8: Top Plate Manual System

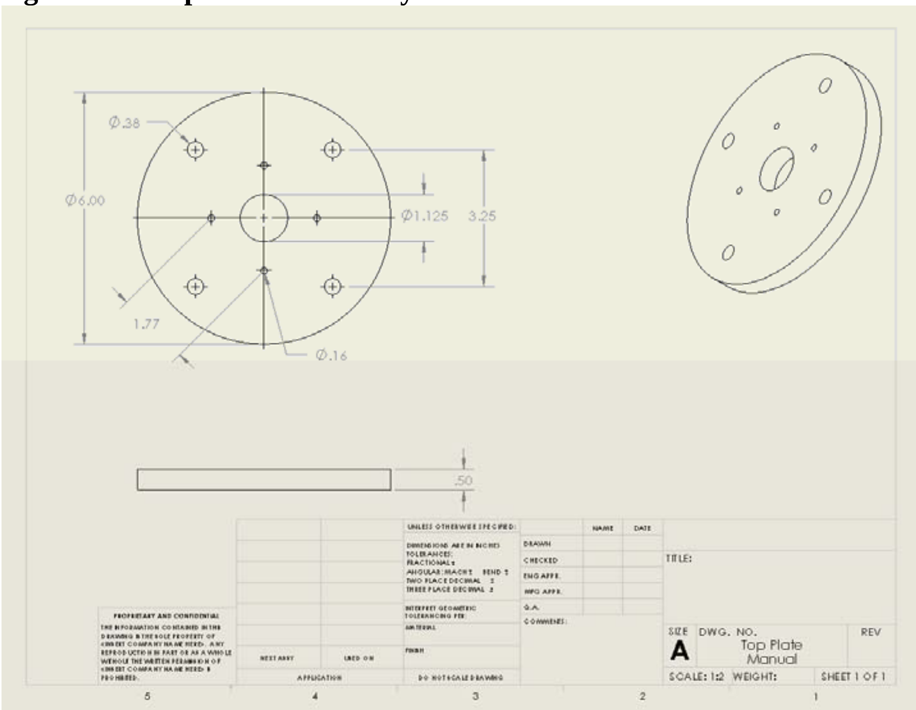
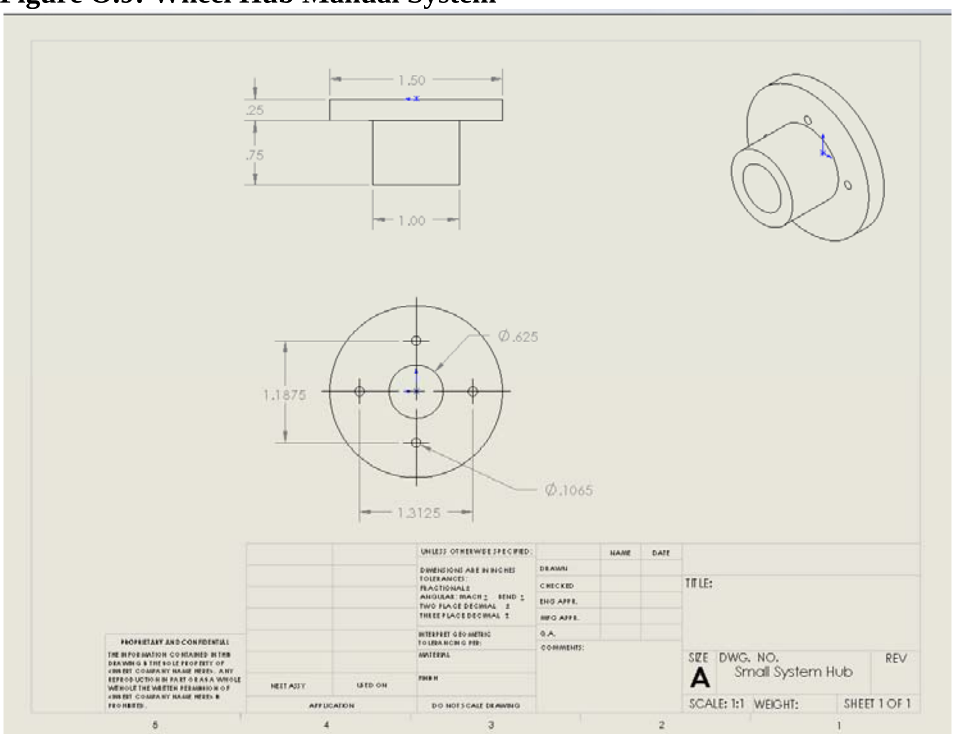


Figure O.9: Wheel Hub Manual System



CAD Model:Big Manual System

Figure O.10: Control Wheel Plate

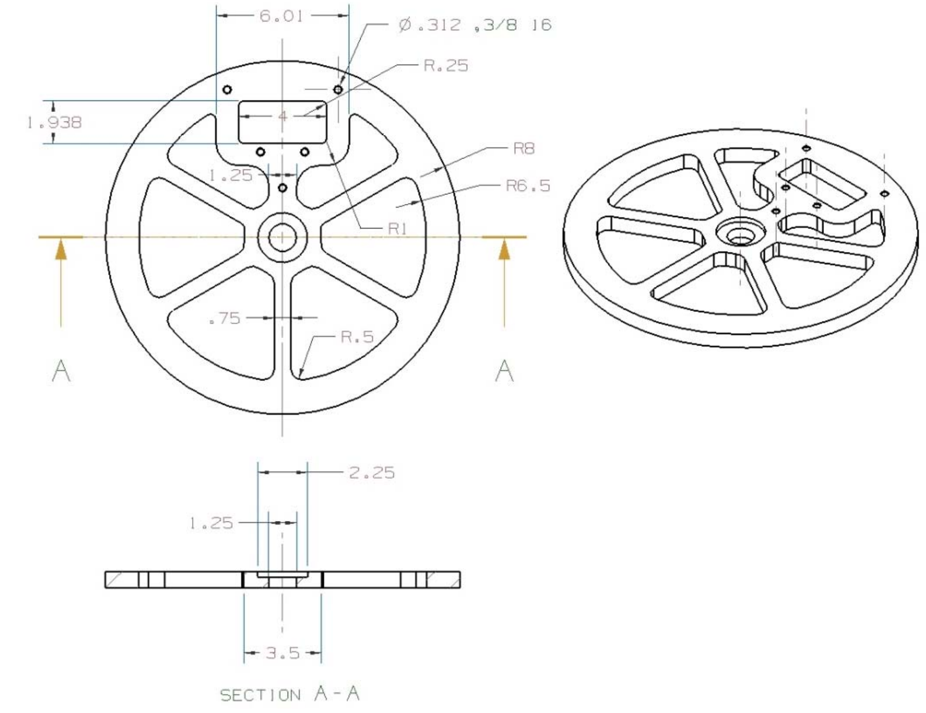
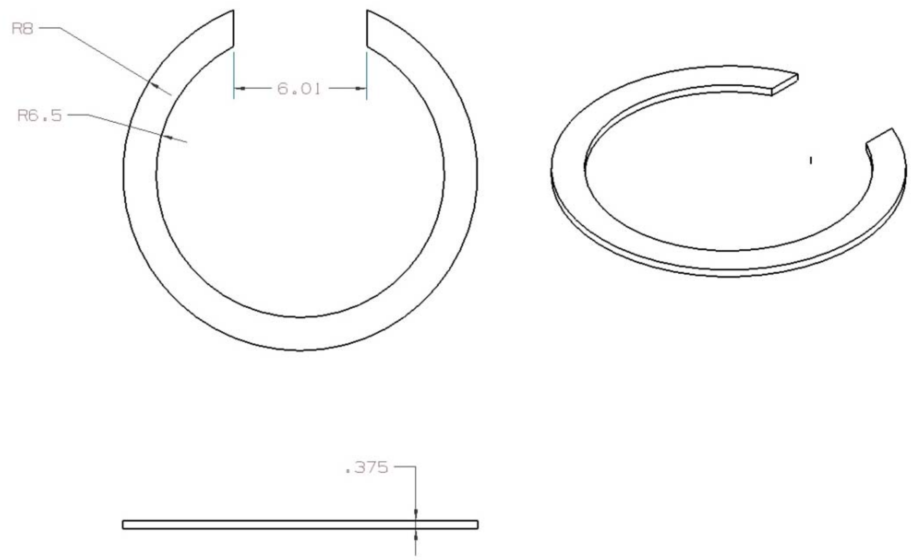


