

Ege Turan
Winter 2025

V3 Centrifuge Design Cycle

Problem: Produce a centrifuge to unmix fluid inputs, *with additional safety, accessibility convenience, and control features*. This was a successful V3, named “Kirby”!

Our V3 system builds on the skeleton/prototype V2 system. V3 adds an enclosure, additional safety and control features, replaces the screen (from a character LCD to a pixel OLED) for better icons and communication, and audio (including music) functionality.

Requirements: [BIOE123_Centrifuge_Requirements_2025](#)

V3 Proposal: [BIOE123_V3projectProposal_TeamA8](#)

Troubleshooting Notes: [Troubleshooting Best Practices Reflection/Sharing \(Group\) - A8](#)

Team Bring Up Plan for V2, upon which V3 is built: [BIOE123_V2bringupPlan_TeamA8](#)

The V2 (V3 extends on it) - specific design, testing, and assessment processes can be found at:

[BIOE123_V2centrifugeDesignCycle_TeamA8](#)

[BIOE123_V2mechanicalSubsystem_TeamA8](#)

[BIOE123_V2sensorSubsystem_TeamA8](#)

[BIOE123_V2actuatorSubsystem_TeamA8](#)

[BIOE123_V2controlSubsystem_TeamA8](#)

The version-controlled code is available here: <https://github.com/ege-turan/bioe123centrifuge>

Shared Root Trace Matrix for V3 Centrifuge (Measurements are given in each section, or sheet page for each subsystem, linked tables are included in this sheet)

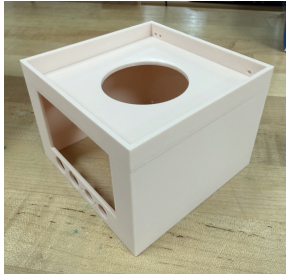
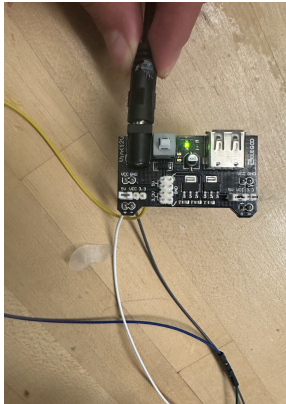
Linked here (living, updating): [centrifugeDesignCycleV3traceMatrix](#)

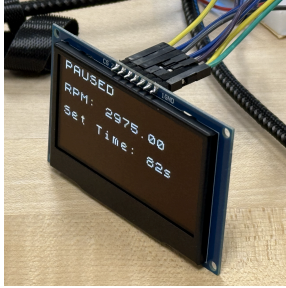
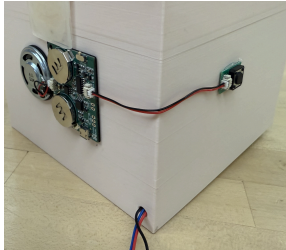
Presentation Slides: [CentrifugeSystemPresentation_EgeTuran](#)

Important tables and plots to be highlighted from our experimentation have been linked/included in this document, but please see the trace matrix for the full extent of verification and validation tests that were conducted.

We also include the trace matrix sheet in this document along with a link to the full spreadsheet at a later section, jump there by clicking: [Trace Matrix](#)

V3 Improvements Table

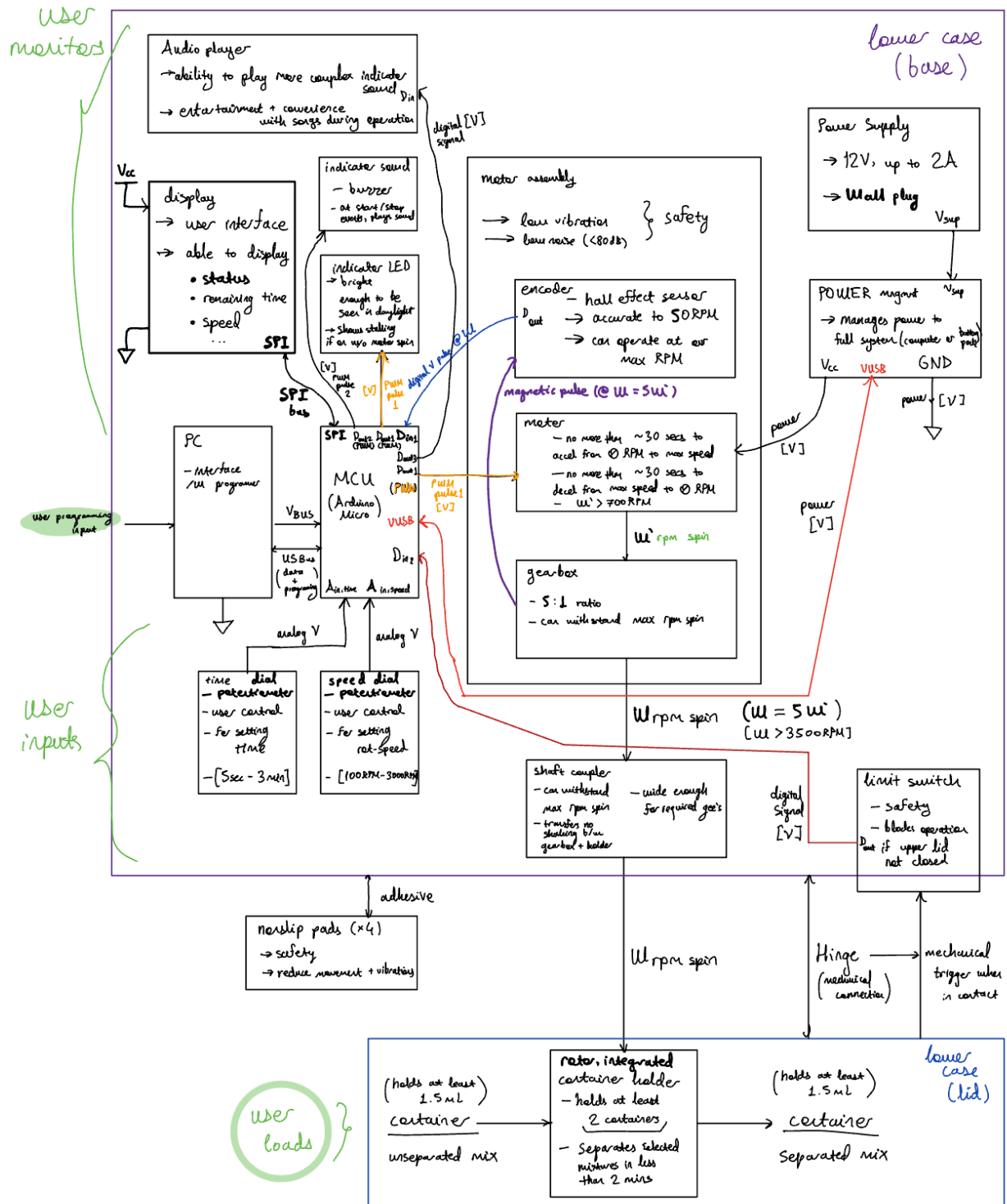
New Requirements	Design Element	Motivation	Results (for detailed tests, see the trace matrix)
The system should be enclosed for less noise and to prevent any high-speed, dangerous projectiles ejecting and harm users and people around the centrifuge	Case Enclosure 	1. Less noise (DB) 2. Safer	Successful
The system shall be external-battery-powered	Battery → Wall plug 	More convenient and even fun to use, transportable	Battery pack was dysfunctional; we instead used wall-power to power the entire system with one DC plug. It is still easy to transport since all the user has to carry additionally is a wall adapter.

			
The system shall display helpful icons for setup and operation The system's display shall be visible in low light, very bright light, and from side views.	OLED Display 	Safer, more accessible, more convenient and even fun to use Better visibility especially from sides and at lower light	Successful
The system shall provide audio cues to the user for safety and convenience	Sound system 	Safer, more accessible, more convenient and even fun to use	Successful
The system shall be able to withstand vibrations. The system shall not move on its own.	Non-slip pads 	Safer, more accessible, and more convenient to use	Successful

The system should be easily usable allowing for quick turn on/ off with addition to other functions like speed up/ slow down.	Buttons 	Easy use for users. More safe as users can stop the centrifuge if needed.	Successful
The system shall not start spinning unless safety precautions (closing the case/enclosure is taken)	Limit switch 	More safe and decrease the chance of accidental damages to user, properties, and samples	Successful

In addition, V3 should inherit all requirements from V2 and successfully fulfill them

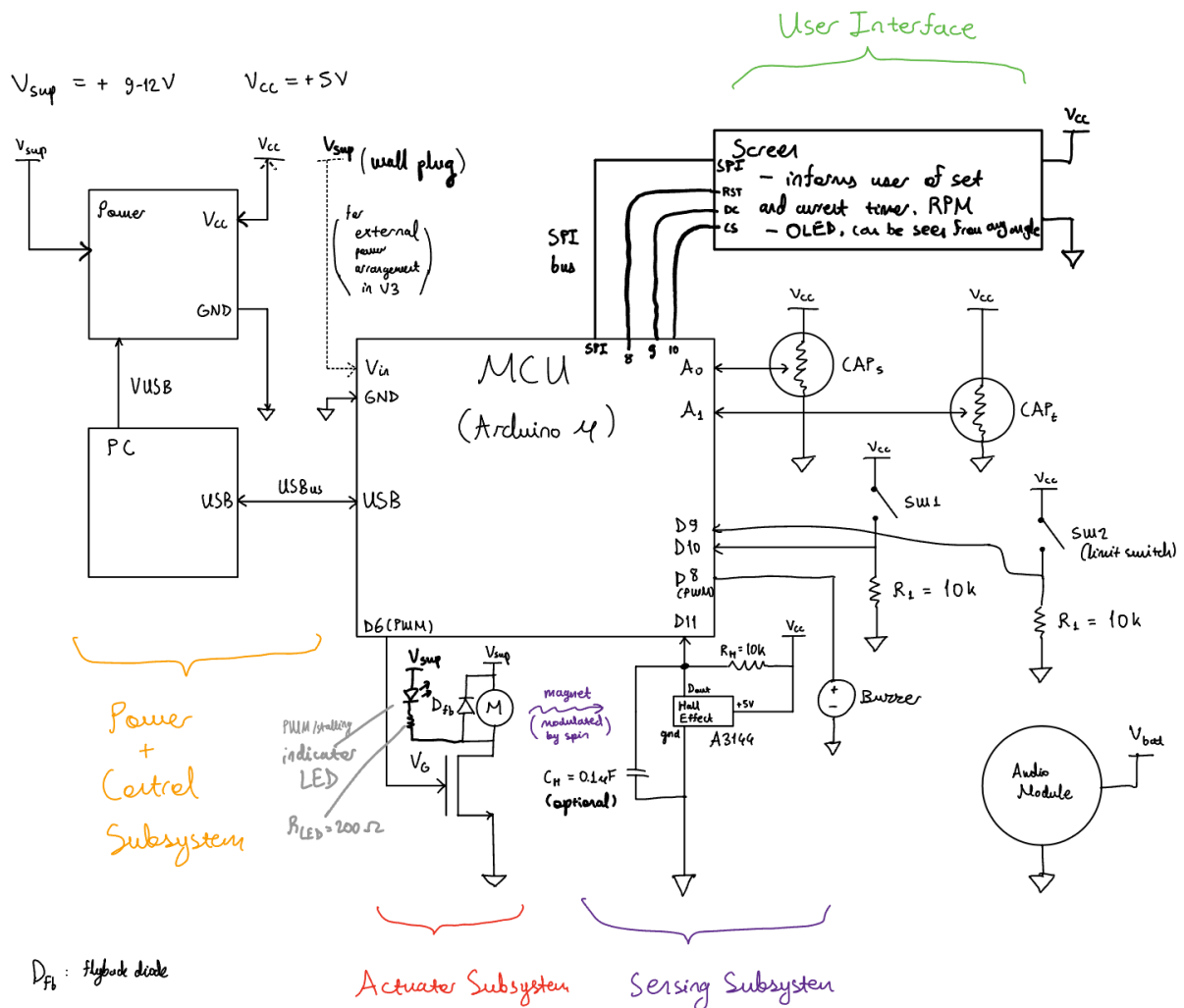
Figure 1: Updated V3 Centrifuge Block Diagram



All inputs and outputs (and their units are labeled with arrows).

User/operator interactions are highlighted in green. Block diagram of a centrifuge system illustrating the interaction between user inputs, control interfaces, and mechanical components. The system includes a user interface for displaying status and settings, an Arduino-based MCU for processing, motor assemblies with Hall effect sensors for speed control, and a rotor integrated holder for separating mixtures in containers, with safety and power management features such as an external case.

