Programmable Vibration Table with Eagle Medical

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Executive Summary

This project aimed to repair and upgrade a vibration table used for package testing for the sponsor, Eagle Medical - a medical packaging and sterilization company based in Paso Robles, California. The current vibration table is not programmable and lacks circuit diagrams, making it difficult to repair. In addition, it is not functional due to internal circuitry issues and power requirements. To address these issues, the team will implement several upgrades to improve the product and allow for better random cyclic vibration testing. A full assessment of the existing vibration table will be conducted to ensure the viability of these proposed modifications for a successful outcome. The document provides information on the project's background, objectives, and project management, including the design process, project timeline, and Gantt chart.

Additionally, the document will provide information regarding our morphology, conceptual designs/evaluation, and failure analysis. This document also includes the detailed design, manufacturing plans, testing plans, and testing data/analysis, and instructions for use.

We followed a 5-phase design process typically employed in industry: product discovery, project planning, product definition, conceptual design, and product development. During the Winter Quarter, we went through the first 4 phases, and all of Spring Quarter was spent in product development. In product discovery, we identified the needs of Eagle Medical and investigated other vibration tables on the market. During project planning, we mapped out our key deadlines using a Gantt chart. In product definition, we created the scope of the project and began creating our engineering specifications. In conceptual design, we took those specifications and started evaluating possible concepts using morphology. During product development, we built our prototype and tested it against our engineering specifications.

The key customer requirements were that the new vibration table vibrates according to given standards, outputs frequency data, has vibration schedules, uses microcontrollers, has easily accessible data, updated/reliable electronics, and has a human-machine interface. The customer additionally wanted a circuit diagram, an easily serviceable table, and asked that we salvaged as much of the old table as possible.

Our test plan revealed key results. The aesthetic satisfaction scored a 10. The vibration table achieved our max vibration goal of 18 m/s^2. We showed that the vibration table does have accurate control of the rotations per minute. We also showed that the motor wire temperature did not change, indicating that our wires are properly specified. We showed that the power supply had very little variance, so our electronics should be safe from voltage spikes. We showed that it takes approximately 5.2 seconds to upload a vibration test. We also showed that the emergency stop works with 100% certainty. Finally, we performed GUI unit testing and all units passed.

Introduction

This project is focused on upgrading a vibration table used for testing packages by the sponsors, Eagle Medical, a medical packaging, and sterilization company located in Paso Robles, California. The original vibration table was not programmable and lacked circuit diagrams that allow for easy repair. Additionally, it was not functional due to issues with the internal circuitry and power requirements. To address these issues, we implemented several upgrades that result in a functioning vibration capable of performing cyclic random vibration testing. The upgrades include replacing the old motor, upgrading/replacing current circuitry, inserting a new human-machine interface (HMI), and additional minor adjustments. We provided a full assessment of the existing vibration table and thoroughly documented the viability of these proposed modifications to ensure a successful outcome. The original project scope included upgrading the table such that it met ASTM standards, but this goal was removed after finding that it was infeasible with the tools available.

This document will outline several aspects of the project and provide clarity on the work being done. The background provides information on customer meetings, existing designs, and a summary of technical literature. The objectives will outline the scope of the project and define the problem statement, indications for use, engineering specifications, and a description of the quality function deployment. The project management section defines the design process, the project timeline, and a summary of the Gantt chart. The morphology reveals our early designs for various aspects of this project. The conceptual design and evaluation sections include three fully documented concept sketches for our original scope, although this was later re-evaluated as previously mentioned. The failure analysis section describes potential modes of failure and steps taken to address them. The detailed designs section will go into further explanation of the chosen design and the methods for building it will be outlined in the prototype manufacturing sections. The test plan section outlines how testing was performed and the resulting analyses. Additionally, the Instructions for Use section details how an operator should use the vibration table to run a vibration test.

Background

Customer Observation, Meetings, and Interviews

The first meeting with Eagle Medical was an online meeting introducing the teams to each other and explaining the current objectives and issues with the vibration table. Eagle Medical works on the sterilization of medical packages. The company is moving towards package testing, this table being one of the tools needed to meet ASTM standards. The end goal of this table is to test for shock, impact, and vibration. The table was purchased from a company in China. The programmable logic controller (PLC) was not advanced enough, but the physical frame was functional. The table does purely cycloidal vibrations. The vibrations are meant to simulate trucks, trains, planes, and boats. The team wanted us to come in to troubleshoot the microcontroller and discuss potential new motors to add tests beyond cycloidal vibration.

The second meeting with Eagle Medical was an in-person meeting with Roy Morgan, Lenny Zinn, and Raymond Bishir. At this meeting, we got to evaluate the table and understand the circuits and motors. We were able to determine some of the problems in the electric layout of the circuits. It was determined that the device was tested with a voltage of 220 when the allowable voltage was 110 V. This caused multiple blown fuses and a damaged voltage-controlled capacitor.