Figure O.11: Wheel Handling Covers



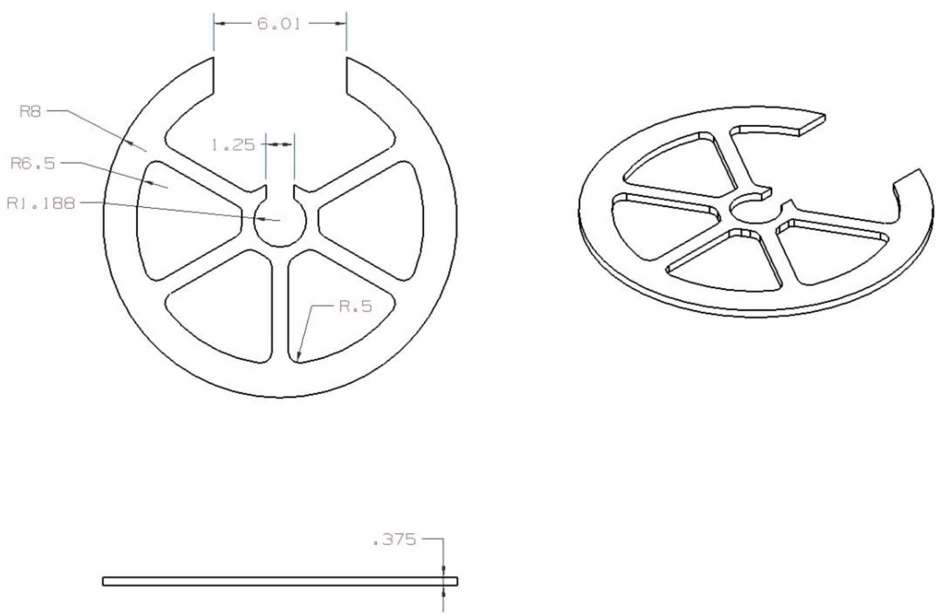


Figure O.12: Wheel Covers at Pendulum Site

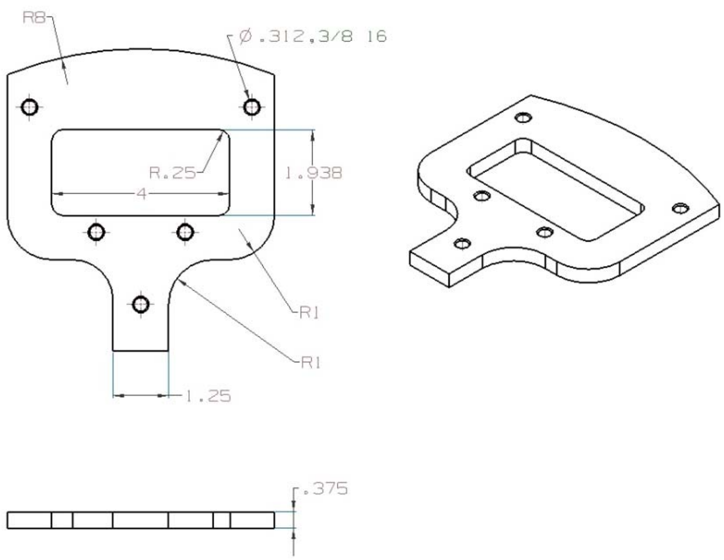


Figure O.13: Pendulum Stopper

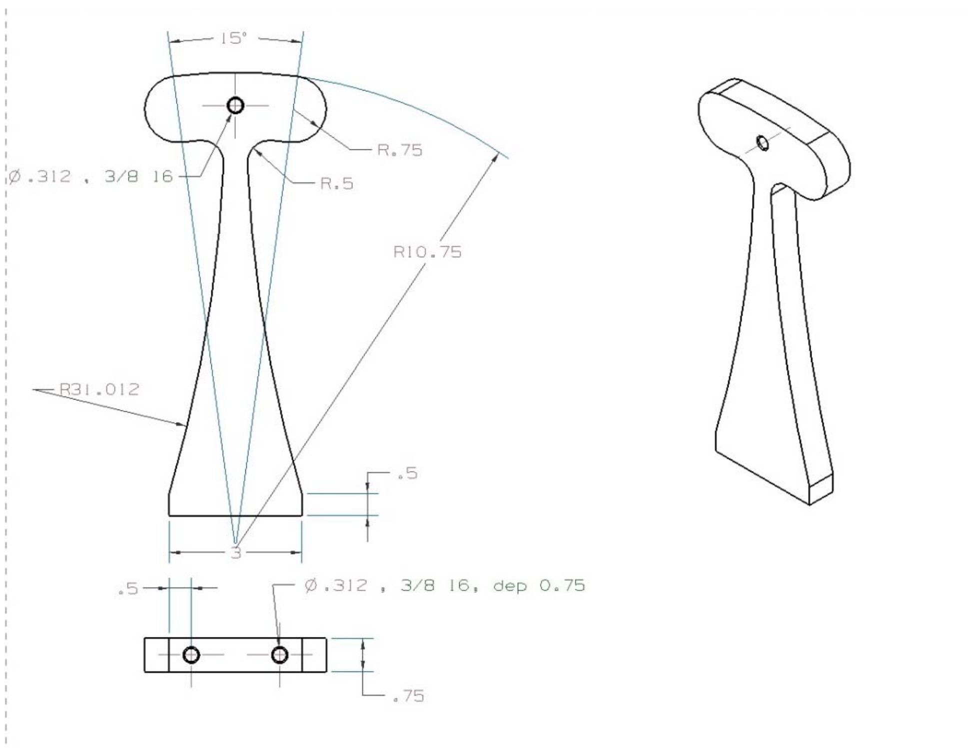


Figure O.14: Pendulum Stopper Support Gusset

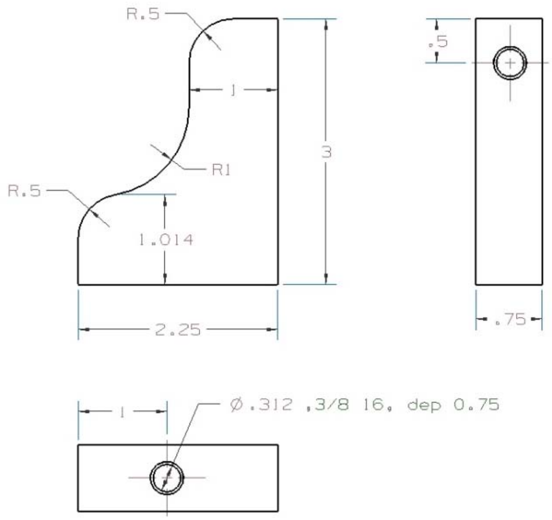


Figure O.15: Lower Portion of Pendulum Arm

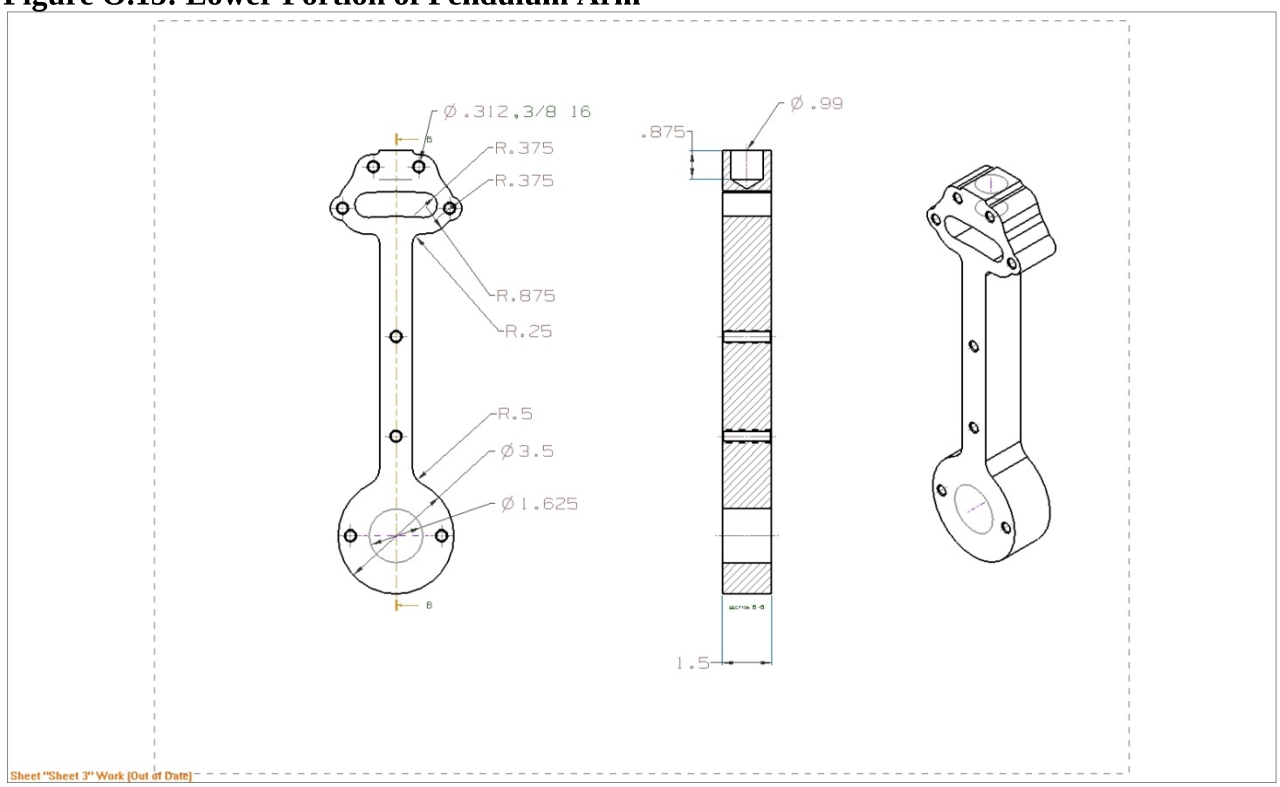


Figure O.16: Angle Limiter Enclosure Box

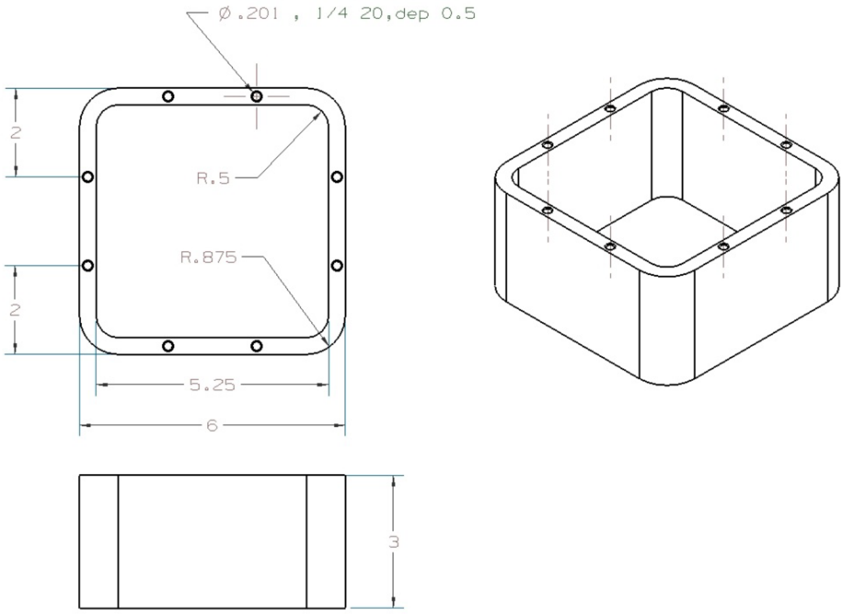


Figure O.17: Angle Limiter Enclosure Box Cover

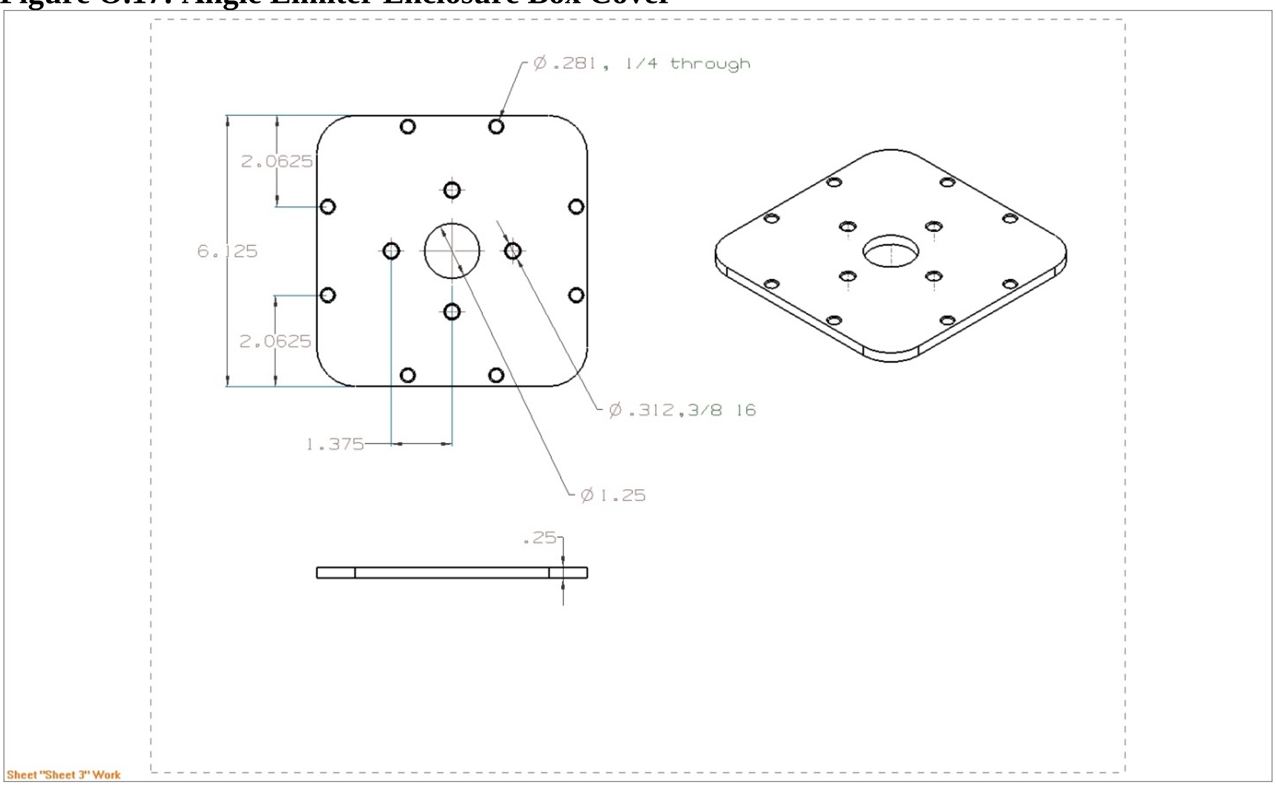


Figure O.18: Angle Limiter Enclosure Box Base

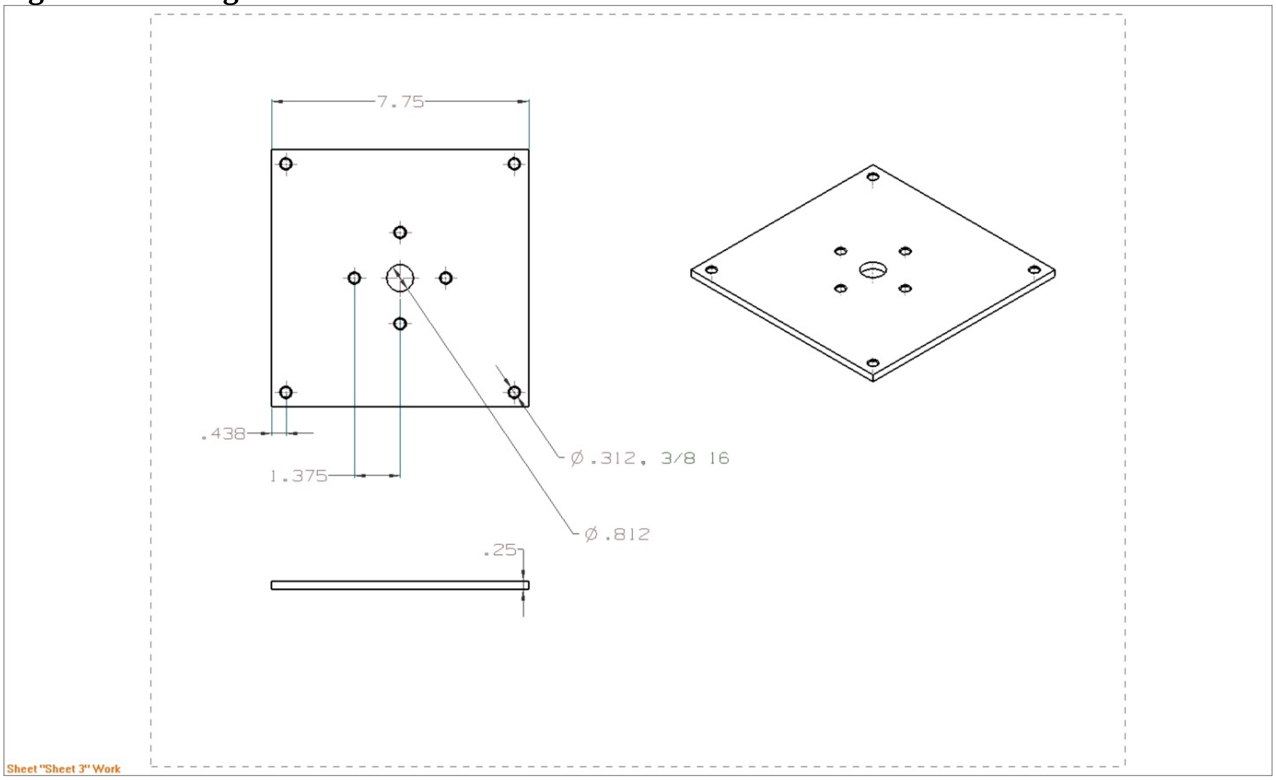


Figure O.19: Upper Bearing Holder