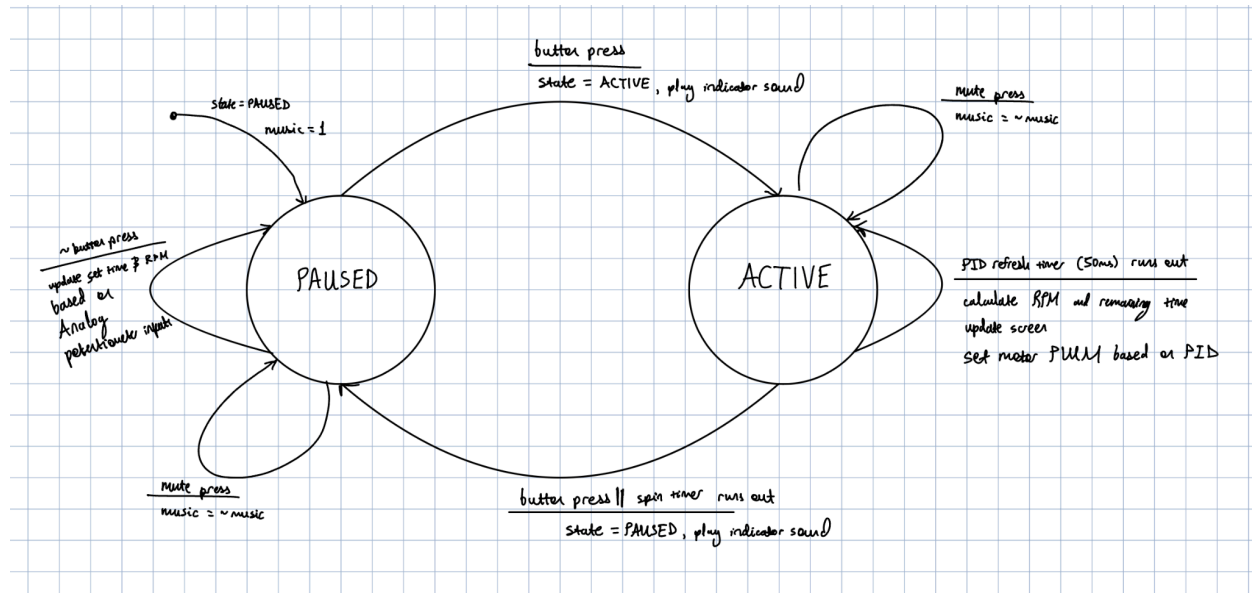
Figure 2: Updated V2 Centrifuge Circuit Diagram



The diode parallel to the motor is an indicator LED, in our case, white. Schematic diagram of a centrifuge system's control architecture, featuring a user interface for setting time and RPM, an Arduino-based MCU for processing, and interconnected subsystems for power control, actuation

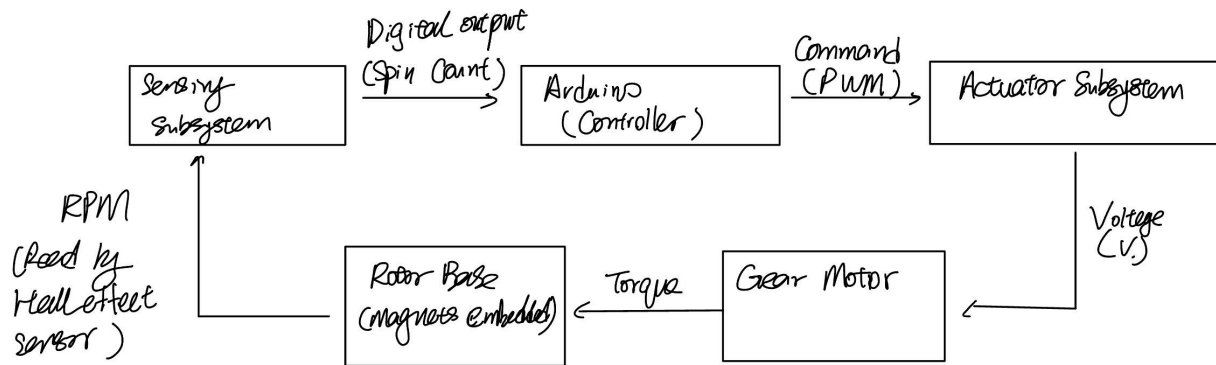
(including a motor and PWM indicator LED), and sensing (with a Hall effect sensor and buzzer). The screen is controlled via a SPI bus (as opposed to I2C in our previous system). The actuator (and optionally the full system) is powered by a 9-12V supply regulated to 5V.

Figure 3: Updated V3 Centrifuge Finite State Machine (FSM)



State diagram illustrating the operational states of a centrifuge system, transitioning between 'PAUSED' and 'ACTIVE' states. The system moves from PAUSED to ACTIVE with a button press, playing an indicator sound, updating set time and RPM based on analog input, and calculating RPM and remaining time. It returns to PAUSED when the button is pressed again or the spin timer runs out, also playing an indicator sound, with PID control refreshing every 50ms to set motor PWM and update the screen. Music can be muted and unmuted by pressing the mute button.

Figure 4: V3 PID Control Diagram



The block diagram for our control subsystem. It is a closed loop control system enabling more fine and accurate control of the speed (RPM). The PID controller starts with user input into the Arduino. Input from the user is then converted into a PWM signal feed into the actuator subsystem that drives the gear motor leading to rotor base rotations. Each rotation is then picked up by the hall effect sensor as the magnet underneath the rotor base will trigger the sensing subsystem. Data regarding how fast the centrifuge is then fused into the controller for motor speed adjustment to achieve the desired RPM set by the user.

V3 System Figures and Demo Video:

We built our V3 system upon our V2 system. The V2 system functioned as the skeleton and the prototype for V3.

Figure 5a: V3 System Diagonal View



Here is an operator demo of the V3 system:

<https://drive.google.com/file/d/18y70nMO5ZVp8TnJLP6V4Mf53VuGIvHBB/view?usp=sharing>

The demo also showcases the system's closed loop PID speed control and the system stopping on its own when the set timer runs out.

Here is a safety demo, showing the system not starting (and stopping) if the lid is not closed (based on the limit switch):

https://drive.google.com/file/d/1kqrG5GRL5SirUuz_T_YSzkTB7nYG6t8g/view?usp=sharing

Figure 5b: Fully-Integrated V3 System Circuit Viewed From the Top

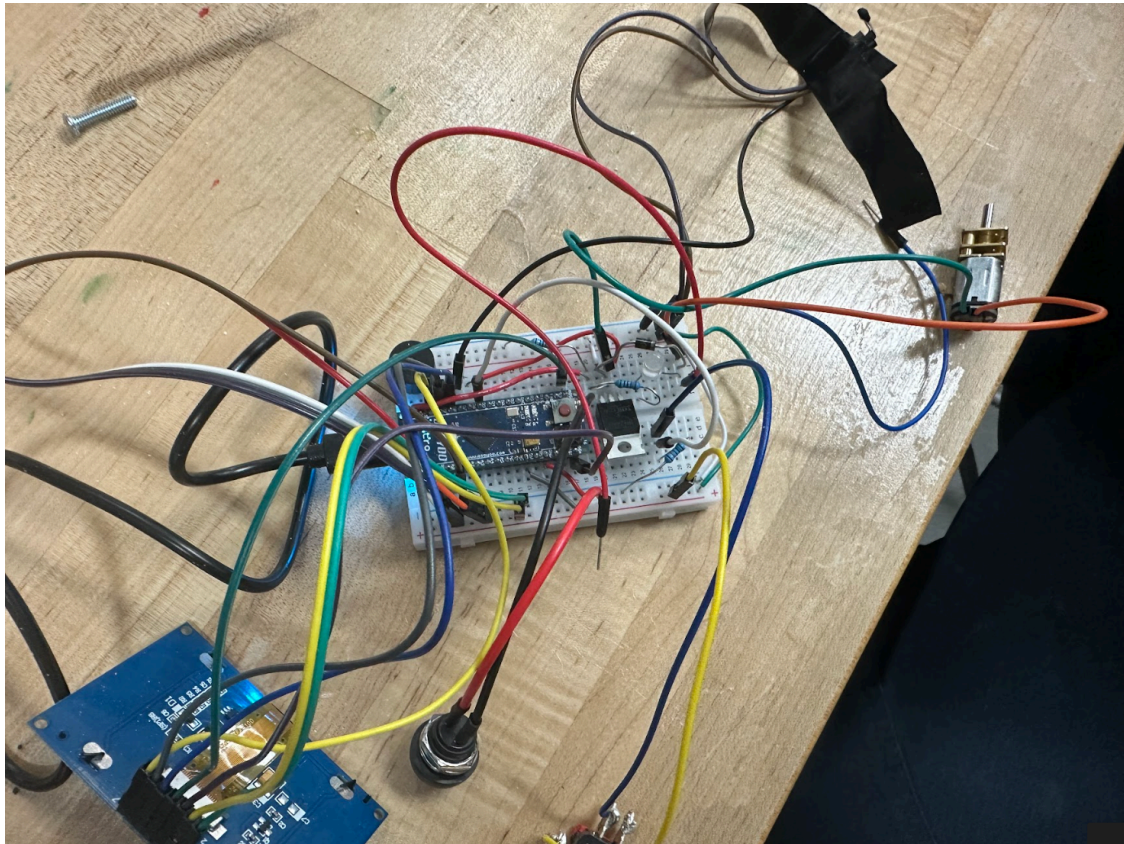
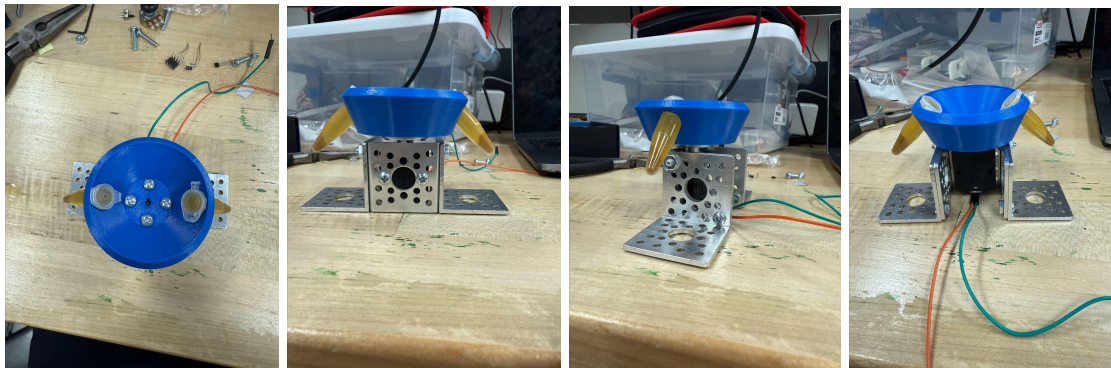


Figure 5c: Rotor Base Mechanical Sub Assembly Detail Figures



The above images are the fully assembled V3 centrifuge taken at various angles. It features a screen to report current speed and time left in the spinning cycle, two knobs for setting speed (RPM) and time (seconds), and the motor base.

Figure 5d: V3 Electrical Systems Soldering Process Images Taken from Top Diagonal (Left Image) and Back Diagonal (Right Image)

