Design and Fabrication of an Experiment for Automated System Identification

Prepared by:
Conrad J. Farnsworth

Faculty Advisors
Dr. Charles Tolle
Professor, Department of Electrical and Computer Engineering

Dr. Alfred Boysen
Professor, Department of Humanities

South Dakota School of Mines and Technology
501 E. Saint Joseph Street
Rapid City, SD 57701

Table of Contents

Abstract

A complete system identification (SYSID) is crucial to the understanding (and eventually the control) of all plants. Unfortunately, to understand the dynamics of a plant, one must take the system to its limits. Simple systems must be created that can be extended to their limits without permanently damaging or altering the dynamics of their behavior. To meet this requirement, a circular, inverted pendulum was designed and built.

1 Introduction

As more and more of the world is coming under automated control, more systems are being discovered that have yet to be identified. In order to fully control a system, it must be identified. The identification procedure involves extending the system to its limits and measuring how it behaves. From there, a mathematical model can be made and the system can be controlled from the model. If an automated system identification algorithm can be created from simple systems, its use as a live identifier can make it invaluable in all systems, especially those which the dynamics are prone to changing suddenly or over time.

This project focuses mainly on the construction of a simple system which can be safely extended to its limits while retaining its original identity. Further information on the analysis and implementation of the software is beyond the scope of this paper at this time.

2 Engineering Requirements

Upgradeable

- Modular Components
- 80/20 tubular supports
- Mounting points for upgrades

Consistent

- High tolerance (¡.0002”) encoder shaft
- ABEC-7 rated bearings

- Press-fit instrument construction

Controllable

- High resolution encoders
- 4:1 torque multiplier
- 168MHz ARM Cortex processor

Changing Dynamics

- NEMA-17 Stepper Motor
- Adjustable Counter Weights
- Greater rotational inertia means different torque response

3 Broader Impact

The impact of pioneering automated system identification software has a worldwide impact. Not only do most consumer and commercial products implement controllers in one form or another, 68% of the systems have unacceptable performance.[1] These systems could range from nuclear power plants to the cruise control in a vehicle. While the plant (any system we are trying to control) may be inherently stable, changes can occur over time which can alter the way a plant responds to control.

An example of a system that would benefit from the implementation of automated system identification would be a power plant. As equipment within the plant ages, the way the plant responds to the controls changes. If a portion of the plant was beginning to lose control, the software could notify operators to replace an aging component. All of this could be done by gauging the response of a piece of equipment as the equipment ages. This has the potential of increasing the lifespan of plant components until a calculated inoperable date.

A second example of the implementation of automated system identification is its passive use in combat aircraft. Aircraft with high agility are inherently unstable. Therefore, control systems must be implemented to keep the plant airborne while the pilot "flies" by adjusting a set point. The control systems are tuned around an aircraft that have dynamics the same as the first day the controller was tuned. Unfortunately in combat scenarios, the aircraft can be damaged while flying which would change the fingerprint that is the dynamics of the plane. If, for example a wing of an aircraft were to become detached mid-flight, the controller would still attempt to keep the aircraft airborne using the same dynamics as a plant with two full wings. With a live, automated system identification control algorithm implemented, the system could evaluate the damage, determine if the damage allows the current control surfaces to keep the aircraft stable, and re-adjust the behavior of each control surface appropriately. If the jet is damaged beyond control, the system could automatically eject an unconscious pilot, or suggest a conscious pilot to abandon the uncontrollable system.

4 Procedure

The procedure involves first digitally drafting an experimental system in SolidWorks. After the drafting is complete, several engineering schematics will be drafted for machining. Following machining, the experiment will be assembled, calibrated, and tested.

4.1 Drafting

It was quickly discovered that drafting the pendulum to a satisfactory condition would require several iterations. A conceptual drawing of the pendulum was drafted in OneNote, it was soon found to be unsatisfactory due to collisions that would occur with wiring (Figure 1).

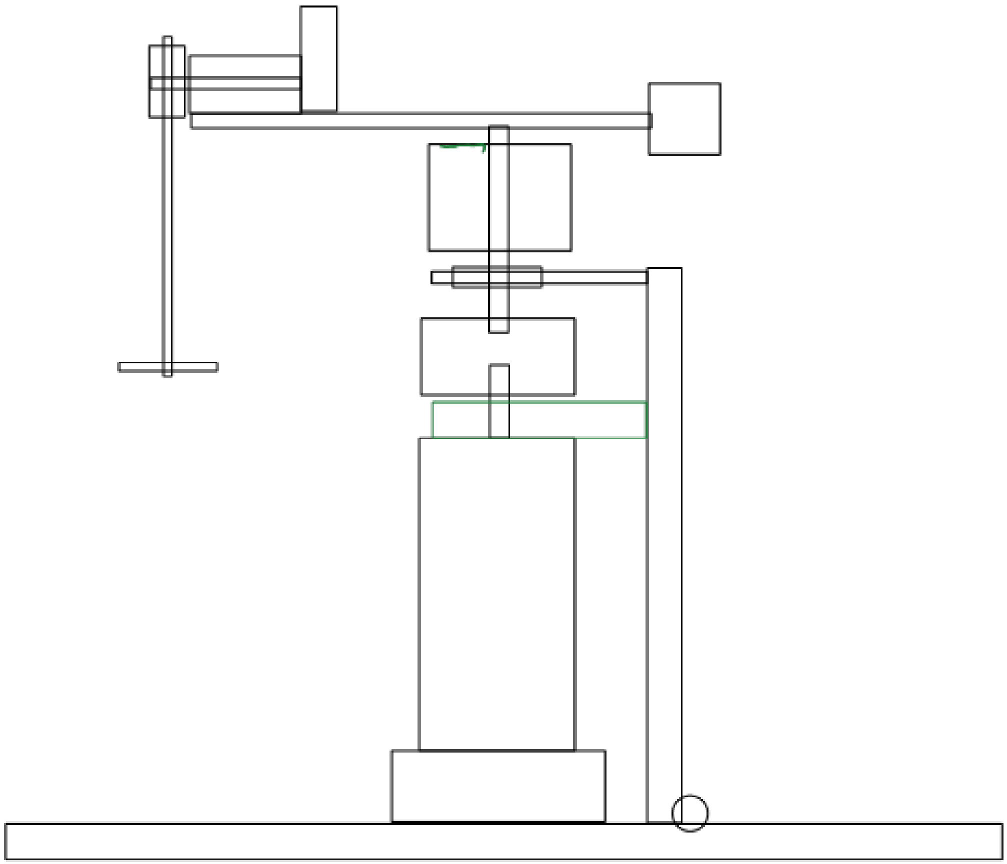

Figure 1: Initial Conceptual Sketch

After initial review suggestions were made and over the course of a week, the pendulum was revised once again to fit the needs of a functioning system. Several more suggestions were made on this revision (Figure 2).

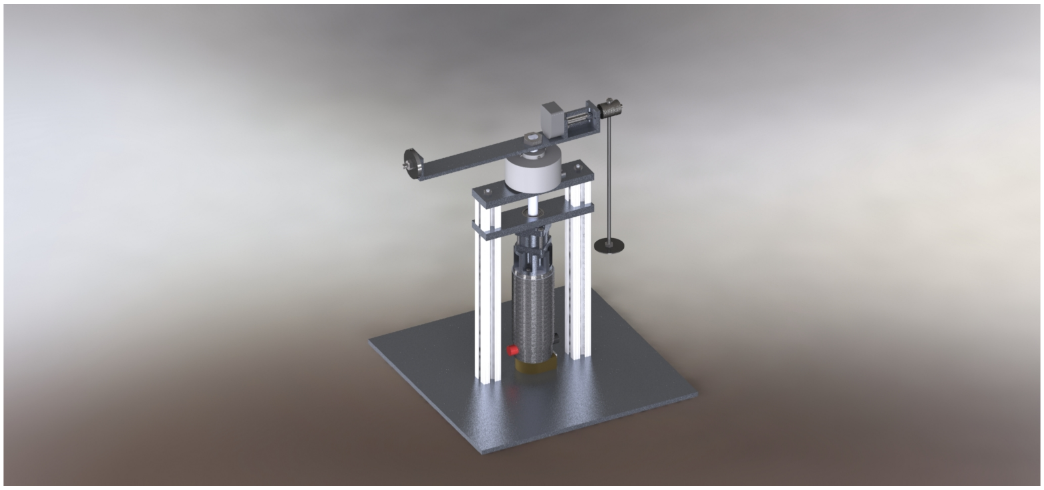

Figure 2: First Revision

Finally, after revising the design a third time it was discovered that the project manager preferred the entire system use an alternate method of fabrication (manual as opposed to CNC). This triggered a redesign of nearly all of the components of the pendulum. A second revision was born (Figure 3).

