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Benchtop Centrifuge for Materials Science

Ryan Schulz
Santa Clara University, rschulz@scu.edu

Thomas Valentine
Santa Clara University, tbvalentine@scu.edu

Abhay Gupta
Santa Clara University, angupta@scu.edu

SANTA CLARA UNIVERSITY

Department of Mechanical Engineering

I HEREBY RECOMMEND THAT THE THESIS PREPARED
UNDER MY SUPERVISION BY

Ryan Schulz, Thomas Valentine, Abhay Gupta

ENTITLED

BENCHTOP CENTRIFUGE FOR MATERIALS SCIENCE

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF

BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

Robert A. Marks — 6/14/17

Thesis Advisor, Dr. Robert Marks — date

[signature] — 6/14/2017

Department Chair, Dr. Drazen Fabris — date

BENCHTOP CENTRIFUGE FOR MATERIALS SCIENCE

By

Ryan Schulz, Thomas Valentine, Abhay Gupta

SENIOR DESIGN PROJECT REPORT

Submitted to
the Department of Mechanical Engineering

of

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in Partial Fulfillment of the Requirements
for the degree of
Bachelor of Science in Mechanical Engineering

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Abstract

The Benchtop Centrifuge was designed to serve for research purposes within the Mechanical Engineering Department at Santa Clara University. The prototype has been completely assembled and is functioning to the desired specifications of applying up to 1000 g's of force for over 4 hours. The current uses are anticipated for separation of particles within materials for material processing and testing. The overall system design has been adapted from a legacy project within the University. Various tests were conducted in order to ensure safety and usability of the system. Through Abaqus analysis and drop-test experiments, it was found enclosure itself can withstand an impact from a bucket at max-speed. The a SolidWorks analysis, the natural frequency of the enclosure was found to be 104.46 Hz, which translates to a rotational speed of 6267.6 RPM; this is well above what the system will be operating at. The team hopes that future students and faculty will be able to expand their current research through the use of this system.

Acknowledgements

Our team would like to acknowledge the following parties:

- Dr. Robert Marks
- Dr. Michael Taylor
- Dr. Timothy Hight
- Dr. Christopher Kitts
- Dr. Terry Shoup
- Don MacCubbin
- Dr. Panthea Sepehrband
- Xilinx San Jose
- Santa Clara School of Engineering
- Kellie Kou (University of Washington)

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Introduction

Introduction

The Mechanical Engineering Department at Santa Clara University is expanding their Material's Science lab facility to incorporate more diverse research. To do this, they are in the process of procuring more equipment and allocating additional facilities to the faculty. Dr. Marks,conducted his Ph.D. thesis on the refinement of ceramic products through use of a centrifuge and, as such, it is a necessary tool for him to continue his research.

Background

From research applications in materials science to industrial applications in agriculture, centrifuges are utilized to provide fast methods of material processing. They are especially important in processes that include precipitation, filtration, and sedimentation. Precipitation is the formation of a solid from a solution, where, in the specific case of centrifuges, the rotating force causes particles settle at the ends of their container. Filtration involves selection of specific particles based on their size. Sedimentation forces particles of various densities and sizes to settle at different rates. Within a centrifuge, substances are dispensed into test tubes and rotated at high speeds. The high rotational speed causes a force to be applied to particles within the test tubes causing particular particles within the substance to settle at the bottom of the test tubes. [1]

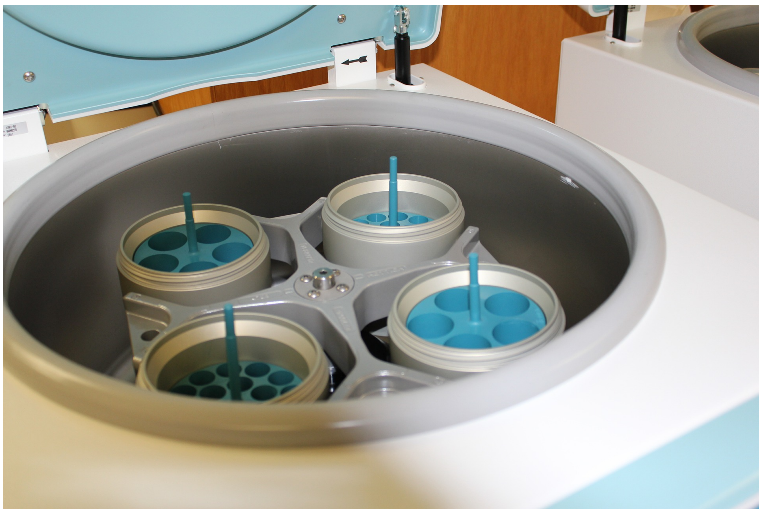


Figure 1: Swing Bucket Benchtop Centrifuge [2] *Public Domain*

Motivation

The Mechanical Engineering Department at Santa Clara University is expanding their research both in diversity and in depth. One area of research that is applicable to the department involves separation of particles dispensed in fluid through the use of a centrifuge. Our team of Santa Clara University mechanical engineering students decided to build a centrifuge to enhance this research.

This project is seen as worthwhile, because it incorporates many engineering theories learned in the classroom to hands-on experience. The project is seen to be highly beneficial to the University and allows us as students to give back to the University. Our team aims to advance the capabilities of the Materials Science laboratory. It allows for the Mechanical Engineering Department as a whole to advance the University's contribution to academia and furthers individual professors' research capabilities.

A previous team attempted to build a similar product for Dr. Marks but ran into difficulties with fabrication which rendered their centrifuge non-functional. As a team we drew from their design as well as their report and it was a useful starting point for the project, letting us avoid some of the issues that they ran into during their project.

Review of Literature

Type of Centrifuges- Based on Solution

Centrifuges are needed in the process of separation of solutions to attain high-quality materials. However, centrifuges have a large variation of design, because they must be tailored to their specific application. Some of the parameters that must be taken into account are the amount of material tested, the force required for separation, and the size of particles that are being separated. For designing a centrifuge for separating particles based on their size, centrifuges can be divided into two categories: rotating devices and stationary devices. [3]

1. Stationary Centrifuge

In a stationary centrifuge, the solution is dispensed into a conical or cylindrical shaped container, where the denser substances move to the outside of the container while the remaining substances fall closer to the center. A screen scroll centrifuge is an example of a stationary centrifuge as shown in Figure 2. This centrifuge is generally utilized for applications in separation of crystalline, granular, or fibrous materials.[4]

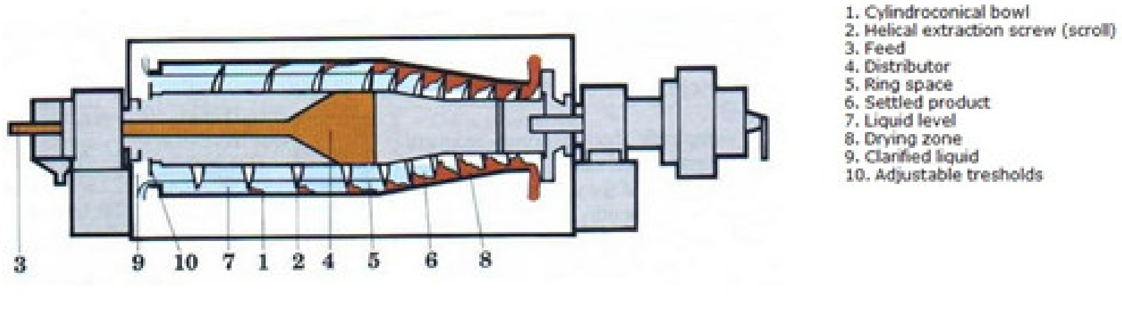


Figure 2: Screen Scroll Centrifuge [1] *Permission to Reproduce*

2. Rotating Centrifuge

Alternatively, in a rotating centrifuge, the solution is placed in containers that are spun rapidly (Figure 3). As the force from the centrifugal acceleration is applied to the fluid, the denser particles will become settled at the bottom of the containers. Following this, the containers go through a decanting process, where either the dense particles or the remaining fluid is kept, depending on the specified application. [5] Figure 3 below shows a diagram of how a rotating centrifuge operates for both a fixed angle and a swinging bucket centrifuge. This specific diagram shows a swinging bucket centrifuge, where the test tubes are suspended at 90 degrees, optimizing the force applied to the substance.

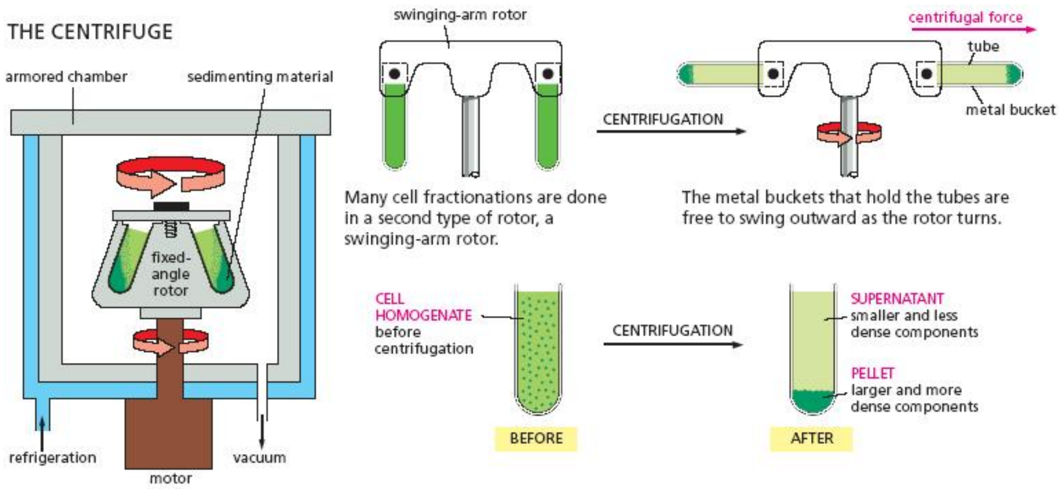


Figure 3: Rotational Centrifuge [6] *Permission through Creative Commons*

Type of Centrifuge - Based on Force

Generally, centrifuges require high forces for proper applications. The applied force is dependent on the radius of rotation and the speed of the centrifuge. Higher speeds and a higher radius produce higher forces, but both of these enhancements can be costly improvements for the overall design of the centrifuge. High speed centrifuges can be divided into two major categories: industrial centrifuges and ultracentrifuges.[7]

1. Industrial Centrifuge

Industrial centrifuges are extremely large and have low rotational speeds. The high force is due to a large moment arm, which is also known as a large radius of rotation. Decreasing the rotational speeds allows for less dependence on high voltages; therefore, there are lower safety concerns and electronic cost overhead. However, the increase in size has major cost increases to the overall structure as the enclosure must be expanded to encapsulate the entire system.[7]

2. Ultracentrifuges

In contrast, ultracentrifuges, in addition to holding smaller containers, have extremely high rotational speeds up to 230,000 RPM [8], but lower moment arms. The high costs of these centrifuges are highly dependent on the motor and electronic system. The motor must have low-wear components resulting in higher costs to incorporate higher fatigue strength within the motor. Figure 4 below is a diagram of the internal components of an ultracentrifuge.

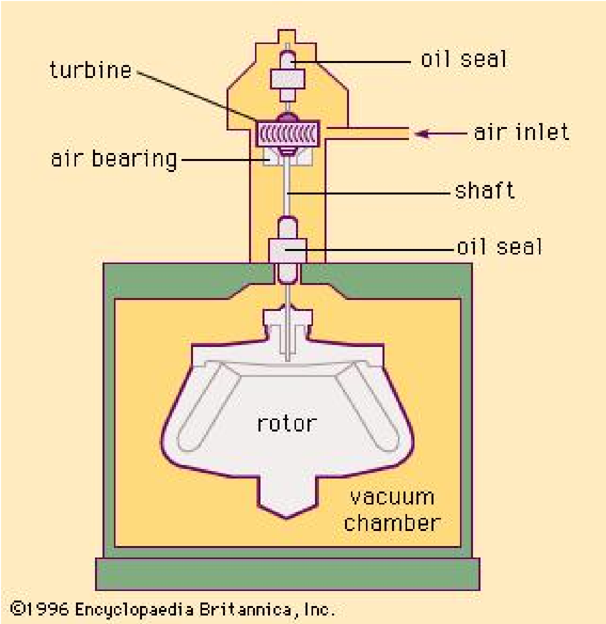


Figure 4: Ultracentrifuge [8] *Public Domain*

Recent Advancement - Magnetic Bearings

There have been significant advancements in centrifuges over the last decade. One recently developed centrifuge is a magnetic centrifuge. In 2013, mechanical engineers from South Korea inserted magnetic bearings within a rotating centrifuge to eliminate the use of a vacuum chamber. Their team remarked that vacuum components occupy about fifty percent of the volume within centrifuge systems, producing bulky and mechanically complicated systems. Moreover, a vacuum chamber requires complicated methods to create a seal between the vacuum and non-vacuum components. Overall, the baseline benefits of the magnetic bearings are a simpler, thinner centrifuge. [9]

Problem Statement

The purpose of our design group was to design a centrifuge for the Mechanical Engineering Department at Santa Clara University which will be able to maintain a force of 1,000 g's for up to 4 hours in a safe and reliable manner.

System-Level Chapter

Customer Needs

Acknowledging that the purpose of this project is to produce a functioning materials science centrifuge, the most important customer to contact for our project was our advisor, Dr. Robert Marks of Santa Clara University. He has previously used centrifuges for alumina powder research for his graduate thesis at UC Berkeley. After conversing with Dr. Robert Marks, he made it clear that he desired a centrifuge that could reach 1,000 g's of force for up to 4 hours.

Another source with whom we talked was Dr. Panthea Sepherband, also of Santa Clara University. Having utilized centrifuges often in the past, she was familiar with the American Society of Testing and Materials (also known as ASTM) standards for the construction and use of centrifuges. These standards are widely accepted and therefore must be passed in order for our design to be commercially viable. The standards impacted many of the safety subsystem goals by stressing the importance placed on safety of the user during machine run-time.

The last source interviewed was Kellie Kou, a student researcher at the University of Washington studying cellular, molecular, and developmental biology. She currently uses centrifuges on a daily basis and informed us about the necessity of having a refrigeration system in order to conduct almost any medical testing using a centrifuge due to the friction created by the system in operation. This heating has the ability to spoil most biological samples and therefore a refrigeration system is necessary if our design is to be converted for biological research applications.

After initially talking to these three sources, we went back to Dr. Marks to converse more about his needs. Although the other sources were helpful in researching what our system level requirements were, the actual true customer of our product was going to be Dr. Marks and therefore his requirements were focused on the most. He ended up deciding that, for the undergraduate research that the centrifuge would be utilized for he had some more flexible requirements. The research demanded that the system would produce up to 1,000 g's of centrifugal forcing for up to 4 hours. To improve the accessibility of this centrifuge towards the students, Dr. Marks wanted a device that could hold up to 15 vials to allow multiple students to use the device at one time. Lastly, since the system was to be utilized by students, he wanted the centrifuge to be simple enough to be operated by users who had little to no experience with centrifuges. Our group looked into potentially adding a refrigeration system into our device, however Dr. Marks believed that would require a larger team than our group of 3 Mechanical Engineers given the timeline we had to produce a functioning prototype.

In addition to these baseline requirements, we wanted to develop a system that allowed for easily replaceable parts. Therefore many of the internal parts can be purchased from common online vendors. Additionally, we wanted to make it so that the maintainence and replacement of parts is simple enough that an untrained student would be capable of doing it with minimal instructions. Given that students will be using this in the future and that our team will not be around for maintenance it is important that posterity will be able to use the device far into the future.

System-Level Requirements

Overall we designed a centrifuge that conformed to the following criteria:

- Produces a maximum of 1,000 g's and a minimum of 200 g's
- Operate for at least 4 hours
- Withstand potential impact from failure
- Provide ability to upgrade motor
- Utilize a swing bucket design
- Hold a capacity of at least 15 test tubes during operation
- Reach 63 percent of the desired forcing at 60 seconds
- Cost less than most competing models
- Maximize standardized parts to lower cost and increase repairability
- Minimize training required through intuitive design

See Appendix 1 for a complete break down of PDS/Requirements

System Sketch with User Scenario and Explanation

The overall system direction has changed over the course of the year. However, the functionality requirement was met at the end of the project. The system description and use case is described below.

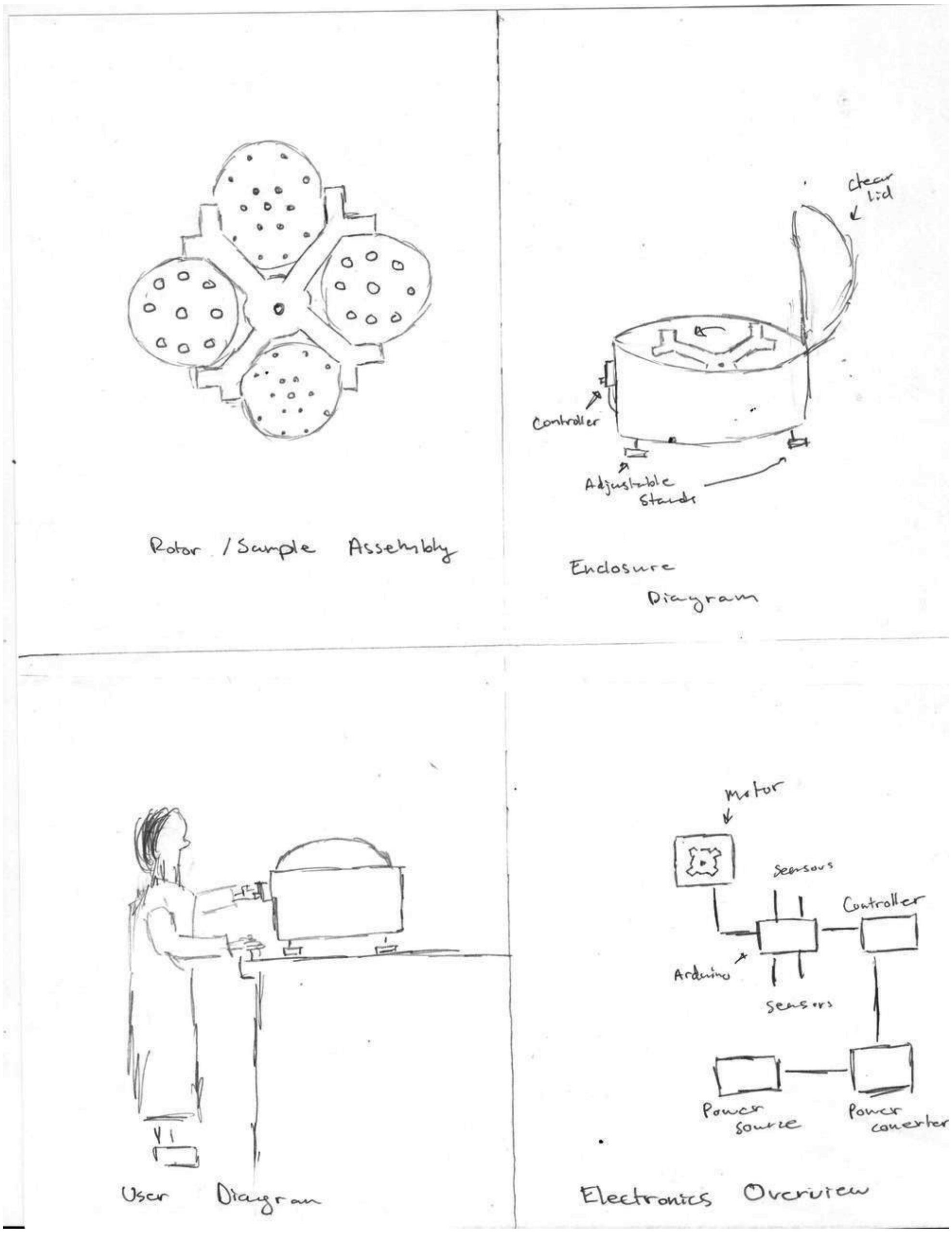


Figure 5: Graphic of System

The sketch above shows user operation of the centrifuge. It is broken down into four sections. The top left section shows how the rotor and test tube holders will look from a top down view. The top right image is an external drawing of the system. The bottom left image is a simple user diagram showing how the centrifuge will be placed in the laboratory. Lastly, the bottom right image is a brief controls overview, where the sensors, controller, power, and motor are laid out. This control system is discussed later in the electronics section. The centrifuge is able to be utilized by one person. The safety protocols outlined in the appendix should be followed to minimize the risk of harm to the user, those in the vicinity, and the surrounding environment.

The users of the centrifuge will consist of students and faculty who are involved with research. These personnel will be providing their own testing samples. An example of a research application would be removal of particles from a particular substance for purification of the substance. A specific case of this application would be for separating and removing agglomerates from alumina powder. Agglomerates in alumina powder cause stress concentrations after the powder is completely processed. To increase the overall strength of the material, the agglomerates must be removed. A current method in removing the agglomerates is to place vials of the alumina powder in a centrifuge and force them to the ends of these vials. With these agglomerates removed, the new processed alumina powder has much higher toughness and strength properties.

Since the centrifuge will be utilized within the Material Science Laboratory in the Mechanical Engineering Department of Santa Clara University, the users will be required to follow safety protocols for safe operation.

The operation process can be found under the **Operating Manual** section.

Functional Analysis

Main Function

The system should provide a force of up to 1,000 g's.

Sub-Functions

The sub-functions of the centrifuge will vary based on specific research applications. Individual's modifying the components of the centrifuge (such as the gearbox or motor) due to its variable design can also change the functions of the centrifuge.

- Single operation lasts up to four hours
- Ramp-up time to desired speed (63 percent of desired speed) is under 60 seconds
- Automatic shut-off system either by timer or safety system
- Ability to hold 15 test samples
- Swing bucket rotor
- Each test sample can have a volume up to 15 ml

- Ability to hold a variety of test tube sizes

Inputs/Outputs

Table 1: Input/Output Properties of the System

Inputs	Outputs
- Arduino Program inputted, compiled & executed - Accelerometer readings are normal	- Activate relay to energize motor with necessary power to achieve desired speed - Begin program timer as input by user
- Accelerometer detecting unstable vibrations - Accelerometer detecting device is tilted/moved - Program ends after designated time	- Trip relay to de-energize motor and drive system - Initiate timer before solenoids unlock to ensure centrifuge is stopped
- User programs Arduino to change speed mid-operation - Time at current speed has elapsed	- Arduino commands the controller through the Digi-pot to change power supplied to motor

Benchmarking Results

Table 2: Centrifuges within the Current Market

System Name	Cost	G Force	Speed	Number of Samples
Thermo Scientific Heraeus X1	$6400	25,800g	15200 RPM	26
Cole Parmer MS-3400	$2500	1,800g	3400 RPM	4
Labnet Z206	$1600	4,200g	6000 RPM	6
EBA 200	$1400	3,460g	6000 RPM	8
EBA 200S	$2500	6,150g	8000 RPM	8

The competing market hits a variety of different market segments. The Thermo Scientific Heraeus XI focuses on high force applications and with a large number of testing samples, which are achieved at at high costs. In contrast, the EBA 200 carries a low number of samples with a lower maximum force, but at a low cost.

Our centrifuge can easily compete with these other devices, as our current motor allows up to 3,200 g's with a 1:1 gear ratio. Due to the fact that our customer Dr. Robert Marks only needed 1,000 g's, we utilized a 2:1 gearbox speed reducer to reduce the total speed of the spindle while increasing torque. By doing this, we reduce the time the centrifuge takes to get up to speed, which is useful for producing valid research results.

Although 3,200 g's is a similar force to these devices for the same cost, our centrifuge has taken a different approach in a few ways that help it to stand out. First, it can currently hold up to 56 vials at one time, increasing time efficiency to complete large batches. Different sized vial holders can be purchased to hold many smaller vials or several large vials. Our system is also a swing bucket design, while the majority of other systems are fixed angle; sediment collection at the bottom of the test tubes due to the swing bucket design, allows for easier removal of the sediment. Lastly, our system is versatile because it is easily upgradable and repairable. If a component breaks, it can be replaced with another component without having to send the whole device to a repair center. If more g's are needed, a different motor can be easily inserted; the motor slab and bracket will only have to be redrilled to align with new holes. If the system needs to be shipped out, it can be shipped as parts and assembled onsite, reducing the need for bulk-sized shipping and its associated costs.