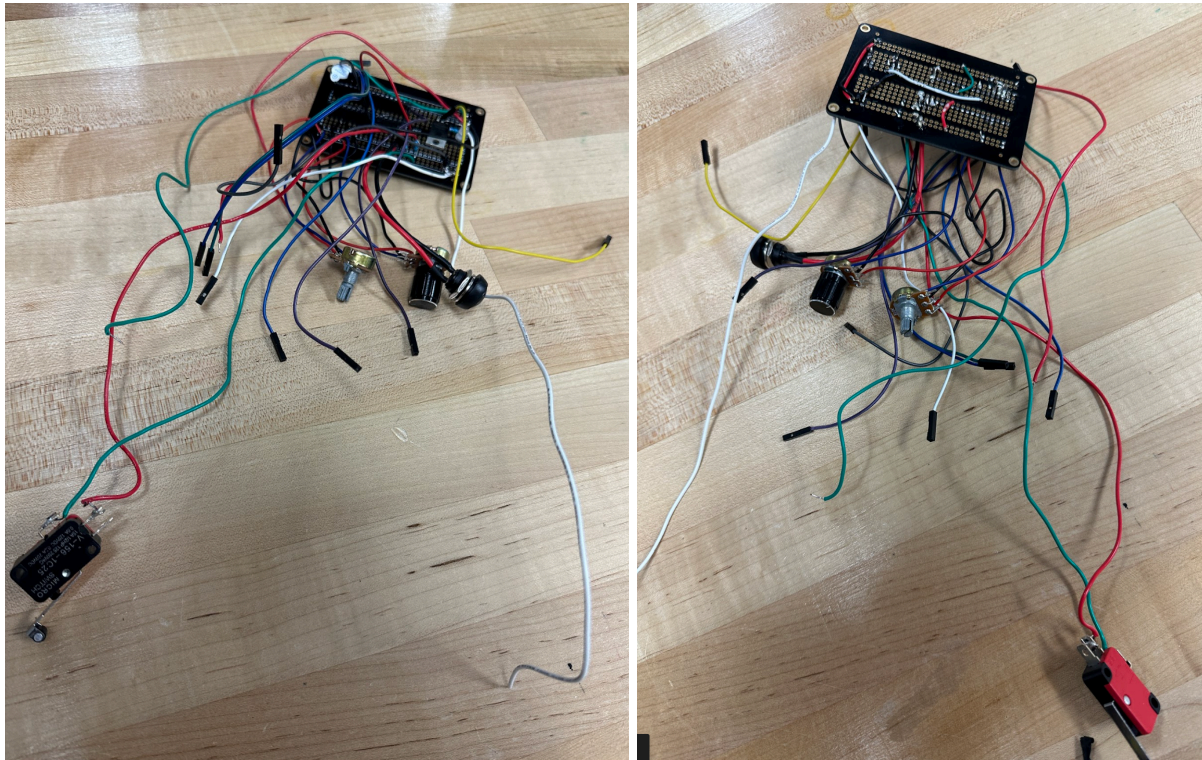
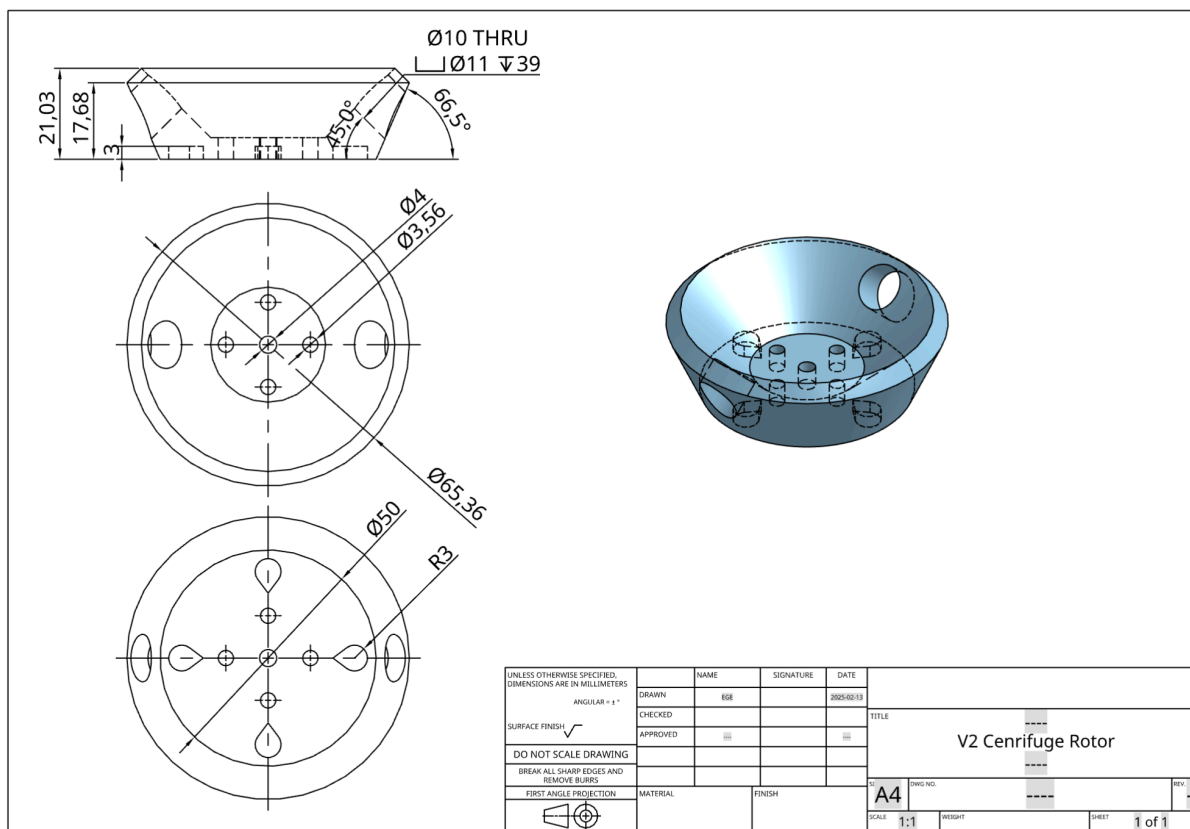


Figure 5e: V3 Mechanical and Electrical Systems Integration Process Images Taken from Top Diagonal (Left Image) and Back Diagonal (Right Image)



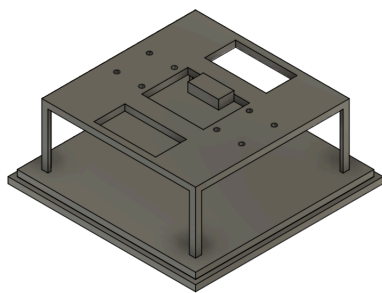
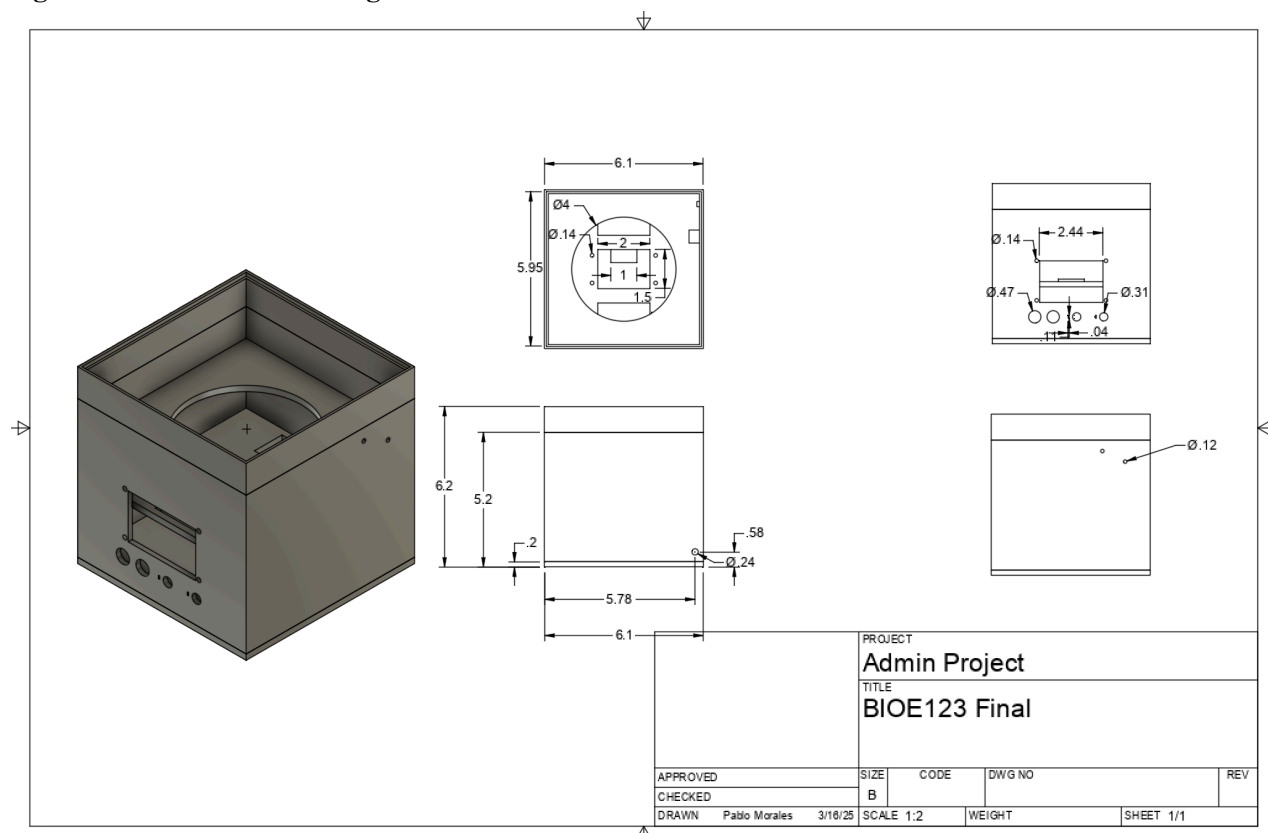
Figure 6a: Technical Drawing of Rotor and Tube Holder:



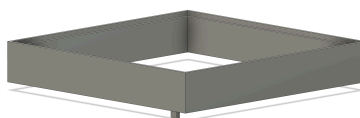
Rotor and Tube Holder CAD Link on OnShape:

<https://cad.onshape.com/documents/3d393e1f4f20ebc8bbd0022b/w/8411983a8f5355a0023782ab/e/a108e3f37d4740ad83a6e7e3>

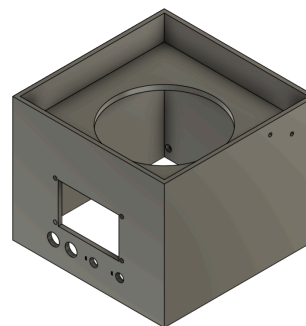
Figure 6b: Technical Drawing of Enclosure:



Bottom Piece



Lid



Main Body

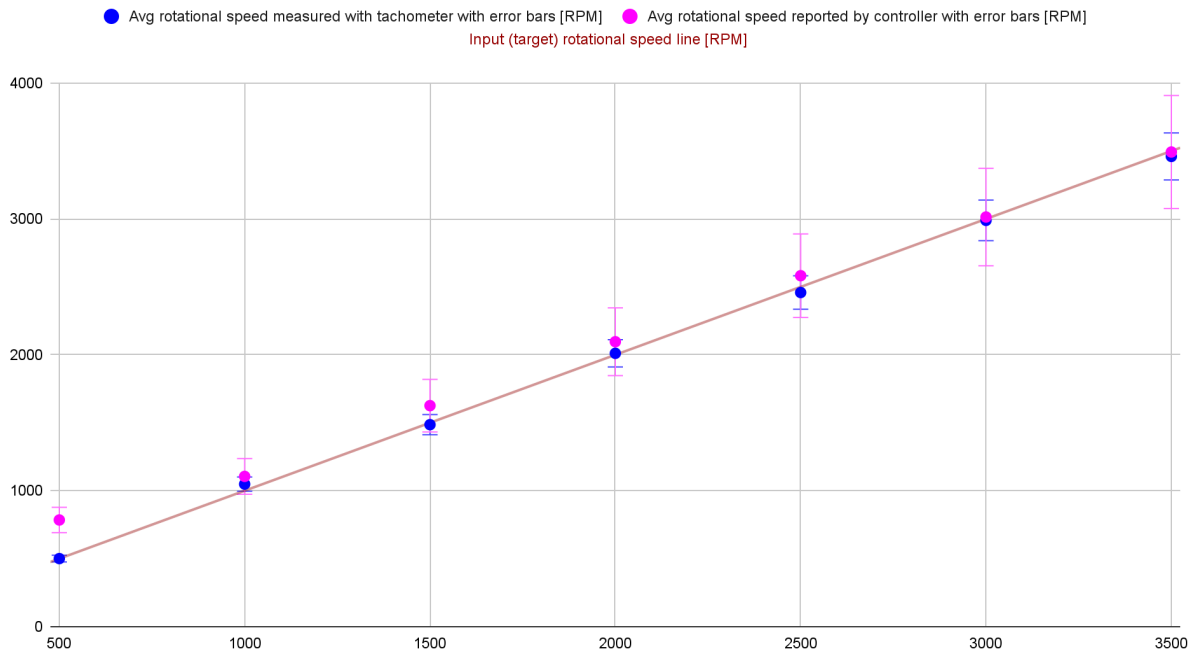
Enclosure CAD link Fusion: <https://a360.co/41VDihs>

TESTING AND PLOTS

We recorded our system's reported (measured by the hall effect sensing subsystem and computed by the Arduino) and actual (real speed measured by the light tachometer) .

Figure 7:

System rotational speed accuracy and precision plot: Measured vs Input (Target) Rotational Speed



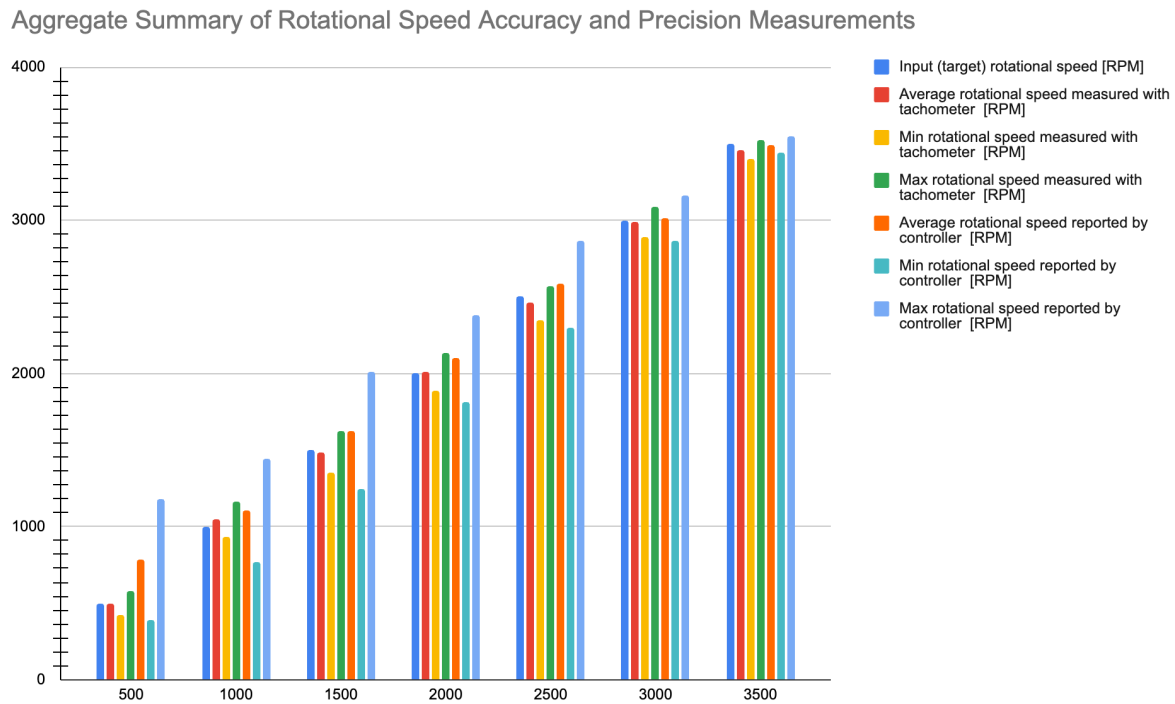
As given in Table: System rotational speed accuracy and precision testing (results recorded between 30 seconds and 2 mins to simulate transient response), for transient state, the system oscillates with the following properties (measured at 500 RPM intervals, between 500-3500 RPM):