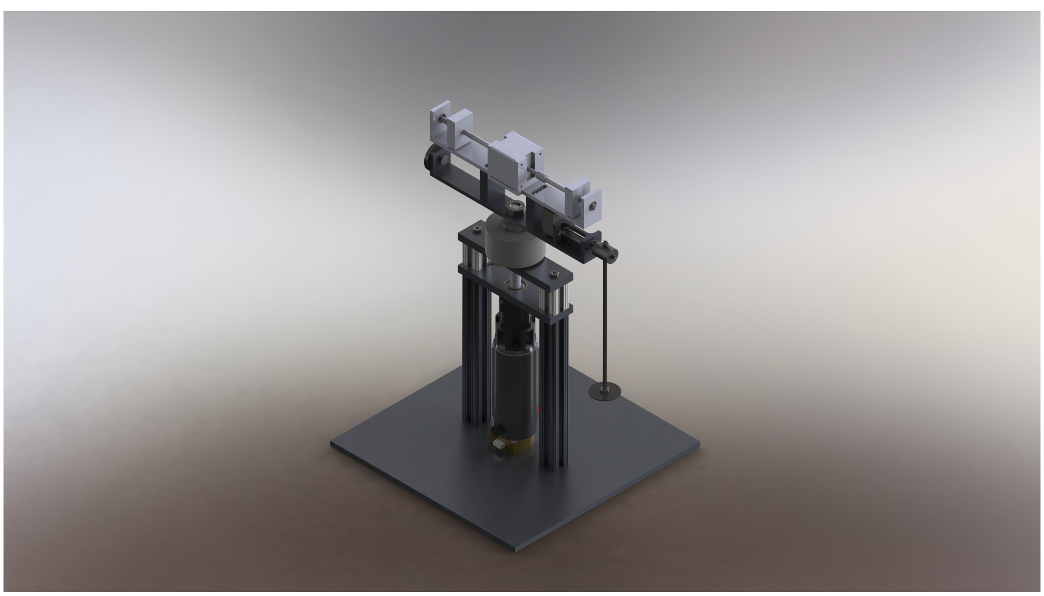

Figure 3: Second Revision

The newest pendulum appeared to fit the design requirements of the project manager, however, it was suggested that a third leg be added to the pendulum to increase stability. This is the current version of pendulum at the time of writing. (Figure 4).

Figure 4: Third and Final Revision

The drafting process is by no means static. There area always little improvements being made that will enhance the performance of the pendulum. As machining continues, the pendulum design is going to be revised such that the next physical iteration will be easier to reproduce.

4.2 Schematics

After the designs were cleared by the project manager, each component was transferred to a solidworks drawing to provide adequate instruction while machining. An example drawing can be seen in figure 5. The rest of the drawings can be located within the appendix.

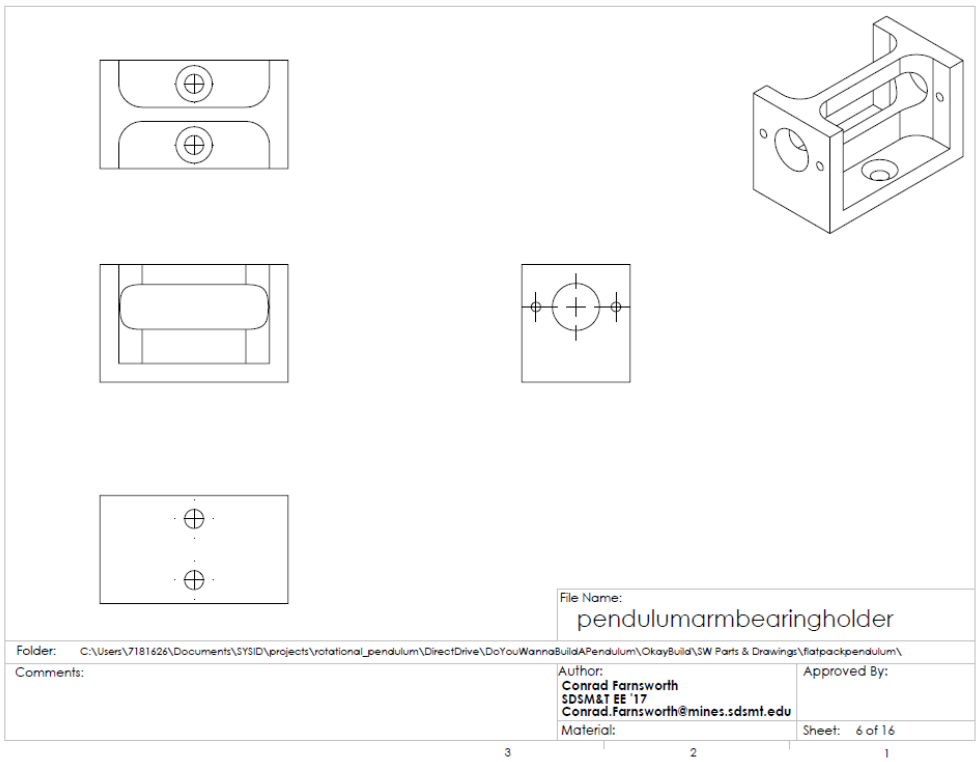

Figure 5: An engineering drawing of the pendulum bearing holder

4.3 Machining

The pendulum was designed with very little required tooling. A standard lathe and mill with digital readouts can turn most of the components of the pendulum. For accuracy's sake, the pendulum arm bearing holder and the two triangular bearing retainers will be CNC machined. At the time of writing, a main torque rod (responsible for transmitting torque from the gear box to the pendulum boom) is nearing completion.

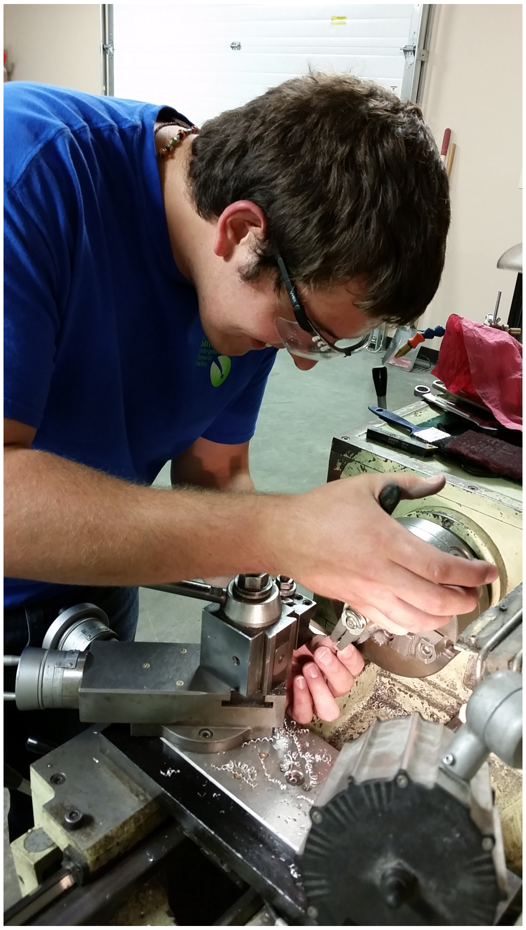

Figure 6: Checking the turned piece

The rest of the machining will be done in the following order:

1. Pendulum Torque Rod
2. Assembly Base
3. All Bushings
4. Pendulum and Torque Arm Booms
5. Bearing Ends and Counterweight Balancing Holders
6. Stepper Motor Retainer

7. Centrifugal Masses
8. 80/20

Cost changes in the mechanical engineering department moved the production of the pendulum to the Advanced Materials Processing(AMP) Center. This put the project on a secondary usage of the machining equipment. The production window was therefore limited to a period of time between 5 and 7 pm.

4.4 Assembly

The assembly begins by affixing nuts to the threaded rods that run through the center of the 80/20. Place the threaded rods through the holes in the base such that the nuts sit within the recessed slots (figure 7).

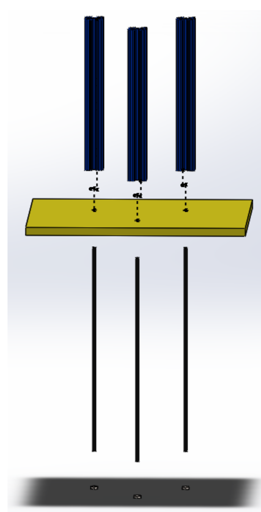

Figure 7: Base assembly

Slide the larger cuts of 80/20 on to the threaded rod. Next, insert the torque rod into the output of the gearbox (figure 8) ensuring that the retainer spring is properly seated in the machined grove within the housing.

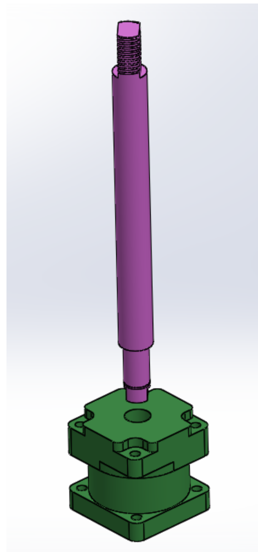

Figure 8: Torque rod in gear box

Place the motor, on the base and affix the shaft coupler on the shaft of the motor. This is the piece with the gear on the end. Slide the spacer over the shaft and coupler and secure it to the motor (figure 9).