Key System Level Issues

Safety: Safety was the number one priority when designing our system. If the device worked flawlessly but was not safe, it would be deemed a failure. We ensured our design was safe for users through the inclusion of multiple safety features. We included servos to lock the lid when the system is running to prevent access to a rotating rotor. However, unlike most other models on the market, we decided to incorporate an accelerometer; this will detect unsafe vibrations or a tilted enclosure and power down the system. In the event of a rotor failure, we utilized 1/4 steel to ensure the any loose components of the rotating system will be contained. This greatly increased the weight and cost of our system, but we deemed it was important to ensure the safety of the user and surroundings. Adding in the servos and accelerometer also made programming the arduino a little more complex, and could potentially impact versatility in the future. If a new motor is implemented that triggers the threshold of vibrations of the current code, it would require an overhaul of the current threshold setting. We deemed this was necessary, as the vibration detection is a crucial feature.

Cost: There are several tiers of centrifuges, where each had its own respective pricing. This is our second priority; we want to offer a design that is the safest, while still being a fiscally competitive option. Although our system does match the prices of other models, the swing bucket design, large test-tube capacity, and versatility make our system stand out compared to others.

Force: Some competing devices were approaching over 5000 g's of force, such as the Thermo Scientific Heraeus X1. This isn't required for the material science research of our primary customer, where only 1,000 g's will be needed. As a result, we were able to purchase a cheaper motor that allowed us to cut back on the cost. Although this makes our device weaker to some competitors, we believe the versatility and option to upgrade the motor in the future makes up for this.

Number of Samples: For our target market of centrifuges, our device will beat any competition with how many test tubes it can spin at once. The trade off to achieve this high capacity of test tubes was that it forced our team to utilize the spin-bucket design, which called for a large and heavier enclosure. However, we believe these swing buckets are a major advantage that makes our design stand out from others.

Spin up time: Our spin up time is under 30 seconds for a fully loaded centrifuge going to top speed. Because our rotor has a large moment of inertia, we initially had to look at motors with high torques. However, we later chose a 2:1 speed reducer increased torque but also increased the spin-up time. The downside of using the 2:1 speed reducer compared to a 1:1 gearbox is large noise within the system, which can be up to 77dB. The large enclosure itself contains some of this noise, and even at full speed ear plugs do not seem to be needed, though they remain a recommended item.

Spin Down Time: Our least concern is the spin-down time. Although it is important for our device to stop in the event of a faulty vibration, we are going to keep the lid locked for a set time (2 minutes) to ensure even at the highest speed the rotor will be completely stopped before the user can open the lid. The reason we chose this method is because most conventional braking systems are costly and may only be usable for a few uses.

System Options

The system options have been outlined in the Criteria Weight Sheet within the appendix. The various systems are differentiated by their power input, motor, which is defined by torque and power, weight, and rotor model. Each change affects the criteria consisting of cost, ease of use, and ramp-up time. These factors help define the best centrifuge system.

Tradeoffs

The biggest potential trade off is between the g-force and ramp-up speed vs. cost. This is because it solely depends on the motor, which is already our most expensive part. The solution to this would to design our centrifuge to have multiple options of motors at different costs to fit our customer needs.

Rationale for Choice

The final system design allows for multiple benefits over the current designs. The safety features of 1/4" steel, solenoids, and accelerometer add weight, complexity, and cost but are deemed important given that user safety is the priority. The motor chosen is of lower speeds given that we are capped at 4,750 RPM through the rotor. The selected gearbox increases the torque to improve ramp up time, but also adds some noise.

Layout of System-Level Design with Main Subsystems

There are three main subsystems:

- Drive System
- Controller & Safety System
- Enclosure

Enclosure The enclosure houses the drive system, controller, and safety system. It also partially works in tandem with the safety system as it is designed to protect the user in a catastrophic failure; the enclosure was designed to be rugged enough for the impacts, while also withstanding the forces and vibrations it will encounter during operation. This enclosure is composed of 1/4" thick A36 steel, mounted together through plain carbonsteel brackets and carbon steel bolts.

Drive System The drive system is what actually produces the centripedal forcing through rotation.It takes input from the control and safety system, which powers up the motor controller to begin motor rotation. This rotation is translated to the rotor via the gearbox and spindle utilizing couples. The drive system also incorporates a tachometer so the user can verify their programmed forcing is actually being achieved.

Control and Safety System The controller is in the lower half of the enclosure. This system takes input from the user and controls the motor controller to power the drive system via relays and a digital potentiometer. It read from the accelerometer to ensure the operating environment is safe, while locking the lid via solenoids to prevent user contact with a spinning rotor.

Team and Project Management

Project Challenges and Constraints

Challenges

There are multiple challenges that we encountered in the design and prototyping stages of the centrifuge. The major challenges are listed below:

- Agreeing on a circular vs. boxed enclosure
- Learning how to program in C for the Arduino
- Learning the necessary electrical engineering to wire the system
- Finding a cost effective motor that met our needs
- Abaquus computational analysis for impact tests were not accurate

- Ensuring the 2:1 speed reducer would meet our specifications
- Machining Vendors did not prefer metal from a different external vendor, due to difficulty with the jig

First, for the enclosure, we looked at the possibility of a cylinder and a rectangular prism. The cylindrical enclosure was better as there were fewer critical points; however, the issue was finding a circular piece of steel in the appropriate dimensions and within the budget, Since the specifications were taking too long to meet, we decided to look into the boxed design. The selected box design retained the legacy project's bolt-analysis [10], which can be found in Appendix C.

Another difficulty was coding the Arduino, because our team lacked experience in programming in C. Members on our team tackled this issue by reaching out to fellow Computer Science and Electrical Engineers for assistance. In addition, two of our team members ended up taking a course on C to understand how to program the Arduino. We also had some professors, as mentioned above, assist us when some of the code didn't function properly.

Similarly, when the team was having issues with the Electrical Engineering we reached out to sources for help. One such difficulty was trying to use the Arduino in place of the potentiometer of the controller. While the system should have worked as it was built, there was a floating input voltage across the Arduino board which could not be eliminated so a digital potentiometer was needed to make the system function properly.

Finding a motor was a lengthy process, as we scoured online for a viable motor. Most motors were either large industrial AC motors that were too pricey or cheap and not powerful enough. By reaching out to fellow mechanical engineers within the industry, we gained some advice and where we could purchase appropriate motors. Grainger ended up having a single motor option that would meet our specifications at an affordable price.

To ensure that our enclosure would be strong enough to withstand an impact, we conducted an Abaqus simulation. However, the simulation provided data that did not seem accurate. To test the simulation, a simple case was proven to be consistent with our hand calculations, but the overall data still seemed inaccurate. As a result we decided that experimental testing would be more appropriate.

The 2:1 speed reducer needed to be integrated to give extra torque. However, the manufacturer, Adantex, only had data for 1:1 gearboxes for the required speeds. By contacting Adantex, we worked with their engineers for over a week to come to a solution. They did some extra simulations for us to ensure that their custom 2:1 speed reducer would work in the conditions we needed.

To save cost, we brought external metal to the machinist. They told us they normally do not do this due to complications with the jig, but given that we were using clearance holes, the machining company said it would work. However, we still had complications with the jig and a lot of our holes were 1/4" off on one side. As a result, we had to have some of the sheets re-machined. Later on, during the week before the Senior Design Conference, another sheet was not aligning up with the rest. The turn around time was too long for the conference so we had to customize our brackets to make up for the off-set holes.

Constraints

Overall, we were constrained by $2,500 which was difficult as we underestimated the cost of externally machining the plates. Time was also an issue when were trying to design our system. Given the ability of more time, we believe we could have added a integrated a third party refrigeration system to the unit, but we are currently constrained to the academic school year which inhibited us to do this. A lot of research would have needed to be done to find good thermal insulation and an appropriate refrigeration unit.

To reduce costs and because we wanted to utilize the swing bucket design, we decided to re-use the previous group's rotor. This rotor is rated for a maximum rotational speed of 4,750 RPM. This constraint was beneficial, as it set a hard ceiling for how fast and how many g's we could actually produce.

As we designed our enclosure, we realized we were constrained by the natural frequency. If the rotor does get upgraded along with the motor in the future, the maximum RPM the enclosure can take before it hits resonance is 6,200 RPM. To change this, the fundamental enclosure would have to be modified itself.

Budget

Initially, we bought two types of motors, two types of controllers, and our tachometer from Grainger. This was great as it provided the products to us within 2 days of us ordering them which allowed us to test them. Their return policy of a year from purchase date was great for testing purposes. Once we decided on the tachometer and one of the motors and controllers, we were already $1,200 in. Doing a search online, we found the tachometer and motor online for almost $400 less; as a result we ended up purchasing those online so we could return the more expensive items to Grainger. Without doing this, we actually would've gone over our budget.

Bringing metal to machine shops to machine them was way cheaper than purchasing the metal from the machine shop itself. To cut costs on materials, we decided to purchase our metal externally and bring it to the machinist. Although this was cost effective and fast, it caused more headaches in the future as the machine shops had trouble setting up the metal in their jig due to imperfect cuts.

When possible, we also used Amazon to purchase our components. Our group already had individual Amazon Prime memberships which offered free 2-day shipping, and Amazon had really competitive prices. For components we could not purchase on Amazon we went through McMaster. We could have done better by compiling everything into one order. We had 5 McMaster orders, which could have been consolidated into 2 or 3. Although McMaster has fast shipping at an exceptional low cost, the costs do add up.

To add extra money to our project, we attempted to sell the previous group's motor and controller. However, after looking into the possibility of someone actually needing that specific motor and the difficult procedure to clear this with the department, we decided against it. It remains an potential source of funding for Dr. Marks should he decide that a more powerful motor is necessary to run his research.

Refer to the Budget spreadsheet in Appendix D for a detailed sheet of the budget.

Timeline

Fall Quarter

In the fall quarter, we spent a lot of our time analyzing the previous team's design. A few weeks were spent purchasing parts in attempt to get their motor working again. Our team achieved success, but our results proved that the motor the previous team planned to use was way too slow due to a 5:1 speed reducer, and its torque a little lower than we hoped as well. The controller for the motor was only designed for that specific motor, so that also could not be re-purposed. A decision was made, however to keep the rotor the team previous purchased based on the fact swing bucket rotors are better for materials science research compared to fix angle rotors. Because the spindle specifically worked with the rotor, we kept that too for future purposing. In the latter half of the Fall quarter, CAD models were produced of the rotor and swing buckets, in order to analyze the rotor assembly's second moment of inertia. Using the computed values from SolidWorks, we were able to narrow down the output power of 1/6 HP required for our motor to produce a time constant of 60 seconds for our system.

Winter Quarter In the winter quarter, we purchased a motor, controller, and arduino to start tinkering with the drive system. The enclosure began its design through SolidWorks, while we also worked on modeling impact tests. The impact tests on Abacus did not work properly, so we took 1/8th A36 steel from the previous group's enclosure and performed impact tests on them. We performed a natural frequency analysis to ensure our enclosure would not hit resonance After multiple iterations of the enclosure, we finally purchased the A36 steel and at the end of the quarter.

Spring Quarter In the spring, we had the steel sheets machined. When the steel was returned, a lot of the sheets were not machined properly on one side. The jig they used was not properly set up, so some holes farthest from our zero point were 1/4" off. We had to go back and get some sheets re-machined, while we had to custom machine holes into some of our own brackets. The Arduino was programmed to work with the motor using a digital potentiometer. We had troubles getting the arduino to power the motor through all speeds, and spent a lot of time working with teachers and friends. We got our project assembled the day before the presentation due to backlog from our machining company on getting us back our fixed plates, but our device worked for the competition.

Refer the Gannt Chart in Appendix 2 for a graphical represenattion of our time-line.

Design Process

Our approach to this project was to first fundamentally create a working centrifuge that could be used for research next year. However, recreating an exact product that is on the market is not innovative. We took a spin on this by adding three distinct features that separate it from other models available at its price range. We initially used the swing bucket design, which is better for Material Science research and increases the capacity of vials. Where we really wanted to make our project different was the versatility. When designing our enclosure through multiple iterations, we designed it so that it can be easily upgraded and reparable.

Risks and Mitigations

Many of the risks and mitigations are outlined in the safety report attached in the appendix. The major risks involve machining dangers, operational dangers, and electrical components. These issues should be handled with proper protocols outlined in both the safety report and machine guidelines for Santa Clara University.

The major functional risks are mainly in regards to high rotational speeds. The high rotational speeds will be secure under the armoured enclosure. The enclosure is to be designed with thick steel sheets, where the material is able to withstand high strain energy. The high ductility and high toughness corresponds to a high strain energy, giving the armoured enclosure the ability to withstand a possible rotor impact due to failure. Other electronic components and machining components are outlined in the safety report.

Overall Management

Since our team is more compact we all had to make a serious commitment to the team in terms of project work and personal responsibility. While this requires constant effort from each team member, it also means that each team member is constantly appraised of the work of one another and able to keep one another in check.

As such we did not require a team leader like larger groups do since there does not need to be a supervisor in order to keep individuals on task. Instead we all constantly kept track of one another's contributions, splitting up the work in the fairest possible way. To this effect we have implemented a three-strike system to keep track of whether or not an individual has been an active contributor to the team and keeping the team as a whole honest to its responsibilities, as to be voted on by the other two members. After receiving three strikes, it has been decided that the offending team member will be re-evaluated as a member of the group and potentially evicted.

By the end of the project, only a single strike was put into effect and this procedure has proven to be an extremely effective measure against irresponsibility.

In situations where all group members are not able to make it to a team meeting or a meeting with a third party, it was also decided that a present party will record the engagement and send a copy to the offending member in order to keep all team members constantly appraised of the status of the project.

Subsystems

Drive Subsystem

The drive system is what actually produces the centripedal forcing through rotation.

It is composed of:

- Dayton 4Z529D 1/3rd HP Motor
- 6061 Aluminum Motor Mount
- 6061 Aluminum Gearbox Bracket
- Andantex R3200-2 2:1 Gearbox
- 1045 Cold Rolled Steel Spindle
- Swing Bucket Rotor and Vial Holder
- Steel Ball Bearing
- Black-Oxide Alloy Steel Couples with Buna-N Spider
- Dart DM800 Tachometer
- Dart Pulse Sensor

It takes input from the control and safety system, which powers up the motor controller to begin motor rotation. This rotation is translated to the rotor via the gearbox and spindle utilizing couples. The drive system also incorporates a tachometer so the user can verify their programmed forcing is actually being achieved.

The following is the requirements for the drive subsystem:

- Single operation lasts up to four hours
- Produce centripetal forcing of 1,000 g's
- Ramp-up time to desired force is under 60 seconds
- Ability to hold 56 test samples
- Swing bucket rotor
- Each test sample can be a volume up to 15 ml
- Ability to hold different test tube sizes

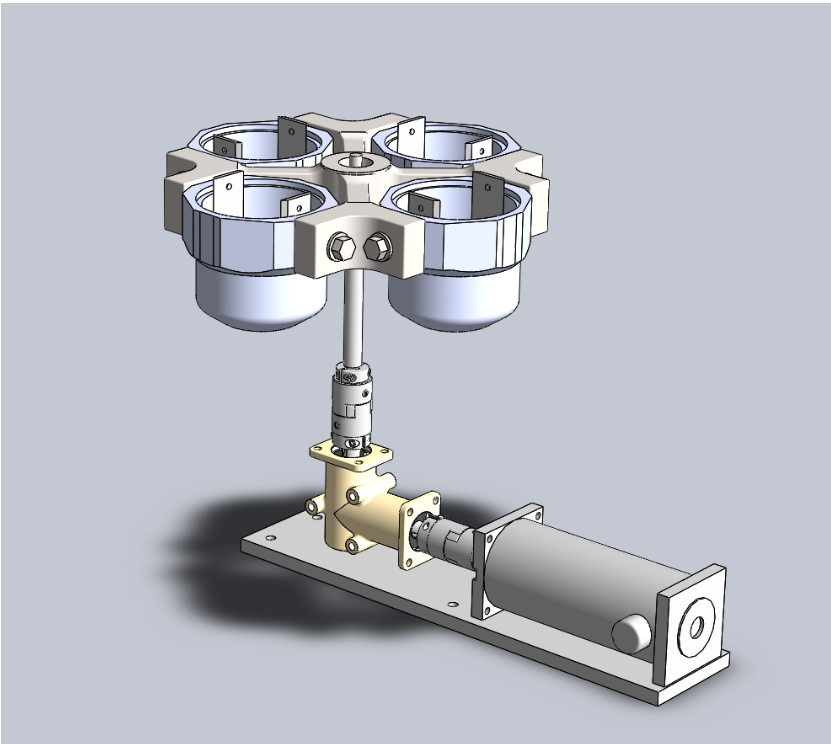


Figure 6: Drive System (Solidworks)

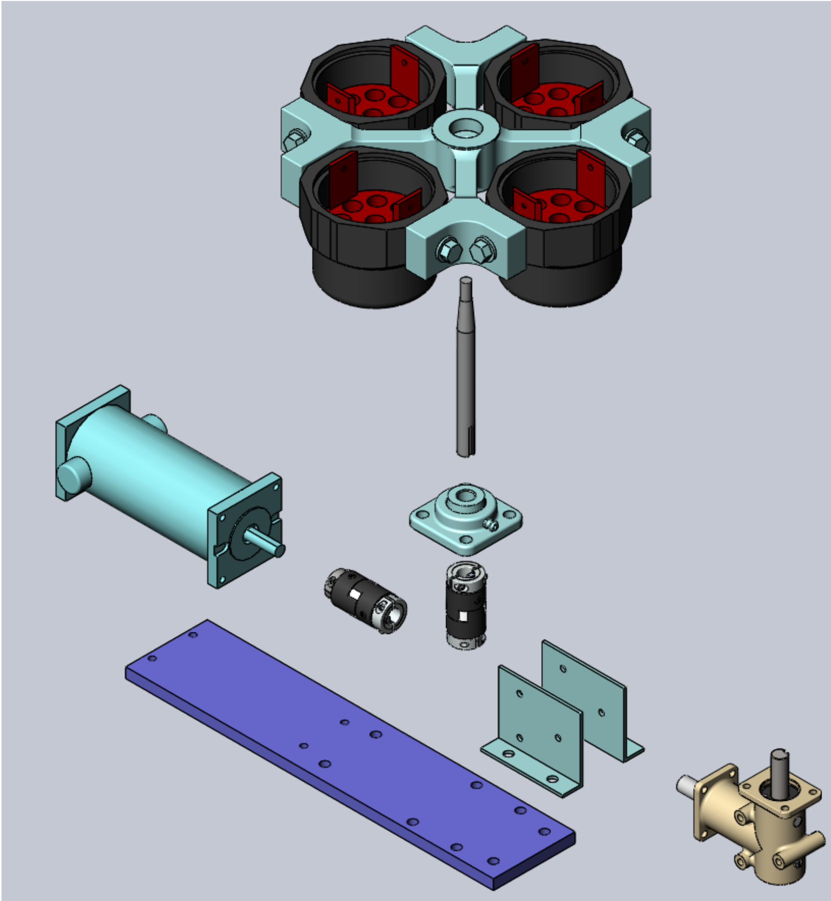


Figure 7: Exploded View of Assembly

Motor and gearbox: The motor is the main unit of our entire system. The motor in combination with the gearbox will determine the torque applied and maximum speed; this ultimately determines the ramp up time and G-force applied to the samples. Initially our goal of 3,000 G's needed 4,000 RPM, so we selected the Dayton 4Z529D. The motor is fully enclosed non-ventilated continuous duty. This means it's rated to run up to 8 hours at a time and is internally cooled with its chassis design. At 24 volts of supplied power, it reaches up to 4,200 RPM with 1/3rd of a horsepower. The motor we chose for this project is a brushed motor; the brushes last 2,000 hours and are easy to change. We made this decision based on the fact that brush-less motors are going down in cost and it is entirely possible that they will be the cheaper option in the coming years. Looking into gearboxes we selected Adantex's 1:1 Ratio 3200 90 degree gearbox. When our target g force changed to 1,000 g's we looked into changing our motor to a less powerful and cheaper one. However, these motors all had lower torques, which would affect our ramp up time. We decided to switch to Adantex's 2:1 Speed Reducer 3200-2 gear box. This cut the speed in half to 2100 RPM, which brought our maximum force to 986 g's and it was also quite noisy due to beveled gears. Although this was a little short of our target of 1,000 the 2:1 speed reducer almost doubled our torque, providing us with a ramp up time of around 15 seconds. Although there were some trade offs, we deemed the benefit of a faster spin up time more crucial for our centrifuge.

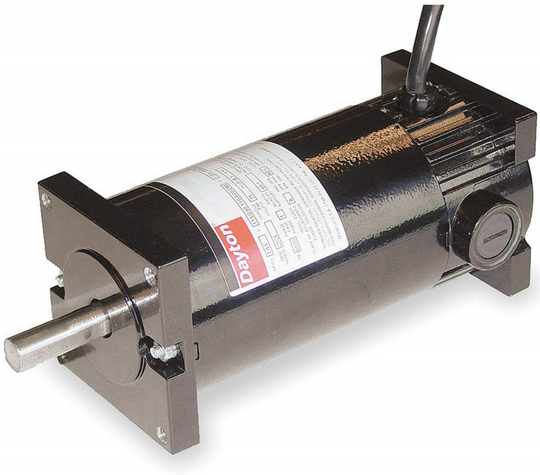


Figure 8: Dayton 4Z529D Motor [11] *Reproduced without Permission*

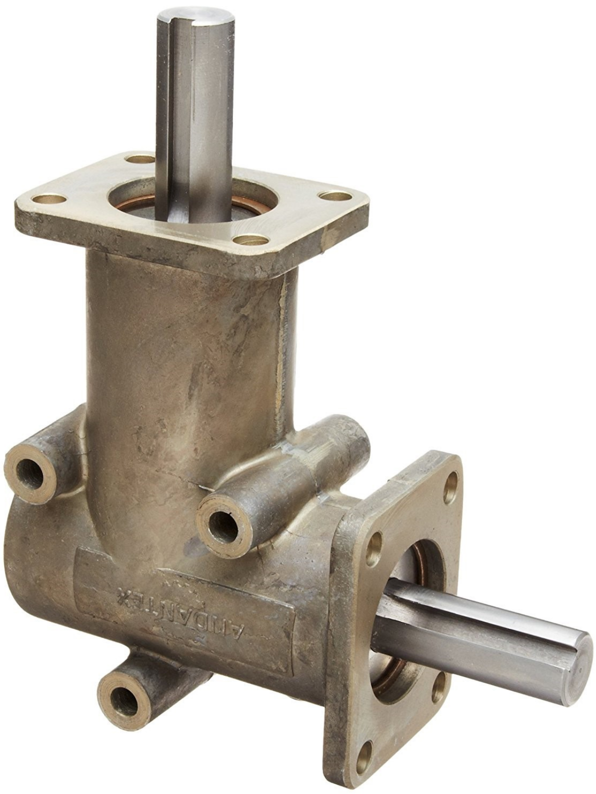


Figure 9: Andantex 3200-2 Right Angle Speed Reducer 2:1 [12] *Reproduced without Permission*

Rotor: In favor of the swing bucket design and large capacity, we decided to use the legacy rotor, a Jouan C4. The rotor was made out of iron, and was quite heavy and had a high second moment of inertia. Smaller rotors would much lower less second moment of inertia, but would not hold many vials and require higher rotational speeds. Due to the extra torque we generated from using the 2:1 speed reducer, the large second moment of inertia would not be an issue. This design had the pro's of a swingbucket design, large vial capacity, and the ability to utilize multiple vial sizes at once. This rotor was limited to a 4750 maximum RPM, which is not an issue for our current system. The rotor will be connected to the drive system through the spindle and a lock nut.