PID control coefficients: Kp = 0.7, Ki = 1.5, Kd = 0.03, selected to be more accurate at higher (operational) rotation speeds	Table: System rotational speed accuracy and precision testing (results recorded between 30 seconds and 3 mins to simulate transient response)										For error bars	
Input (target) rotational speed [RPM]	Average rotational speed measured with tachometer [RPM]	Min rotational speed measured with tachometer [RPM]	Max rotational speed measured with tachometer [RPM]	Average rotational speed reported by controller [RPM]	Min rotational speed reported by controller [RPM]	Max rotational speed reported by controller [RPM]	Range (amplitude) of rotational speed measured with tachometer [RPM]	Range (amplitude) of rotational speed reported by controller [RPM]	Error of average rotational speed measured with tachometer compared to input (target) [%]	Error of average of rotational speed reported by controller compared to tachometer reading [%]	Average error of average rotational speed measured with light tachometer compared to input (target) [%]	Average error of average of rotational speed reported by controller compared to tachometer reading [%]
500	500.5	421	580	784.565	387.13	1182	79.5	397.435	0.1	56.75624376	0.2019727891	11.80930717S
1000	1048.5	935	1162	1105.38	765.06	1445.7	113.5	340.32	4.85	5.424892704		
1500	1486	1352	1620	1626.09	1241.3	2010.88	134	384.79	-0.9333333333	9.427321669		
2000	2011	1888	2134	2096.42	1809.94	2382.9	123	286.48	0.55	4.247637991		
2500	2458.5	2351	2566	2582.4	2298.03	2866.77	107.5	284.37	-1.66	5.039658328		
3000	2989.5	2890	3089	3014.16	2866.67	3161.65	99.5	147.49	-0.35	0.8248871049		
3500	3460	3400	3520	3492.68	3439.66	3545.7	60	53.02	-1.142857143	0.9445086705		

This table evaluates the rotational speed accuracy and precision of a centrifuge system using PID control ($K_p = 0.7$, $K_i = 1.5$, $K_d = 0.03$), optimized for higher speeds, with results recorded between 30 seconds and 3 minutes. It compares target speeds (500–3500 RPM) to speeds measured by a tachometer and reported by the controller, assessing averages, minima, maxima, ranges, and errors. At 500 RPM, the tachometer-measured average speed is 500.5 RPM (0.1% error from target), while at 3500 RPM, it's 3460 RPM (0.2019% error), showing high accuracy.

Controller-reported speeds closely align, with errors generally below 1% compared to targets. Variability (ranges) increases with speed, e.g., 79.5 RPM at 500 RPM versus 60 RPM at 3500 RPM for tachometer measurements. The average error between tachometer and controller readings remains low, typically under 1%, indicating consistent performance. Higher speeds show slightly larger absolute ranges but smaller relative errors, confirming the PID tuning's effectiveness at operational speeds. The table highlights the centrifuge's reliability, with minimal discrepancies between measured and target speeds, supporting its precision for applications requiring stable high-speed rotation.

Figure 8: Aggregate Summary of Rotational Speed Accuracy and Precision Measurements



The above is a graph (Figure 8) visualization of the above table. One interesting trend that can be extracted from the graph is that the percent error during high RPM between set RPM and measured RPM is low. Contrary, the percent error is high during low RPM settings. This can be attributed to the fact that the PID setting is optimized for higher RPMs.

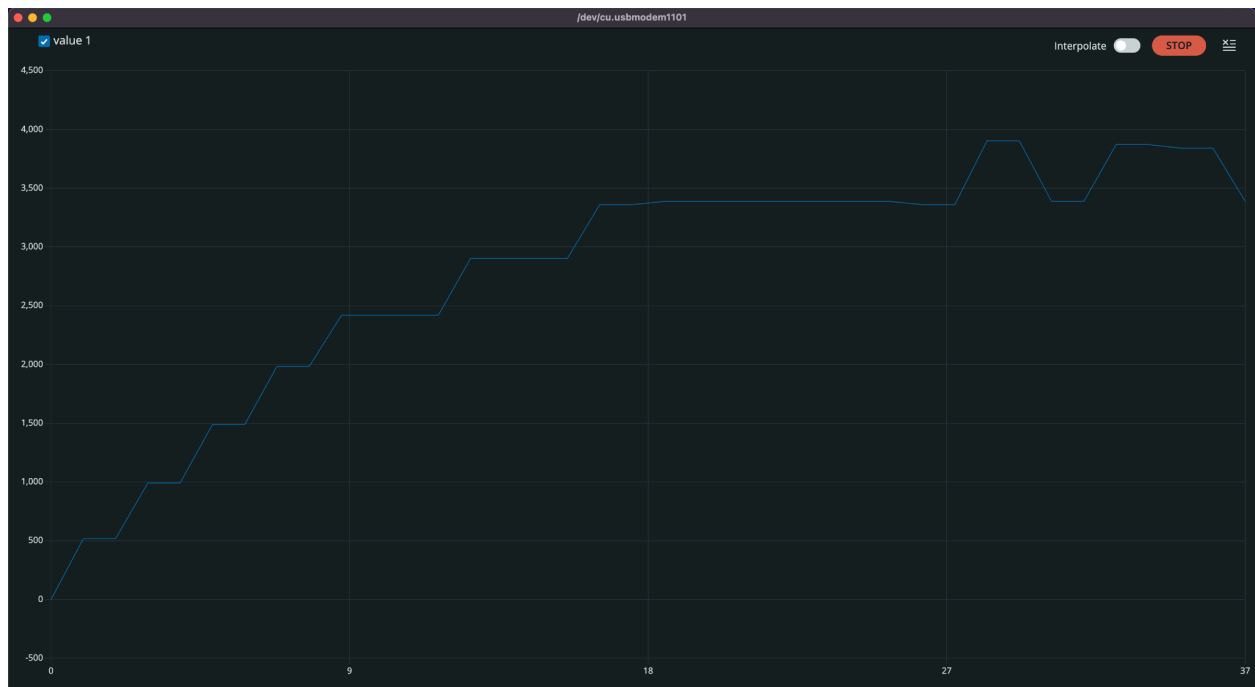
Integrated System Control Tests:

We measured the deviation from input (target) rotational speed and the amount of time it takes to reach that speed consistently.

We included our system's rotation speed versus time plot as the control system following properties (measured at 500 RPM intervals, between 500-3500 RPM):

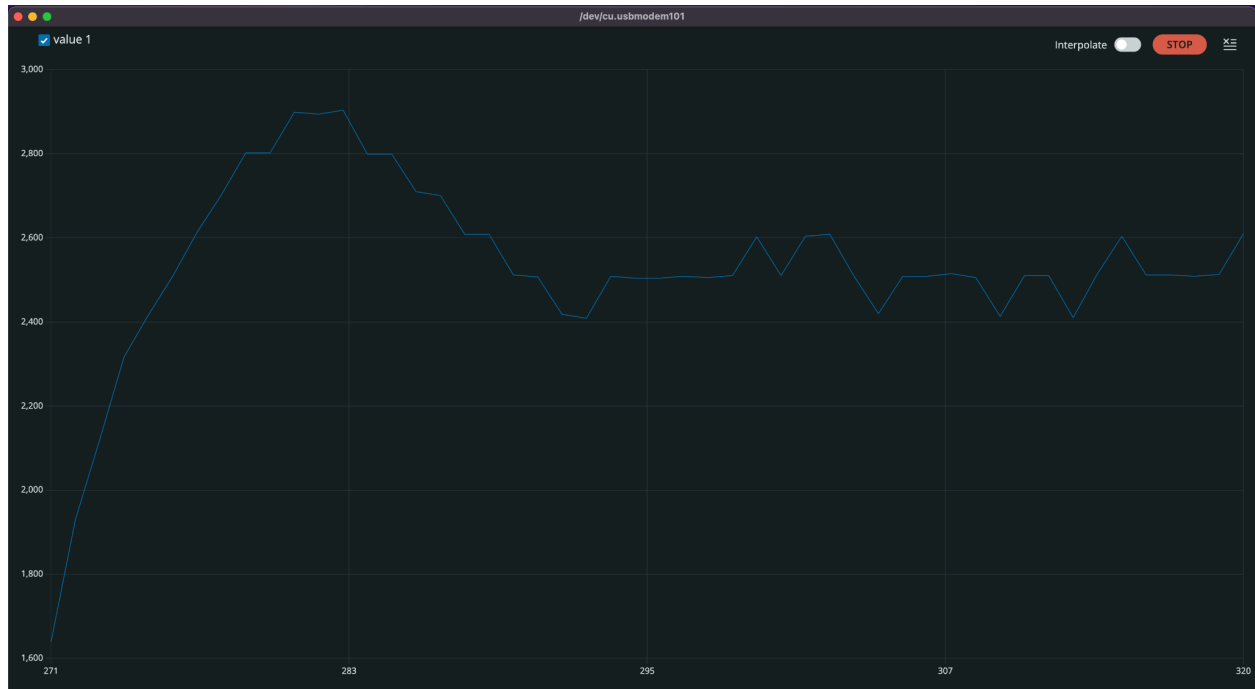
This is supported by the information in [Table: System rotational speed accuracy and precision testing \(results recorded between 30 seconds and 2 mins to simulate transient response\)](#).

Figure 9: Ramp-up test for max speed 3500RPM, plot shows speed over samples, samples are collected every 50 ms:



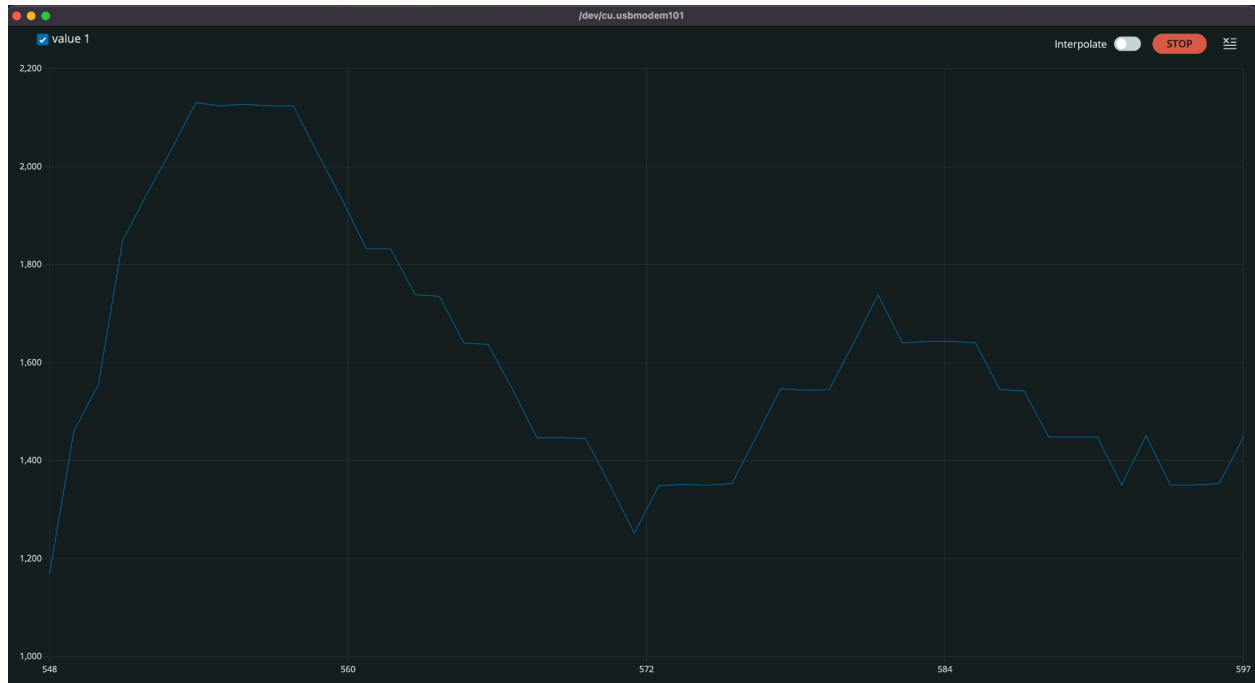
From $[28 \text{ samples} * (50 \text{ ms} / \text{sample})]$ it takes about 1.4 seconds for our system to ramp up to maximum speed. This is lower for slower input (target) rotational speeds).