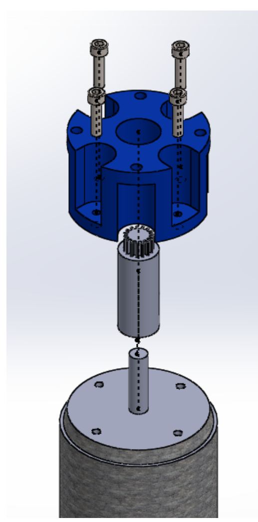

Figure 9: Shaft Coupler and Spacer Affixed to Motor

Place the gearbox assembly on top of the motor coupler (with the gear on the end) ensuring that the gear properly meshes with the other gears in the gearbox (Figure 10).

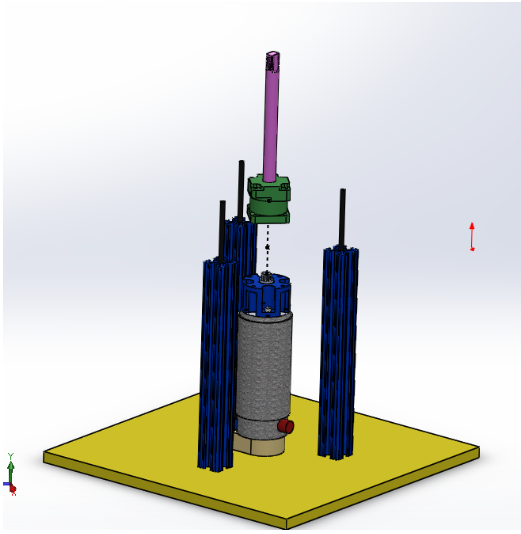

Figure 10: Gearbox Assembly Affixed to Motor

Next, slide the bottom bearing assembly onto the threaded rods and onto the main torque shaft. Secure the gearbox to the spacer and bottom bearing retainer (Figure 12). Tighten the four securing bolts around the main torque shaft.

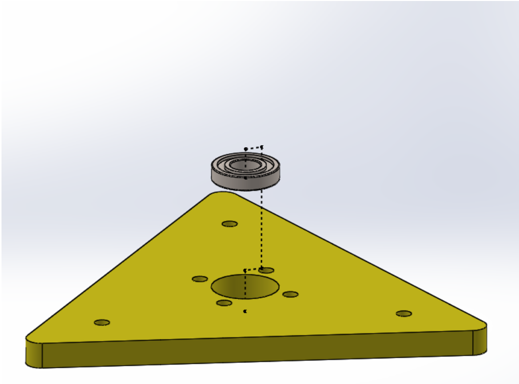

Figure 11: Bearing Press-Fit Into Bottom (Top as Well) Bearing Retainer

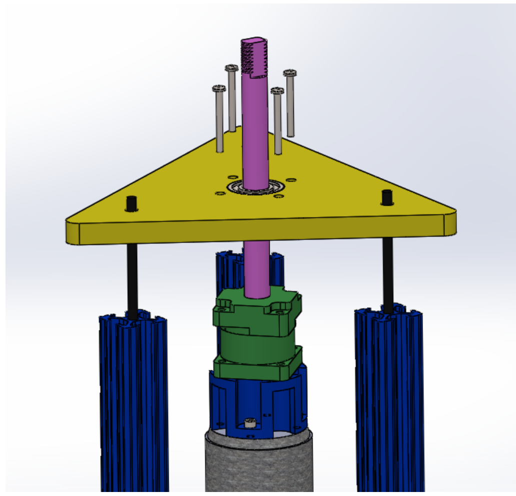

Figure 12: Bearing Press-Fit Into Bottom Bearing Retainer

Add the remaining pieces of 80/20 to the top of each threaded rod. Finally, place the top bearing retainer on the main torque shaft and the rest of the threaded rods. Tighten assembly together.

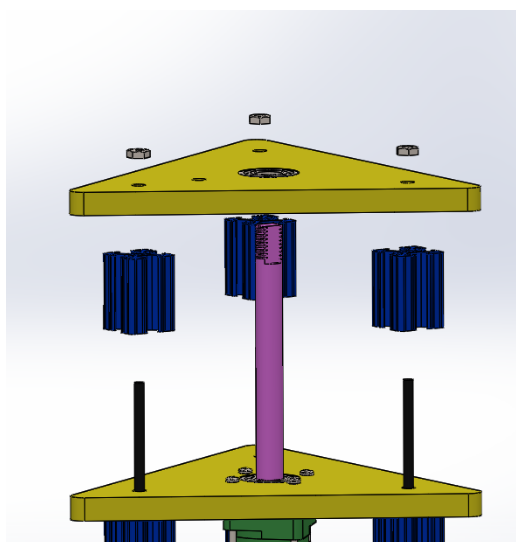

Figure 13: Top Bearing Retainer Sliding Over Main Torque Rod

Secure the slip ring on the top bearing retainer (Figure 14).

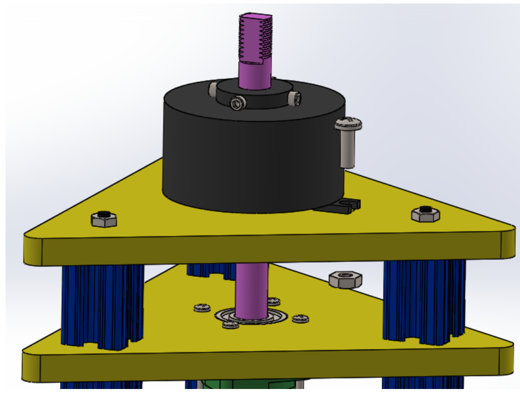

Figure 14: Installing Slip Ring

Assemble the main pendulum by first assembling the centrifugal assembly. The stepper motor, bearing holders, and the two retaining sections should be bolted onto the assembly first.

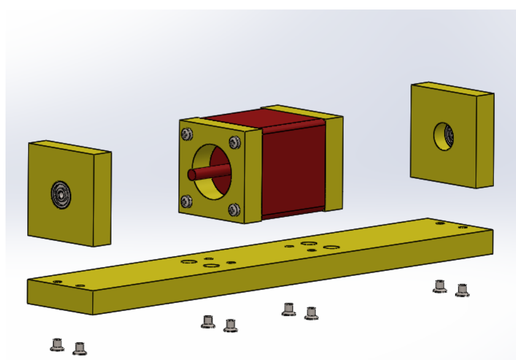

Figure 15: Assembling Centrifugal Assembly

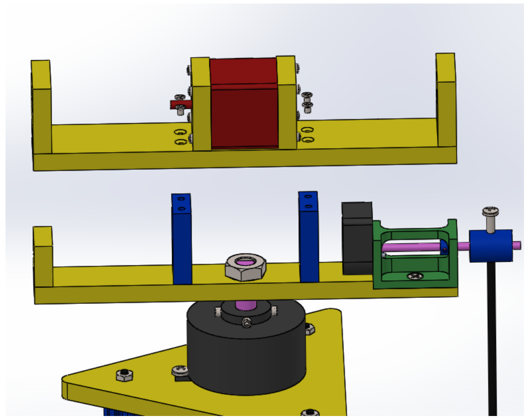

Figure 16: Assembling Centrifugal Assembly

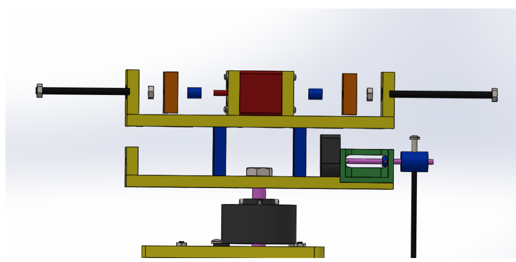

Figure 17: Assembling Centrifugal Assembly

After this, bolt the two spacers, counterweight holder, and main pendulum assembly (with encoder and arm) to the bottom section. Slide this section onto the main torque shaft and bolt it on.