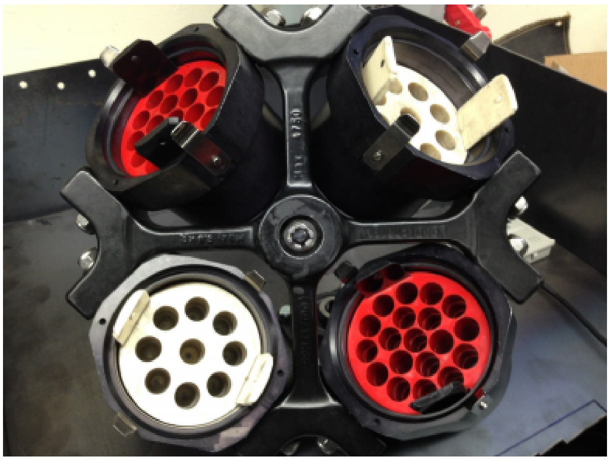


Figure 10: Legacy Rotor

Spindle: Given that our Adantex gearbox 3200-2 had a 0.625" diameter and the previous groups spindle was 0.630", our team decided to utilize their machined spindle to cut cost and time. Their spindle already had the taper for the rotor, and was made out of 1045 Cold Rolled Steel, which is easily machined. We performed a fatigue test on the spindle itself to ensure it would not be troubled by fatigue in the system's lifetime. After confirming fatigue was not an issue through a SolidWorks analysis along with the previous groups tests, we used the mill and lathe to shorten the spindle down in length and diameter. We then machined a D-shaft on the end so a set screw could be utilized to bind it with the couple.

Figure 11: Legacy Spindle

Bearing: To support the radial load from the spindle, we needed a mounted flange ball bearing in the middle of the enclosure. We purchased a unit from McMaster-Carr; its bearings are steel and are doubled sealed for resistance to dust and contaminants. They are housed within a nickel-plated cast iron house for good corrosion resistance and durability. The 0.625" diameter model allows for speeds up to 9,500 RPM, way above the rotors maximum of 4,750 RPM. The maximum radial load is 2,150 pounds which is also well above the load that will be encountered in our system. The bearing utilized is self-aligning, to compensate for up to 2 degrees of misalignment. This was an easy decision to make, as McMaster-Carrs other mounted ball bearings had lower RPM's or were of way higher cost due to being food-grade.

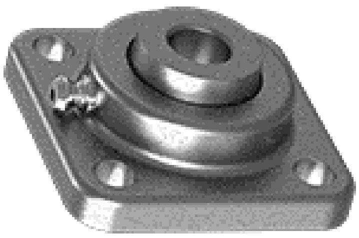


Figure 12: Stainless Steel Four-Bolt-Flange Bearing [11] *Reproduced without Permission*

Couples: To transmit power between the motor, gearbox, and spindle we had to utilize couples. We looked at a options such as machining our own, but decided a third party couple would be best. We looked at rigid and flexible couples, but after discussing with Professor Shoup, a flexible couple was chosen as it allows for 0.015" parallel misalignment and a 1 degree angular alignment. Although we were going to carefully attach the system together and it was measured out so the components would be aligned, this misalignment capability allowed for some wiggle room and easier installation. Our motor has a 0.5"diameter drive shaft, while the gearbox and spindle had 0.625" shafts. The flexible couples had a lot more options for connecting different sized shafts, which cemented our decision. The couples were made out of black oxide alloy steel; they were rated for 11,000 RPM and 43-in LBs of torque. Our motor output at most 6.5 in-lbs, which translates to a maximum of 13in-lbs to the spindle; these couple's specifications were well within our operating parameters. The coupling locked into the respective shafts with a set screw that bit into the keystock or D shaft. The disc that connected the two couples together was a Buna-N spider. We chose this type of spider over Hytrel and Polyurethane due to its ability to better damp vibrations.

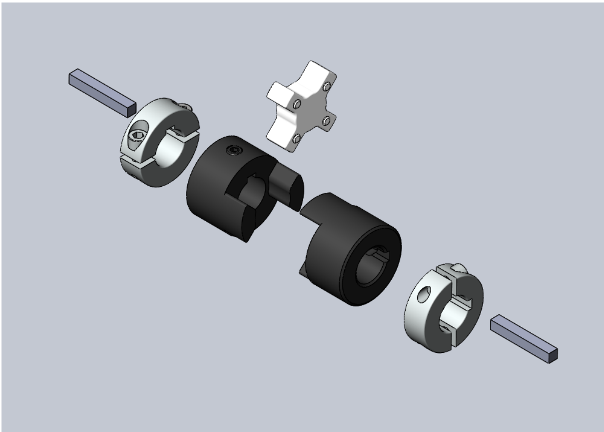


Figure 13: Exploded View of Couple Assembly

Motor Slab: In order to keep up with our design goal of have a versatile centrifuge, we needed a way to easily mount different types of motors and gearboxes. Given that the base of the enclosure is a large 24" x 24" quarter inch thick sheet of A36 steel, we realized that it was not as machinable as we desired. As a result, we utilized a slab of 6061 aluminum. 6061 aluminum is easily machinable and fairly cheap and accessible compared to other metals. This slab would have pre-drilled holes to connect itself to the bottom plate of the enclosure. In the future, if a different motor needs to be inserted, the current slab could just have new holes drilled in.

Gearbox Bracket: The Andantex 3200-2 gearbox had to be mounted to the motor slab or base somehow. We decided to utilize 0.125" thick 6061 aluminum and machine our own brackets. The brackets are L-shape, and raise the gearbox so its input shaft is concentric with the motor's output shaft. In the future if a different gearbox is utilized or if the shaft needs to be raised or lowered for a new motor, the 6061 aluminum is easy to machine and modify. To damp vibrations between the gearbox and the brackets, we inserted foam washers on the bolt between the edge of the bracket and the gearbox itself.

Controller Subsystem

The controller is in the lower half of the enclosure. This system takes input from the user and controls the motor controller to power the drive system via relays and a digital potentiometer.

It reads from the accelerometer to ensure the operating environment is safe, while locking the lid via solenoids to prevent user contact with a spinning rotor.

Tachometer and Pulse Sensor: To ensure that output speeds from the program were accurate, we decided to integrate a tachometer into our unit. It was pricey, but deemed necessary in case of user error or wear and tear from parts did not produce the speeds a user intended. Our Dayton 4Z529D motor had a threaded hole in the back, designed for a 10-32 metric pulse sensor to be inserted. Dart offered pulse sensors, so we chose one that had 10 pulses per revolution. Dart DM800 was chosen for the tachometer and display. It allowed for speeds from 0-10,000 RPM and had alarm outputs that could be triggered if a threshold is reached. This tachometer was chosen as it was a simple device. When it turns on, no interaction from the user is necessary to get it working, and it is very simple to use. Because the speed of the rotor is important more than the motor, our team programmed the tachometer to read 20 pulses per revolution rather than 10 pulses per revolution, so it would display the speed of the spindle. We also programmed the tachometer to list the average RPM's over a second, so the numbers would not drastically jump or change.

Figure 14: DART DM800 Tachometer [11] *Reproduced without Permission*

Figure 15: Dart 10 Pulse-per-Rev Encoder [11] *Reproduced without Permission*

Controller: Due to issues with interfacing the motor directly with the Arduino, it was necessary to buy a separate controller which acted as a go-between for the Arduino and the motor. For this purpose we purchased a Dart 38EG41 Controller, which was designed specifically for the type of DC motor that we used. While it would have been preferable to use the Arduino to run the entire control system, the Arduino we had was not robust enough to run the system and the risk of frying it was great enough to look into other options.

Figure 16: DART 38EG41 [11] *Reproduced without Permission*

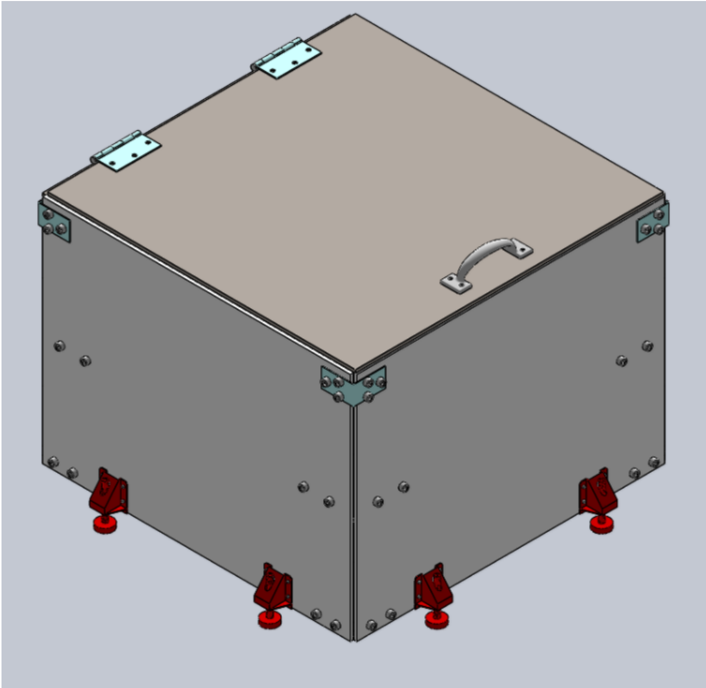


Figure 17: Enclosure CAD Assembly

Enclosure Subsystem

The chassis subsystem was designed to support all loads and forces the system would encounter during operation. It also works in tandem with the safety subsystem by providing safety to the users in the event of an impact.

When designing the system, the safety of users was the utmost priority in mind. We initially looked into reusing the previous group's chassis, but the legacy chassis was too small in terms of height for our new gearbox, and it hit the natural frequency during operation which was an issue.

We initially were going to tackle the design with a circular cylinder, however we could not find a cylinder that was wide enough at the proper thickness and cost. Machining a circular cylinder was also difficult as most manufactures did not have the capability to machine such a large cylinder. As a result, our group decided to go back to the original design of a box. However, to improve the strength and increase the natural frequency we doubled the thickness of the panels.

Overall, we went with A36 quarter inch thick steel. The base of the device is 24" x 24", and the walls are 24" by 18". The nuts are grade 8 zinc plated steel nylon nuts, while the bolts are grade 8 black oxide alloy steel bolts. The brackets used to connect the panels together are plain carbon steel, 0.10" thick.

We did experience some issues when machining our product. We brought metal panels from one vendor to the machining vendor. This was done as a cost saving effort, as it was almost

50% cheaper than buying the metal from the machining vendor. The machining vendor had issues setting the panels up in jigs, and the parts did not align with the brackets properly and were way out of tolerance. We had to have several parts re-machined with metal from the machining vendor, which used up a good chunk of our budget. In the future, we recommend to have the machinist cut the panels out after laser cutting holes, rather than using pre-cut panels in jigs to laser cut holes.

For testing purposes, we did FEA analysis, vibration testing, experimental drop testing, and used the bolt sheer analysis from the previous group, all which can be found in the Testing section.

Arduino Code Description

The code that the Arduino Uno uses to run the system utilizes the Serial Peripheral Interface Library, or SPI Library. SPI is a synchronous serial data protocol used by microcontrollers for communicating with one or more peripheral devices quickly over short distances, which in this case is the digital potentiometer, or digipot. This code is reproduced in the Appendix.

As can be seen in the comments of the code,the centrifuge may operate at 135 discrete speeds ranging from 420 RPM to 2090 RPM. Due to an issue with the digital potentiometer, any value over 135 will cause the centrifuge to max out its speed. Therefore, while the working range for the input is technically 0-255, in reality it worked out to be 0-135. [13]

In the current iteration of the code, the input value is 50, which results in a centrifuge speed of 900 RPM. While the input to RPM ratio is not completely linear, with fine tuning every desired speed specified to us by Dr. Marks is achievable on the centrifuge, as is specified in the comments of the code.

Electrical System Description

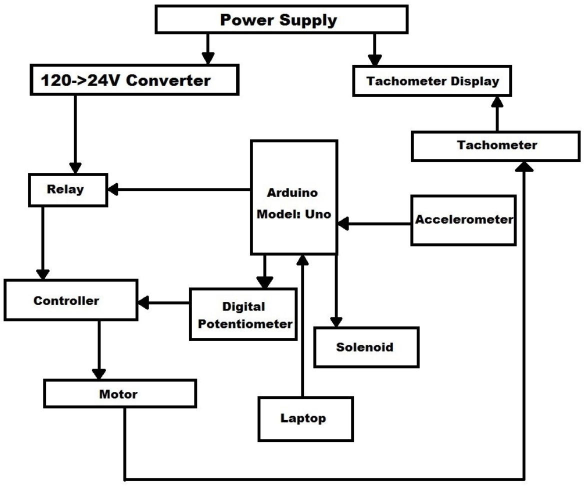


Figure 18: Breakdown of Electrical Subsystem

As is shown in Figure 18, the circuit begins with the power supply which runs both to a 120->24V Converter and the Tachometer Display. The Converter then runs through the relay to the Controller for the Motor. The relay and the Controller are both run by the Arduino (for the Controller the Arduino first runs through a digital potentiometer). The Tachometer display both powers and receives input from the Tachometer which is hooked up to the back of the Motor.

The Arduino runs a program which it receives from the laptop which starts by activating the Servos and locking the lid of the centrifuge. If the centrifuge is tipped at any point during operation, the accelerometer will trigger an automatic shutoff of the system which will be done by the Arduino depowering the relay which supplies power to the Controller.

Options and Trades

Due to the open-ended scope of our project, we had numerous options when sourcing materials. As was mentioned in the Motor Subsystem Section, there was the choice between a brushed and brushless motor to drive the system. The difference between the two is that brushed motors have parts that need replacement with use whereas the brushless do not. Our team decided to go with a brushed motor since it was cheaper but with the addition of manual which details the process of how to replace the motor's brushes and of how to replace the motor entirely if another model motor needs to be swapped in.

Other options we dealt with as a team include the choices made regarding which pieces of the legacy project to keep and which ones we wanted to discard. In the end, we decided that: the rotor and buckets could be used as they were, the spindle could be converted into one that would work for the design, and the enclosure itself could be used for testing the A36 steel (see System Integration section). As a team we made the decision to discard the motor and associated controller as they would not work for our design parameters, even though we would have saved money by doing so.

Detailed Design Description

Analysis

Impact Test Analysis

An analysis of the enclosure was done in order to ensure user safety. The rectangular design of the enclosure can be seen in Figure 19 below. The sides of the enclosure are 1/4th inch thick A36 low-carbon steel. This material was chosen due to its high toughness; therefore, it can absorb a large amount of energy. This design was produced by a prior design team; however a complete analysis of the structure was never developed.

A finite element impact analysis was taken for the enclosure. The system was tested for the case of a bucket shearing through its bearings and impacting a side of the enclosure. This analysis was modeled within a commonly used commercial software, Abaqus. This impact is a high safety risk for the user as it can lead to serious injury of the operator or nearby equipment. It is potentially dangerous, but an unlikely scenario. Although such an event is highly unlikely, we believe such a malfunction to be the most physically dangerous situation a user could be subjected to; we wanted our design to ensure the safety of the user and nearby equipment. The system is placed within the material science laboratory. Therefore, the work environment of the system will be essentially stagnant under room temperature for all operations.

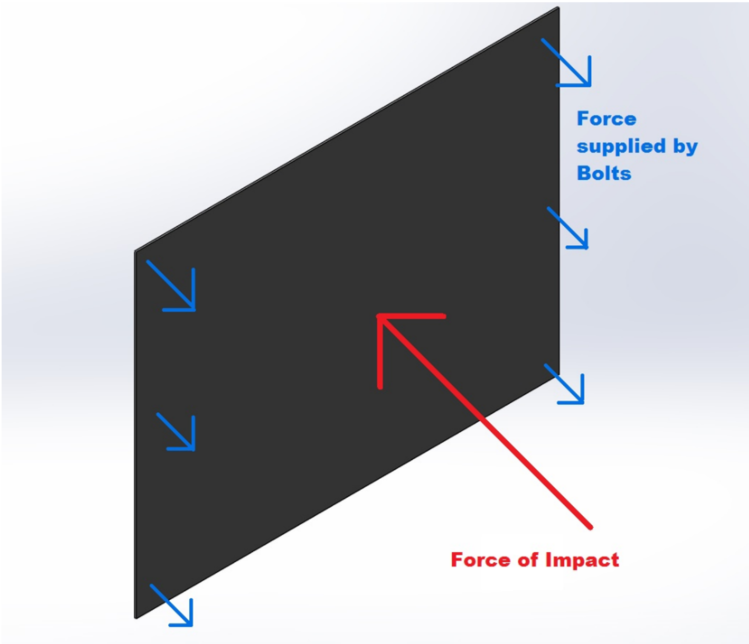
Assumptions

There were several assumptions made for modeling of this system. The bucket was given an orientation of highest stress upon impact; therefore, it has the least amount of contact area upon impact. The input velocity was placed perpendicular to the plate, resulting in higher stresses as well. In addition, the bucket was modeled to impact the center of the plate to maximize the stresses within the material and ignore possible failure at joints. A separate analysis was made for the joints. The model assumes stress-strain based on stress-strain curves of A36. The stress-strain curves are based on a tensile test and is assumed to be accurate for deflection on a plate. The model of the bucket was simplified for accurate mesh creation in Abaqus, but the overall mass of the bucket was consistent with the true mass. A common surface coefficient of 0.5 was utilized within the model, because there was no additional surface treatment made to the plates.

Free-Body Diagram

As can be seen in Figure 19, the force of impact, set to impact at the center of the plate (demarcated in red) will not be resisted uniformly at the boundary as Abaqus assumes but will actually be resisted at each of the points where there are bolts, marked here with blue arrows.

Figure 19: Free Body Diagram of Impact



Material Properties

The table below shows the material properties for A36 steel. The figure below shows the stress strain response of A36 steel under tensile loading.

Table 3: A36 Plate Material Properties [14]

Material Property	Value
Young's Modulus	200 Gpa
Yield Stress	250 Mpa
Ultimate Tensile Stress	489 Mpa
Poisson's Ratio	0.26
Density	7.80 g/cc

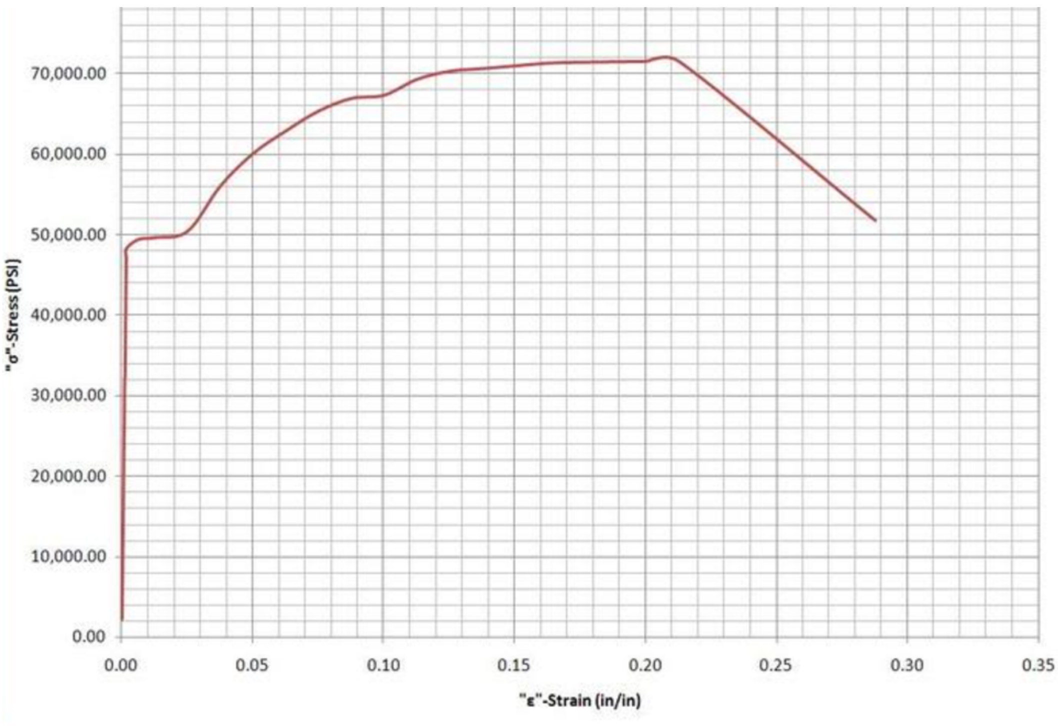


Figure 20: Stress vs. Strain Curve for A36 Steel [14]

Simplifying Elements

The buckets were simplified to be completely solid rather than being hollow in order to allow Abaqus to completely mesh the object. In order to maintain the same mass of the bucket, the density was reduced accordingly. The bucket was modeled as a rigid object, because the fracture of this object is not of concern for the safety of the system. The enclosure was also simplified to only a plate with impact centered on the plate in order to see whether direct impact will cause fracture. Modeling impact near the boundaries can be achieved if the model showed no fracture at the center. This, however, will only add stresses to the joints and this can be analytically solved by hand. The spinning bucket will only have rotational energy during normal operation. The rotational kinetic energy of the system was converted to translational kinetic energy for modeling the impact on the plate.

External Conditions/Loads Applied

The applied load on the system was input as a velocity for the impact of the bucket. The plate was made to be fixed at all boundaries. In the actual assembly, the system is held together by bolts, but modeling the fixed locations on the bolts will only add extra stresses to the bolted areas and this is not of concern for this model. The stresses on the bolts are addressed through hand calculations and can be further addressed through modeling if necessary.

The forces on the system were calculated through the required maximum G-force for material separation. The maximum G-force for the system was calculated to be 986 g's, which occurs when the rotor is spinning at 2100 RPM. From the angular velocity, the resulting kinetic energy was calculated to be 638 J upon impact of the bucket against the side of the enclosure. These calculations are shown within the appendix.

Table 4: Impact Properties

Measurements	Value
Mass of Bucket	1.1 kg
Kinetic Energy of Bucket	638 J
Rotational Velocity	220 rad/s
Tangential Velocity	34.06 m/s
G-Force	986 (unitless)

Expectations for the Output (Mode of Failure)

The mode of failure that is being analyzed is through fracture from the impact resulting in stresses greater than the ultimate tensile stress. The critical point for the system would be the point of impact as it will experience the highest stress. The failure is dependent on the material used for the plate, because a material with higher toughness allows for more absorption of energy, resulting in lower chances of failure. In addition, the thickness of the plate also accounts for absorption of energy, as the greater the plate thickness, the more energy the material can absorb.

Hand calculations for modeling impact are extremely complicated and, therefore, only a model was created for impact. The main issue for hand calculations is that the model has a changing contact area during impact, resulting in a stress function dependent on the changing contact area of the bucket against the plate. In addition, since the bucket does not have a common geometry, a function cannot be easily made for analytically solving the changing contact area. As discussed above, the initial conditions for the model were hand calculated and are shown in the appendix.

Since the three dimensional Abaqus analysis for impact is difficult to compare with hand calculations, a simple beam stress case was made to ensure the material had an accurate representation of the system. Figure 21 below shows an image of the beam deflection. The hand calculations are within the appendix. [15]

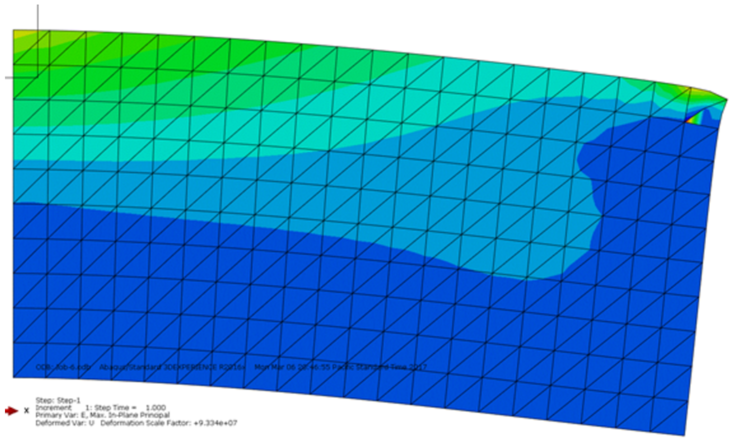


Figure 21: Simple Simulation for Beam Deflection to Ensure Abaqus Analysis was Properly Configured

Addressing Problems

There were some issues that arose during modeling of the system. A major problem of the system was modeling the bucket as a rigid body. Abaqus did not allow for contact forces on the system with the bucket modeled as analytically rigid. However, this issue was solved through modeling the bucket with high stiffness and the stresses on the bucket were ignored in the results. Another issue that occurred in the model, as mentioned earlier, was that the bucket couldn't be meshed through importing the model. Therefore, the model was simplified to be completely solid with an equivalent mass to the actual bucket.