Figure 10: Ramp-up test for max speed 2500RPM, plot shows speed over samples, samples are collected every 50 ms:



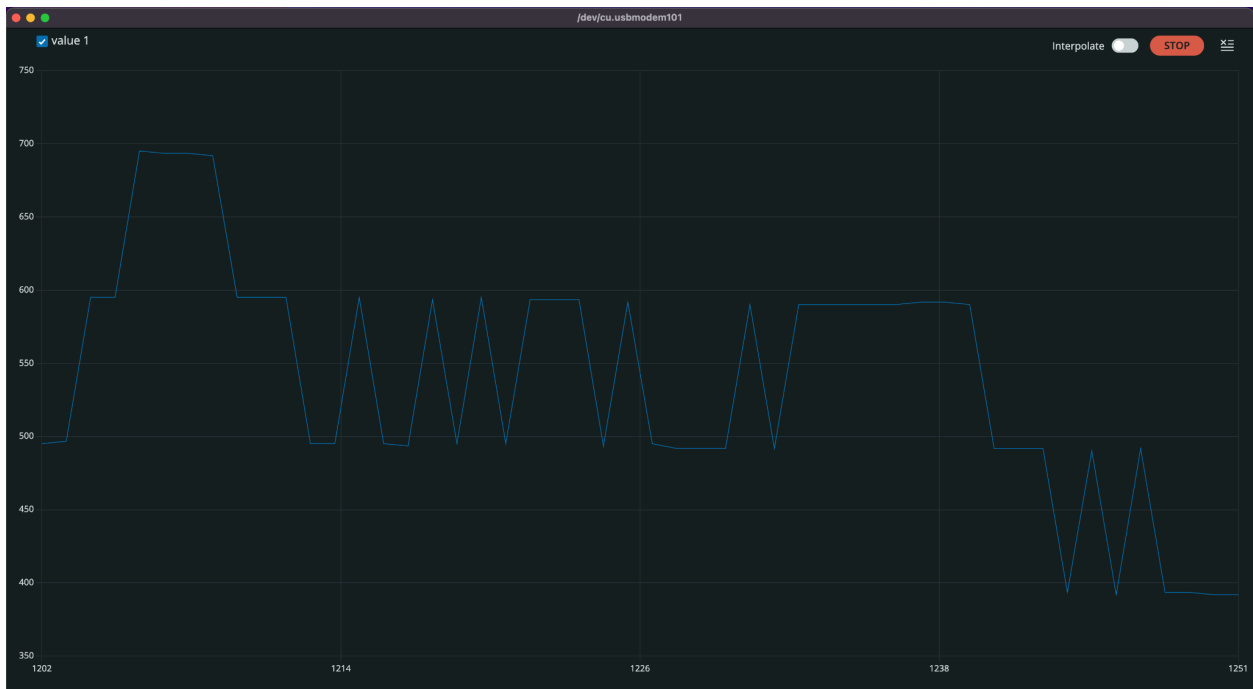
The above graph traces RPM overtime when V2 centrifuge is set to operate at 2500 RPM. As shown, there is a slight overshoot as the system spins from 0 rpm to 2500 RPM (overshooting to around 2900 RPM). After this brief overshoot, the system is able to maintain a speed around 2500 RPM by oscillating around this set RPM value.

Figure 11: Ramp-up test for max speed 1500 RPM, plot shows speed over samples, samples are collected every 50 ms:



The above graph traces RPM overtime when V2 centrifuge is set to operate at 1500 RPM. As shown, there is a slight overshoot as the system spins from 0 rpm to 1500 RPM (overshooting to around 2100 RPM). After this brief overshoot, the system is able to maintain a speed around 1500 RPM by oscillating around this set RPM value. However, due to the fact that the PID controller system is optimized for higher RPM, the oscillation is higher in magnitude than the 2500 RPM situation.

Figure 12: Ramp-up test for max speed 500 RPM, plot shows speed over samples, samples are collected every 50 ms:



The above graph traces RPM overtime when V2 centrifuge is set to operate at 500 RPM. As shown, there is a slight overshoot as the system spins from 0 rpm to 500 RPM (overshooting to around 700 RPM). After this brief overshoot, the system is able to maintain a speed around 500 RPM by oscillating around this set RPM value. However, due to the fact that the PID controller system is optimized for higher RPM, the oscillation is higher in magnitude than the 2500 RPM situation.

As given in [Table: System rotational speed accuracy and precision testing \(results recorded between 30 seconds and 2 mins to simulate transient response\)](#), for transient state, the system oscillates with the following properties (measured at 500 RPM intervals, between 500-3500 RPM):

PID control coefficients: $K_p = 0.7$, $K_i = 1.5$, $K_d = 0.03$, selected	Subtable: System rotational speed accuracy and precision testing (results recorded between 30 seconds and 3 mins to simulate transient response)
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to be more accurate at higher (operational) rotation speeds					
Input (target) rotational speed [RPM]	Average rotational speed measured with tachometer [RPM]	Min rotational speed measured with tachometer [RPM]	Max rotational speed measured with tachometer [RPM]	Range (amplitude) of rotational speed measured with tachometer [RPM]	Error of average rotational speed measured with tachometer compared to input (target) [%]
500	500.5	421	580	79.5	0.1
1000	1048.5	935	1162	113.5	4.85
1500	1486	1352	1620	134	-0.9333333333
2000	2011	1888	2134	123	0.55
2500	2458.5	2351	2566	107.5	-1.66
3000	2989.5	2890	3089	99.5	-0.35
3500	3460	3400	3520	60	-1.142857143

Actuator-Subsystem Testing and Plots

Table: Loaded Rotor Subsystem Speed and Current Draw Test at DC Voltage

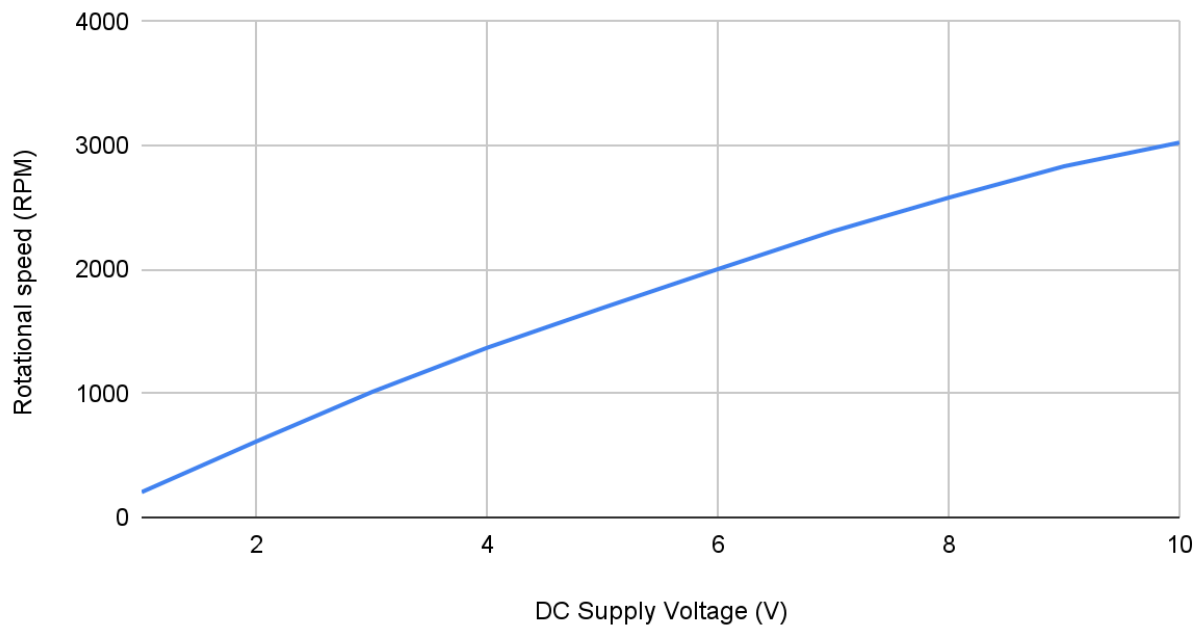
DC Supply Voltage (V)	Rotational Speed (RPM) measured with tachometer	Current draw (mA)	Power draw (W)
1	204	35	0.035
2	615	43	0.086
3	1013	49	0.147
4	1370	60	0.24
5	1691	74	0.37
6	2004	91	0.546
7	2310	111	0.777
8	2580	132	1.056
9	2833	156	1.404

10	3024	184	1.84
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We plotted these preliminary results and saw the following relations:

Figure 13: Rotational speed vs DC supply voltage for loaded V3 centrifuge

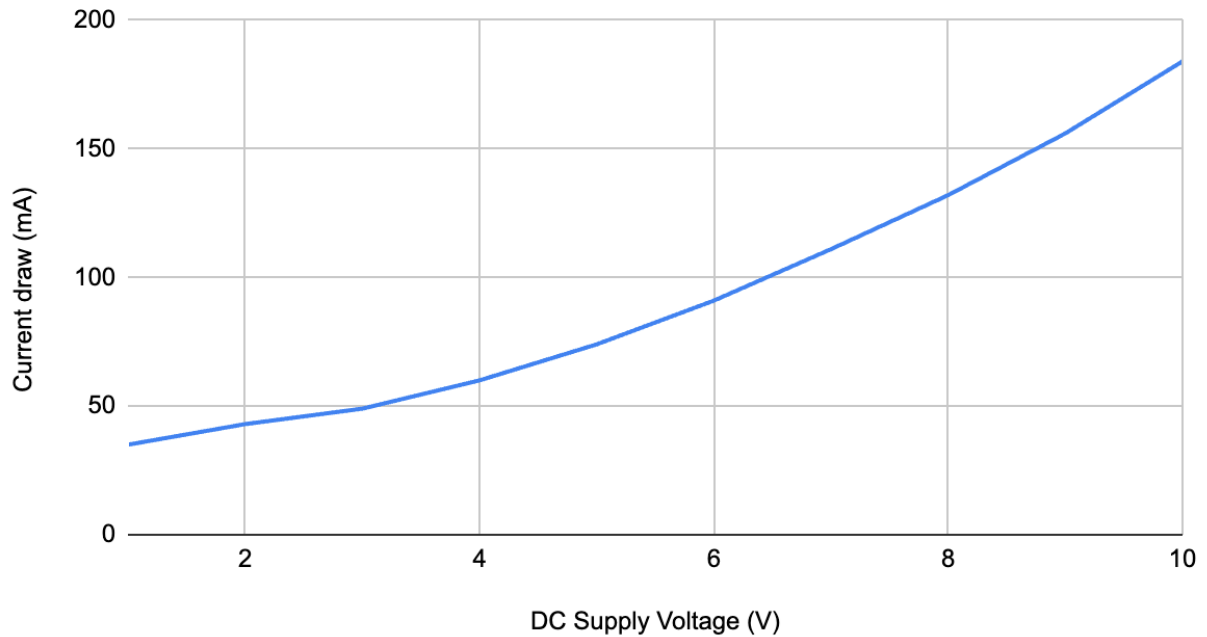
Rotational speed vs DC supply voltage for loaded V2 centrifuge



The graph presents the relationship between rotational speed (in RPM) and DC supply voltage (in V) for a loaded V2 centrifuge. The x-axis represents the DC supply voltage, ranging from 0 to 10 V, while the y-axis represents the rotational speed, ranging from 0 to 4000 RPM. The plot shows a positive correlation, where an increase in DC supply voltage leads to a higher rotational speed. The curve follows a non-linear trend, with the rate of increase in RPM diminishing at higher voltages.

Figure 14: Current draw vs DC supply voltage for loaded V3 centrifuge

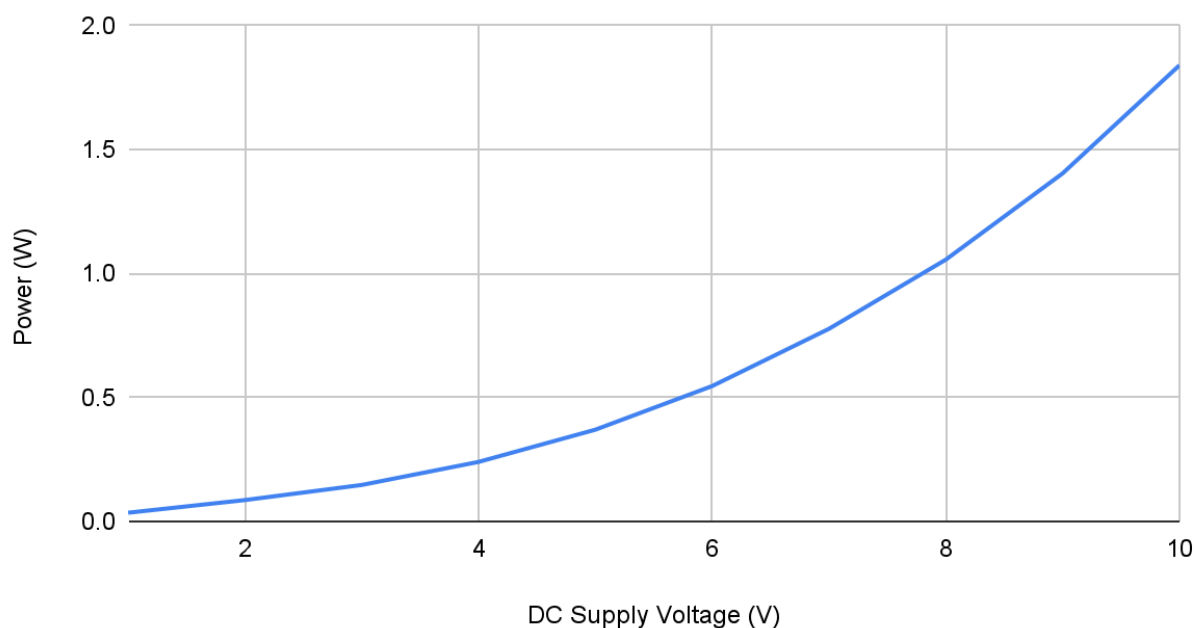
Current draw vs DC supply voltage for loaded V2 centrifuge



The graph illustrates the relationship between current draw (in mA) and DC supply voltage (in V) for a loaded V3 centrifuge. The x-axis represents the DC supply voltage, ranging from 0 to 10 V, while the y-axis represents the current draw, ranging from 0 to 200 mA. The plot shows a positive correlation, where an increase in DC supply voltage results in a higher current draw. The trend appears nonlinear, with the rate of increase in current becoming more pronounced at higher voltages.