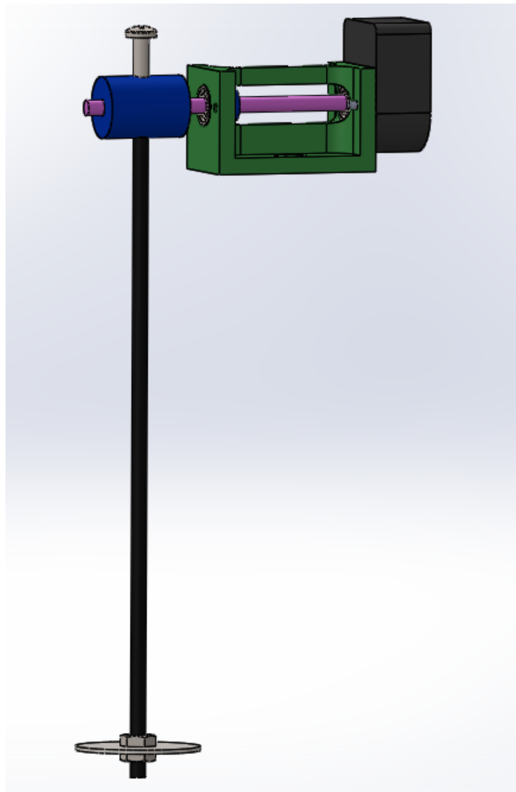

Figure 18: Pendulum Assembly With Encoder

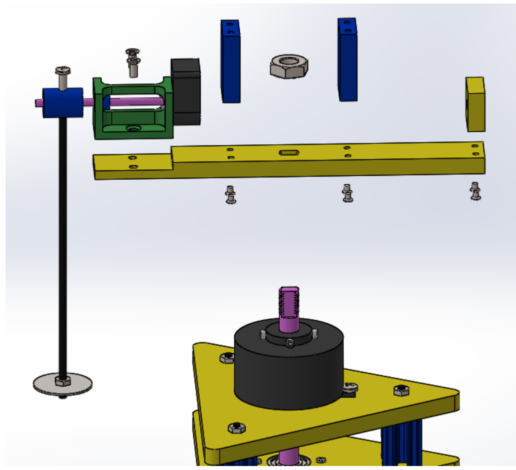

Figure 19: Method for Affixing Main Pendulum Boom Assembly

Next, place the centrifugal assembly on top of the bottom section.

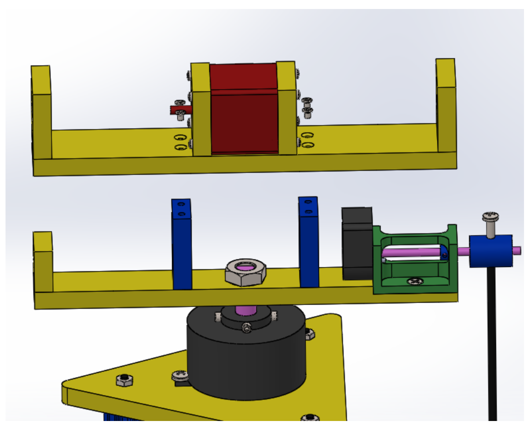

Figure 20: Assembling Centrifugal Assembly

Insert bolts into the two spacers bolted to the bottom assembly and tighten. Attach the remaining threaded rods to the stepper motor on the centrifugal assembly. After this has been done, wire the unit up the the motor controller board and encoder board.

4.5 Calibration

Calibration is planned to take place directly after assembly. The entire process will include checking the tightness of all of the component bolts, preforming velocity consistency tests, and oscillating the pendulum while taking measurements from both encoders.

4.6 Experimentation

The direct-drive rotational inverted pendulum will be used to test the effectiveness of automated system identification software as the dynamics of the pendulum are changing. The pendulum will be configured to initiate a swing-up process which will bring the pendulum within the controllable angular range of the system. As the system reaches a stable state, a controlled jitter will be injected into the system to destabilize the system. This will be done several times and at different positions of the centrifugal masses to observe the change in the system response with the different centrifugal mass positions.

5 Results

At the current time, there are no results to report as the pendulum is still in the machining phase. Results will be published within the next iteration of this paper.

6 Discussion

Construction of simple systems is still important up to this day as they are utilized to test the complex mathematics behind the physics of their operation. A well studied system saves time and ultimately money when trailblazing new methodology for identifying complex systems. My six-week experience with the design and development of this pendulum has given me a realistic insight of the design and fabrication process of simple physics experiments.

7 Conclusion

After working on the pendulum project for six weeks, an entire re-design was completed. The at the time of writing, the project is well into the manufacturing of the pendulum. Much was learned over this summer in the realm of research and manufacturing that will be applied to the pendulum during the rest of its construction, testing, and experimentation.

8 Appendix

This section is reserved for engineering diagrams and notes.