Originally, the results showed that the stresses on the system were lower than yield stresses and the system was believed to withstand fracture. However, through analysis of the pre-processing, it was determined that the mesh sizing and the element interpolation type were giving incorrect results. The model was refined to have quadrilateral elements over the linear elements and the seed sizing was refined to give more elements along the plate.

The expected results were that the stresses due to impact on the plate would be below the ultimate tensile strength of A36. However, the actual results showed that the stresses exceeded the ultimate tensile stresses. These unexpected results were assumed to be caused from improper set up of the analysis. Therefore, the modeling inputs were rechecked and a simple case model test was produced. The new impact test used a low kinetic energy to ensure that the system is accurately modeling the impact. The model was confirmed to be accurate as the stresses for this case were below ultimate tensile stress. A discussion of the further analysis are within the next section.

Results & Discussion

The results from the model are shown below in Table 5. The maximum stresses were shown to exceed both the yield strength and the ultimate tensile strength of A36. The results are reasonable due to the fact that the system is rotating at high speeds, producing a large impact force. The results were two magnitudes larger than the ultimate tensile strength. Once the system stresses exceed yield stress, the plate should be analyzed for the true stress limit over the engineering stress limit. However, since the stresses are much greater than the ultimate tensile engineering stress, it can be assumed the stresses exceed true stress as well.

Table 5: Output Stresses from Model

	S.Mises Pa	S.Max.Prin Pa	S.S11 Pa	S.S22 Pa
Minimum at Element	1.01E-18	-4.25E+08	-7.35E+08	-7.55E+08
Maximum at Element	1.81E+11	1.06E+11	7.45E+09	4.90E+09

The results show that the centrifuge will fracture upon impact. This is of concern for the operator as this simulation shows that the current design won't meet required safety guidelines. However, through discussion with Professor Michael J. Taylor, it was determined that even with careful modeling, the model is probably not an accurate representation of impact, once stresses surpass ultimate tensile strength. As discussed, this simulation shows that the stress on the plate exceeds the ultimate tensile stress; however, it does not account for the method of fracture propagation. Fracture propagation is currently a key area of research for commercial software and has limited approaches for simulation. The next step on the analysis is to model fracture. This process, however, will require many hours of work and a experimental test may be more appropriate for analysis. The drop test can be created with a system having equivalent kinetic energy of an object hitting the plate. [15]

The changes that are recommended from the current FEA analysis are not feasible for this project. The analysis shows that increasing the material thickness will give a better resistance to impact, but the current results don't provide an appropriate wall thickness applicable for the current enclosure. The analysis shows that the steel thickness must exceed 1 inch, which is, by observation, much greater than the allowable thickness for the system and will add too much weight to the system. Therefore, a fracture analysis is necessary to provide more appropriate changes for the enclosure.[15]

Models were made for various scenarios to address various characteristics, such as optimal plate thickness and minimum kinetic energy transferable to the plate. Figure 22 below addresses impact with a 1/8" plate thickness. The material of the plate was A36 low carbon steel. The output stresses were shown in Table 5 above.

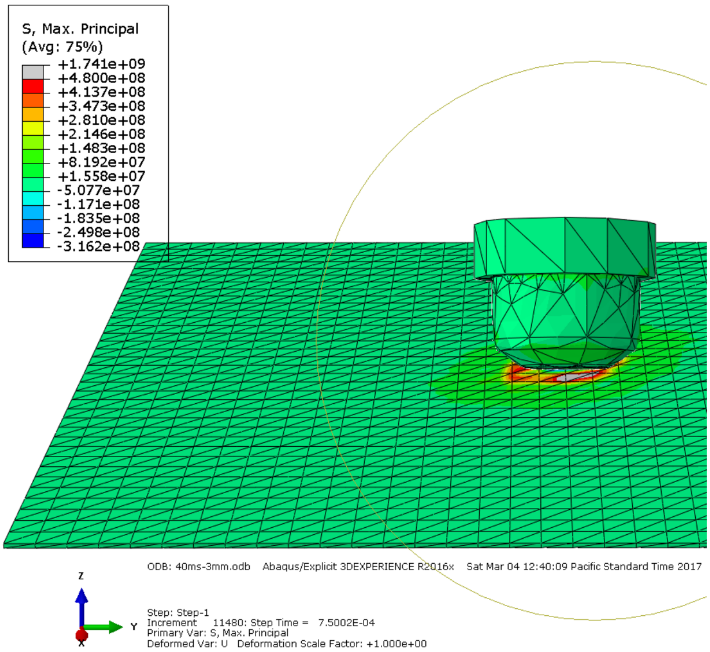


Figure 22: Abaqus Visual of Impact Velocity of 40 m/s and 1/8" Plate Thickness

Based on the previous model, the impact was tested for a larger plate thickness to see if the larger plate will retain stresses under the ultimate tensile stress. A visual model of the impact is shown in Figure 23 below. However, when increasing the plate thickness, the stresses were still above ultimate tensile stress of A36. This confirms need for modeling fracture on the system. It can be assumed that a 1 in. thick steel plate should prevent fracture. Therefore, since the maximum stresses within the model are still exceeding the ultimate tensile stress of the material, it can be concluded that fracture must be modeled in order to achieve an accurate impact results as discussed above.

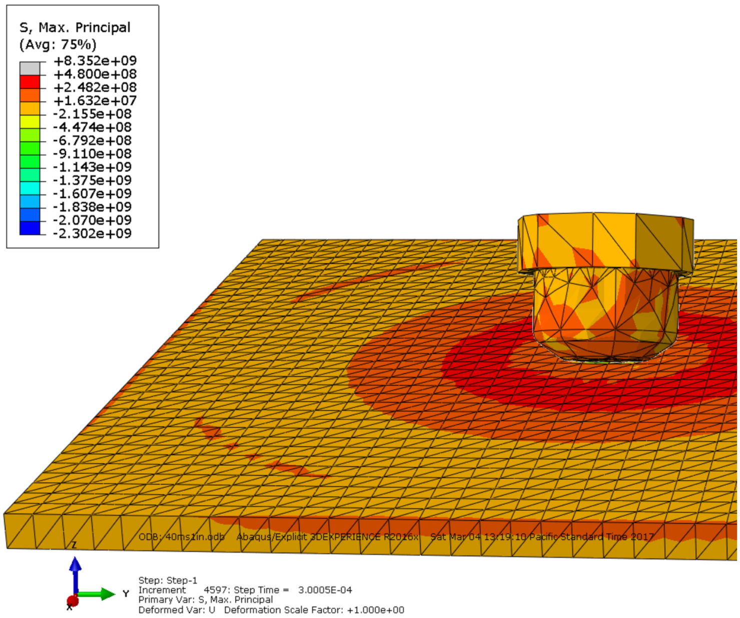


Figure 23: Abaqus Visual of Impact Velocity of 40 m/s and 1" Plate Thickness

Lastly, a model was made for the stresses for a 1 inch plate with a low impact energy transfer. This was made in order to show that the maximum stresses were not always being exceeded for any modeled impact. The model showed that the maximum principal stresses were well below the yield stress as they were approximately 3E+8 Pa, where the yield stress is about 5E8 Pa. This confirms that there will be some plastic deformation to the material on impact for a 1 inch steel plate. However, it still cannot be concluded if the fracture results in the entire plate breaking upon impact.

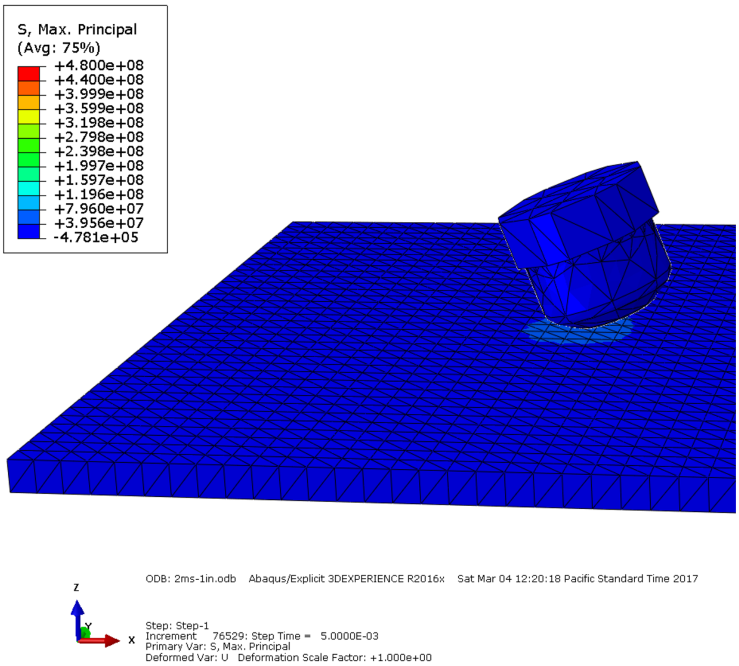


Figure 24: Abaqus Visual of Impact Velocity of 2 m/s and 1" Plate Thickness

Conclusion

Overall, this analysis showed that a physical impact test or a fracture model is required for the appropriate results. The model wasn't able to accurately provide information on the fracture characteristics and further modeling of fracture is to be done. The results showed that increasing the thickness of the plate gives lower maximum stresses; however, these stresses still exceed the maximum permissible stresses for the material. This supports the conclusion that fracture modeling provided valuable data. Once an appropriate model is made, the optimal material and plate thickness can be selected in order to minimize the cost and maximize the safety. In addition, an alternative and more accurate representation of the impact can be produced through an actual physical test of the impact. A drop test will be done in order to show that the system can withstand impact. In this drop test, an equivalent kinetic energy will be utilized to give testing similarity.

This analysis helped learn to model impact and see how to compare the results with the expected response of the system. Another lesson learned was that simulation of impact is a complicated process and that there is still need for physical testing of impact. The analysis also showed how varying material thickness and material properties affects the stress on the system.

Frequency Analysis

Another area of concern is the possibility of the system being run at resonant frequency. This would cause the vibrations in the system to increase uncontrollably and our system should be well outside the range for resonance and beating. The previous group did an overall system analysis for resonant frequency and found that their system would hit resonant frequency during standard operation. Their results are tabulated in Table 6 below.

Table 6: Original Frequency Analysis

Tabular Data

	Mode	Frequency [Hz]
1	1.	41.586
2	2.	44.82
3	3.	50.998
4	4.	55.007

This resulted in a total redesign of the system to increase natural frequency of the enclosure. A rough estimate of the natural frequency of the system is given by the equation below [16]:

$$\omega_{n1} = \sqrt{\frac{k}{m}} = \sqrt{\frac{t_1^3 C_1}{m_1}}, \tag{1}$$

where k is the stiffness of the system and m is the mass, t_1 is the material thickness, and C_1 is a function of other constant system properties. In the new design, the overall system's weight was doubled resulting in a natural frequency of about double, since the thickness of the plates was doubled. This resulted from the stiffness being a factor of thickness cubed. A simple calculation is shown below [16]:

$$\omega_{n2} = \sqrt{\frac{k}{m}} = \sqrt{\frac{t_2^3 C_1}{m_2}} = \sqrt{\frac{(2t_1)^3 C_1}{2m_1}} = 2\sqrt{\frac{t_1^3 C_1}{m_1}} = 2\sqrt{\frac{k}{m}} = 2\omega_{n1}, \tag{2}$$

The simulation for frequency was recomputed for the new designed system. As expected, the resulting frequencies were about double the frequencies from the last system. The results are tabulated below in Table 7.

Table 7: Updated Frequency Analysis

Mode #	Frequency(Rad/sec)	Frequency(Hertz)	RPM	Period(Seconds)
1	656.34	104.46	6267.6	0.00957854
2	764.27	121.64	7298.4	0.0082212
3	811.37	129.13	7747.8	0.0077439
4	811.61	129.17	7750.2	0.0077416
5	829.18	131.97	7918.2	0.0075776

As seen with the system specifications above, the system's motor can only run up to 4200 rpm, whereas, the system's first mode frequency is at 6267.6 rpm. This shows that the system is well outside the range of concern for natural frequency. The images below show the output of the simulation run for the frequency tests.

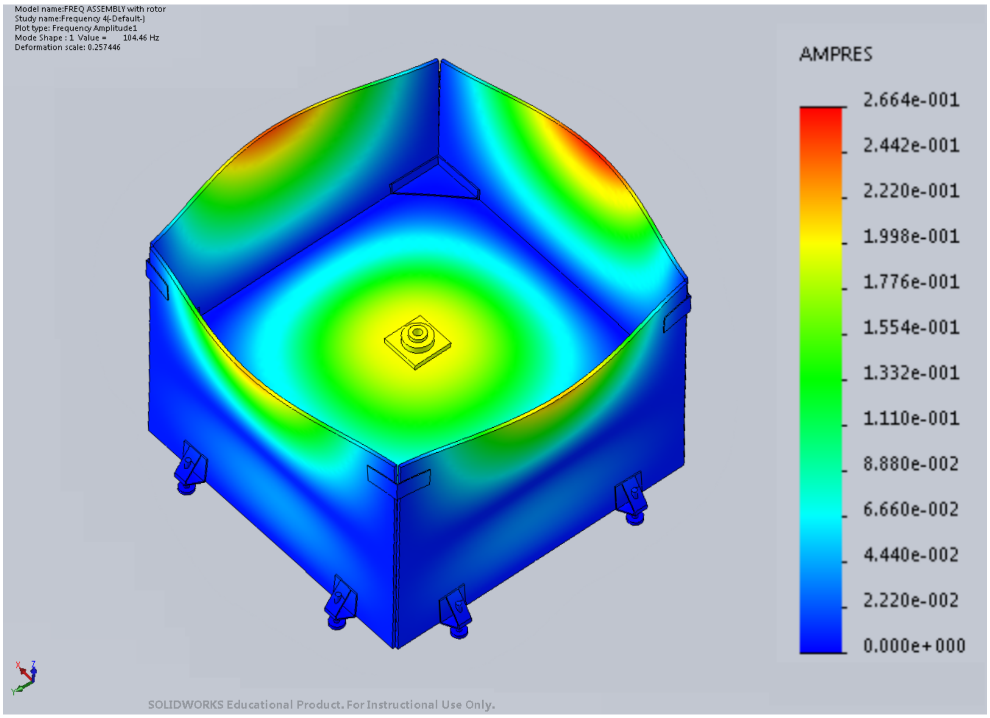


Figure 25: SolidWorks Visual of Frequency Test (Isometric View)

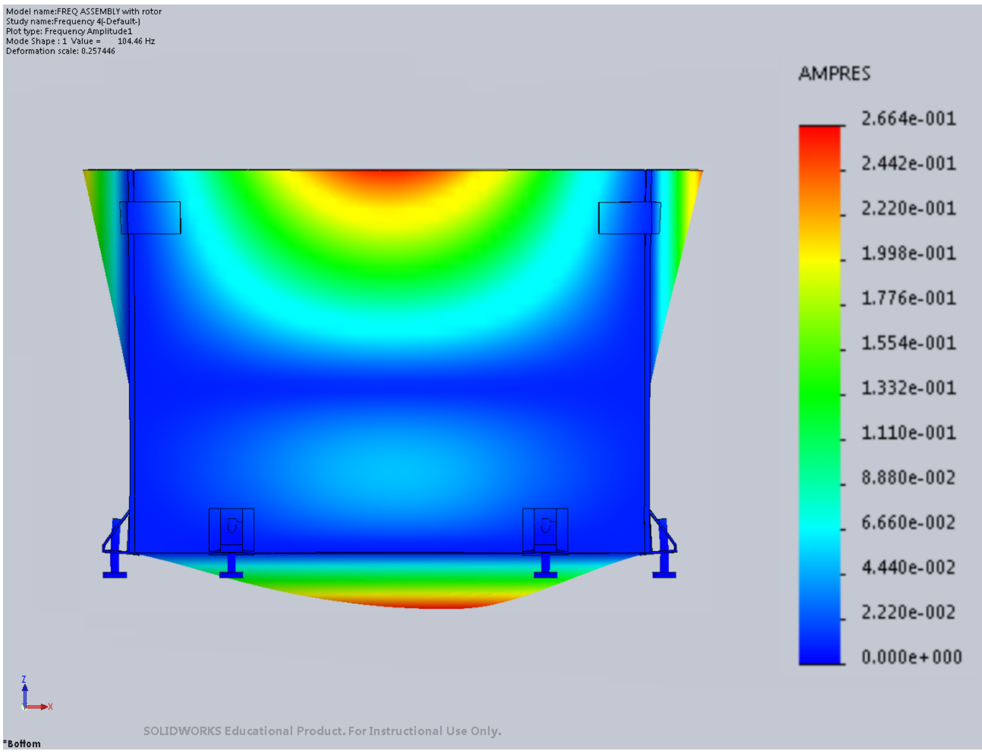


Figure 26: SolidWorks Visual of Frequency Test (Horizontal View)

Creep Analysis

A creep analysis was taken in order to ensure the lifespan of the spindle. The spindle will be exposed to constant load from the weight of the rotor and buckets. This may cause fatigue failure of the spindle. Therefore, a creep analysis was taken and showed that the maximum stresses were held at 8.37E5 Pa after 3,000 hours of operation, which is significantly under the expected yield strength of the spindle at 5.3E8 Pa. The visual output of the simulation is shown in Figure 27 below. In this figure, the red spectrum represents stresses near 8E5 Pa, the green represents 4.6E5 Pa, and the dark blue represents 7.5E4 Pa. The gradient for the stresses are shown in the diagram within the figure.

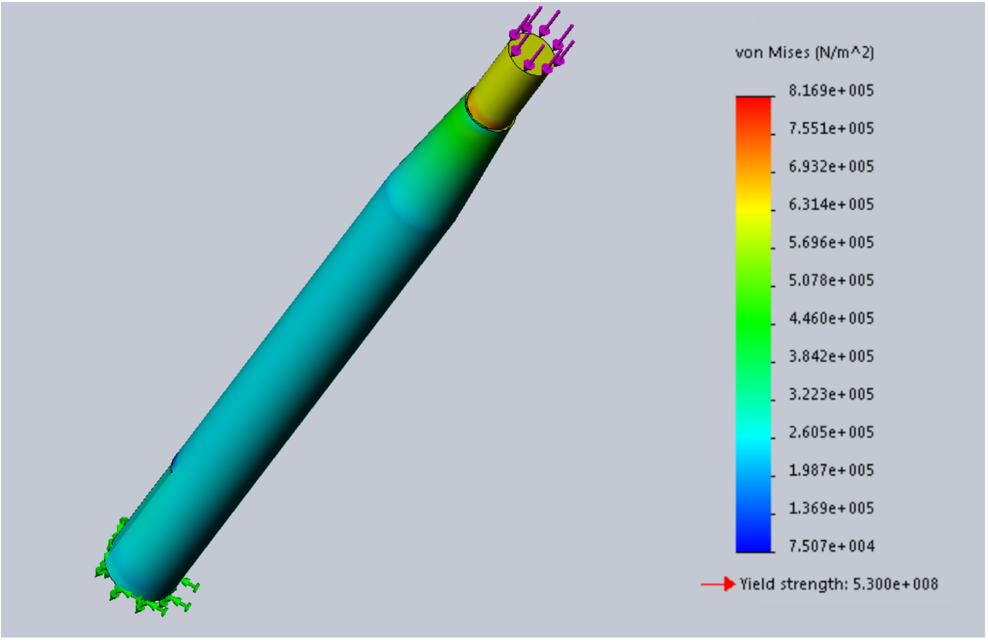


Figure 27: SolidWorks Visual of Creep Test

Enclosure Experimental Test

As mentioned earlier, the FEA test for the impact of a bucket on the plate showed that the plates will fracture. Therefore, the plates were experimentally tested with a drop test. Using a similar approach to the FEA test, the test was made through equivalent kinetic energy for our test case. A 45lb weight was dropped from a two story building onto a 1/8’" steel plate. This resulted a kinetic energy transfer of greater than 632 joules, which is how much energy the system must withstand. The deformed plates after the test are shown in Figure 28 below.

Figure 28: Deformed Plates after Impact Test

The plates were locked on three tables to resemble the actual system. The center of the plate was suspended in air and the weight was dropped onto the plate. The results show that the plates can withstand a single impact, but won't be able to be used after. This lead to our team deciding that doubling the thickness of the plates is appropriate because it will cause the system to be able to withstand the impact even better than it had in this experiment. In addition, as discussed earlier, the thicker plates resulted in a higher resonance frequency, which is necessary for our system requirements.

System Integration, Test, and Results

Both FEA and physical testing were used to decide if the material enclosure chosen was acceptable. The situation which caused the most concern for the team was the instance of a bucket shearing through its brackets and having a direct impact with the center of one of the walls at the top speed for the centrifuge. For the FEA, the first sample tested was the legacy model's sheet metal thickness of 1/8" A36 Steel. The bucket was modeled as a point force impacting the center of the wall with the maximum possible velocity. It was shown to surpass both yield and ultimate tensile strength, which would indicate that the structure was not sufficient to withstand the force of impact.

This result was interesting to the team, as the legacy team's calculations had indicated that the sample metal would do perfectly fine under these circumstances. With the consultation of one of our faculty advisers, the team decided to model the same example but with 1" A36 Steel (a thickness which we were assured the bucket would not be able to puncture with it's kinetic energy of 638 J). However the FEA still showed that the centrifuge enclosure would not be able to withstand the impact and so the team turned to other options.

As such, the team decided to commit to physical testing using the samples which had been left to us by the legacy project. Using a drop test and an equivalent kinetic energy, the legacy samples were subjected to the potential forcing the centrifuge would be under duress.

Experimental Protocol

Table 8: Experimental Protocol Outline

Evaluation	Location	Time	Equipment	Accuracy	Trials	Expected Outcome	Formulae or Assumptions	Man-Hours
Wall Safety	Lafayette Appt.	3/8 – 3pm	45lb Weight, Plate	6in away from sides	2	No Fracture	$U_T = \sigma * \epsilon$ $mgh = \frac{1}{2}mv^2$	4
Locked Lid	Material Science Lab	5/14 – 8am	Centrifuge Assembly, Force Gauge	0.1 N	30	Lid cannot open with 120 N of force	Force Gauge sensor is equivalent to human force	2
Vibration	Material Science Lab	5/14 – 10am	Centrifuge Assembly, Motion Sensor	0.1mm amplitude	8	< 0.5mm amplitude vibrations	Sensor is accurately measuring displacement	5
Max Speed	Material Science Lab	5/15 – 10am	Centrifuge Assembly, Computer	+_1 rpm	5	+_5 rpm of 2000 rpm	Small Rotational discrepancies	1
Adjustable Speed	Material Science Lab	5/15 – 1pm	Centrifuge Assembly, Computer	+_1 rpm	20	Each Speed Test should be +_5 rpm || Testing by increment of 100 rpm	Rpm to Velocity conversion: v = ω r	3
Ramp-Up Time	Material Science Lab	5/15 – 3pm	Centrifuge Assembly, Computer, Stop Watch	< 3min	5	1min ramp up time	Time constant = 63% of steady state	1
Level System	Material Science Lab	5/14 -3pm	Centrifuge Assembly, Phone Gyroscope App	+_1 degree	3	+_0.1 degree	System will be level on sides if level at center	20 min

Experimental Plate Test Rationale With safety being our priority, the biggest hazard with our Benchtop Centrifuge is that an impact to the enclosure. Rotating at such high speeds, although unlikely, it is possible for a swing bucket to sheer off through a failure of the bolt or the bucket chassis itself. In this scenario, the bucket would turn into a projectile hurling at the enclosure wall with extremely high levels of kinetic energy. The enclosure would have to absurd all of this kinetic energy while maintaining integrity. The enclosure can deform its shape to withstand this impact, but it cannot rupture or fracture. Although our team has already done impact testing through computer simulations, we want to test the scenario in real world conditions. We have A36 steel plates of 1/8 th thickness left behind from the legacy team to test and deform. By dropping a weight from a significant height, the weight can achieve kinetic energy levels similar to a bucket sheering off in the worst case situation. These impact tests will challenge the integrity of the A36 steel plates themselves, but will also challenge the bolts and nuts we are using to ensure they can also withstand the forces of an impact. In our testing experiments, we can add in factors of safety to ensure that our enclosure would maintain integrity; we are already planning on doubling the thickness of our enclosure to ¼", but can also drop the weight so its kinetic energy is higher than any potential situations our enclosure might encounter. These tests will confirm that our enclosure design is capable of withstanding the worst possible impact. Although computer simulations can provide insight for our project, doing experimental testing in real world situations can provide experimental data that computer simulations cannot provide.