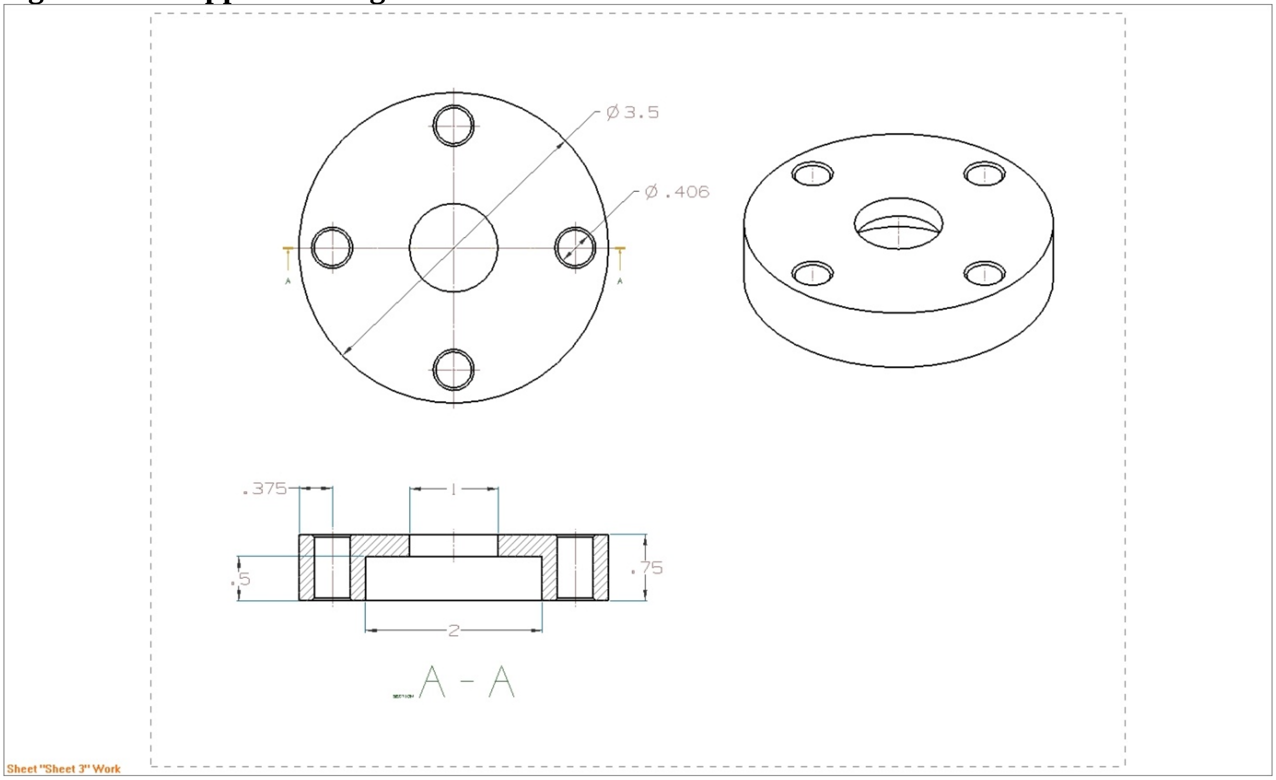


Figure O.20: Lower Bearing Holder

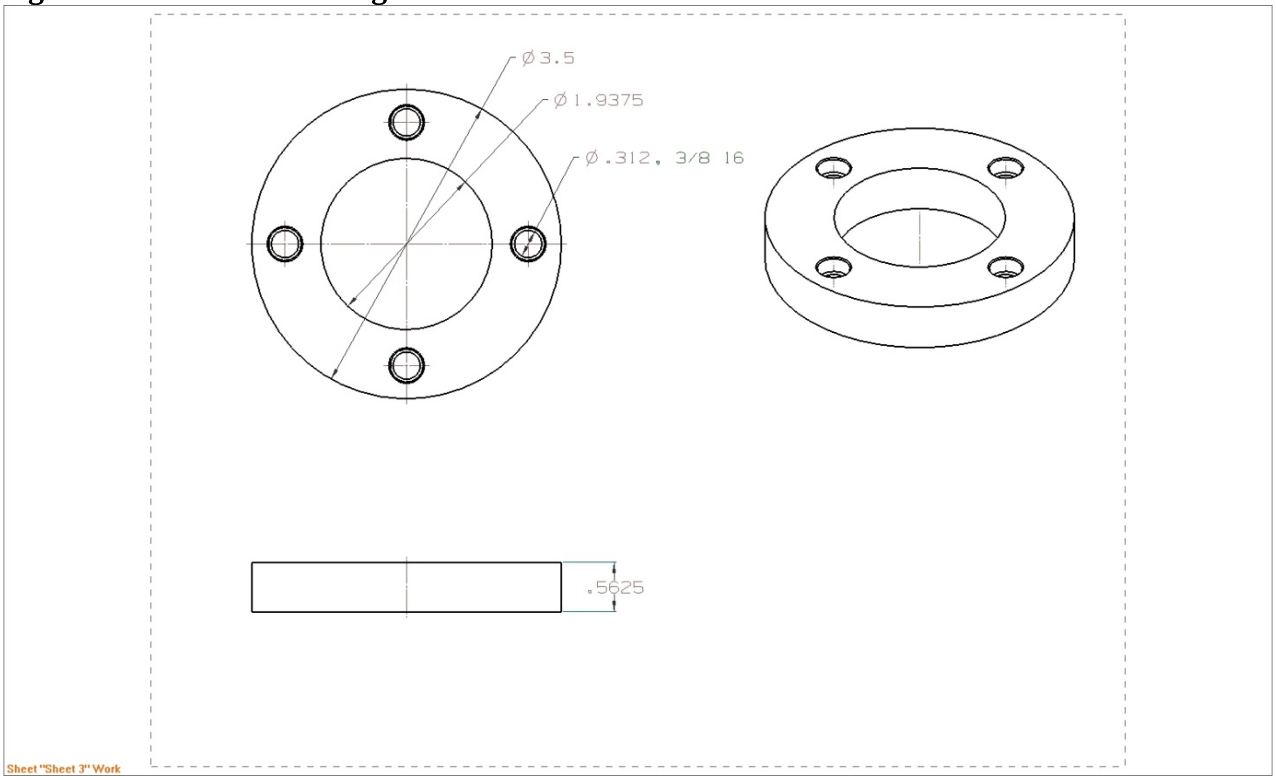


Figure O.21: Angle Limiter Stopper Pin

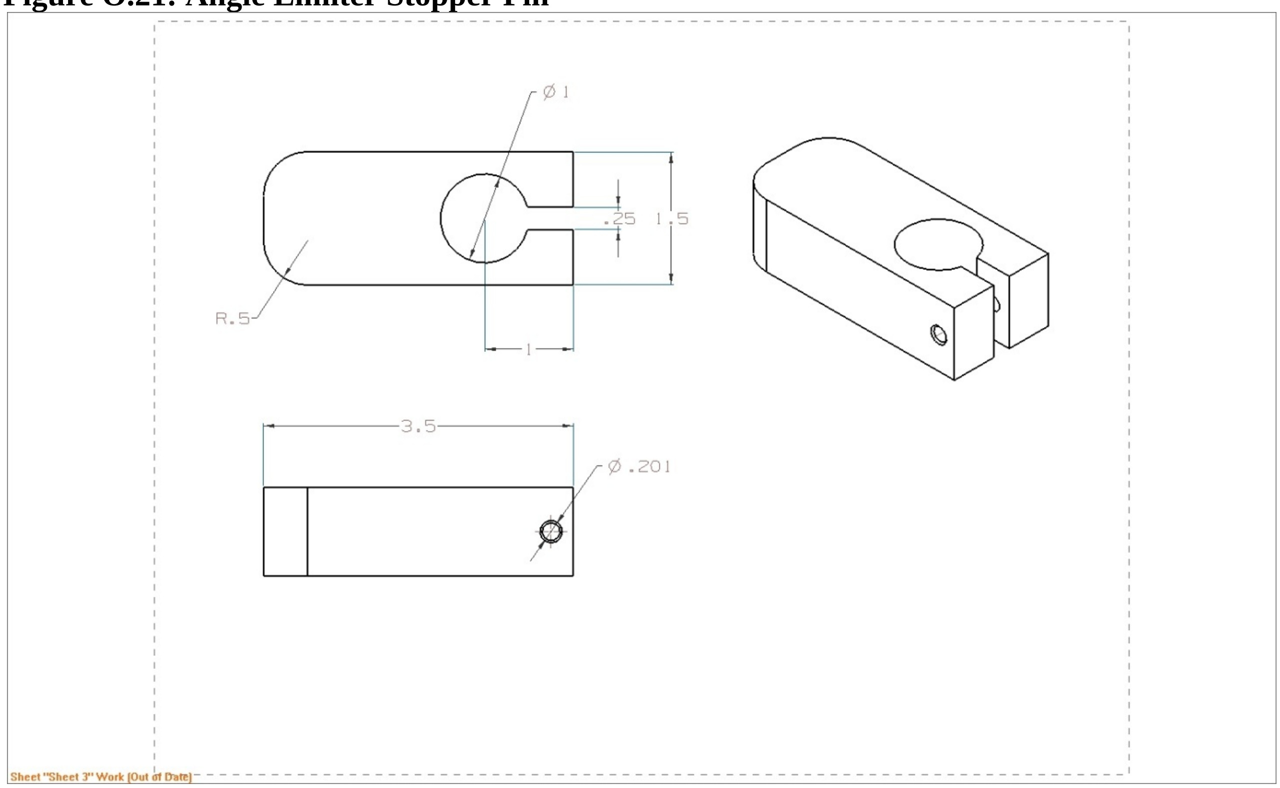
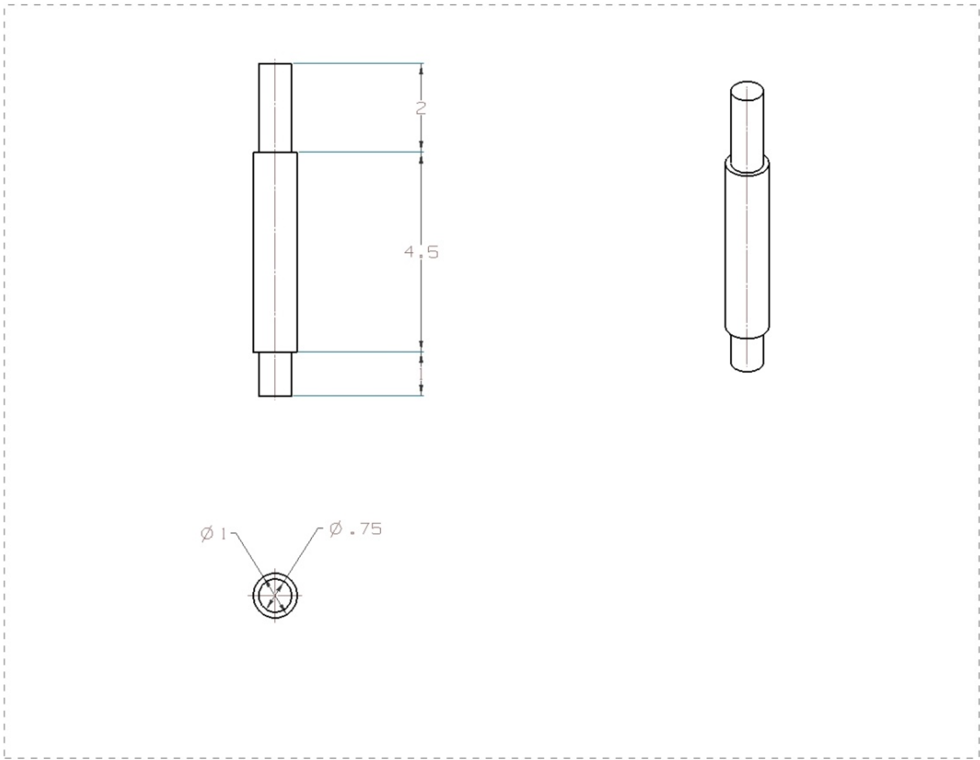


Figure O.22: Control Wheel Connecting Shaft



Sheet "Sheet 3" Work

Designsafe Results for Manufactured Components

Since all our designed parts are very solid and simple components and are not likely to be potentially-dangerous., Designsafe was only conducted to assess the risks and hazards in the three assembled systems. Major problems come from the misoperation of the viewers, and their hazard level are significantly reduced by our risk reduction methods, which is presented in APPENDIX B.