8.1 Engineering Drawings

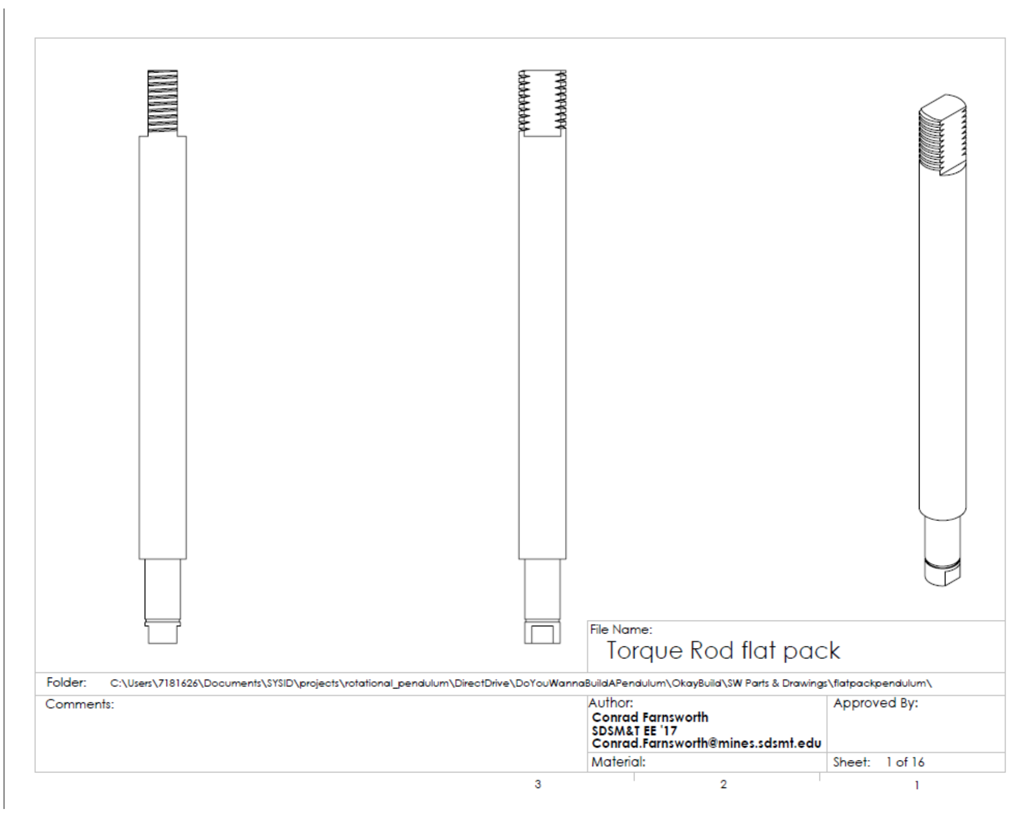

Figure 21: Main torque shaft

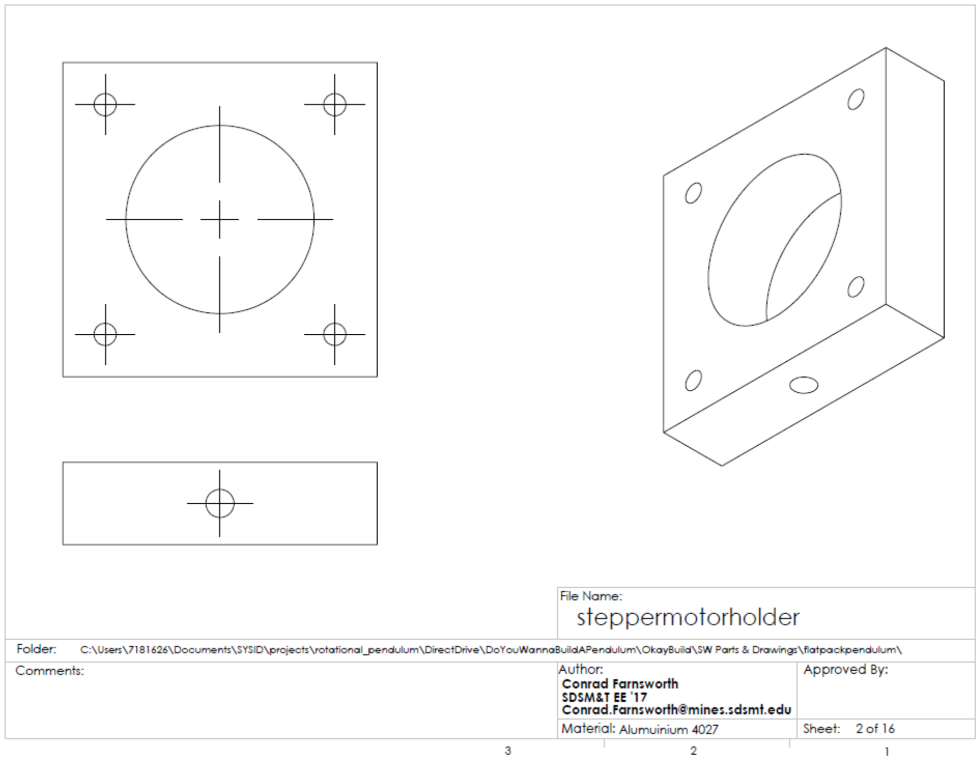

Figure 22: Stepper motor holder

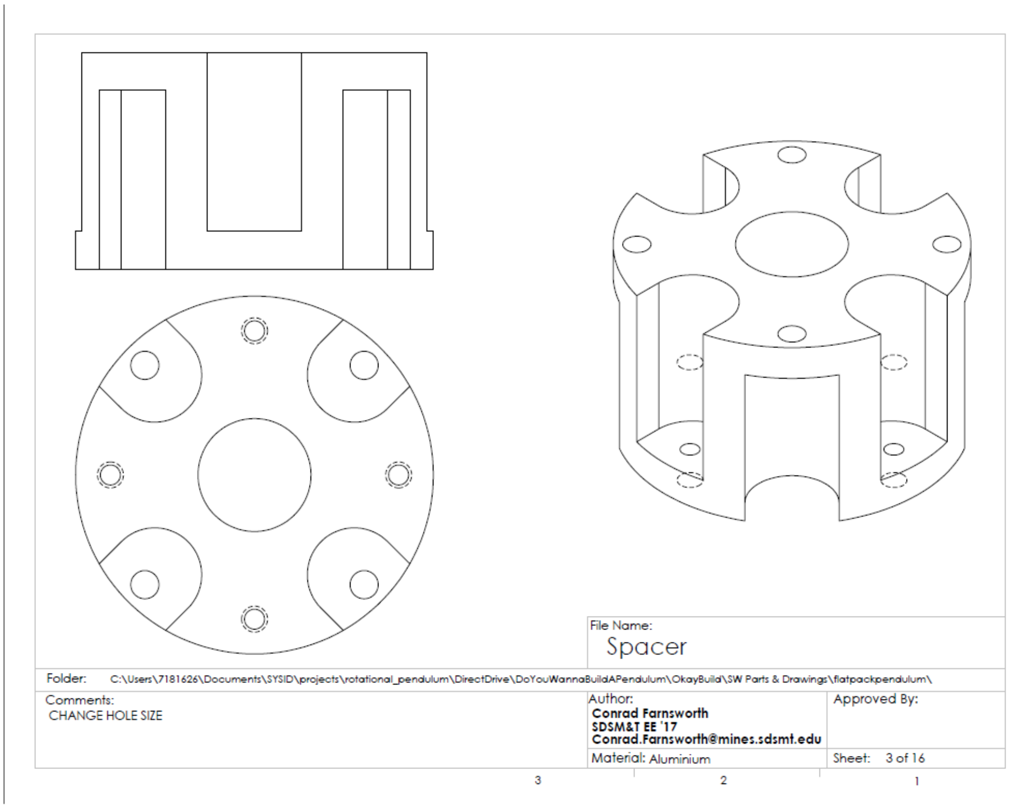

Figure 23: Spacer unit

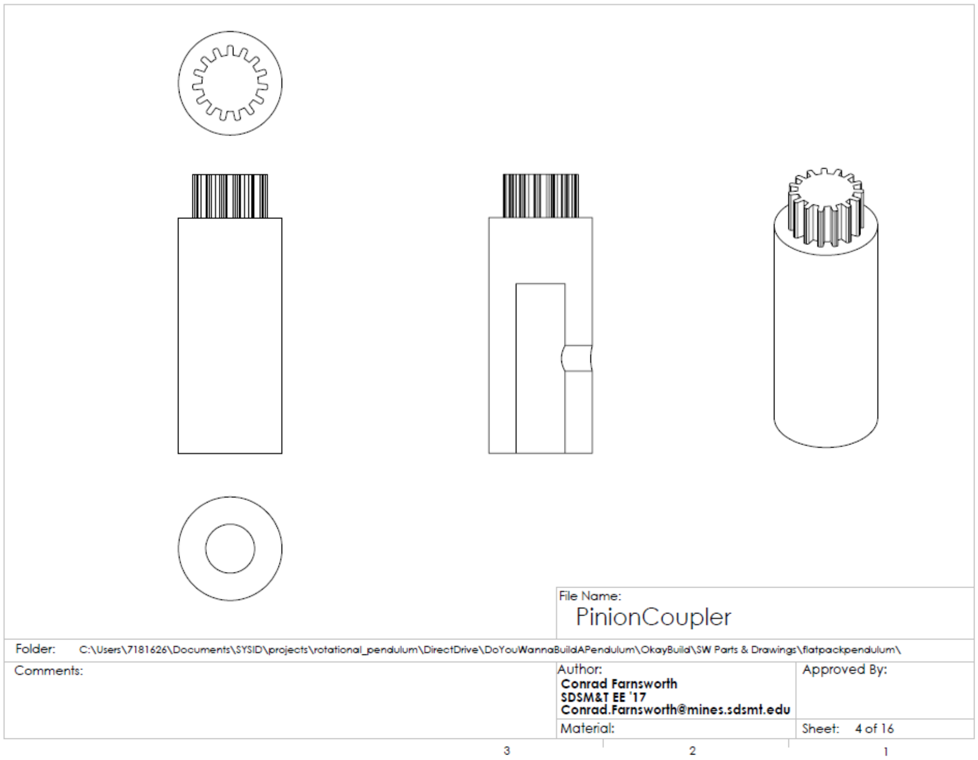