Plate Test Plan

Evaluation Criteria/Thesis: The experiment is testing if the enclosure plates will break upon impact of an internal component. The criteria for this test is for the plates to absorb the energy on impact and have no fracture occur. The impact energy on the test is calculated to be the same or greater than the impact energy of the internal impact case.

- When/Where: The test was taken in March in Lafayette Apartments.
- Special Equipment: The equipment used in this experiment is two tables to support the plate held horizontally. The plate will be drilled into the table to represent the fixed edges of the system. In addition, the center of the plate will be unsupported during impact test in order to correctly evaluate the material toughness. Caution tape will be used around the test to ensure safety of the people near the test. There will be a 45lb weight used for impact on the plate.
- Accuracy: The accuracy needed in this experiment is to have the impact of the weight be near the center of the plate.
- Number of Trials: The number of trials are based on the deflection that occurs at impact. Currently, the plan is to take two trials in order to reassure the plates will withstand impact.
- Expected Outcome: The expected outcome is that the plates will plastically deform, but

they will be able to absorb enough energy that the plates will not fracture. The weight may break, but the steel plate should still be intact.

Relevant Formulae

The equation below is utilized to find the kinetic energy at impact. The impact velocity can be compared to the velocity utilized in the FEA impact test. [17]

$$KE = \frac{1}{2} m v^2, \tag{3}$$

where KE is the kinetic energy, m is the mass, and v is the velocity. The toughness is also ensured through calculation of the area under the stress strain curve. This toughness is reconfirmed with the displacement of the plate upon impact. The toughness is related to the energy of the system,

$$U = \frac{P^2 L}{EA}, \tag{4}$$

where U is the strain energy, P is the load, L is the length, E is young's modulus of elasticity, and A is the cross-sectional area. [15, 17]

Assumptions: There were a few assumptions made in this experiment. The plate will only be attached to the table at two ends vs. all 4 ends in the actual system. This cause more stress to be dissipated to the screws connecting the plate to the table, but the material is assumed to absorb a similar amount of energy. In addition, the thickness of the plate is reduced to 1/8" vs. the actually set up of 1/4". The plates will deform more for the 1/8", but are being used to accommodate for a factor of safety. Lastly the impact of a dropped weight is assumed to have the same force as an internal impact. This assumption seems valid due to the fact that the impact energy is equivalent for the each case.

Results and Comparison to Predictions

The experimental protocol was followed and all the tests except the lock lid test met the specifications. The locked lid system feature is still being implemented as the purchased solenoids couldn't meet our design specifications. The wall safety test is described under the analysis section and it showed that the system plates could withstand impact at full rotational speeds.

The vibration tests were also completed through both an FEA analysis and the experimentally. The experimental results matched our predicted and FEA results in that resonance frequency was higher than the operating range of the system. The speeds were easily adjustable to any range and the maximum speed was able to be retained for four hours. The system met the leveling requirement of 1 degree; however, the rotor was about 0.3 degrees offset from level. This didn't meet the expected outcome, but met the overall system requirements. Lastly, the ramp-up time fell to about 22 seconds. This greatly exceeded both the baseline requirements and the expected results for the system.

Operation and Repair Documentation

Operating Manual

Pre-Operation Instructions

1. Ensure centrifuge is on a stable foundation before operation.
    - Use a level to verify all legs are set to the same height.
    - If necessary, adjust the height of each individual leg using an Allen wrench.
2. Ensure that the laptop connected to the Arduino has the necessary Arduino IDE and files.
    - The Arduino IDE is found at *https://www.arduino.cc/en/Main/Software*.
    - The files *open.ino*, *close.ino*, and *run.ino* are found in Appendix H.
3. Upload *open.ino* to disengage the servos by clicking the right facing arrow in the top left of the sketch window.
4. Open centrifuge lid.
5. Load in test tubes evenly around all 4 tube holders.
    - Ensure that vials are equally distributed to avoid imbalance issues.
6. Upload *close.ino* to re-engage the servos by clicking the right facing arrow in the top left of the sketch window.
7. Ensure that servos have locked the lid by trying to open the system after lock has been activated.
8. Plug in the remaining parts of the system to the outlet.
9. Open the run.ino arduino file.

10. Read through the comments in the code and select which value from 0-255 will operate the centrifuge at the desired speed.
    - Example: a value of 0 would operate the centrifuge at 840 RPM.
    - Example: a value of 110 would operate the centrifuge at 3500 RPM.
11. Set the time delay for the necessary run time.
    - The time is set in milliseconds so every thousand adds up to one second.
12. Set the desired speed and time for the centrifuge by following the comments in the code.
13. Upload the sketch (the Arduino program) to the centrifuge by clicking the right-facing arrow in the top left of the sketch window.
14. Ensure correct rotational speeds are achieved by checking the tachometer display on the front of the centrifuge.
15. Remain within eyesight of the centrifuge during operation.

Post-Operation Instructions

1. Centrifuge will automatically stop at the end of desired operation time.
2. Unplug the power cords while keeping the Arduino cable connected.
3. Check that there is no rotation of the system.
4. Upload *open.ino* to disengage the servos.
5. Open lid and remove test tubes.
6. Upload *close.ino* to re-engage the servos.
7. Clean up wires to remove any tripping hazards.
8. Disconnect Arduino from the computer.

Emergency Shutdown

In case of emergency, the centrifuge can immediately be shutdown by unplugging the Arduino from the laptop. By doing this, the power will stop flowing through the relay and the motor will be de-energized. However, the rotor itself may still be spinning as it needs time to spin down.

Troubleshooting

If there is no power to the centrifuge:

- Check that all cables are connected, including the two power cords and the Arduino cable.
- Make sure that run.ino is loaded into the Arduino, using the procedure outlined in the Operating Manual section.
- If the previous two options have not worked, unplug all the connected cords and disassemble the enclosure.

    1. Check that there are no loose connections, which will be listed by order of likelyhood.
    2. Check that all the pins of the digital potentiometer, which is a MCP4131, are connected to the proper nodes. The pin out of this device is included in Appendix H in the first comments of the Arduino code. Additionally check that all connections between the Arduino and the breadbroad including the 5V and the ground.
    3. Make sure that the power runs cleanly from converter to relay to controller to the DC motor, as well as the grounds from each jump.

If the tachometer display is not working properly:

- Unplug all connected cords and disassemble the enclosure.
- Carefully plug in the tachometer cord, checking the connections on both ends and making sure the tachometer is grounded out.
- If the tachometer display is lighting up but there is no read-out despite the motor turning, the issue is with the tachometer itself not the display.

If the lid will not lock/refuses to unlock:

- Make sure that you are running open.ino or close.ino correctly, as outlined in the operation manual.
- If the lid will not open, use the whatever means necessary to open it.
- Once this is done, test the servos and make sure that they are operating properly. This can be done by hooking up the Yellow cable to 5V, the Brown to Ground, and the Orange to 5V. Orange is the Signal wire and providing a 5V input will cause the servo to turn at max speed.

Repair Manual

Removing the rotor and middle plate requires two people. Do not attempt this without another person or you may injury yourself as well as the centrifuge.

Do not attempt to move the centrifuge without two people, as the device weighs over 400 pounds. If moving the centrifuge is required for repair, ensure that whatever surface the centrifuge is to be moved onto can support its weight.

1. Ensure device is not operating or spinning down.
   - If unsure that the rotor is at a standstill, wait 5 minutes.
2. If the lid is locked, upload *open.ino* to disengage the servos by clicking the right facing arrow in the top left of the sketch window.
3. Unplug all power cords.
4. Open the lid completely.
5. Remove all four buckets from the rotor.
6. Using a Crescent wrench, loosen the lock-nut on top of the rotor and remove the rotor itself from the spindle.
   - **Caution:** A good amount of force might be needed to loosen the nut and remove the rotor from the spindle.
7. There is a bracket that connects the middle plate to the side plates on the enclosure. Using the appropriate Allen wrench and the Crescent wrench, remove the 16 screws that hold the bracket to the side plates. Do not fully remove the screws, but just the nuts themselves.
   - **Caution:** Do not remove the nuts that hold the brackets to the middle plate itself.
8. While another individual pulls up slightly on the middle plate using the cut out slots, remove all 16 screws that connect the bracket to the side walls.
9. Remove the middle plate with the brackets still attached.
   - The motor, gearbox, controller, spindle, and couple should be accessible now.
10. To remove the couples between the gearbox and spindle, loosen the Allen screw on the side of the couples and shaft collars. Remove the spindle and the couples from the assembly.

11. Loosen the Allen bolt on the couple between the motor and gearbox. Remove the three nuts and bolts attaching the gearbox to the L-bracket itself to remove the gearbox and couples from the assembly.
    - Only the motor and L-brackets should be left on the aluminum slab now.
12. With the help of another individual turn the entire assemble so it is lying on either side.
    - **Caution:** Do not lay the assembly on the front or the back panels.
    - **Caution:** Be careful of the lid when turning enclosure.
13. Using a Phillips screw driver, remove the three wires connecting the motor to the controller and the three wires connecting the pulse sensor to the tachometer
14. On the bottom side of the enclosure, remove the screws holding in the motor. Have another individual hold the motor itself so it does not drop. Remove the motor with its attached pulse sensor from the enclosure.
    - **Caution:** Be careful to not snag or cut the plastic shielding on the cords for the motor or pulse sensor.
15. With the help of another individual, remove the L-bracket by removing the nuts and bolts.
    - Now all components of the drive system should be removed except the tachometer and the aluminum slab.
16. With the help of another individual, remove the aluminum slab by removing the nuts and bolts.
17. To remove the tachometer, first remove the power cord from the tachometer unit itself using a Phillips screwdriver. Using a small Phillips screw driver to remove the two small screws on the side of the display. Slide the unit out from the front plate.
18. Replace or upgrade desired parts, and re-assemble as necessary.

Cost Analysis

Overall, our budget will be more than enough to produce a high quality product. The Xilinx grant provides an extra $1000 for us, which will improve the longevity of our design while improving its overall power. Without the Xilinx grant, our budget was cutting it close to how much we needed.

There will be a few major differences between production and prototype costs.

- Rotor cost will be added to production costs
- Bulk pricing will decrease production costs
- Spindle design will not have the outsource cost
- High volume software licensing potential

There are several cost advantages that come with setting up a production line. However, the cost of our rotor was not accounted for in the prototype, as it was an item we already had. The cost of the rotor nearly counters the cost saving advantages that come from mass production. The table below shows expected cost for both prototype and products. Given that we want to make our product low cost but highly adaptable, both low power and higher power designs are featured in this table.

The cost breakdown can be found in a table in Appendix A.

Business Plan

The Benchtop Centrifuge for Materials Science is intended to be a low price product specifically for the university research and third world markets. The draw of the product is its low price point of $2,750 while still meeting the requirements of laboratory needs. This low price point was achieved by designing the product for university level material's science needs, and by working with manufactures to receive discounts through bulk order pricing. Outlined below is a business plan that our team believes it could achieve $266,600 within two years.

Introduction/Background

Research into and the verification of material properties is a necessary part of the design process. In order to fabricate the material intended for research, separating materials based on their state of matter and/or density is often required. This process is known as sedimentation and relies on gravity to separate the materials. Often the normal force of gravity is not enough to produce this effect on its own and so it is necessary to increase the forcing on the sample. This can be done with a centrifuge, which rotates the sample at high speeds which replicates the effects of a higher gravitational field.

Goals and Objectives

The Benchtop Centrifuge for Material Science is intended to be a low price product specifically for the university research market, particularly in third world markets where a less expensive centrifuge may be the only option. The team hopes to achieve a return on investment within 2 months, while not saturating the market immediately. Therefore our goal is sustainable growth, attempting to produce 10 centrifuges per month.

Description of Product

The Benchtop Centrifuge for Material Science offers cost-effective material refining capabilities. By rotating its samples at high speeds, it can expedite the settling of different parts of the sample based upon their density, also known as sedimentation. This can be used to purify samples either by purifying existing examples or by separating samples into their composite parts, both of which are useful features. Currently the model is set-up for 56 vials but can easily be converted to a different number by changing out the interior of the swing-buckets. Additionally, our design was made fully adaptable by allowing for other motors or spindles to be easily swapped into the design based on the design needs of the consumers.

Potential Markets The Benchtop Centrifuge for Materials Science is designed for the small laboratory setting. Its easy set-up, simple run procedure, and low price make it ideal for frugal or new laboratories. While our centrifuge was originally developed for use at Santa Clara University, it is important to note that there are other universities and research institutions which are also conducting material science research and therefore have a verifiable need for the device. Given that many of the institutions and universities which we would be appealing to have limited budgets, it would make sense to base ourselves somewhere near a demonstrable supply of consumers.

Competition

The primary competition for our design are other material science centrifuges, which can range anywhere from $1400-$6400 in cost and are described in Table 2. Since our centrifuge also falls within that range, it is important that we show both the safety and the effectiveness of our design, as those are the two categories where we excel over our competition. In safety, the centrifuge itself is guaranteed to protect the consumer in even the most extreneous circumstances which is not a claim that all of our competitors can make, since they have express limits on run times and top speeds which our design can easily handle. In terms of effectiveness, most of our competitors have fixed-angle centrifuges which produce a lower quality sediment than swing-bucket and so our design would have a better final product for material research. Additionally, our design can hold almost double the number of vials as any of our competition which allows for more efficient research.

Sales/Marketing Strategies

Since our team is building a centrifuge that is less expensive than competitors models while still capable of similar functionality, it is important to market our price above all else. Since the centrifuge we are creating is specifically tailored towards material science research, it would most likely be needed at universities or research institutions where the division is just being started or is underfunded.

Since we would not have the reputation of other companies whom we would be competing with, our marketing strategy would be dependent on showing the reliability and effectiveness of our design. To combine these two concepts, it would be best for our marketing division to embark on a tour around various universities and institutions where there is a verifiable need for the centrifuge and displaying it to the consumers directly, as opposed to trying to sell the centrifuge online or by mail-order. Our sales team would likely be a combination of at least one engineer and one salesperson, the engineer to troubleshoot in case of any errors and the salesperson to promote the product.

Manufacturing Plans

Benchtop Centrifuge for Material Science would have parts ordered separately before assembled, modified, and tested in a facility. A minimum of 14-21 days is required to ensure the product is ready to hit the market. This duration includes shipment of different parts, modifications, and testing. The A36 steel plates and 6061 aluminum slab and L-brackets would be machined by BT Laser in Santa Clara. They machine these out of larger sheets they keep in stock, so their turn around time is two days. Dayton and Dart can ship the remainder of the drive components within 3 to 5 days, while McMaster Carr ships the couples and brackets within 2 days. Andantex and MisumiUSA would need two weeks to ship the connecting shaft and gearbox. The centrifuge itself takes about 2 to 3 hours from two workers to assemble the device itself. Theoretically, if all parts arrive in the morning, the device could be shipped out to the customer within the same day. As we ramp up and achieve more customer orders, we would look into facilities in China that can mass produce these items faster and cheaper if given massive orders as they would set up facilities specifically for our centrifuge itself.

Product Costs

Based off of our research on our current suppliers, we found that we would be able to receive discounted bulk pricing if we order in large enough quantities. Currently we do not have the appropriate funds to purchase everything for multiple centrifuge devices in a single order, but the suppliers provided estimates based off of a bulk order discounts given for ordering a large amount annually. Table 9 below represents the cost to build 10 centrifuge units. Note that these prices are considerably lower than the prototype cost due to the bulk pricing.

Table 9: Cost for 10 Units

Cost for 10 Units	
Motor	$ 2,000.00
Gearbox	$ 1,950.00
Controller	$ 2,900.00
Tachometer	$ 2,200.00
Plates	$ 7,000.00
Accessories	$ 500.00
Spindle	$ 1,000.00
Rotor	$ 3,000.00
Aluminum	$ 600.00
Couples	$ 600.00
	$ 21,750.00

Services or Warranties

Our team believes that our device will function properly for times to come as we are using a multitude of devices inside our centrifuge that are already tested for longevity and quality. The current motor, gear box, controller, and tachometer already have two year warranties through Dayton, Dart, and Andantex. As a result, we will provide a two year warranty for the device itself, where the user would have to ship the device to our factory. If the component has a warranty through its original manufacture, we will replace them through the manufactures RMA process. If it is not a part from Dayton, Dart, or Andantex, we will replace the item ourselves and ship the item back to the consumer.

Financial Plan

Our financial plan was influenced by our budget from the initial investment. Given that we cannot rely on any initial funding from an external source, we needed a plan that would have the lowest initial debt to our team; however, this would also cause us to start rolling into large production at a slower rate. With a cost of $2,175 per device for the first month due to waiting for shipments, we would basically expect almost no profit for that month. That left us in debt of of $10,925 for producing 5 devices. We expect that we can manage this with credit cards as there are normally 2 months before you have to pay. During this waiting period, we would take our initial prototype and travel advertising our centrifuge and taking pre-orders.

The second month, we can anticipate making another 5 devices, but selling 8. This would practically offset the costs for both the first and second month. We know we could assemble the device within 3 hours with two workers, so the time of assembly is a negligible expense. Given experience we anticipate it would take only 1.5 hours to assemble and test each device, allowing for mass production still with only 2-3 people. Throughout the rest of the month, we would spend time personally advertising to labs and universities. As we continue to ramp up production and sell more devices through our advertising we will eventually start making larger and larger profit, and by 6 months we anticipate $20,900 and $62,300 by one year. At the end of two years, we would make $266,600 profit by ramping up production. At this time is when we would look at expanding to third world market applications, as our device can be shipped cheaply disassembled. Meanwhile, we would look into moving production over to Asia where we can lower our production costs while ramping up production itself, due to the lower cost of labor.

For a full break down of the two year cash flow sheet, refer to Appendix D.

Engineering Standards & Constraints

Safety

Since centrifuges are powerful rotational systems, there is a large amount of kinetic energy stored in the system. We are planning to create safety systems in the centrifuge that will manage internal instability, keep the system locked during operation, and be capable of bringing about a rapid stop of the centrifuge if there is an issue in the operation of the system.

To manage the internal instability, it will be necessary to install a safety system which while be able to tell if there are uneven loads placed on the separate arms of the centrifuge. One way to do this would be to use a mercury switch, which maintains the level of a device and if is disturbed could lead to the automatic shutdown of the centrifuge. To keep the system locked is a simple matter, since we can simply install an electronic lock which will not allow the system to be open unless the system has completely slowed. The more interesting challenge is how the centrifuge will slow down in an emergency. If it were simply to be a power system shutdown, the system would take at least as long to slow down as it did to speed up in the first place. It is therefore important to look into other options.

One such option would be to be to install a physical rubber brake into the system which would fall against the spindle in case of emergency and cause it to come to a complete stop. While this system would be an effective way to shutdown the system, if it were to be used often then it would wear down and require replacement, much as car brakes do. It is therefore important to gather information about the expected life of the brake under these circumstances and to decide if it is worth the investment.

Another potential option would be to initiate a pulse of reverse forcing in order to quickly lower the rotational inertia of the system by lowering the speed of the centrifuge. The main issue of this solution is that when this forcing is in effect, all of the friction of slowing down the spindle is concentrated in the motor and gearbox which are two of the most integral systems in the centrifuge. It is therefore important to make sure that the maximum possible forcing on the system would fall within its factor of safety.

An issue that the team is currently dealing with in this subsystem is the fact that both of these methods do nothing to deal with what happens to the energy in the centrifuge. If the rotational inertia present in the system is transferred directly into one of the buckets and launches it into the side of the container, it would be a tremendous safety risk. The only real way to deal with this potentiality is to reinforce the walls of the system and potentially test it by intentionally sabotaging the system and seeing if it is capable of withstanding the force.

Usability

As the majority of users of this centrifuge will be students who have never used a centrifuge before, it is important to keep the centrifuge easy to use. To accomplish this, we have chosen to go with an Arduino controller since that will allow us to decrease the amount of training necessary to use the device as it will allow the system to interact with a computer.

This is in comparison to the usual system of centrifuges, many of which come with custom controllers. These custom controllers are unique and often take significant research in order to use to their full ability. By switching to an Arduino controller it also makes it easier to switch motors in the design, as a new controller does not need to be accounted for.

Economic Considerations

Since one of our goals is marketing this centrifuge to third world communities, it is important to keep cost in mind while designing the device. This is a constant struggle in our project since we are simultaneously pursuing more powerful motors in order to increase the breadth of applications that our device will be able to successfully complete.

Since this is a sliding table, we have decided to make the system easily compatible for a variety of motors. While this is more effort for us as a team to create a universal set of controls, we believe it will be an important step in bringing this centrifuge to the world. It will allow for the motor to match the specific application which it is needed for, switching out easily if another is required.

Health Considerations

As some of the materials which will be centrifuged are potentially hazardous to ingest, it is important to make sure that the system is completely encapsulated. It is important to make sure that there is no way for a testing material to come into unintentional contact with the user, whether that be in the form of particles or an aerated gas. As was mentioned in the safety section, the system will only operate if the lid is closed so it is the responsibility of the group to ensure that the seal is capable of providing sufficient protection to the user.

Sustainability Considerations

Sustainability was the another main consideration for the interchangeability of motors. By allowing for the setup to be used for a variety of purposes and applications, it decreases the amount of centrifuges that would need to be purchased. It limits the amount of used material to the various motors and test containers.

Summary and Conclusion

In summary, the Benchtop Centrifuge for Materials Science will be designed to serve the Materials Science department at Santa Clara University. There is a focus in the design towards allowing for easy re-purposing of the design for various applications which will expand the reach of the project.

Other focuses in the design include making sure that the design is safe for users to use and keeping the design cost-efficient by eliminating extraneous features. In the future, it is hoped that the project will be expanded by outfitting the device with a more powerful motor and by including a refrigeration system to allow it to be used in fields other than Materials Science.

Overall Evaluation of the Design

The design, while not entirely aesthetically pleasing, does accomplish the required job in the most cost efficient and safe way. The rectangular enclosure was a more cost efficient enclosure than the cylindrical option and yet the design is still capable of withstanding the maximum impact from device failure. The Arduino control system combined with the accelerometer and solenoid locking system are a needed accessory in order to keep the user safe in the instance that there is an error in operation. As far as the mechanical requirements of Dr. Marks, the centrifuge is capable of accurately maintaining the necessary range of speeds for the needed periods of time.

Suggestions for Improvement

If there were to be more funds available to this experiment, the cylindrical enclosure would be an improvement that could easily improve the safety of the enclosure. This would be by reducing the critical points of the system and making the interior of the system uniform. A brushless motor could be used to replace the current brushed motor which would reduce the need to replace brushes every few years. For this centrifuge to be used for medical purposes, the device could be outfitted with a refrigeration unit as that would allow the samples to be adequately cooled while being centrifuged. If the centrifuge is having issues with heat at high speeds then exhaust holes could be drilled into the lower compartment as that would allow for the centrifuge to cool quickly while maintaining the structural integrity of the top compartment.

Lessons Learned

One of the first and most important lessons learned over the course of this project was the ability to deal with vendors. It is expected that all of us will have to deal with vendors later in the working world and our experiences in this project with getting what we had ordered and allowing for the time and budget for corrections to be made were something that our team had not initially expected. As a team, we decided that we should have budgeted at least two more weeks for the construction of the centrifuge since some of our parts only came in the very week of the design conference. Sourcing the parts from various vendors also proved challenging as we were required to machine parts of the spindle down to size in order to work with the coupling system.

The Electrical and Computer Engineering to create the functioning Arduino system also proved challenging for the team despite the background work team members had done. Thankfully, faculty resources, notably Dr. Kitts, made this challenge into an opportunity for learning. In the future, it might have been prudent to include an Electrical Engineer on the team for the centrifuge mechanics. There were also issues with the potentiometer to control the speed which at first was attempted solely using PWM control from the Arduino but eventually had to be done by means of a digital potentiometer due to interference from the microcontroller board itself.