5. Manufacturing Processes

Manufacturing the Small Active/Passive System

Manufacturing this system will require the use of a mill, drill press, and several different taps. All of these processes will take place in the machine shop in the basement of GG Brown, supervised by Bob Coury. The mill will be used to drill holes that require precise placement and spacing. All other holes will be drilled using a drill press. After these holes are drilled taps will be used to create threads as necessary. Since all of these parts are made out of aluminum feed rate of 0.007 ipr will be used, coupled with a speed of 150-400 sfm.

Manufacturing the Large Passive System

1. Wheel:
The main body of the wheel and the covers (both aluminum and ABS) will be first water jet cut to get major shape and. Then the aluminum parts will be milled with 2000 rpm and 0.8”/sec. Then fasten together the main part and the two aluminum cover plates and drill the hole for pendulum shaft.

2. Lower part of the pendulum:
Machining: First water jet cut to get major shape and then mill at 2000 rpm 0.8”/sec.

3. Stopper:
Machining: First water jet cut to get major shape and then mill at 2000 rpm 0.8”/sec.

4. Wheel angle limiter:
Machining: First water jet cut and then mill.

6. Assembly

The assembly of each of the devices will be done in the X50 lab. Some of the subassemblies might be constructed offsite and tested in the lab. The infrared transceiver, for example, will be soldered in Josh’s home workshop and/ or in the X50 lab, Professor Awtar’s lab or in the electronics shop at Parking and Transportation Services.

We do not feel that we will have any mechanical failures before, during or after assembly for a number of reasons. Our smaller devices are based on an existing prototype that has already been proven, and our designs have addressed some of the mechanical shortcomings of the existing model already. The large device has been designed to be able to withstand a very high level of abuse, and the hardware components that are to be used are rated for much more strenuous conditions than this device will likely ever be exposed to.