Figure 24: Pinion Coupler

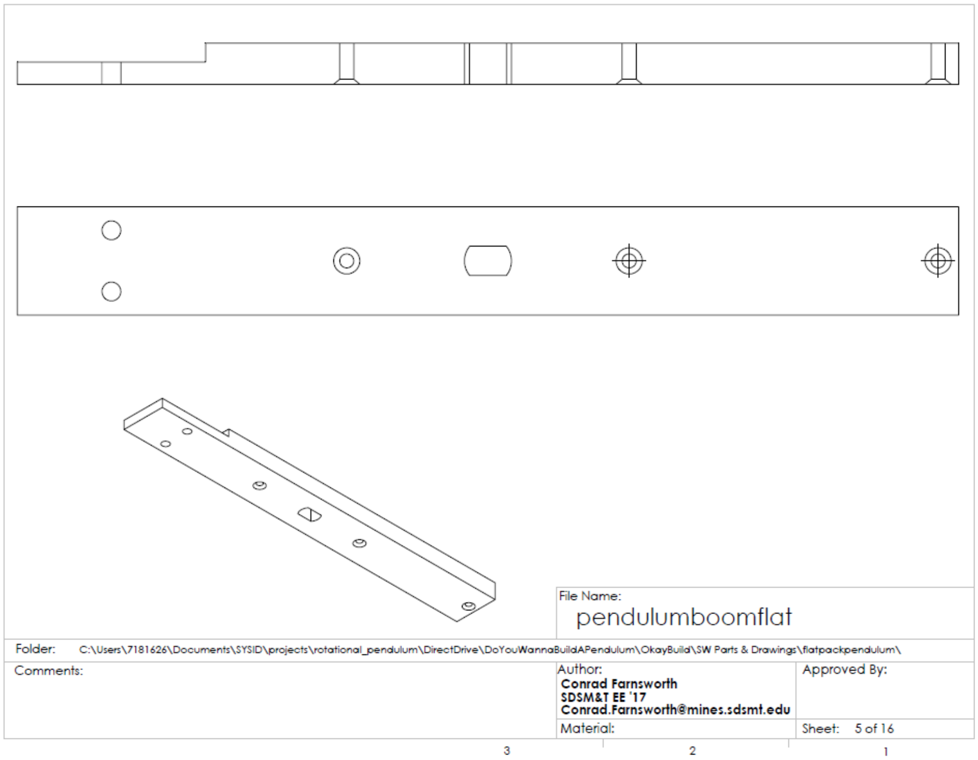

Figure 25: Pendulum boom base

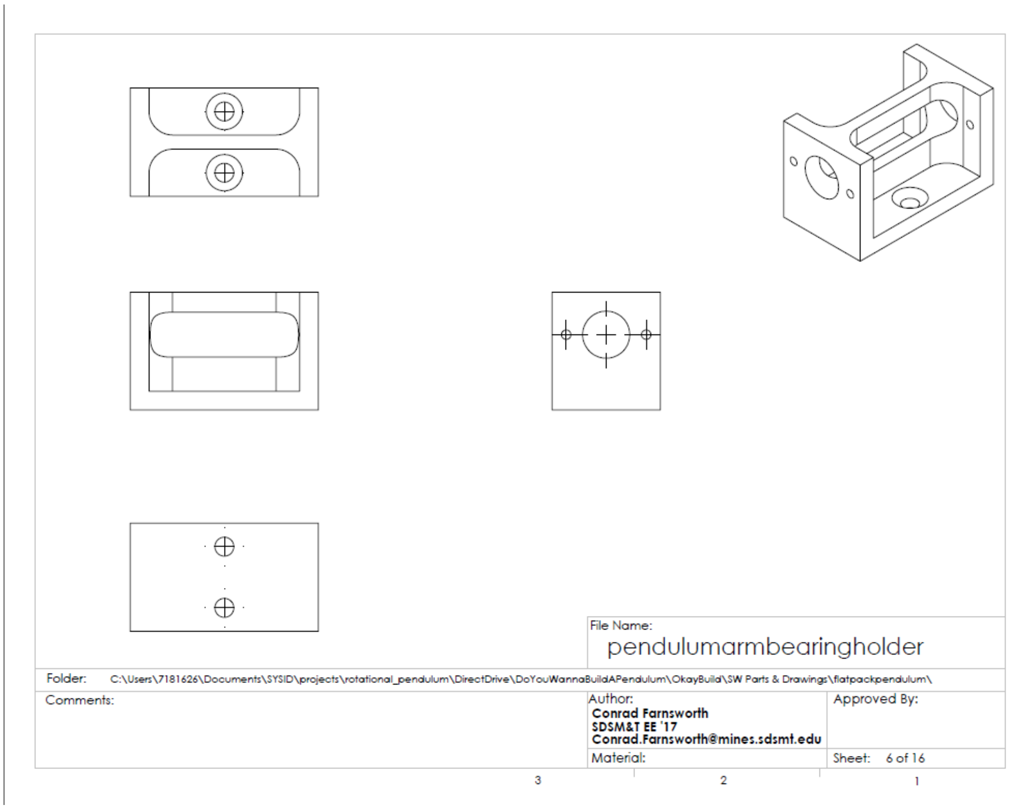

Figure 26: Pendulum bearing holder

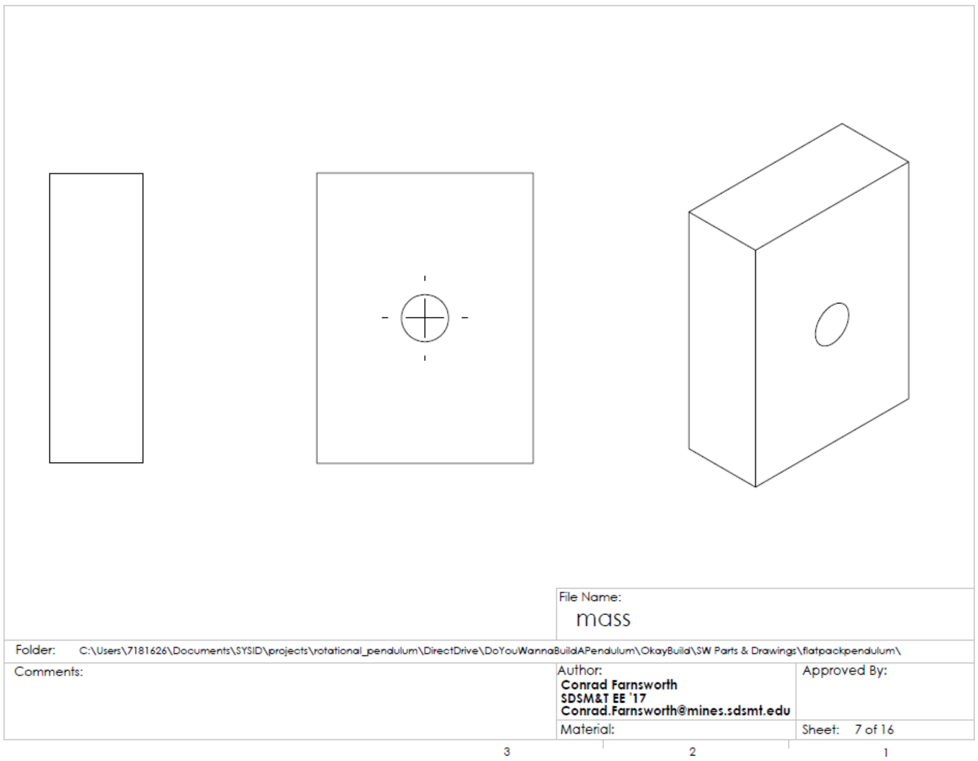

Figure 27: Mass (manufactured out of steel)