The final lesson which was learned from this project was the fallibility of computer testing. While we as a team are still not sure as to why our FEA analysis was ineffective, our physical testing showed our enclosure to be able to withstand the necessary forces. To our team this taught us the lesson of always double-checking the results of any test if possible, especially if that test is digital. While digital technology is rapidly improving, it is too easy to overlook a crucial datum and thereby invalidate the results. If there is ever an option between the two, our team has shown the superiority of physical testing.

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Appendix A: Budget

Table 10: Initial Budget Analysis for Centrifuge Project

Date	Vendor	Item	Cost	Remaining
	SCU	Funding	$ 1,500.00	$ 1,500.00
	Xilinix	Funding	$ 1,000.00	$ 2,500.00
10/20/2016	Amazon	24V Converter	$ (24.88)	$ 2,475.12
2/9/2017	Grainger	DC Controller	$ (401.63)	$ 2,073.49
2/9/2017	Zoro	Tachometer	$ (235.29)	$ 1,838.20
2/9/2017	Amazon	Dayton Motor	$ (217.12)	$ 1,621.08
3/1/2017	Amazon	R3200-2 Gear	$ (198.61)	$ 1,422.47
3/2/2017	McMaster	Couples motor	$ (83.89)	$ 1,338.58
3/3/2017	Grainger	Pulse	$ (150.74)	$ 1,187.84
3/21/2017	Amazon	Cable + Relay	$ (11.88)	$ 1,175.96
4/5/2017	Maxx Metals	Steel	$ (183.24)	$ 992.72
4/5/2017	Amazon	Solenoid	$ (15.98)	$ 976.74
4/21/2017	BT Laser	Machining	$ (338.60)	$ 638.14
4/24/2017	McMaster	Couple Shaft	$ (158.11)	$ 480.03
4/28/2017	McMaster	Aluminum	$ (82.04)	$ 397.99
5/2/2017	McMaster	Bolts	$ (74.65)	$ 323.34
5/5/2017	Amazon	Digipot	$ (7.62)	$ 315.72
5/9/2017	Home Depot	Bolts	$ (11.42)	$ 304.30

Appendix B: Timeline

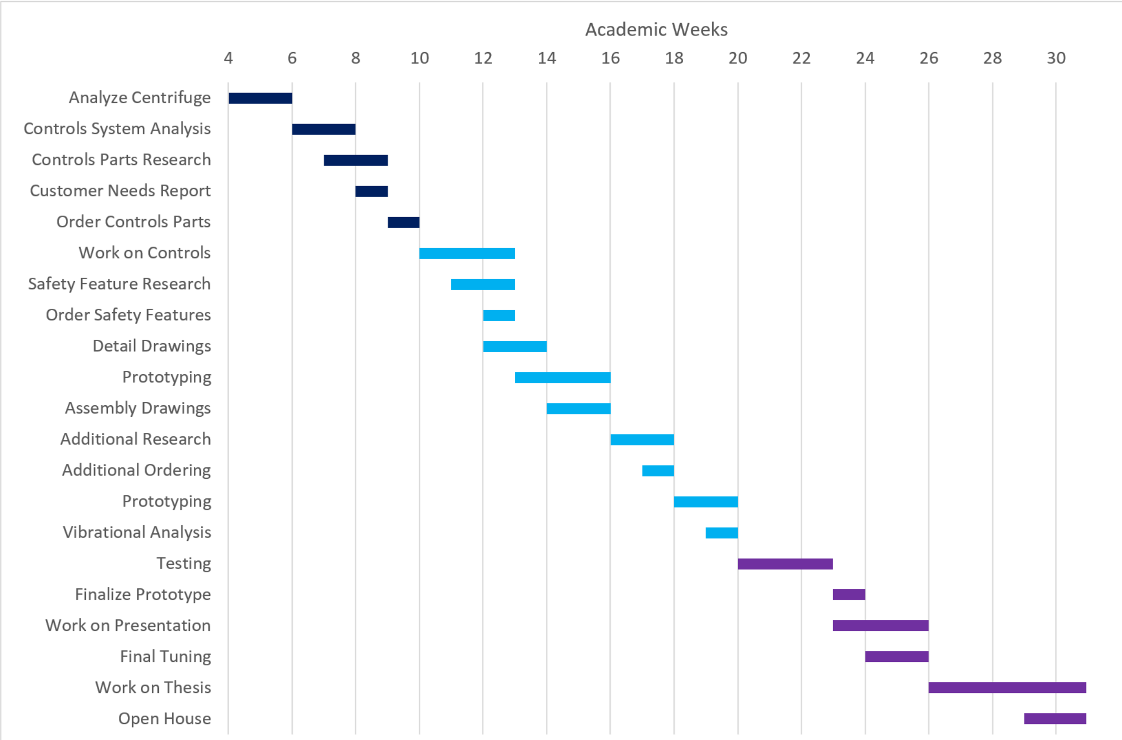


Figure 29: Gannt Chart of Entire Academic Year

Table 11: Weekly Goals for Fall Quarter

Week	Goals
4	• Finish Oral/Written Report • Achieve Lab Access • Finalize advisor meeting times
5	• Analyze previous centrifuge and motor • Determine what parts are still operable • Finish funding requests
6	• Begin analysis and research on parts needed • Order new motor if needed
7	• Research controls system • Determine controller best fits project needs
8	• Complete Customer Needs Report
9	• Ensure all parts are ordered • Begin planning and work on arriving parts
10	• Begin work on controls systems

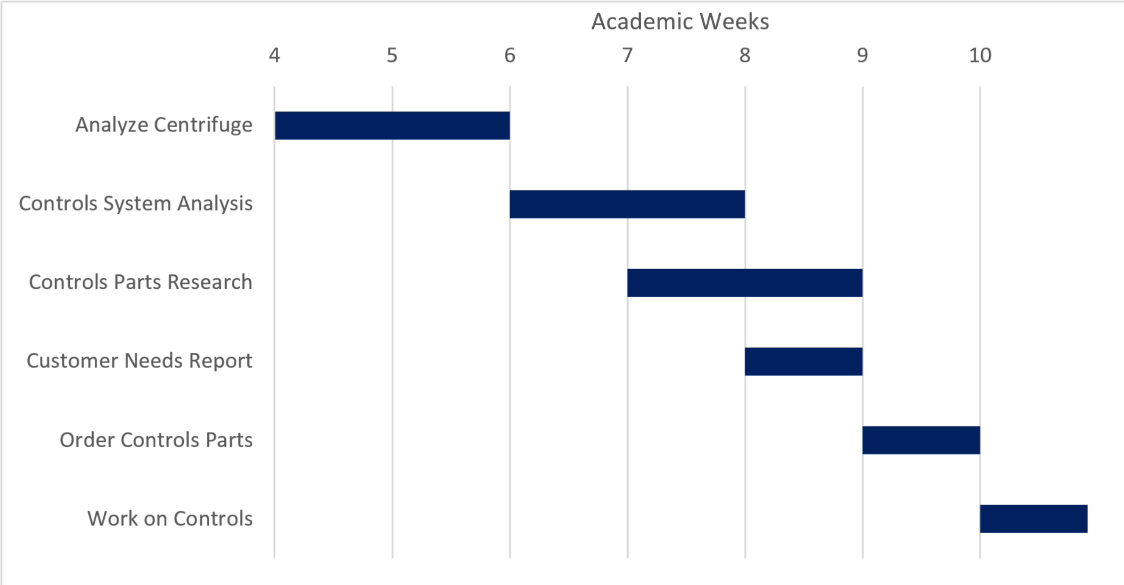


Figure 30: Gannt Chart for Fall Quarter (Weeks 1-10)

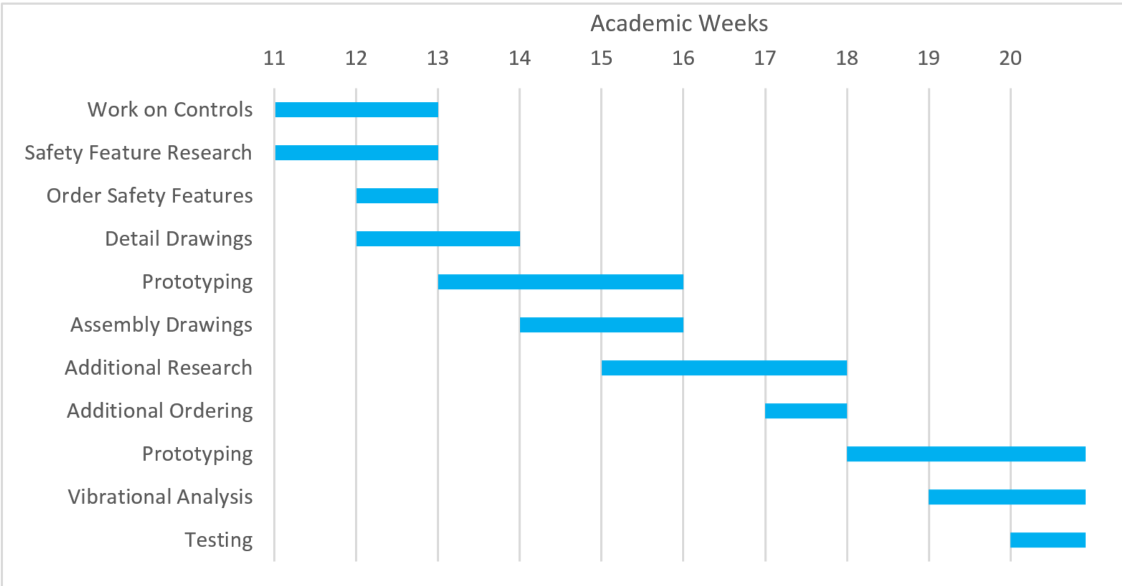


Figure 31: Gannt Chart for Winter Quarter (Weeks 11-20)

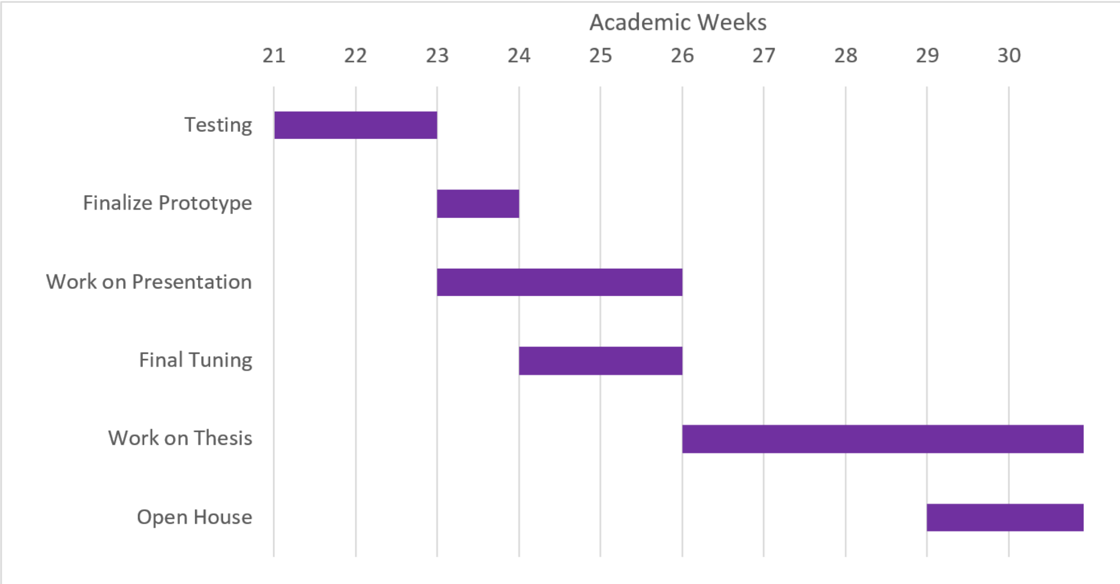


Figure 32: Gannt Chart for Spring Quarter (Weeks 21-30)

Appendix C: Design Analysis Results

C1. Maximum Allowable Design Load for Joint in Shear

$\tau_{yp} = 57{,}000$ psi

A= Cross sectional area of bolt= 0.049 in

F_s= Factor of safety=2

P= Maximum allowable load

Since there are 12 bolts per face the following should hold true:

$$\frac{P}{12\times A} \leq \frac{\tau_{yp}}{F_s}$$

$P \leq 11172$ lb

C2. Impact Force of Bucket When Centrifuge is Spinning 4000 RPM

v= linear velocity
d= rotor diameter= 0.3905 m
RPM= 4000

$$v = \frac{\pi * d * RPM}{60}$$

= 81.786 m/s

F= Impact force

m= Mass of bucket= 0.5 kg

s= Distance for bucket to slow down= 0.5 in= 0.0127 m

$$F = \frac{m * v^2}{s}$$

= 29601.1 lb

Since there are 12 bolts per face the following should hold true:

UTS= Ultimate tensile strength of bolt= 120,000 psi

A= Cross sectional area of bolt= 0.049 in

F_s= Factor of safety=2

$$\frac{F}{/12} \leq \frac{UTS}{xA/Fs}$$

$$2466 \quad \text{lb} \leq 2940 \text{ lb}$$

C3. Shaft Torsion

Rotor's Moment of Inertia = 0.046112 kg m^{-2}

Max speed = 4000 RPM= 419 rad/s

Shaft Diameter = 14 mm

1045 Cold Rolled Steel Shear Strength = 450 MPa

C3.1. Angular Acceleration Required to Reach Max Speed

$\alpha = (\omega - \omega_o)/ t$

Assuming max speed is reached in 2 minutes (120 seconds)

$\alpha = (419 - 0) / 120$

$\alpha = 3.492$ rad/s^2

C3.2. Torque Required to Reach Max Speed in 2 Minutes

T = I * α

T = 0.046112 * 3.492

T = 0.161023 Nm

C3.3. Moment of Inertia of Circular Shaft

$J = \Pi*(D_{shaft})^4 / 32$

$J = \Pi*(0.014)^4/ 32$

$J = 3.771 * 10^{-9} m^4$

C3.4. Torsional Stress in Circular Shaft

$\tau_{max} = T * R\text{-}_{outer} / J$

$\tau_{max} = 0.161023 * (0.014/2) / 3.771 * 10^{-9}$

$\tau_{max} = 298903$ Pa

C3.5. Factor of Safety of Shaft

FOS = Yield Strength / Max Stress

FOS = $450 * 10^{6} / 298903$

FOS = 1505.5

Appendix D: Business Plan

Month	1	2	3	4	5	6	7	8
Monthly Costs								
Marketing	$50	$50	$50	$50	$50	$50	$50	$50
Cost per 10 Units	$21,750	$21,750	$21,750	$21,750	$21,750	$21,750	$21,750	$21,750
Volume	5	5	10	12	12	12	12	15
Total Cost	$10,925	$10,925	$21,800	$26,150	$26,150	$26,150	$26,150	$32,675
Sales								
Price	$2,750	$2,750	$2,750	$2,750	$2,750	$2,750	$2,750	$2,750
Volume	0	8	10	10	12	12	15	15
Income	$0	$22,000	$27,500	$27,500	$33,000	$33,000	$41,250	$41,250
Inventory								
Produced	5	5	10	12	12	12	12	15
Sold	0	8	10	10	12	12	15	15
Stock	5	2	2	4	4	4	1	1
Peroid Cash Flow	-$10,925	$11,075	$5,700	$1,350	$6,850	$6,850	$15,100	$8,575
Cumulative Cash Flow	-$10,925	$150	$5,850	$7,200	$14,050	$20,900	$36,000	$44,575

Figure 33: Months 1-8

	9	10	11	12	13	14	15	16	17
	$50	$50	$50	$50	$50	$50	$50	$50	$50
	$21,750	$21,750	$21,750	$21,750	$21,750	$21,750	$21,750	$21,750	$21,750
	15	20	20	20	20	20	24	24	24
	$32,675	$43,550	$43,550	$43,550	$43,550	$43,550	$52,250	$52,250	$52,250
	$2,750	$2,750	$2,750	$2,750	$2,750	$2,750	$2,750	$2,750	$2,750
	14	16	20	22	20	22	22	26	24
	$38,500	$44,000	$55,000	$60,500	$55,000	$60,500	$60,500	$71,500	$66,000
	15	20	20	20	20	20	24	24	24
	14	16	20	22	20	22	22	26	24
	2	6	6	4	4	2	4	2	2
	$5,825	$450	$11,450	$16,950	$11,450	$16,950	$8,250	$19,250	$13,750
	$50,400	$50,850	$62,300	$79,250	$90,700	$107,650	$115,900	$135,150	$148,900

Figure 34: Months 9-17

18	19	20	21	22	23	24
$50	$50	$50	$50	$50	$50	$50
$21,750	$21,750	$21,750	$21,750	$21,750	$21,750	$21,750
30	30	30	30	34	40	40
$65,300	$65,300	$65,300	$65,300	$74,000	$87,050	$87,050
$2,750	$2,750	$2,750	$2,750	$2,750	$2,750	$2,750
28	28	32	32	35	35	38
$77,000	$77,000	$88,000	$88,000	$96,250	$96,250	$104,500
30	30	30	30	34	40	40
28	28	32	32	35	35	38
4	6	4	2	1	6	8
$11,700	$11,700	$22,700	$22,700	$22,250	$9,200	$17,450
$160,600	$172,300	$195,000	$217,700	$239,950	$249,150	$266,600