Figure 15: Power draw vs DC supply voltage for loaded V2 centrifuge

Power draw vs DC supply voltage for loaded V2 centrifuge



The graph shows the relationship between power draw (in W) and DC supply voltage (in V) for a loaded V2 centrifuge. The x-axis represents the DC supply voltage, ranging from 0 to 10 V, while the y-axis represents the power draw, ranging from 0 to 2 W. The plot indicates a nonlinear increase in power consumption as the DC supply voltage rises, with the power draw accelerating at higher voltages.

All of the original plots and data table can be viewed at the “Actuator Tests” page of:

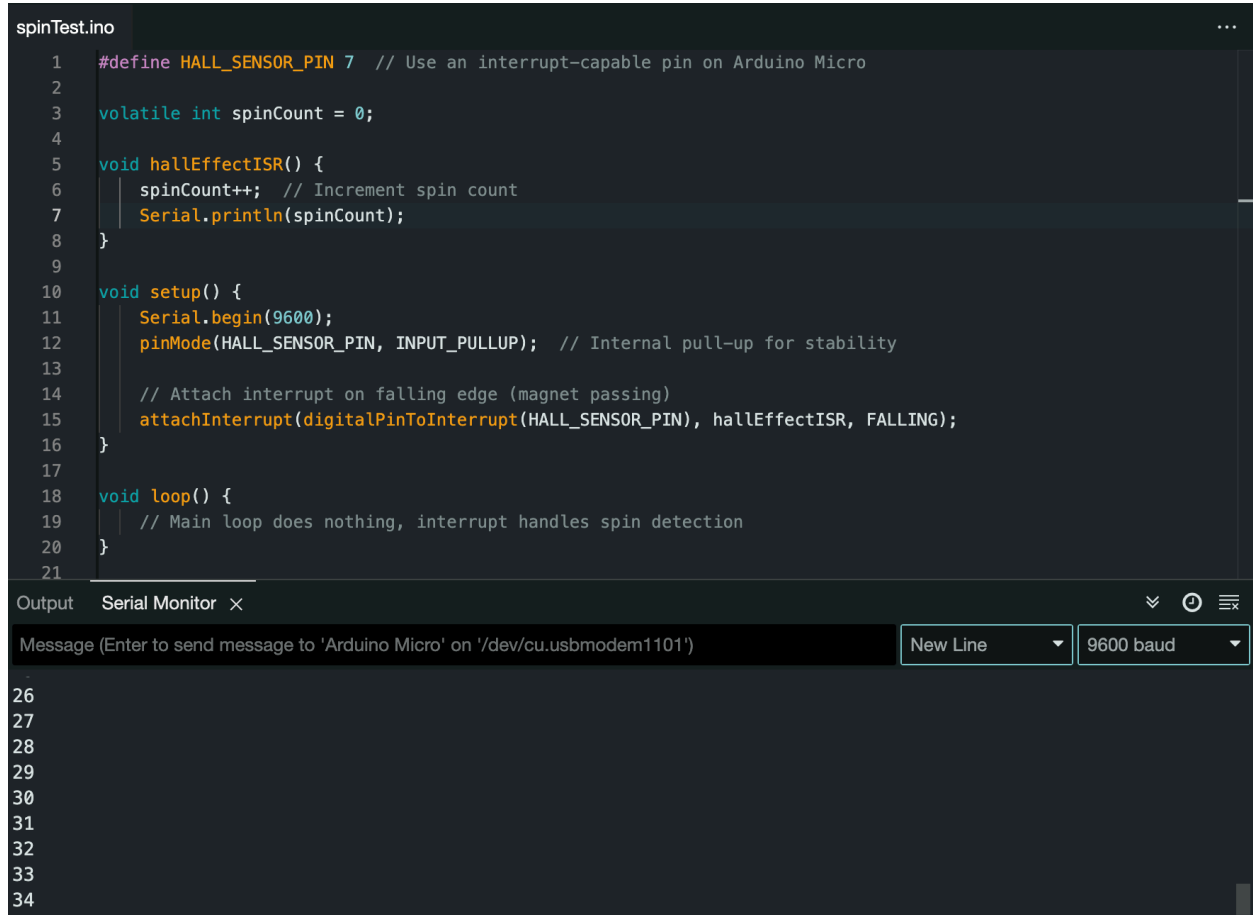
<https://docs.google.com/spreadsheets/d/1mNgJeoTzswgJd1rSyPCjOrciThfCIveF7gMHAUpdS84/edit?usp=sharing>

Counting spins test for sensing/tachometer subsystem:

We isolated our subsystem fully and spun our rotor by hand to record spins and test the accuracy of our counting, which is important for our down-the-line rotational speed calculations and controls.

Here is our code and serial monitor output of number of spins. We found that at our operational orientation (about 1 cm away from the rotor magnet attachment), our tachometer is very accurate, does not miss spins or overcount).

Figure 16: Spin test code



The screenshot displays the Arduino IDE interface. The top pane shows the code for `spinTest.ino`, which is a sketch for counting spins using a Hall effect sensor. The code includes a preprocessor directive for the sensor pin, a global variable for the spin count, an interrupt service routine (ISR) to increment the count and print it, and a main loop that does nothing while the ISR handles the spin detection.

```

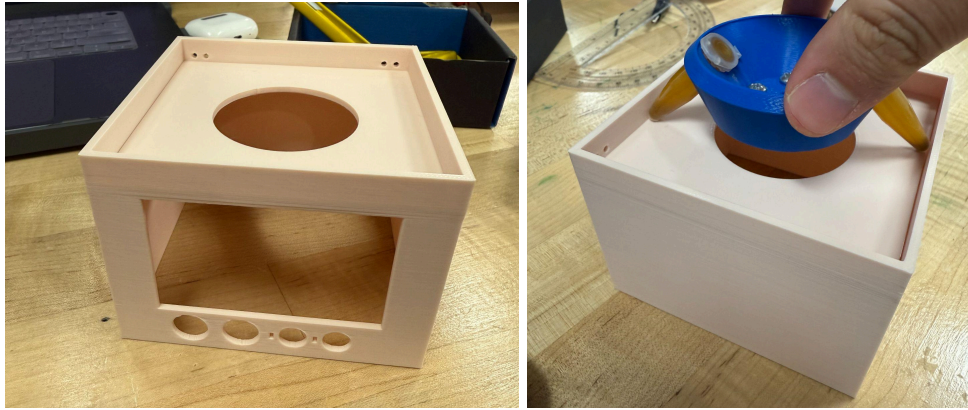
1  #define HALL_SENSOR_PIN 7 // Use an interrupt-capable pin on Arduino Micro
2
3  volatile int spinCount = 0;
4
5  void hallEffectISR() {
6      spinCount++; // Increment spin count
7      Serial.println(spinCount);
8  }
9
10 void setup() {
11     Serial.begin(9600);
12     pinMode(HALL_SENSOR_PIN, INPUT_PULLUP); // Internal pull-up for stability
13
14     // Attach interrupt on falling edge (magnet passing)
15     attachInterrupt(digitalPinToInterrupt(HALL_SENSOR_PIN), hallEffectISR, FALLING);
16 }
17
18 void loop() {
19     // Main loop does nothing, interrupt handles spin detection
20 }
21

```

The bottom pane shows the Serial Monitor window, which is currently empty, indicating that the code has not yet been executed or that the output has not been captured.

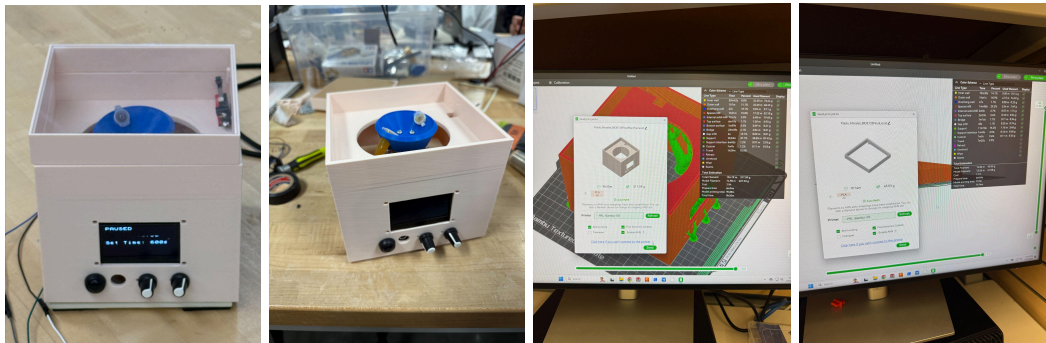
Enclosure Case:

Figure 17a: Early prototype of enclosure case viewed from top front (left image) and diagonal side (right image)



The above image is our first enclosure case design. After we printed it out, it was slightly smaller than what we needed it to be as it is hard for the rotor base and motor to fit in. The space between the tube and enclosure is not enough, resulting in the tube colliding with the case. Additionally, the distance between the holes where the knobs are going through is not spaced enough for easy access and control.

Figure 17b: Second and final rendering of our enclosure. Pictures to the left demonstrate new sizing of our new enclosure and pictures on the right demonstrate images of our new enclosure being printed. (3 overall prints, bottom piece was not captured due to being printed by TA's)



The second iteration of our design aimed to create a more ambient and functional enclosure for our rotor while addressing button size requirements, electrical space, and stability. The new enclosure also served as a table to elevate the motor system, ensuring it remained separate from electrical components to allow the rotor to spin freely.

To achieve this, we designed three key components:

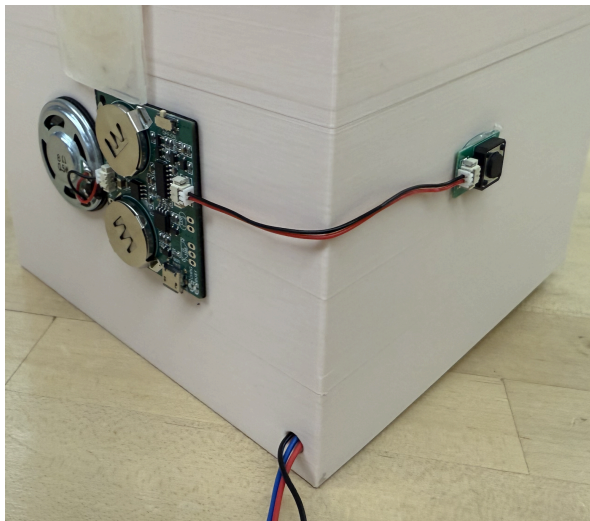
Main Frame: This structure divided the centrifuge into upper and lower sections with a horizontal wall featuring a hole for the rotor. It also included cutouts for buttons, potentiometers, screen, and a hole for wiring access to facilitate power connections.

Bottom Piece: This component raised the motor system to align properly with the mainframe using a table like design. It also housed the breadboard and wiring, while incorporating a built-in bumper to prevent the motor from slipping out of its holder, addressing a previous issue.

Lid: The lid acted as an activation mechanism by pressing a lever onto the limit switch to start operation. Additionally, it featured an indent for a viewing window, allowing users to observe the system in action.

Speaker Subsystem:

Figure 18: Speaker subsystem attached to the side of the enclosure case

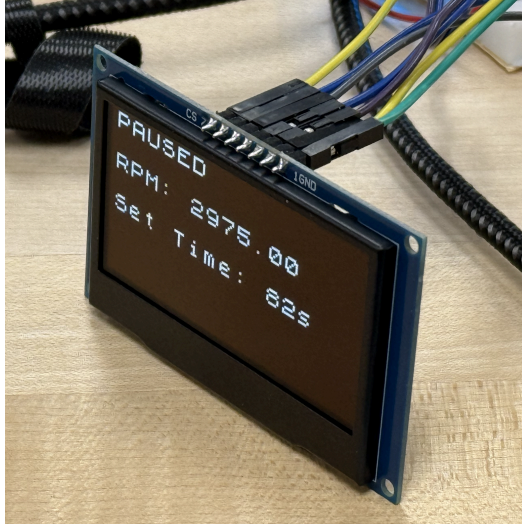


The speaker subsystem is a new addition to our V3 design, primarily intended to add a fun and engaging element to the product. It is securely attached to the side of the enclosure, with a conveniently exposed button on the case for easy access. The integrated sound system has a memory capacity of 7 Megabytes, allowing storage of a select number of audio files. For our initial launch, we've included the song "You Spin Me Round (Like a Record)" by Dead or Alive (1985), which humorously aligns with the centrifuge's function. On a full charge, the speaker subsystem can continuously play music for up to 23 minutes.