7. Experimental/Validation Plan

Our design will be tested in stages. Some very basic testing has already been done to validate the use of infrared to transmit our data from the optical encoder to the motor controller. Further refinement will be done to ensure that the setup will have the capacity to transmit the volume of data needed, to ensure that interference from ambient light won’t cause problems and to finalize the power budget for the transmitter side of the circuit, as this will determine the final selection of the solar cells to power it. The majority of this testing will take place in Professor Awtar’s lab. After final assembly, the active device will be tested to determine the operational parameters needed in order to program the PLC for the final controller setup. For the lab setup, we will be using a NIDAQ and LabView to record our data. The small passive device will be tested and tuned to make it difficult but not impossible to balance the pendulum and to make sure that each of the components is fully functional. Similar testing will be done on the large passive system, but with the goal to be that the pendulum is relatively easy to balance. For each, the first major test would come after each complete device is fully assembled. We anticipate that our first major test will take place on or around March 23rd. We would like to have Professors Im and Awtar present as well as Mr. Bowditch, but we understand that schedules are often difficult to coordinate. Machining of the custom parts will be done concurrently for all three devices, but we are under the impression that the smaller two of the three will be the first to be ready for testing.

APPENDIX O-A: FMEA TABLES

Assembly	Part	Function	Mode	Cause	Effects	Action	Occurrence	Severity	Detection proper maint	RPN
All Systems	Pendulum Bearings	Supports pendulum arm and reduces friction allowing the arm to move freely.	Seizing	Lack of lubrication, wear, overload, poor installation	Lose of primary function.	Ensure proper loading of bearings; Sealed bearings to maintain lubrication. Check for over-tightening of bearing.	2	7	1	14
			Lose/Wobbles	Lack of maintenance, overloading, wear, yielding of materials.	Could lead to detatchment	Replace worn bearings that feel 'lose' (have more than rotational motion); Ensure proper loading of bearings.	3	3	2	18
			Detatchment	Serve lack of maintenance, sever overload.	Lose of primary function. Potential safety (debris) hazard.	Replace worn bearings that feel 'lose' (have more than rotational motion); Ensure proper loading of bearings.	1	10	1	10
	Control-Wheel Bearings	Supports the wheel with the pendulum; in the case of the automatic system also the electronics.	Seizing	Lack of lubrication, wear, overload, poor installation	Lose of primary function.	Ensure proper loading of bearings; Sealed bearings to maintain lubrication. Check for over-tightening of bearing.	3	7	2	42
			Lose/Wobbles	Lack of maintenance, overloading, wear, yielding of materials.	Could lead to detatchment	Replace worn bearings that feel 'lose' (have more than rotational motion); Ensure proper loading of bearings.	4	4	2	32
			Detatchment	Serve lack of maintenance, sever overload.	Lose of primary function. Potential safety (debris) hazard.	Replace worn bearings that feel 'lose' (have more than rotational motion); Ensure proper loading of bearings.	2	10	1	20
	Control Shaft to Wheel Attatchments	Transmit controling torque to the wheel with the attached pendulum.	Slipping	Under-tightened bushing, wear	Reduction in control, possible detatcment	Ensure bushings/keyways are properly tightened. Use thread-locker during final assembly/repair	1	7	2	14
			Seperation	Defective part, over-tightening/cracking	Lose of primary functions, potential safety hazard.	Tighten components to manufacturer's specifications, inspect parts during assembly/maintenance.	2	10	3	60

Large Manual	Torque-Overload Protection	0
		0
Small Active		0
	Motor	0
		0
	Motor Controller	0
		0
		0
	Power Supply	
	Solar Cells	
	Optical Angle Encoder	

APPENDIX O-B: DESIGNSAFE ANALYSIS

designsafe Report

Application:	Small System	Analyst Name(s):	Inverted Pendulum Exhibit Team
Description:		Company:	University of Michigan
Product Identifier:		Facility Location:	
Assessment Type:	Detailed		
Limits:			
Sources:			

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	mechanical : cutting / severing Sharp Edges of the machining parts may hurt the installer	Minimal Occasional Possible	Moderate	Make better finish on the edge of the parts and add warning label	Minimal None Negligible	Low	
All Users All Tasks	mechanical : drawing-in / trapping / entanglement Cables for the infrared system may entangle when the wheel turns.	Minimal Occasional Negligible	Low	other design change	Minimal None Negligible	Low	
All Users All Tasks	mechanical : pinch point Multiple pinch points between the pendulum arm and the base.	Serious Frequent Possible	High	Fixed enclosures / barriers	Serious None Negligible	Low	
All Users All Tasks	mechanical : fatigue The drop botton will fail after many clicks	Serious Frequent Possible	High	Add warning labels	Serious None Possible	Moderate	
All Users All Tasks	mechanical : impact The end weight of the pendulum has a large impact on the things hit by it.	Serious Remote Unlikely	Moderate	Fixed enclosures / barriers	Serious None Negligible	Low	
All Users All Tasks	electrical / electronic : electrical noise 2 Channels of the data transfer system may interfere with each other.	Catastrophic Frequent Probable	High	Try to isolate two data transfer LEDs from each other.	Catastrophic None Negligible	Low	
All Users All Tasks	ergonomics / human factors : interactions between persons Hard to understand by kids.	Minimal Frequent Probable	High	Add labels.	Minimal Remote Possible	Low	
All Users All Tasks	radiation : infrared radiation Infrared LEDs may hurt eyes.	Catastrophic Remote Unlikely	Moderate	fixed enclosures / barriers	Serious None Probable	Moderate	

designsafe Report

Application: Small Manual System

Description:

Product Identifier:

Assessment Type: Detailed

Limits:

Sources:

Analyst Name(s): Inverted Pendulum Exhibit Team

Company: University of Michigan

Facility Location: Ann Arbor

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	mechanical : cutting / severing Sharp edges of the machining parts	Minimal Occasional Possible	Moderate	Make better finish on the edge of the parts and add warning label	Minimal None Negligible	Low	
All Users All Tasks	mechanical : pinch point Multiple pinch points between the pendulum arm and the base. Pinch points exists between the control wheel and the table.	Serious Frequent Possible	High	Enclose the system and make enough clearance between the control wheel and table	Serious None Negligible	Low	
All Users All Tasks	mechanical : fatigue Bearings may fail after years in operation	Catastrophic Remote Negligible	Moderate	Use multiple bearings at each end of the shafts	Catastrophic None Negligible	Low	
All Users All Tasks	mechanical : impact Spider coupler may be destroyed due to a great impact at the stops.	Serious Occasional Probable	High	Search for more durable products	Serious Remote Unlikely	Moderate	
All Users All Tasks	ergonomics / human factors : excessive force / exertion People may turn the wheel too fast and cause unexpected problems.	Slight Frequent Probable	High	Add limiting clutch	Slight None Negligible	Low	
All Users All Tasks	ergonomics / human factors : human errors / behaviors People may press down against the control wheel.	Slight Frequent Probable	High	Add warning label	Slight None Negligible	Low	

designsafe Report

Application:	Large Manual System	Analyst Name(s):	Inverted Pendulum Exhibit Team
Description:		Company:	University of Michigan
Product Identifier:		Facility Location:	Ann Arbor
Assessment Type:	Detailed		
Limits:			
Sources:			