Figure 35: Months 18-24

Appendix E: Detail Drawings

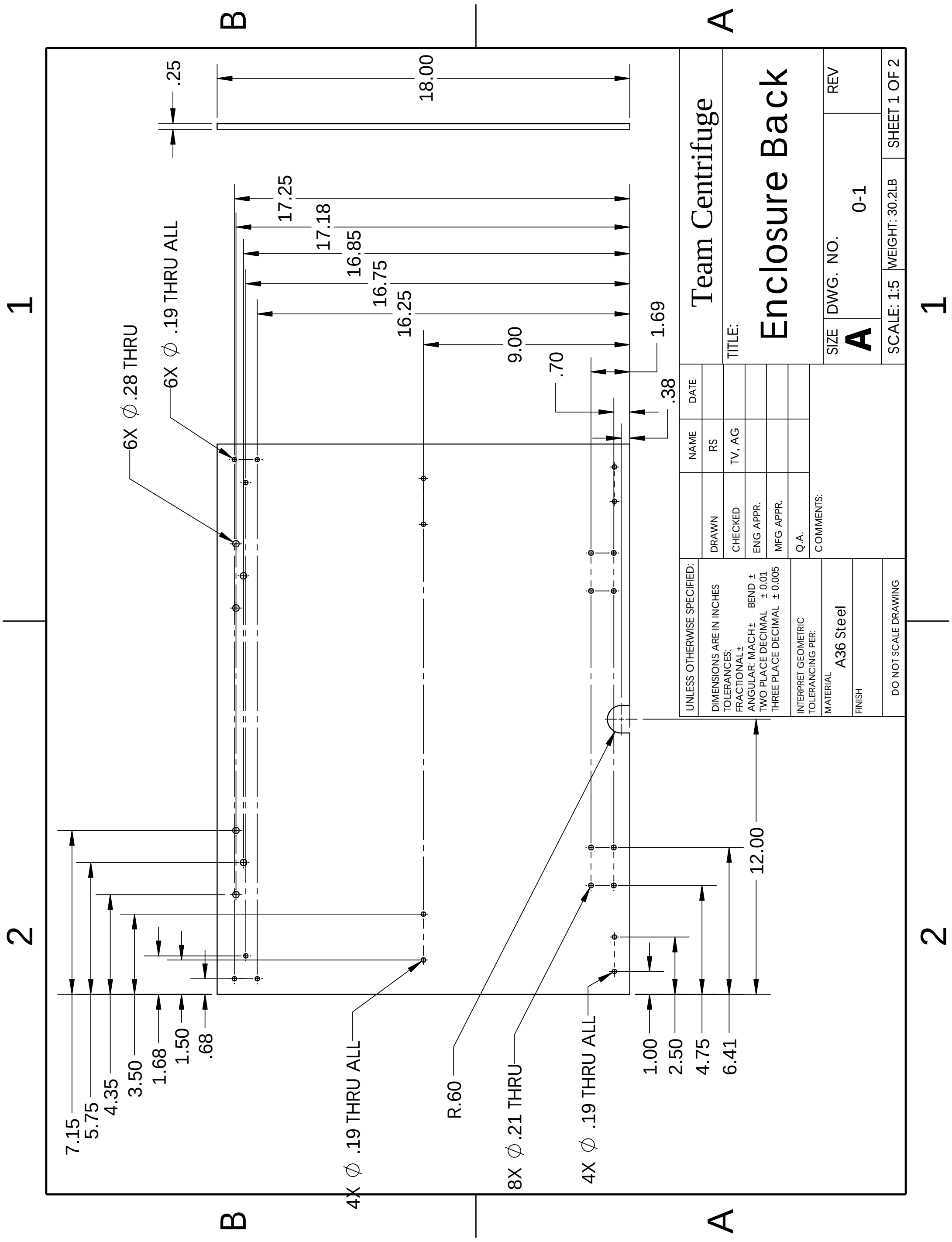


Figure 36: Dimensional Drawing of Enclosure Back Plate

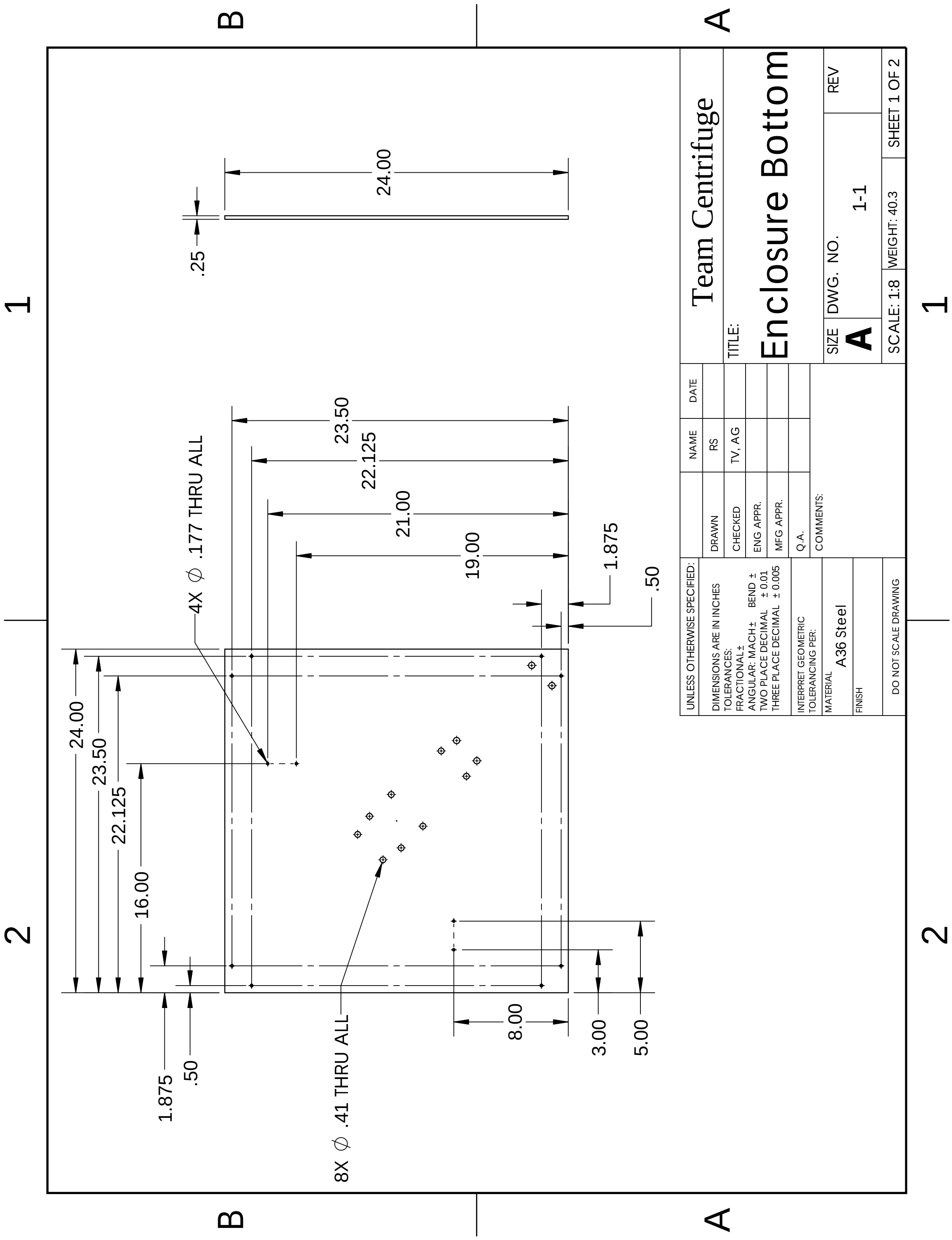


Figure 37: Dimensional Drawing of Enclosure Bottom Plate

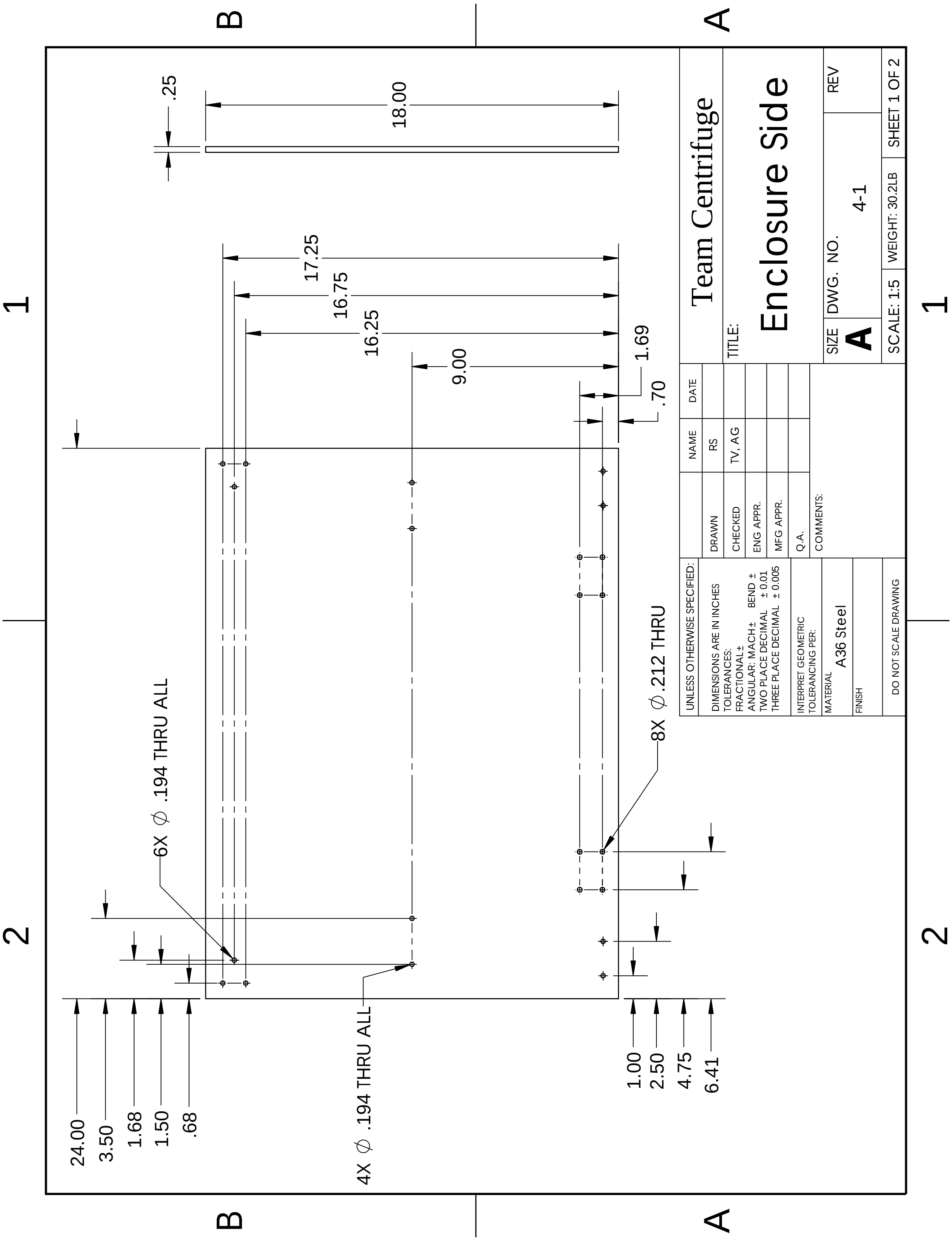


Figure 38: Dimensional Drawing of Enclosure Side Plate

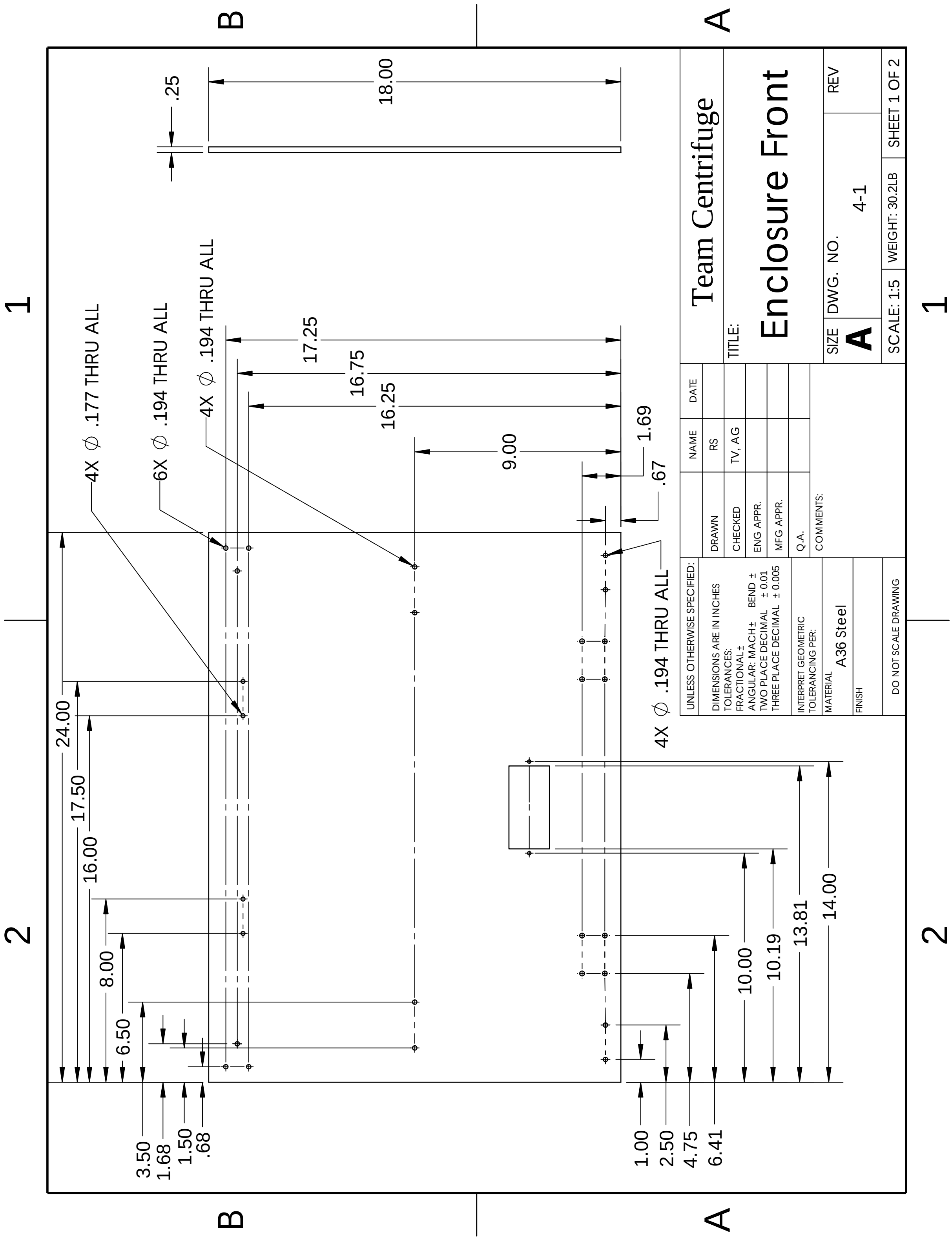


Figure 39: Dimensional Drawing of Enclosure Front Plate

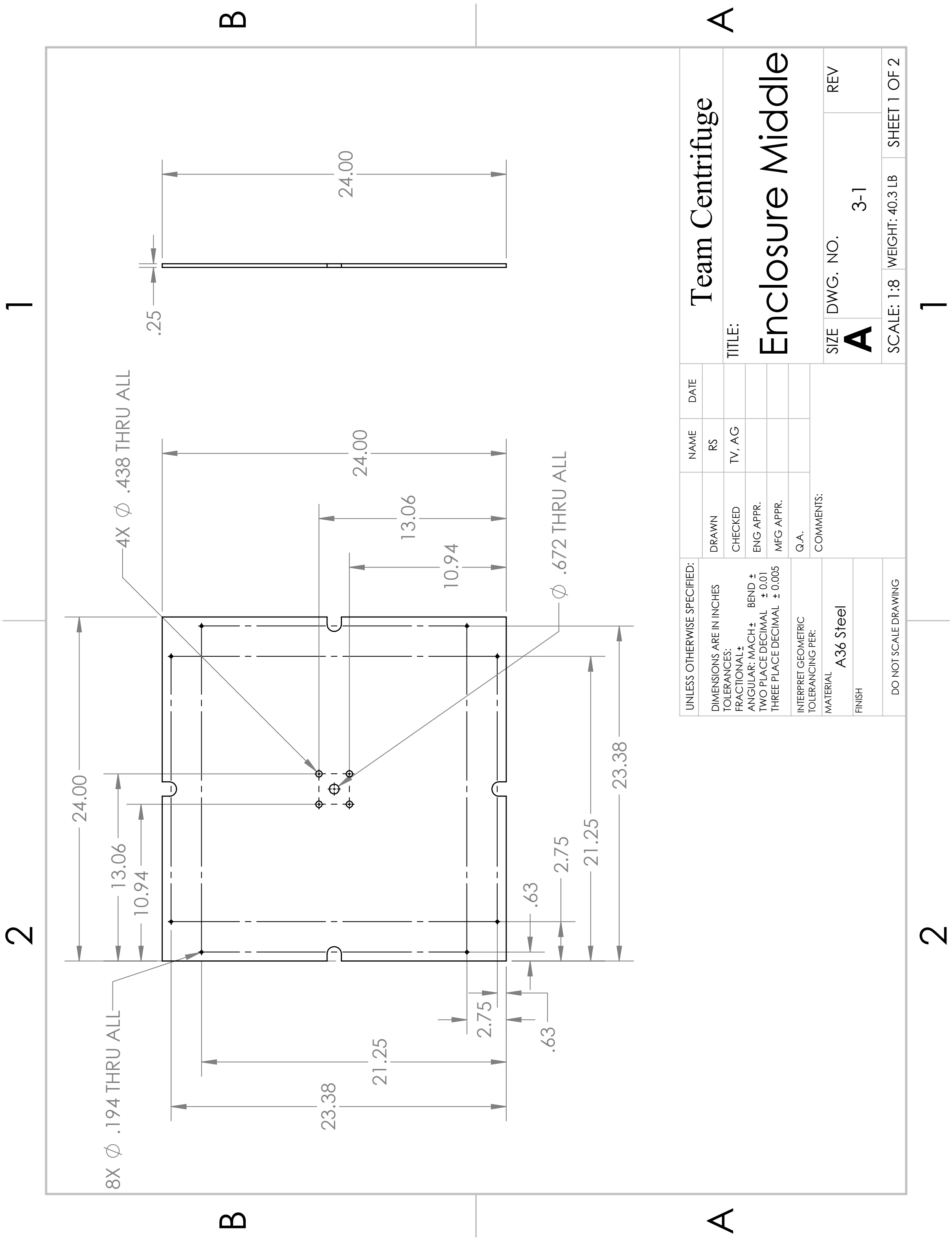


Figure 40: Dimensional Drawing of Enclosure Middle Plate

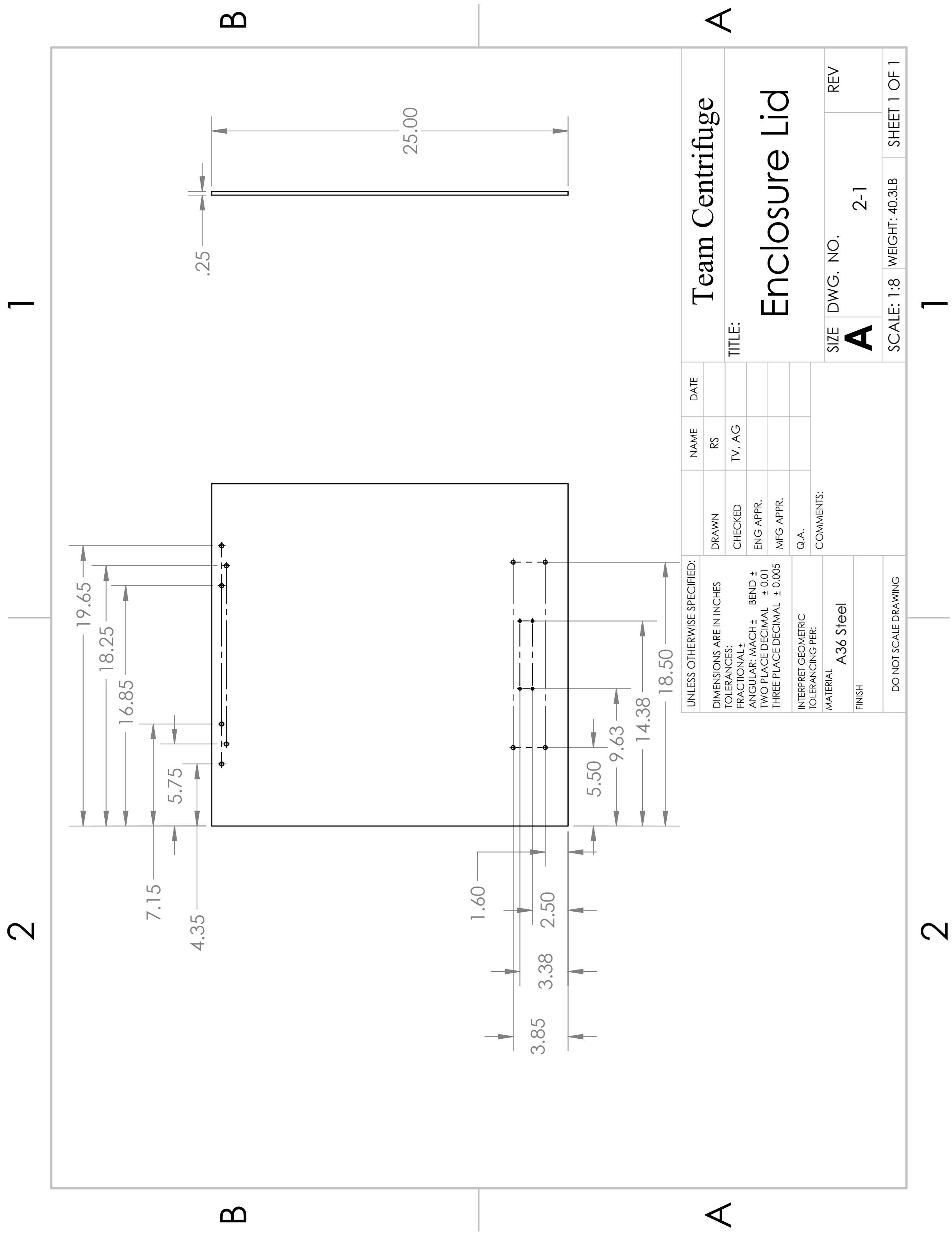


Figure 41: Dimensional Drawing of Enclosure Top Plate

Appendix F: Design Evaluation

Design Project = senior design one **System=** centrifuge **Date=** 8-Nov-16

	TARGET or	DESIGN IDEAS																			
CRITERIA	FACTOR	1 = Baseline		N-M		N-M L-R		H-M L-R		H-M		L-R		P-P N-M L-R		P-P H-M L-R		P-P H-M		P-P L-R	
Time – Design	15	15		15		20		20		15		15		70		70		70		70	
Time – Build	50	50		50		45		45		50		50		10		10		10		10	
Time – Test	35	35		35		35		35		35		35		20		20		20		20	
Time Score	10		10		10.00		10.78		10.78		10.00		10.00		18.13		18.13		18.13		18.13
Cost – Prototype	$ 500.00	$ 500.00		$ 1,500.0		$ 2,000.		$ 1,500.		$ 1,500.		$ 500.00		$ 4,000.		$ 4,000.		$ 3,000.		$ 2,000.	
Cost – Production	$ 2,000.00	$ 2,000.0		$ 3,000.0		$ 2,500.		$ 2,500.		$ 3,000.		$ 2,500.		$ 3,500.		$ 3,500.		$ 4,000.		$ 3,500.	
Cost Score	10		10		22.50		26.25		21.25		22.50		11.25		48.75		48.75		40.00		28.75
Cost	2	3	6	3	6	2	4	3	6	3	6	3	6	2	4	2	4	2	4	2	4
Torque	4	3	12	2	8	2	8	6	24	6	24	4	16	2	8	6	24	6	24	4	16
Safe	5	3	15	3	15	2	10	3	15	3	15	4	20	3	15	3	15	3	15	4	20
Efficient	2	3	6	4	8	4	8	5	10	5	10	3	6	4	8	5	10	5	10	3	6
Easy to Use	2	3	6	3	6	3	6	3	6	3	6	3	6	2	4	2	4	2	4	2	4
Lightweight	1	3	3	3	3	5	5	5	5	3	3	5	5	5	5	5	5	3	3	5	5
Time Constant	3	3	9	2	6	2	6	5	15	5	15	3	9	2	6	5	15	5	15	2	6
		3	0		0		0	1	0		0		0		0		0		0		0
		3	0		0		0	1	0		0		0		0		0		0		0
		3	0		0		0	1	0		0		0		0		0		0		0
		3	0		0		0	1	0		0		0		0		0		0		0
		3	0		0		0	1	0		0		0		0		0		0		0
	TOTAL		57.0		39.5		30.0		69.0		66.5		66.8		3.1		30.1		36.9		34.1
	RANK																				
	% MAX		82.6%		57.3%		43.5%		100.0%		96.4%		96.8%		4.5%		43.7%		53.5%		49.5%
	MAX	69.0						BEST													

NOTE: User fills in Purple areas, gold areas are calculated or fixed
Light blue areas filled from prioritizing matrix

BASELINE = Current Design

Timescore(i)=Timescore(B)*(TD(i)/TD(B) + TB(i)/TB(B) + TT(i)/TT(B))/3
Costscore(i)=Costscore(B)*(Cprot(i)/Cprot(B) + Cprod(i)/Cprot(B))/2
Total(i) = SUM(Factor(j)*Comparison(i,j)) + (Timescore(B)-Timescore(i)) + (Costscore(B) - Costscore(i))

Comparison(i,j) = 5 if idea "i" is much better than baseline for criteria "j"
Comparison(i,j) = 4 if idea "i" is better than baseline for criteria "j"
Comparison(i,j) = 3 if idea "i" is same as baseline for criteria "j"
Comparison(i,j) = 2 if idea "i" is worse than baseline for criteria "j"
Comparison(i,j) = 1 if idea "i" is much worse than baseline for criteria "j"

Design Idea Descriptions

2 N-M
3 N-M L-R
4 H-M L-R
5 H-M
6 L-R
7 P-P N-M L-R
8 P-P H-M L-R
9 P-P H-M
10 P-P L-R

Term	Desciption
N-	New, higher torque
L-	Lightweight, smaller
H-	High speeds, low torque
S-	Same
P-	Solar Panel
M	Motor
R	Rotor
P	Power Supply

Figure 42: Criteria Weight Sheet

Appendix G: Moment of Inertia Analysis

Stationary Analysis

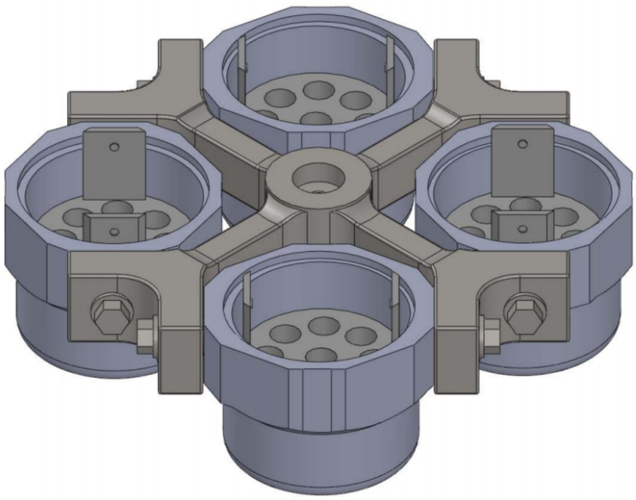


Figure 43: Model of Rotating System

```
Mass properties of assembly not spinning
     Configuration: Default
     Coordinate system: -- default --

Mass = 7.42093872 kilograms

Volume = 0.00343859 cubic meters

Surface area = 0.74492421 square meters

Center of mass: ( meters )
        X = 0.00000000
        Y = -0.03235206
        Z = 0.00000000
```

Figure 44: Physical Properties

```
Moments of inertia: ( kilograms * square meters )
Taken at the output coordinate system.
        Ixx = 0.06884604        Ixy = 0.00000004        Ixz = 0.00000000
        Iyx = 0.00000004        Iyy = 0.10898209        Iyz = 0.00000004
        Izx = 0.00000000        Izy = 0.00000004        Izz = 0.06884604
```

Figure 45: Second Moment of Inertia Values

Rotational Analysis

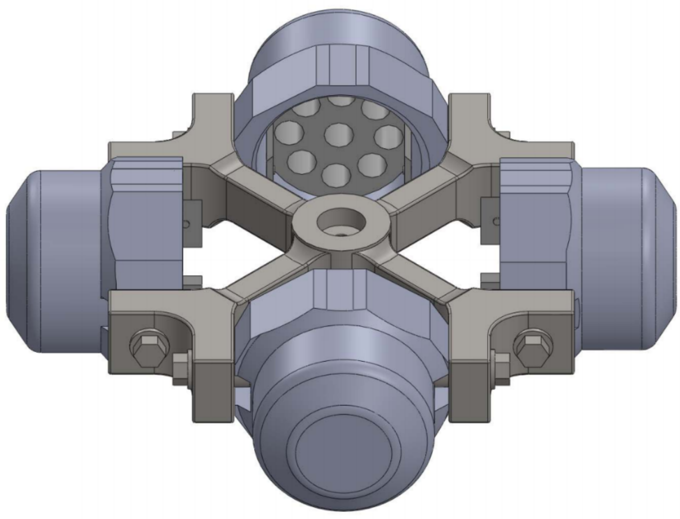


Figure 46: Model of Rotating System

```
Mass properties of assembly spinning
     Configuration: Default
     Coordinate system: -- default --

Mass = 7.42093872 kilograms

Volume = 0.00343859 cubic meters

Surface area = 0.74492421 square meters

Center of mass: ( meters )
        X = 0.00000000
        Y = -0.01395556
        Z = 0.00000000
```

Figure 47: Physical Properties

```
Moments of inertia: ( kilograms * square meters )
Taken at the output coordinate system.
        Ixx = 0.07968257        Ixy = 0.00000004        Ixz = 0.00000000
        Iyx = 0.00000004        Iyy = 0.14566127        Iyz = 0.00000004
        Izx = 0.00000000        Izy = 0.00000004        Izz = 0.07968257
```