OLED Display:

We made our system more accessible and safer by using an OLED display instead of an LCD display (Figure 20).

Figure 20: OLED (SPI) Display at Control Screen

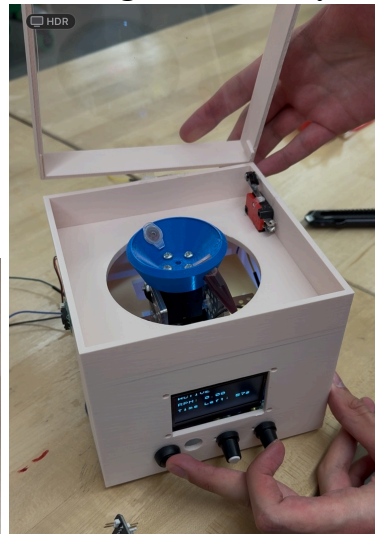
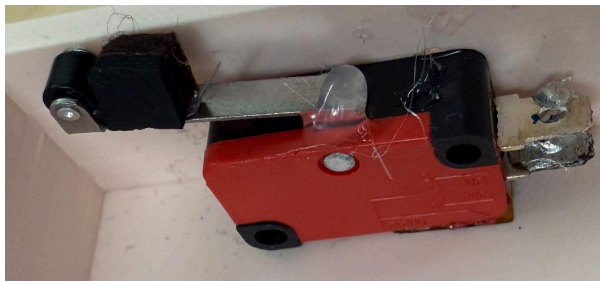


Compared to the previous LCD (I2C) version, this improvement allowed our screen to:

- be viewable from a larger range of angles
- be viewable at darker and lighter environments
- have a faster refresh rate for faster feedback to user
- be more pleasant to look at
- be able to display more information pertaining to safety and control

Limit Switch + Safety Lid:

Figure 21: On the left is the limit switch and on the right is the safety lid



The limit switch is integrated into our design primarily as a safety feature, ensuring user protection and preventing equipment damage. By automatically disabling centrifuge operation when the lid is not properly closed, the limit switch significantly reduces the risk of injury, such as fingers getting caught, and prevents potential damage to the motor. For stability, the limit switch is securely attached to the enclosure using hot glue. The safety lid itself is 3D printed and

incorporates a transparent acrylic panel, allowing users clear visibility of the centrifuge's spinning mechanism during operation.

Further Testing and Documentation

Documentation:

All V3-specific artifacts (including CAD and manufacturing files) can be found here: [V3](#)

Hazard Analysis: [V3 Hazard Analysis Second Cut Activity \(Group\)](#)

V3 System Test Results

V3 Trace Matrix included in [BIOE123_V3traceMatrix_TeamA8n](#) multiple organized pages. In summary, V3 PASSED most of our tests and is overall a SAFER, EASIER, MORE ACCESSIBLE, and MORE CONVENIENT system. However, it also failed some tests, namely: the battery subsystem test (arriving battery is a defect), and the button response time. See the trace matrix for details and notes.

Discussion Summary for V3:

The V3 design, build, and test cycle went smoothly, benefiting from our well-functioning V2 system and increased experience from previous iterations. The design and assembly were straightforward, but the enclosure case posed challenges. Our initial design was too small, and the rotor base lacked sufficient height for effective spinning. After three iterations, we finalized a case that accommodates all components, includes a middle divider for motor and rotor support, and prevents tube collisions. For future builds, we will take more accurate initial measurements and account for tube space during operation. Additionally, improving internal wire management with designated pathways would aid debugging. Overall, our team collaborated effectively throughout the process.

V3 Takeaways:

Lessons Learned:

- Follow a systematic **design-build-test** cycle for engineering projects.
- Take precise measurements and leave tolerances when designing enclosures
- **Double-check** dimensions before assembling components.
- Maintain **clear circuit documentation** for reproducibility.

Future Steps:

- Improve wiring and solder all components onto a protoboard.
- Use a **larger case** for easier internal access.
- Design a rotor base with more tube-holding spaces.
- Upgrade to a **higher RPM motor**.
- Develop a new rotor base and case for **larger objects (e.g., 15 mL tubes)**.

Bringup and debugging notes for V2, which V3 inherited:

BIOE123_V2bringupPlan_TeamA8

1. The controller subsystem can effectively read in the frequency signal inputted from the sensing subsystem and convert that into a RPM.
2. The controller can effectively communicate with the actuator and generate an output (PWM) that effectively adjusts the RPM of the actuator.
3. How to integrate user input...as RPM or as a demand PWM? How to decide whether this demands an interrupt or a polling scheme?
4. What is a good step-by-step workflow to get PID values (currently, it feels like guessing)?
5. We only have 3 interrupt pins. We use 2 on the screen and 1 on the hall effect sensor, meaning our button is on a polling basis. Will this cause challenges/problems? How can we mitigate this?

Solutions:

We are reading through the Arduino PID library documentation and using incremental development & version control (GitHub) for our code.

<https://github.com/ege-turan/bioe123centrifuge>

We will keep up good communication as we design, build, and test in parallel. Make sure test conditions match for the control subsystem with the final design with setup and intent.

V1 and V2 takeaways for V3 (some inherited from V2):

1. To satisfy speed setting requirements such as 2.1.2 and 2.1.3, we need to improve V1c with some way of controlling and maintaining speed to a higher resolution and accuracy. Similar to V1b, our V2 needs to have an encoder or some other way of internally sensing speed so that we can adjust duty cycle and motor speed to get to and maintain specific speeds.
2. To satisfy safety and stability requirements, we need to improve have the V2 center of mass be much lower than that of V1c. We have seen with V1a and V1b that a lower center of mass causes less vibrations and more resilience to inclined surfaces. For this, we may consider adding weights at the bottom or keeping heavy components near the bottom in our packaging. V2 had a lower center of mass, which helped a lot, but it still vibrated and moved, so we added the nonslip pads to our BOM for V3.
3. To satisfy 2.2.1 (The centrifuge stops automatically after set duration), we need to have sufficient user interface to enter timing requests. We may decide to use a screen and buttons or some other way of inputting / selecting a duration. V1 did not have a way to set a duration, so it relied on the operator to set the duration with a chronometer. This did not allow for the required automation.
4. We saw in 7.2.2.3 that there is a large amount of vibration that is visible by human eye at max setting. The machine moves around during operation on a flat lab bench, which is unsafe. We may decide to incorporate nonslip pads at the bottom or better/tighter connections overall with tighter tolerances to allow less vibration. We may also include some ways of vibration absorption such as cushioning or even simple suspensions/dampeners. Additionally, use of CAD to create a holding box can become an option.
5. As seen in 7.2.2.4, we recorded high noise levels during operation ($>100\text{dB}$). We may resolve this by using more quiet motors or having an insulating enclosure for the rotation unit that blocks out sound coming out from the motors.
6. For more safety in addition to sound isolation mentioned in 5, we would like to have a safety enclosure that is closed and covers the rotating mechanism during operation.
7. We learned during demos and also while working on our V1s that step-by-step tests and incremental building significantly increases the efficiency of bringup and mostly

eliminates debugging efforts by making each failing subcomponent clear. We will incorporate this knowledge into bringing up V2.

8. Mise en place! Having all the components and tools accessible and ready significantly boosts efficiency and joy while building. This includes block and circuit diagrams!
9. To be able to satisfy requirements in section 5 such as being able to separate anticoagulated blood, the centrifuge will be spec'd to spin at up to 4000 RPM reliably, so we will need to consider more strongly our motor and gear choices for V2. V1c came closest to these speeds, but we will need even stronger motors or higher gear ratios for V2.

Trace Matrix

Shared Root Trace Matrix for V3 Centrifuge (Measurements are given in each section, or sheet page for each subsystem, linked tables are included in this sheet)

Linked here (living, updating): [📄 BIOE123_V3traceMatrix_TeamA8](#)

Important tables and plots to be highlighted from our experimentation have been linked/included in this document, but please see the trace matrix for the full extent of verification and validation tests that were conducted. Since we build our V3 upon our V2 system, there are many overlapping tests and specifications. Some new specifications that are unique to V3 are highlighted in the following trace matrix.

Specification #	Specification Description	Test to Perform	Relevant Requirements	Specification Value [units]	Measured Value [units]	Notes
1.1.1	Microcentrifuge tube volume	Measure the max fluid inside the microcentrifuge tube	1.1	>1.5 mL	1.5 ml PASS	

1.1.2	Placement hole diameter	Measure the placement hole diameter	1.1	1.5 mL microcentrifuge tube diameter $\pm$ 0.1 mm	PASS	
1.1.3	Placement Hole Stability	Place container in placement hole and spin at max speed keeping count of the stability at set speed for max duration of centrifugation (2500 rpm, 90 seconds)	1.1, 2.1.1	3800 rpm, 90 seconds → PASS/FAIL	Stable for 90 s @ max speed PASS	
1.2.1	Max number of containers held by a rotor unit	Count number of viable container (satisfying 1.1)	1.1, 1.2	2 (count)	2 Pass	

		holding holes				
1.2.2	Container holding safety angle	Count number of viable container (satisfying 1.1) holding holes	1.2	Slipping angle >20°. The container on any side starts to slip at 20°. Rotor unit can hold both containers at angles up to 20° when not in operation	PASS	
2.1.1.1	Power rail soltage stability	Measure the voltage of the main power rail during operation at max speed to confirm it remains within tolerance	2.1.1	5V ± 0.5V	5.1V PASS	

2.1.2.1	PWM output range	Attach PWM output of microcontr oller to oscilloscop e to check predetermi ned PWM duty cycles that can be reached (0%, 20%, 40%, 60%, 80%, 100%)	2.1.2, 2.1.1	Confirm PWM duty cycle outputs at 0%, 20%, 40%, 60%, 80%, 100% → PASS/FAI L	Measured with oscilloscop e for pin D6. PASS	
2.1.1.2	Centrifug e rotational speed range	When VCC is equal to 12V, record appropriate max speed (rpm) with a tachometer	2.1.1	> 2500 RPM	3720 RPM	

2.1.2.1	Speed setting Increments	Verify the motor speeds at PWM output duty cycle at 0%, 20%, 40%, 60%, 80%, and 100% to confirm fine control increments.	2.1.2, 2.1.3	Increment ≤ 100 RPM → PASS/FAIL	PASS 0 RPM, 116 RPM, 802 RPM, 1232 RPM, 1556 RPM, 2832 RPM --> minimum difference is 116RPM	
2.1.2.3	Encoder function	Verify that the encoder registers a rotation	2.1.2	Rotation recorded on microcontroller → PASS/FAIL	PASS	
2.1.2.4	Encoder max speed recording	Verify that the encoder can record rotation at our maximum RPM	2.1.2, 2.1.1	Max RPM recorded on microcontroller → PASS/FAIL	PASS	

2.1.2.4	Encoder min speed recording	Verify that the encoder can record rotation at our minimum RPM	2.1.2, 2.1.1	Min RPM recorded on microcontr oller → PASS/FAI L	PASS	
2.1.3.1	Speed setting accuracy	Set speed to 2000RPM, 1000RPM. Check whether the speed can be maintained with up to ~5% error for a minute	2.1.3	<5% error within a minute	PASS, error 3%	NOTE: Lower RPM fluctuates more. Tachometer reading range: 980 - 1180 RPM. Set to 1000 RPM. Tachometer reading range: 1960 - 2120 RPM, Set to 2000 RPM. Tachometer reading range: 3789 - 3860 RPM, Set to 3800 RPM.
2.1.6.1	Container Strength	Test container integrity by gradually increasing rotational speeds	2.1.6	Withstand speeds up to 4000 RPM → PASS/FAI L	Fail (max speed 3800)	

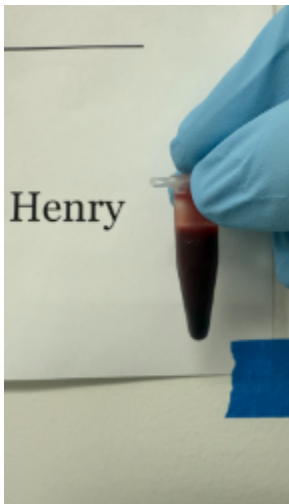
		(1000, 2000, 4000 RPM) and recording strain limits.				
2.1.6.2	Rotational speed stability	Monitor speed fluctuations during operation at various set points (2500 RPM, 1500 RPM) to confirm <5% deviation with a tachometer	2.1.6	<5% speed error → PASS/FAIL	Pass	
2.1.6.3	Ramp-up speed timing	Record the time taken for the centrifuge to reach maximum speed from rest	2.1.6	<10 sec	1.5 sec PASS	

2.1.6.4	Ramp-down speed timing	Record the time taken for the centrifuge to stop completely from max speed after power-off	2.1.6	<10 sec	5 sec PASS	
2.2.1.1	Duration range	The operator set the duration of centrifugation up to at least ~10 min	2.2.1	>10min	11 min PASS	
2.2.1.2	Duration automatic	The centrifuge stops automatically after set duration	2.2.1	PASS/FAIL	PASS	
2.2.2.1	Duration setting increments	Centrifuge system allows operator to set the duration of centrifugation	2.2.2	PASS/FAIL	PASS	

		ion up to at least ~10 min				
2.2.2.2	Duration setting increments	Centrifuge shall allow the operator to set the duration of centrifugation in increments of ~30 sec or less	2.2.2	PASS/FAIL	PASS	
2.2.3.1	Duration setting accuracy	Centrifuge allows the operator to set the duration of centrifugation to within ~5% accuracy	2.2.3	PASS/FAIL	PASS	
3.1.1	Initiation command	User have a distinct initiation command to start	3.1	PASS/FAIL	PASS(user s have button to initiate process)	

		centrifugation.				
3.2.1	Cancellation command	Centrifugation comes to a halt within ~0.5 sec after a cancellation command from the operator	3.2	PASS/FAIL	PASS	
4.1.1.1	Indicator for completion of centrifugation audio	Centrifuge indicates to the operator when centrifugation and ramp-down have completed	4.1.1	PASS/FAIL	PASS	