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

User / Task	Hazard / Failure Mode	Initial Assessment Severity Exposure Probability	Risk Level	Risk Reduction Methods /Comments	Final Assessment Severity Exposure Probability	Risk Level	Status / Responsible /Reference
All Users All Tasks	mechanical : cutting / severing Sharp edges of the machining parts	Minimal Occasional Possible	Moderate	Make better finish on the edge of the parts and add warning label	Minimal None Negligible	Low	
All Users All Tasks	mechanical : pinch point Pinch points existsbetween the control wheel and the table	Serious Frequent Possible	High	Enclose the system and make enough clearance between the control wheel and table	Serious None Negligible	Low	
All Users All Tasks	mechanical : fatigue Bearings may fail after years in operation	Catastrophic Remote Negligible	Moderate	Use multiple bearings at each end of the shafts	Catastrophic None Negligible	Low	
All Users All Tasks	mechanical : impact Spider coupler may be destroyed due to a great impact at the stops	Serious Occasional Probable	High	Search for more durable products	Serious Remote Unlikely	Moderate	
All Users All Tasks	slips / trips / falls : instability The center of mass is relatively high. The system may tip over.	Catastrophic Remote Possible	High	Making the base on the ground heavier	Serious None Negligible	Low	
All Users All Tasks	ergonomics / human factors : excessive force / exertion People may turn the wheel too fast and cause unexpected problems.	Slight Frequent Probable	High	Add limiting clutch	Slight None Negligible	Low	
All Users All Tasks	ergonomics / human factors : human errors / behaviors People may bend the pendulum arm	Serious Frequent Probable	High	Add warning labels	Serious Remote Possible	Moderate	

Appendix P: Description of Engineering Changes

Servo-Motor Controller
The servo-motor controller was changed from a servo-amplifier that operates using voltage controller to a servo-amplifier that uses current-control.

Large System Pendulum Weights
Aesthetically the large system pendulum weights will remain the same. The change will occur in the filling of the weight. The pendulum weight was an empty hallow stainless steel sphere. It was determined that weight did enough mass for the system to be easily balanced. This sphere was then filled with sand for the Design Expo and will later be filled with lead shot to further increase the weight and ease of balancing.

Small System Stabilizing Hub

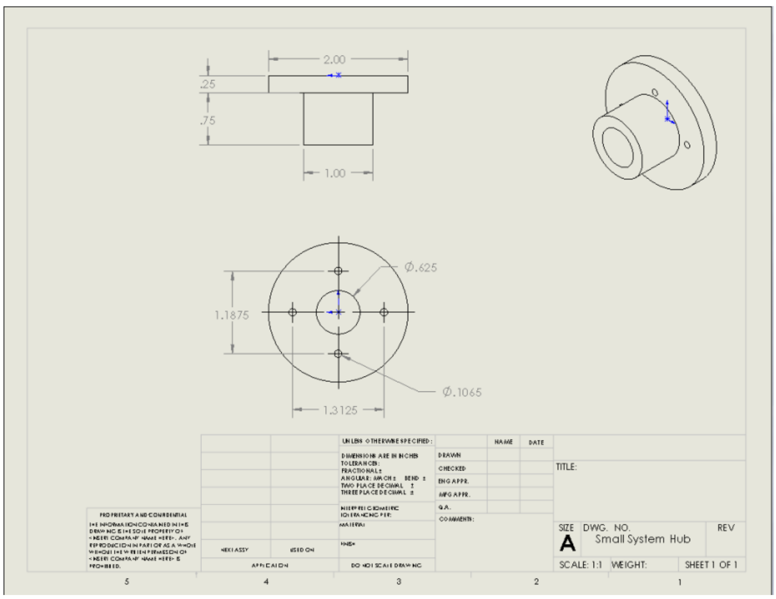


Figure P.1: Small System Stabilizing Hub

The stabilizing hub shown in Figure P.1 was added on the top of the control shaft on the small manual system. This hub was added to remove wobble in the horizontal plane while the wheel was spinning.

Small System Pendulum Weights

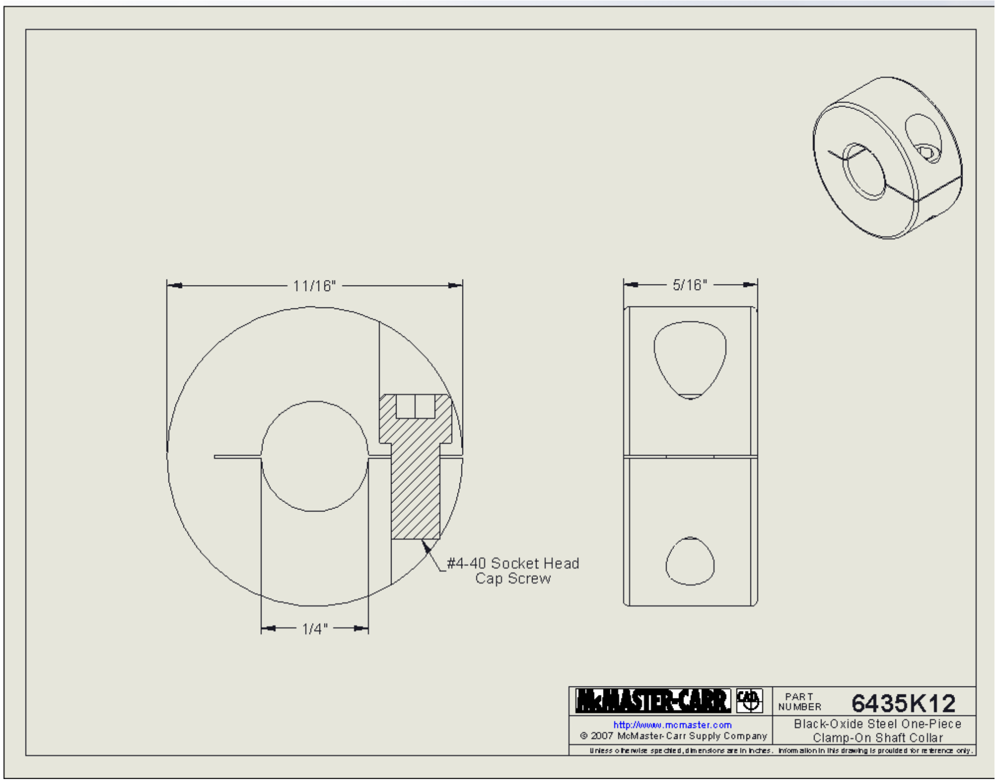


Figure P.2: Shaft Collar Pendulum Weights – Old System

The shaft collar shown in Figure P.2 was replaced with a ½" ball bearing welded to a 6-32 set screw. This altercation was made to increase the aesthetic continuity across all three designs.