Figure 48: Second Moment of Inertia Values

Hand Calculations for Rotational Analysis

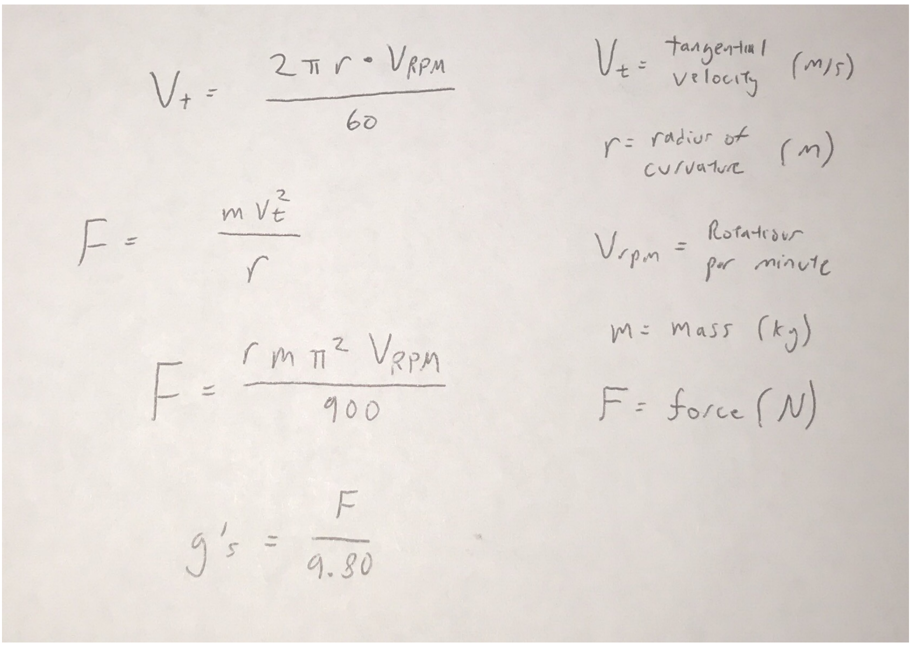


Figure 49: g-force Equation

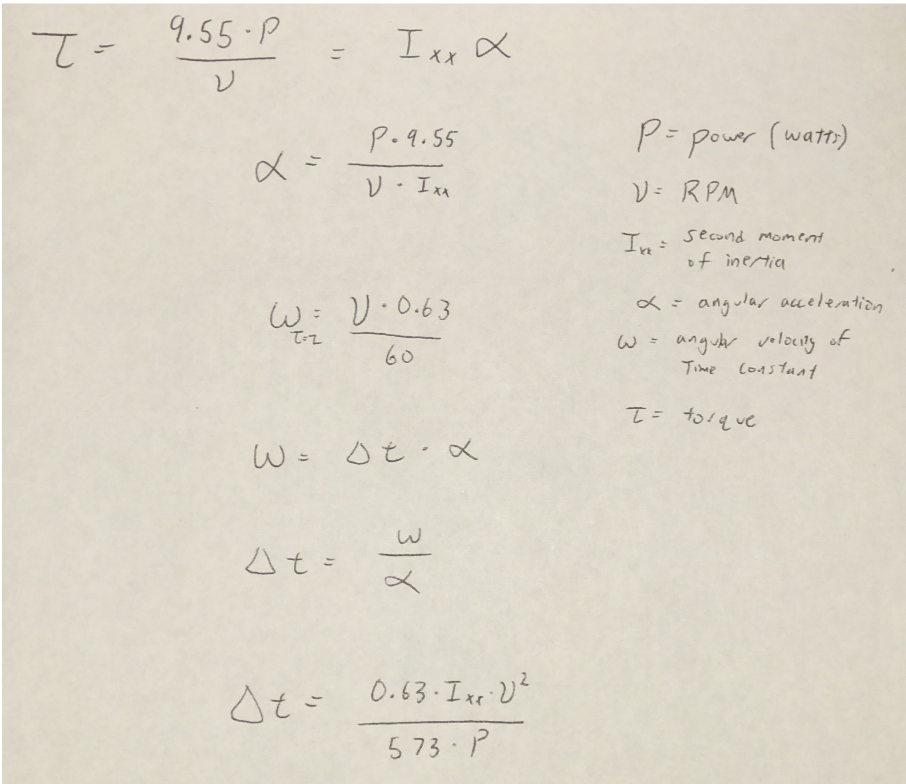


Figure 50: Ramp-up Time Equations

Appendix H: Computer Code

Arduino Code

run.ino

```
#include <SPI.h>

byte address = 0x00;
int CS= 10;
int gate = 4;
//To wire up the arduino to the digipot, it is important to make sure
//all the pins are matched up.
//Arduino 10 -> digipot 1
//Arduino 13 -> digipot 2
//Arduino 11 -> digipot 3
//Ground -> digipot 4
//5v -> digipot 5
//controller lo-> digipot 6
//controller wiper -> digipot 7
//controller hi-> digipot 8
void setup()
{
pinMode(CS, OUTPUT);
pinMode(gate,OUTPUT);
SPI.begin();
Serial.begin(9600);
}


void loop()
{
digitalWrite(gate,HIGH);
//this is the line which affects the output speed of the centrifuge
//goes between 0 and 255
//0 -> 840 RPM
//25 ->  1200 RPM
//50 ->  1800 RPM
//75 ->  2400 RPM
//85 ->  2670 RPM
```

```
//90 -> 2870 RPM
//100 -> 3000 RPM
//105 -> 3300 RPM
//110 -> 3500 RPM
//115 -> 3700 RPM
//125 -> 4000 RPM
//135+ -> 4175 RPM
digitalPotWrite(50);
//set the necessary time by means of a delay, with each 1000
//multiples of the delay being 1 second e.g. delay(5000) would
//wait for 5 seconds. If a second speed is required, put it after
//the delay. This can be done as many times as necessary
digitalWrite(gate,LOW);
exit(0);
}


int digitalPotWrite(int value)
{
digitalWrite(CS, LOW);
SPI.transfer(address);
SPI.transfer(value);
digitalWrite(CS,HIGH);
}
```

Appendix I: PDS

Table 12: Design Requirements

Criteria	**Units**	**Target**
Cheap	US Dollars	<2,500
Torque	Gravities	>3,200
Safe	Seconds to Auto-Shutoff	<1
Efficient	Number of Vials at once	>30
Easy to Use	Minutes Needed to Train	<15
Lightweight	Kilograms	<90
Aesthetic	Average Rating out of 10	>7

Appendix J: Senior Design Conference Materials

Executive Summary

Centrifuge | Santa Clara University

Abhay Gupta, Ryan Schulz, & Thomas Valentine

Introduction

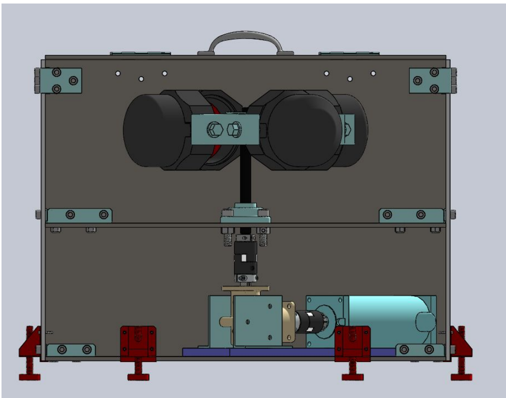
The Mechanical Engineering department at Santa Clara University is attempting to expand its research capabilities; therefore, new equipment is being added to the materials laboratory. Some current devices in the laboratory are a tensile tester, materials polisher, and electron microscope.

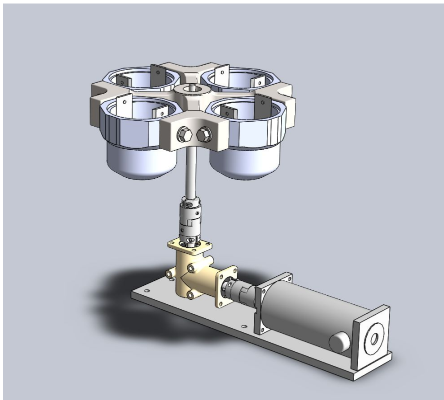
Objective & Device Requirements

Our team is working with Robert Marks, a professor at Santa Clara University, to develop a centrifuge for further materials processing and research. The centrifuge has key functional requirements based on the materials research applications:

- Maximum force: 1000 g's of force
- Ramp up time: 1 minutes
- Total cost: $2,500
- Maximum run time: 4 hours

System Model





System Analysis

The overall centrifuge design was with fatigue, frequency, and toughness analysis. The simulation tests showed that the critical frequencies were factors of 5 times greater than the system's maximum run frequency. The toughness tests also showed that the walls of the enclosure will withstand impact of an internal component.

Conclusion

This centrifuge is being prototyped and fabricated for the purposes of Mechanical Engineering Department. Our team has optimized the requirements of the centrifuge to provide lower overall costs of production and repairs.

Special Thanks to Our Sponsors

BT Lasers | Xilinx | Maxx Metals

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Team Centrifuge

Ryan Schulz || Abhay Gupta || Thomas Valentine
Advisor: Dr. Robert Marks

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Goal

To build a low-cost, high speed centrifuge for the Materials Science research at Santa Clara University

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Background Information

Centrifuges use centrifugal forces to separate liquids of different densities or to separate solids from liquids

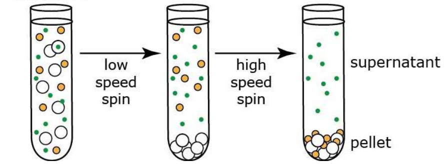

Figure 1: Centrifuge Mechanics

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Research Application

Produce materials with different properties through filtration of particles

Ex: Higher toughness, elasticity, hardness, etc.

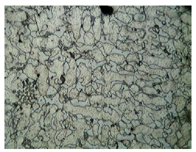
Figure 2: Grain structure of ceramic material

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Ceramic Powder Processing

- Reduce Agglomerates through centrifugal forces
  - Soft Agglomerates
  - Hard Agglomerates

Table 1: Desirable Powder Characteristics for Advanced Ceramics

Powder Characteristic	Desired Property
Particle size	Fine (< ~1 µm)
Particle size distribution	Narrow or monodisperse
Particle shape	Spherical or equiaxial
State of agglomeration	No agglomeration or soft agglomerates
Chemical composition	High purity
Phase composition	Single phase

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Background Information, cont.

Two main kinds of centrifuges

Fixed angle more common due to ease of manufacture and safety

Swing bucket can get higher forcings

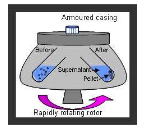

Figure 3: Fixed Angle Centrifuge

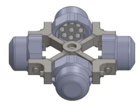
Figure 4: Swing Bucket Centrifuge

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Background Information, cont.

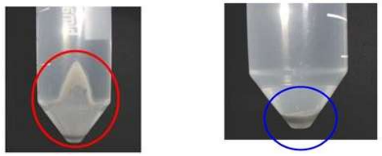

Figure 5: Differences between fixed-angle (RED) and swing-bucket centrifuges (BLUE)

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Base Requirements

- Simple enough to be operated by students
- Forcing of at least 500 gravities, or g's
- Be able to hold at least 10 vials
- Be able to run for at least 4 hours without overheating

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Concerns

Primary

Safety of User
Cost of Product
Ease of Use

Secondary

Versatility
Ease of Repair

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Legacy Project

Team: Jose Lizheno, Nathaniel Tseng, Ryan Tsuzaki (2014)

Pros

- Shear analysis on bolts
- Rotor and spindle were salvaged
- Plates could be used for testing

Cons

- Unassembled and unfinished centrifuge system
- Analysis showed system hit resonant frequency
- Underpowered motor
- Difficult Control System

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Legacy Project (continued)

Tabular Data

	Mode	Frequency [Hz]
1	1.	41.586
2	2.	44.82
3	3.	50.998
4	4.	55.007

Figure 6: Legacy Vibrational Analysis

Figure 7: Legacy motor

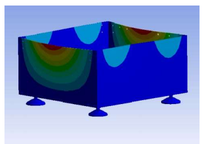

Figure 8: Legacy Vibrational Analysis

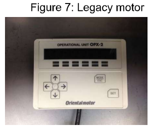

Figure 9: Legacy Controller

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Initial Designs

Cylinder Swing-Bucket Enclosure

- Less critical locations
- More expensive to purchase and machine

Fixed Angle Centrifuge

- Safer design, easier to implement
- Poor sediment quality, more expensive motor

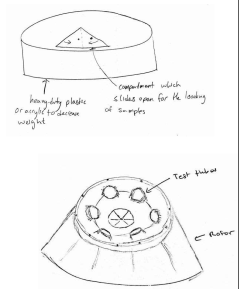

Figure 10: Mock-up Drawings

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Subsystems

- Controller
- Drive system
- Enclosure
- Safety

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Control System

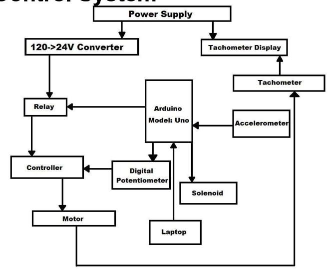

Figure 11: Control System

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Controller

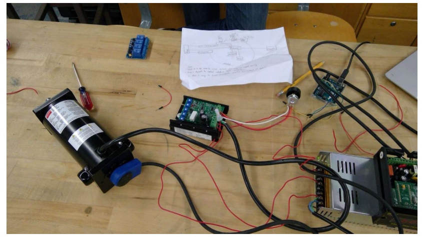

Figure 12: Picture of Arduino Set-up

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Drive System

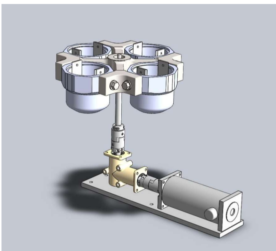

Figure 13: Drive System

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Review of Drive System Requirements

- Produce over 500 g's
  - Prefer to hit 1,000 g's
- Operate for over 4 hours
  - Prefer to operate for 24 hours
- Time Constant <1 minute (¼ HP motor)
- Ease of repairability

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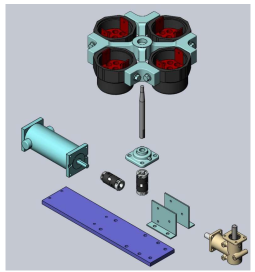
Drive System Breakdown



- Dayton 4Z529D 1/3rd HP Motor
- 6061 Aluminum Motor Mount
- 6061 Aluminum Gearbox Bracket
- Andantex R3200-2 2:1 Gearbox
- 1045 Cold Rolled Steel Spindle
- Swing Bucket Rotor and Vial Holder
- Steel Ball Bearing
- Black-Oxide Alloy Steel Couples with Buna-N Spider
- Dart DM800 Tachometer
- Dart Pulse Sensor

Figure 14: Drive System Breakdown

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Motor: Dayton 4Z529D

- Totally Enclosed Non-Ventilated
- Externally Replaceable Brushes
  - 2,000 hour Brush Lifespan
- Continuous Duty

Figure 15: DC Motor

Table 2: DC Motor Specs

Voltage	24 *Volts*
Power	1/3 *Hp*
Full Load Torque	6.38 *in-lbs*
Max Speed	4200 *RPM*
2:1 Gearbox Out Speed	2100 *RPM*
Max Tangential Speed	144.3 *ft/s*
Max g's	976 *g's*

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Controller

- Dart 38EG41
  - Up to 48 Volts output
  - Up to ⅓ HP
  - Low profile
  - Digital Potentiometer Input
    - 0 to 10 Volts
  - Governor for acceleration and velocity

Figure 16: Dart Controller

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Tachometer and Pulse Sensor

- Dart DM8000
  - 0.1 to 10,000 RPM
  - Averages every second
- Pulse Sensor
  - Hall effect
  - 10 pulses per revolution

Figure 17: Tachometer

Figure 18: Pulse Sensor

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Couple

- Black-Oxide Alloy Steel Flexible Shaft Couples
  - ½" to ⅝" Motor to Gearbox
  - ⅝" to ⅝" Gearbox to Spindle
- Buna-N Spider
  - 1° angular and 0.015" misalignment capability
- 14,000 RPM & 43 in-lbs Torque
- Zinc-Plated Steel Keystock
  - 3/16" x 3/16"
- Clamping Black-Oxide Carbon Steel Shaft Collars

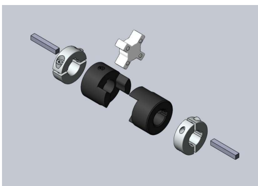

Figure 19: Coupling System

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Bearing and Gearbox

- Andantex R3200-2
  - 50lb Radial Load Capacity
  - 100lb Thrust Load Capacity
  - 77db Maximum Noise Level
  - 2:1 Speed Reducer
  - 23 in-lb Max Input Torque
  - 3,000 hours Lifespan
- 52100 Steel Bearing in Cast Iron Housing
  - 2,150lb Radial Load Capacity
  - 9,500 Maximum RPM
  - Self Aligning Bearing - Lithium Grease
  - ABEC-11

Figure 20: 2:1 Speed Reducer

Figure 21: Bearing

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Legacy: Rotor and Holder

- Legacy Component
- Holds 56 Vials
- Swing Bucket

Figure 22: Legacy Buckets and Rotor

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Legacy: Spindle

- Legacy Component
- 1045 Cold Rolled Steel
- Machined down
  - Diameter and Length
  - "D-shape" shaft

Figure 23: Legacy Spindle

Locking Safety Subsystem

Figure 24: Solenoid

- Initially planning on having automatic shut-off, but too much angular momentum
- Instead decided to have the Arduino operate solenoids which will be lock and unlock the lid

Tilt Safety Subsystem

- Using the accelerometer, the Arduino can shut off by means of the relay if certain conditions are present
  - Centrifuge is tipped over
  - Undesired vibrations are present

Frequency Analysis

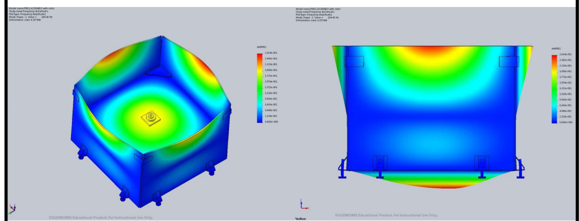

Figure 25: Frequency Analysis

Frequency Analysis

Table 3: Frequency Analysis

Mode #	Frequency(Rad/sec)	Frequency(Hertz)	RPM	Period(Seconds)
1	656.34	104.46	6267.6	0.00957854
2	764.27	121.64	7298.4	0.0082212
3	811.37	129.13	7747.8	0.0077439
4	811.61	129.17	7750.2	0.0077416
5	829.18	131.97	7918.2	0.0075776

Motor's maximum speed: 4200 RPM
Rotor's maximum speed: 4750 RPM

Initial Confirmation of Impact Test Analysis

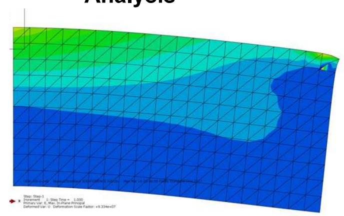

Figure 26: Impact Analysis

Strain Energy (hand calculated)

$$U_I = \frac{P^2 L^3}{EI}$$

Strain Energy FEA

$$U_I = \frac{1}{2} P\Delta$$

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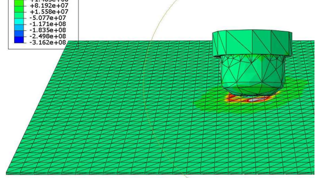
Impact Analysis - FEA

Table 4: Min and Max Stresses at Impact

	S.Mises Pa	S.Max.Prin Pa	S.S11 Pa	S.S22 Pa
Minimum at Element	1.01E-18	-4.25E+08	-7.35E+08	-7.55E+08
Maximum at Element	1.81E+11	1.06E+11	7.45E+09	4.90E+09



⅛" Thickness

Figure 27: Impact on ⅛" Thick A36 Plate

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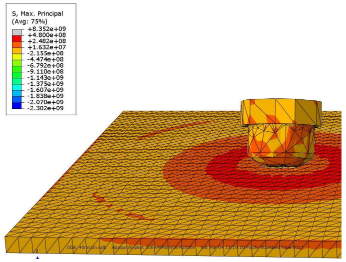
Impact Analysis (FEA cont.)



1" Thickness

Figure 28: Impact on 1" Thick A36 Plate

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Impact Analysis - Experimental

- **Factors of Safety**
  - Weight was dropped at 12.57 feet
  - Plates test were ⅛" inch compared to ¼"

Table 5: Impact Specs

Maximum Energy	0.604 *Btu*
Weight Used	45 *lbs*
Height Needed	10.43 *ft*

Figure 29: Deformed Steel Plates

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Creep Test

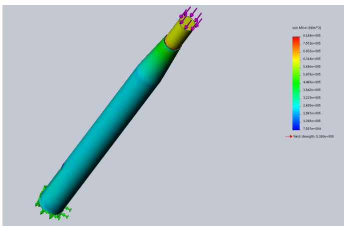

Figure 30: Creep Analysis

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Enclosure

- **A36 Steel ¼" Thick**
  - Base: 24" x 24"
  - Walls: 24" x 18"
- **Nuts and Bolts**
  - Grade 8 Black Oxide Alloy Steel Bolts
  - Grade 8 Zinc Plated Steel Nylon Locknuts
- **Brackets**
  - Plain Carbon Steel 0.10" thick

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Budget

Table 6: Budget

Date	Vendor	Item	Cost	Remaining
	SCU	Funding	$ 1,500.00	$ 1,500.00
	Xilinix	Funding	$ 1,000.00	$ 2,500.00
10/20/2016	Amazon	24V Converter	$ (24.88)	$ 2,475.12
2/9/2017	Grainger	DC Controller	$ (401.63)	$ 2,073.49
2/9/2017	Zoro	Tachometer	$ (235.29)	$ 1,838.20
2/9/2017	Amazon	Dayton Motor	$ (217.12)	$ 1,621.08
3/1/2017	Amazon	R3200-2 Gear	$ (198.61)	$ 1,422.47
3/2/2017	McMaster	Couples motor	$ (83.89)	$ 1,338.58
3/3/2017	Grainger	Pulse	$ (150.74)	$ 1,187.84
3/21/2017	Amazon	Cable + Relay	$ (11.88)	$ 1,175.96
4/5/2017	Maxx Metals	Steel	$ (183.24)	$ 992.72
4/5/2017	Amazon	Solenoid	$ (15.98)	$ 976.74
4/21/2017	BT Laser	Machining	$ (338.60)	$ 638.14
4/24/2017	McMaster	Couple Shaft	$ (158.11)	$ 480.03
4/28/2017	McMaster	Aluminum	$ (82.04)	$ 397.99
5/2/2017	McMaster	Bolts	$ (74.65)	$ 323.34
5/5/2017	Amazon	Digipot	$ (7.62)	$ 315.72
5/9/2017	Home Depot	Bolts	$ (11.42)	$ 304.30

- **Total Cost: $2195.70**
- **Rotor and Spindle**
  - ~$500 more
- **Prototype Cost**
  - ~$2700

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Overall Assembly - Model

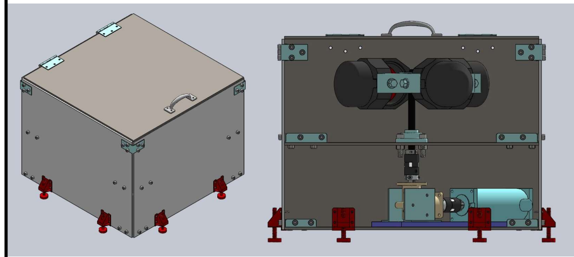

Figure 31: CAD of final product

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Conclusion

- Centrifuge is built and functioning
  - able to achieve the speeds necessary for research
- Metal Lid
  - A36 steel will be used for end product
- Safety systems need to be finalized
  - Accelerometer
  - Solenoids
- Documentation
  - Operation and Repair manuals must still be created

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Things We Learned

- Experimental Analysis is more accurate than simulation analysis
- Overestimate on the time it takes to complete tasks
- Ensure that parts are machined within tolerances

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Demo & Variable Output

Table 7: Variable Output

Motor (RPM)	Shaft (RPM)	G's
840	420	39.0
1200	600	79.7
1800	900	179.3
2400	1200	318.7
2670	1335	394.4
2870	1435	455.7
3000	1500	498.0
3300	1650	602.5
3500	1750	677.8
3700	1850	757.5
4000	2000	885.3
4175	2087.5	964.4

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Questions?

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