5.1.1	Separation of blood	Test whether the centrifuge can successfully separate blood by loading both containers and spinning the centrifuge for up to 10 mins. At the end of 10 mins (or when they get separated), visually inspect separation of the mixture. PASS when the resulting layers are	5.1	PASS/FAIL	PASS	
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		from bottom to top are, solid red blood cells, buffy coat, plasma				
5.1.2	Separation of blood in set amount of time	Record the minimum amount of time that the centrifuge can successfully separate blood.	5.1	< 5 mins	PASS Separate blood in 3 min	
5.2.2	Separation of water and turmeric in set amount of time	Record the minimum amount of time that the centrifuge can successfully separate water and turmeric.	5.2	< 2 mins	1 min separation PASS	

6	General safety	Centrifuge remains single fault safe	6	Addressed in Hazard Analysis	Addressed in Hazard Analysis	Hazard Analysis: https://docs.google.com/document/d/1w6lk4YSnTNI9M4AjFh2qfGlgNklKQ5_tv9cXy7lJWds/edit?usp=sharing and https://docs.google.com/document/d/1QNE3yhR48FOAjvpSjYqlzcTvKBYVFmGi5hetRk8dxDo/edit?usp=sharing
7	Protection against mechanical hazards of centrifuge	Addressed in Hazard Analysis	7	Addressed in Hazard Analysis	Addressed in Hazard Analysis	Hazard Analysis: https://docs.google.com/document/d/1w6lk4YSnTNI9M4AjFh2qfGlgNklKQ5_tv9cXy7lJWds/edit?usp=sharing and https://docs.google.com/document/d/1QNE3yhR48FOAjvpSjYqlzcTvKBYVFmGi5hetRk8dxDo/edit?usp=sharing

7.2.2.1	Instability - overbalance	Place centrifuge at inclined plane (1-15°) ensuring there is no tipping or instability during operation	7.2.2	Angle of instability 5°	PASS	NOTE: Operational and stable, but makes a buzzing sound properly due to motor gear operating at an angle.
7.2.2.2	Instability - off-balance loading	Place unevenly filled containers (one full, one empty) and operate at maximum speed. Observe for tipping or instability	7.2.2	Stable with off-balance loading → PASS/FAIL	FAIL	NOTE: Large Vibration during operation

7.2.2.3	Vibration levels during operation	Test vibration intensity by placing the centrifuge on a surface with accelerometers at all operating speeds	7.2.2	$\leq 5 \text{ mm/s}^2$ maximum vibration intensity	PASS Visual Inspection: No noticable vibration observed during max speed operation.	
7.2.2.4	Noise levels during operation	Measure the sound levels produced during operation at maximum speed	7.2.2	$\leq 80 \text{ dB}$	PASS 77 dB	All decibel sound level tests were conducted with: https://www.checkhearing.org/soundmeter.php
7.2.2.9	Noise levels during operation	Measure the sound levels produced during operation at	7.2.7	$\leq 80 \text{ dB}$	PASS 77 dB	

		maximum speed				
7.2.2.10	Noise levels during operation	Measure the sound levels produced during operation at maximum speed	7.2.8	≤ 80 dB	PASS 77 dB	
7.2.2.11	Noise levels during operation	Measure the sound levels produced during operation at maximum speed	7.2.9	≤ 80 dB	PASS 77 dB	
V3-specific starts at 8 and beyond!						
8						

8.1	Case successfully enclose the centrifuge	Measure the dimension of the parts and make sure the 3D printed case can enclose the centrifuge	V3	Dimension aligned and the parts (control knobs, LED screen) can fit inside the case Y/N	PASS	
8.7	Case enclosure noise reduction	Measure noise level during operation with and without enclosure	V3	< 80 dB with enclosure	74 dB → PASS	
8.2	Noise levels during operation is significantly reduced with case enclosure	Measure the sound levels produced during operation at maximum speed	V3	≤75 dB	PASS 74 dB	

8.3	Case can withstand flying projectile without shattering (flying objects generates roughly 8 N)	Measure the force of 3D printing material can withstand.	V3	Withstand force > 8N	Addressed in Hazard Analysis, not tested due to safety concerns within the scope of this class	
8.4A	Battery can supply 12V and 2A current	Measure the voltage and current output from the battery	V3	PASS/FAIL	FAIL	Battery pack was dysfunctional, we instead used wall-power for the entire system, which PASSES this requirement
8.4B	Heat stability of battery	Measure the operating temperature of the battery when V3 centrifuge is at max speed 3800 RPM for	V3	Battery temperature should not exceed 50 C	N/A	Battery pack was dysfunctional, we instead used wall-power for the entire system, which PASSES this requirement

		10 minutes				
8.5	OLED display Current limit	Measure the current draw of the OLED display	V3	OLED display should not draw more than 2A	PASS 24.7 mA	
8.6	OLED display is bright enough to clearly display information	Observe if the displayed text is visible	V3	PASS/FAIL	PASS	
8.8	Case safety	Observe for any ejected projectiles or structural failures at max speed	V3	No projectiles or failures	Addressed in Hazard Analysis, not tested due to safety concerns within the scope of this class	

8.9	Case vibration damping	Measure system stability and case vibration at max speed using accelerometer	V3	Vibration amplitude < 0.5 mm	PASS Visual Inspection: No noticable vibration observed during max speed operation.	
8.10	Case durability	Conduct drop test from 1 m height and check for damage	V3	No structural damage, functional after drop	Addressed in Hazard Analysis, not tested due to safety concerns within the scope of this class	
8.11	Battery operation	Run system on battery for 30 minutes and measure voltage drop	V3	> 30 minutes operation at full speed	N/A	Battery pack was dysfunctional, we instead used wall-power for the entire system, which PASSES this requirement

8.12	Battery recharge time	Measure time required to recharge battery from 0% to 100%	V3	< 2 hours	N/A	Battery pack was dysfunctional, we instead used wall-power for the entire system, which PASSES this requirement
8.13	Battery safety	Monitor battery temperature during operation and charging	V3	< 45°C during operation and charging	N/A	Battery pack was dysfunctional, we instead used wall-power for the entire system, which PASSES this requirement
8.14	OLED brightness	Measure display brightness at max and min settings	V3	>800 contrast ratio	PASS, 1000 contrast ratio	Source: https://www.winstar.com.tw/products/oled-module/graphic-oled-display/ssd1309-oled.html
8.15	OLED refresh rate	Measure display refresh rate using oscilloscope	V3	> 60 Hz	PASS by arduino screen-refreshing code	
8.16	OLED viewing angles	Measure viewing angle for	V3	> 80° horizontal and vertical	PASS viewable at 80° off	

		>80% visibility			from any direction	
8.17	OLED dark room visibility	Confirm visibility in a dark room with brightness at minimum	V3	Text/icons visible and readable	PASS reliable text displayed, no icons	
8.18	OLED bright light visibility	Confirm visibility under direct sunlight	V3	Text/icons visible under sunlight	PASS viewable under sunlight on sunny day	
8.19	Audio cue loudness	Measure sound level of audio cue at 1m distance	V3	60–75 dB	85 dB ---> PASS	
8.20	Audio cue response time	Measure delay between event and sound output	V3	< 500 ms	0.3 ms --> PASS	

8.21	Audio tone consistency	Measure frequency stability over 10 repetitions	V3	Frequency variation < 5%	PASS by oscilloscope test of Arduino output and by listening	
8.22	Vibration resistance	Measure system displacement on vibration platform at max speed	V3	< 1 mm displacement	PASS Visual Inspection: No noticeable vibration observed during max speed operation.	
8.23	Slip resistance	Place system on inclined plane and increase angle until slipping	V3	> 30° slip resistance	35° --> PASS	
8.24	Button response time	Measure time from button press to system response	V3	< 100 ms	Depends on program cycle, about 500ms at	

					times --> FAIL	
8.25	Button durability	Press button 100 times and check for functional issues	V3	No functional issues after 100 presses	PASS	
8.26	The speaker subsystem can play song stably for at least 10 consecutive minutes	Let the speaker subsystem run for 10 min and observe system stability overtime.	V3	PASS/FAIL	PASS	
8.27	Safety interlock with limit switch	Attempt to start centrifuge with case open	V3	System should not start	System does not start and gives audio feedback --> PASS	
8.28	Limit switch accuracy	Measure response time from case closure to	V3	< 500 ms	500 ms by chronometer timing --> PASS	

		system enable				
8.29	Hinge durability	Open/close case 50 times and check for wear	V3	No significant wear or functional failure	No visible wear or functional failure --> PASS	
8.30	OLED display should be able to display information at all angles	display shall be visible in low light, very bright light, and from side views.	V3	PASS/FAIL	PASS	
8.31	OLED display is able to display useful information such as time left in cycle and current speed in RPM	Observe if OLED displayed relevant information	V3	PASS/FAIL	PASS	

8.31	The speaker is playing an audio signal once the start button is pushed and once the centrifuga tion cycle is done	Listen for an audio signal	V3	PASS/FAIL	PASS	
8.32	The V3 system should be stable without sideway vibration movement during operation at max speed.	Observe for noticable side way movement	V3	PASS/FAIL	PASS	

8.33	The system shall not start spinning unless safety precautions (closing the case/enclosure is taken)	Observe if closing the case will allow centrifuge to start and also if opening the case during centrifugation will stop the cycle	V3	PASS/FAIL	PASS	as demonstrated in safety demo video: https://drive.google.com/file/d/1kqrG5GR_L5SirUuz_T_YSzkTB7nYG6t8g/view?usp=sharing
8.34	The hinge switch can effectively break the circuit and stop the centrifuge	Observe if the limit switch can effectively close the circuit by putting it into the breadboard	V3	PASS/FAIL	PASS	tested with simple limit switch pull-up circuit

8.35	The button communication with the system	Observe if pushing the button can trigger downstream communication with the system such as stopping/starting the centrifuge	V3	PASS/FAIL	PASS	

APPENDIX

Additional Figures:

Early experimentation to adjust coefficients, not labeled in detail but important for development and our understanding.

Figure A1: Ramp up plot cont'd, later samples (y-axis is RPM, x-axis is sample number)

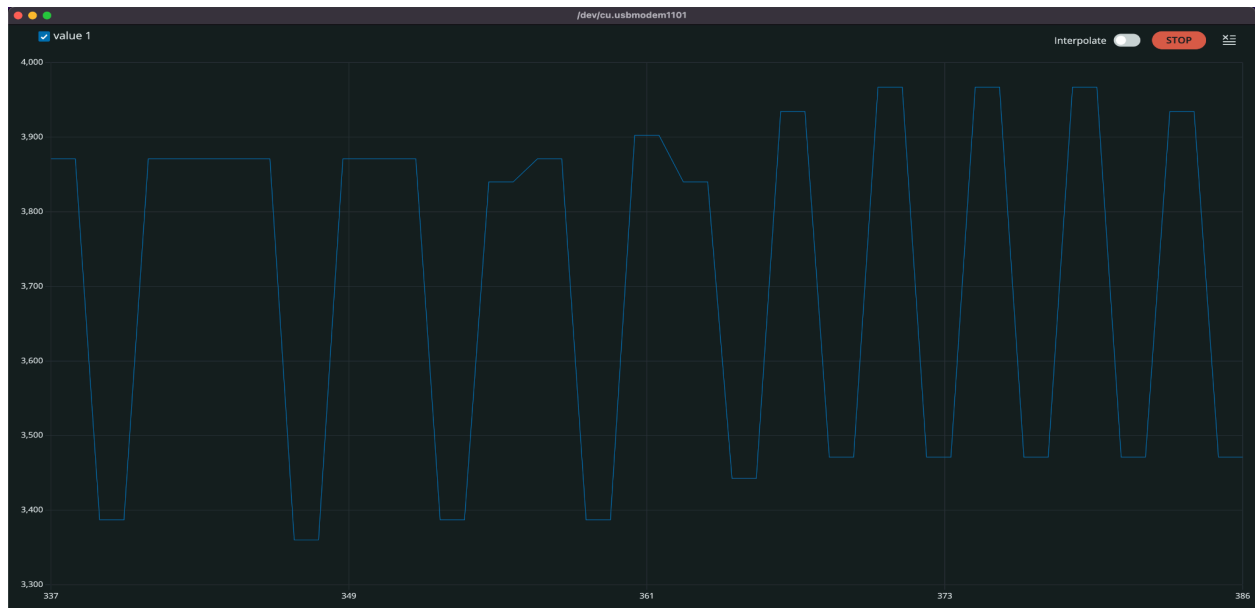


Figure A2: Stability test at the end of 90 seconds, maintaining 3800 RPM average (y-axis is RPM, x-axis is sample number)