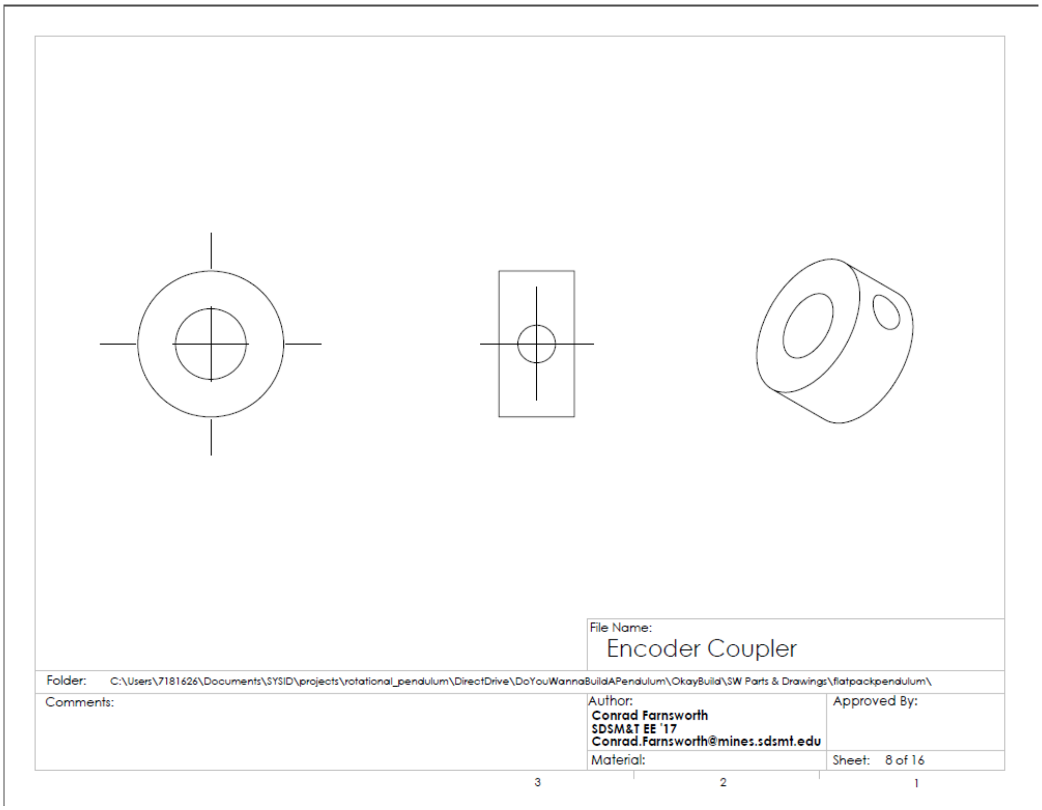

Figure 28: Encoder coupler

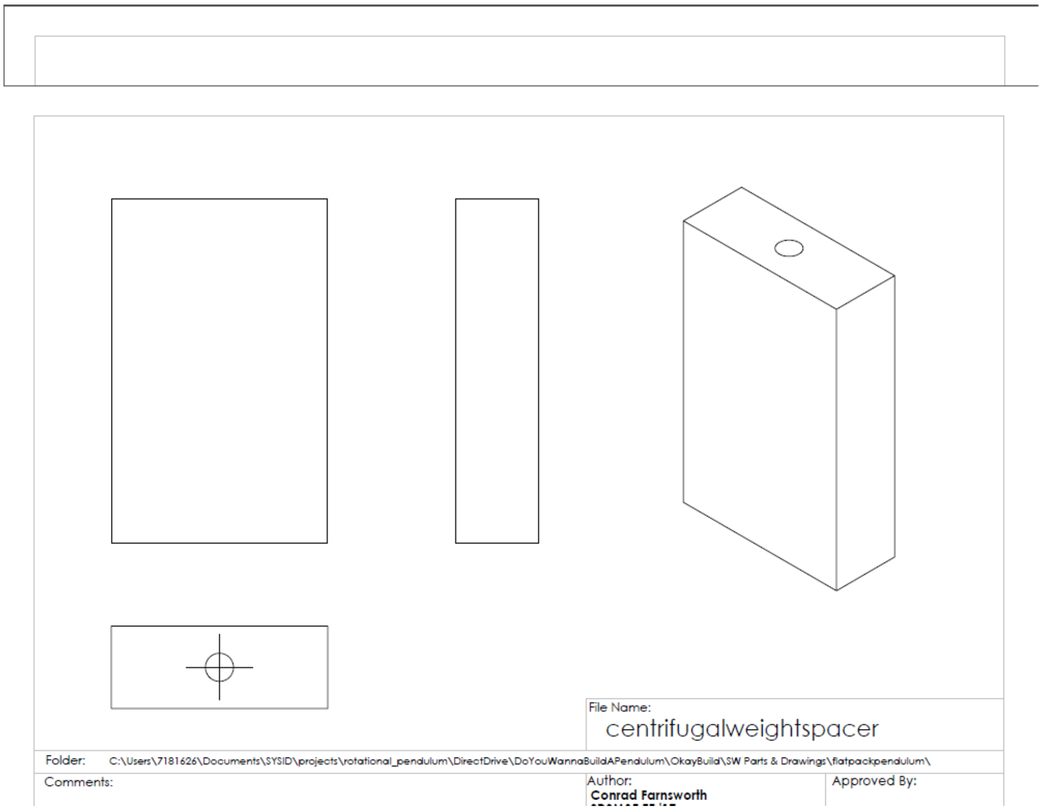

Figure 29: Centrifugal weight spacer

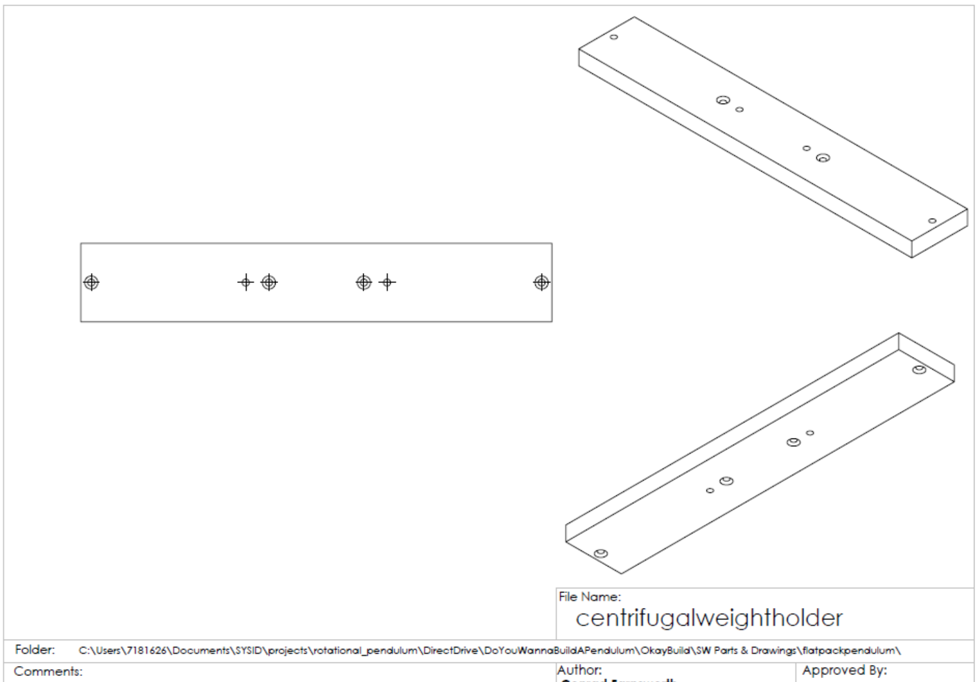

Figure 30: Centrifugal weight holder

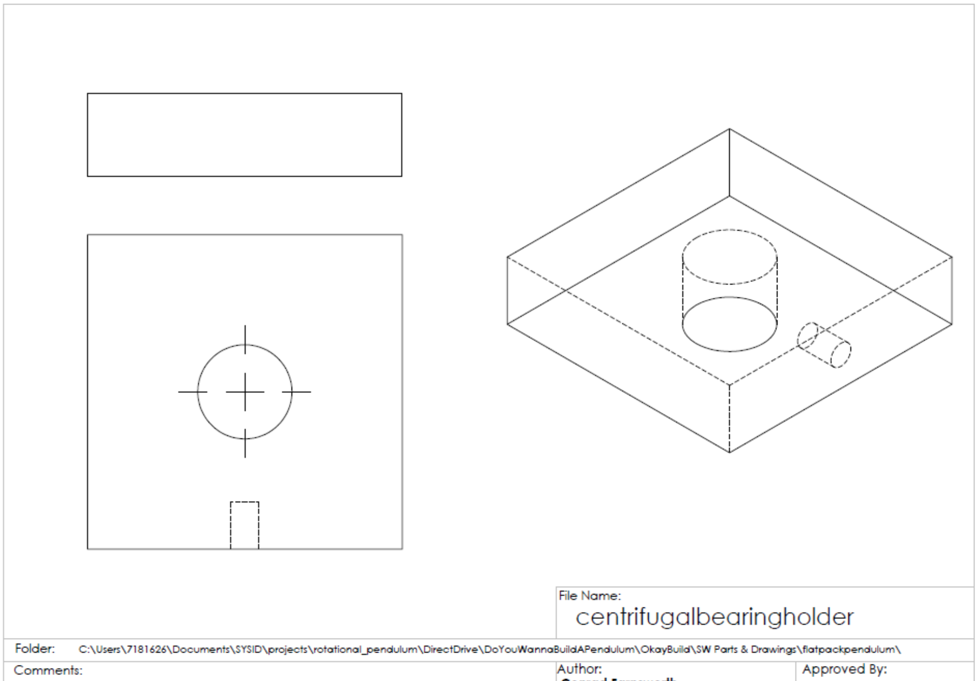

Figure 31: Centrifugal bearing holder

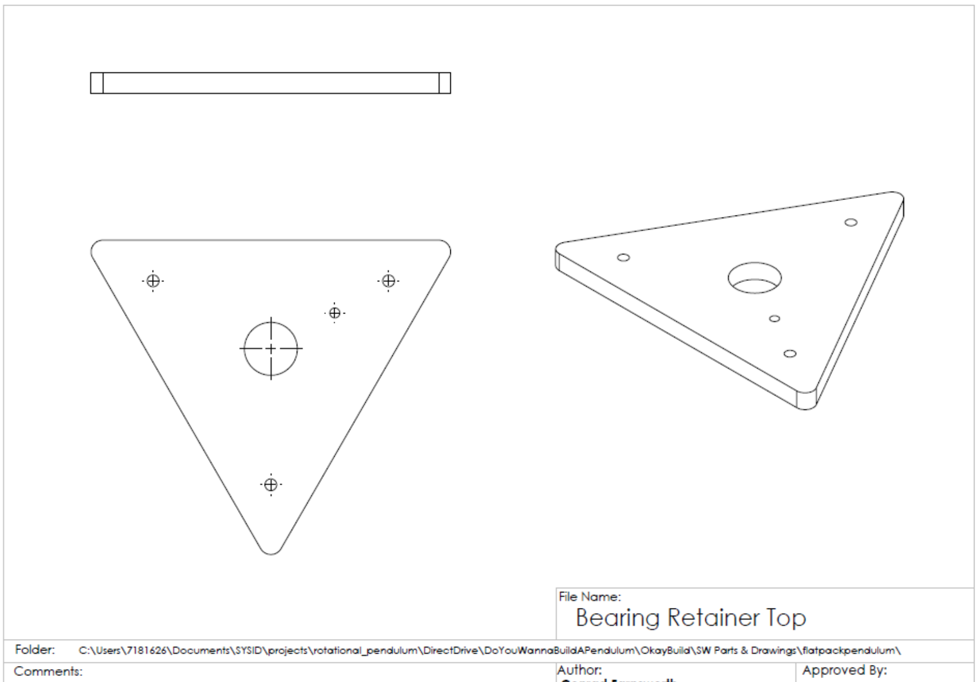

Figure 32: Top bearing retainer

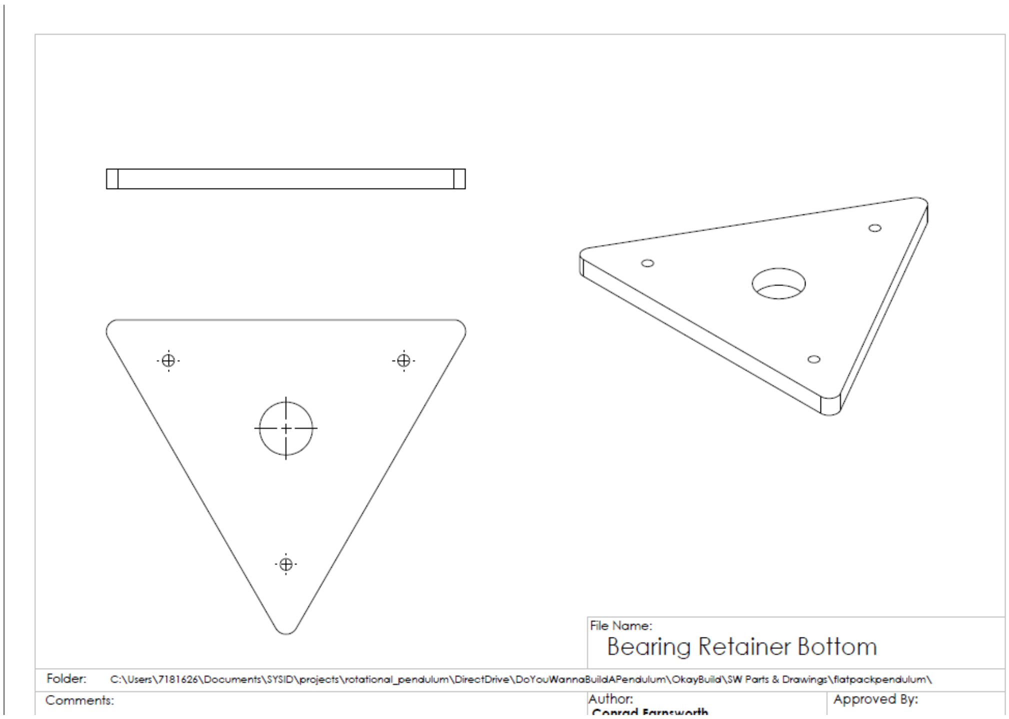

Figure 33: Bottom bearing retainer

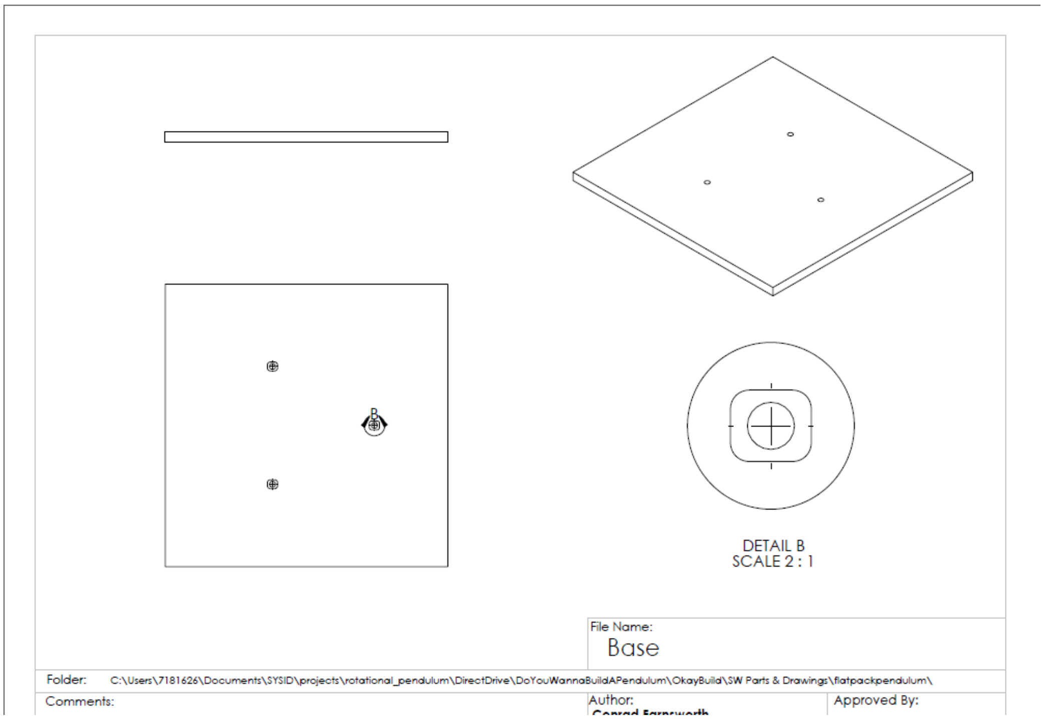

Figure 34: Base

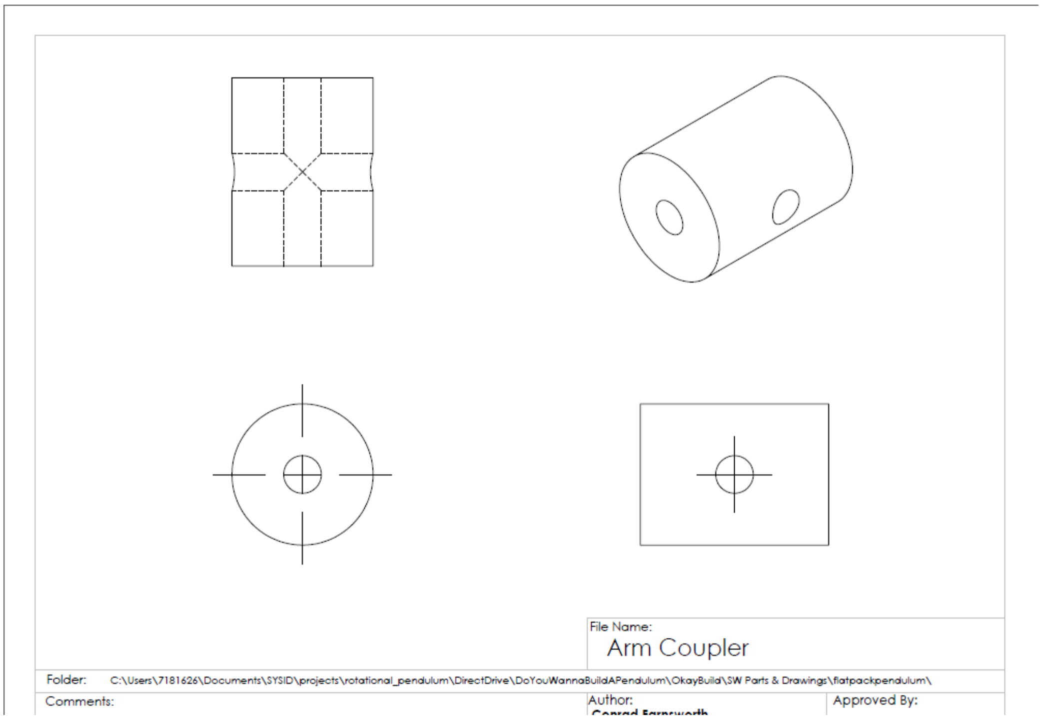

Figure 35: Pendulum arm coupler

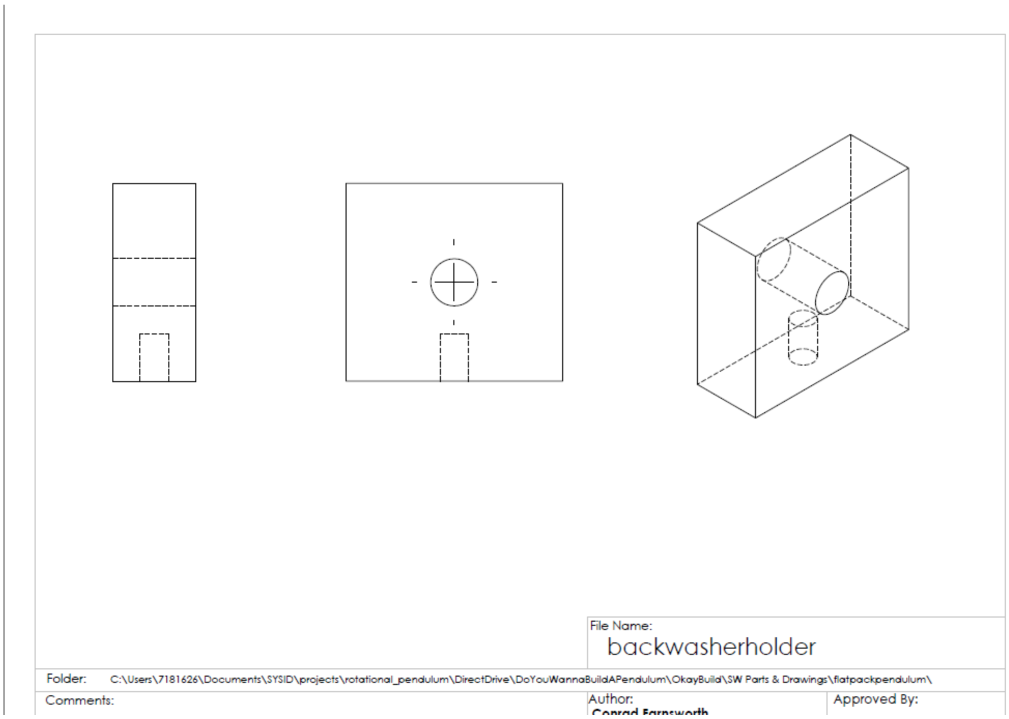

Figure 36: Back washer holder (counterweight)

9 References

[1] *Reducing energy costs by optimizing controller tuning*, volume 2 of *DIT*. Dublin Institute of Technology, 2006.

[2] George D. Greenwade. The Comprehensive Tex Archive Network (CTAN). *TUGBoat*, 14(3):342–351, 1993.

[3] BaneBots Inc. *BANEBOTS P60 GEARBOX PRELIMINARY*. BaneBots.

[4] Pittman Motors. *Brush Commutated DC Servo Motors*. Pittman Motors.

[5] SolidWorks. *Tutorials*. 3DS Inc.

10 Acknowledgments

I would like to thank Dr. Charles Tolle for mentoring me through this project. A proper thanks is also directed towards Dr. Alfred Boyson for his flexibility in accepting hybrid students such as myself into the REU program.