In the following weeks, we met with Professors Lanny Griffin (Biomedical Engineering) and Tom Rhatigan (Electrical Engineering) to discuss the current and future designs we had generated. Both conversations concluded that the scope of physically changing the frame and updating the motor system was going to be extremely difficult in such a small amount of time. On Thursday, March 2nd, we met with vibrations professor Hemanth V K Porumamilla who has built a vibration table before as a graduate student. He outlined the difficulties of accomplishing this task and suggested that we change the scope with the bottom-line that the required motor control, physical redesign, and interpretation of the ASTM standard power density spectrum charts would be near impossible for a senior project. The consensus was that ASTM standards require a vibration frequency of up to 200 Hz; however, the table that was purchased could only go up to 5 Hz. Even with significant redesign and replacement of parts, the frame could not achieve this vibration frequency without risking failure.

After bringing these concerns to Eagle the following week, they agreed that this project scope was infeasible and suggested changing the project to go back to the original intention but remove the need to meet ASTM standards. This includes upgrading the circuitry, evaluating, and possibly upgrading the current motor, and developing an HMI. They also provided us with a basic chart outlining how they would like the motor to run in a simple step-like fashion (see Appendix C).

After this meeting, no new information was given besides updates on the project.

Similar Products

While undergoing background research for the vibration table, it was important to see what research has been done or what was already on the market. Using these similar products as shown in Table 1, different ideas for the assigned vibration table were developed.

Table 1: Similar Products List

Product Name	Description
FA-O Vibratory Flat Deck Table [1]	Shakes material for packages stored in drums, cartons, and kegs
Vibration testing machine for packages [2]	Used to test the anti-vibration capabilities of large pieces of furniture, household appliances, office furniture, and other large objects
Model 1800 Vibration Test System [3]	Includes a touch test vibration controller with a standard performance of 1 – 300 Hz frequency
Vibration Table Model 505-V4 [4]	Vertical Bump Test with a load capacity of 50 kg, frequency of 1 – 5 Hz, 60 – 300 RPM
Presto Vibration Table [5]	Checks to see if packages can sustain a certain round of vibration. The design and function of the machine comply with ASTM D999, TAPPI T-17, and IS 7028(part II) international testing standards.

In Table 1, many of the tables were designed for much larger packages than typical medical packages. Some of the vibration tables tested up to 100 kg of weight. The vibration testing machine for packages [2] even tested for large pieces of furniture. What all these tables had in common was the 2-dimensional axis of vibration and the varying frequencies the vibration acted at. The first table had a similar fastening system as our given table. The third table vibrated at the same required frequencies as the Eagle Medical table.

Patent Search

To confirm that our theorized design changes weren't infringing on any copyrights, a patent search was needed. These patents involved various aspects of the table that we are considering implementing. For example, the patents include an HMI setup, vibration table orientation, different methods of vibration, and a PLC design schematic. Using these patents, inspiration could be drawn while also ensuring no direct plagiarism or copyrighting was done when designing the table. The results of the patent search were summarized in Table 2.

Table 2: Similar Products List

Patent Name	Description
Component factory for human-machine interface migration to a cloud platform [6]	HMI is set up with data being deployed to a cloud platform or website.
Vibration table with circular mounting surface [7]	Vibration table that has the ability for the table to move in the x, y, and z-axis.
Transport Packaging Testing Device [8]	Design using a table that causes migrations using coils and vibrators throughout this design.
Machine that Simulates Movement Produced During Transport [9]	This table simulates the movement of transport like our proposed design. The four legs include ball joints for rotation which can change the angle of the table to show different angles during the transportation process.
System and Method for Controlling PLC and Scalable HMI Template [10]	This patent is about the control of multiple different screens to one PLC and HMI.

The patents shown in Table 2 described general practices when developing the vibration table. In order to not infringe on the copyrights of the second and fourth patents in Table 2, we decided to move away from the three axes of vibration and only resort to two axes of vibration: the x and y-axis. When designing our microcontroller layout, we referred to the PLC and Scalable HMI template [10] to ensure we did not copy their PLC layout.

Regarding the packaging of medical products, if a sponsor is packaging a liquid, extra care must be taken to ensure packaging safety. Improper packaging can lead to product damage, increased distribution cost, and significant environmental impacts. Improper can mean too little packaging or too much packaging, so testing must be done so that the packaging is safe, but not wasteful. [11]

The vibration table will require the use of circuits, one of the deliverables being a circuit schematic since one was not provided in the acquisition of the table. The table will require the use of a DC motor control circuit since it allows for precise tuning. These circuits are usually available in IC form, with voltage ratings between 12V-55V and 3A max current. The relationship between RPM and frequency is given by the following equation: Motor Speed (rpm) = Vibration Frequency (rpm)[12]. The amplitude of vibrations is given by the following equation: $F_{Amplitude} = mass \cdot R \cdot \omega 2$

A PLC is a digital control system that provides easy, programmable control for robotic devices/manufacturing processes. Its core functions include controlling output devices based on pre-programmed parameters, recording run-time data, and controlling machine operations. There are three common types of PLC: modular, rack, and compact. Modular is for large numbers of inputs and outputs. The rack is not useful for our application. Compact – I/O is fixed but good for smaller applications. [13]

Objectives

Problem Statement and Boundary Definition

The current vibration table at Eagle Medical is non-functional, non-programmable, and has out-of-date electronics. This project specifically works with upgrading the electronic circuitry and human-machine interface (HMI) of this table. Modifications can be made to the sheet metal structures that compose the frame and internal casings, but these should be as minimal as possible. The original table dimensions should be kept the same and the table must be able to vibrate at certain controlled speeds.

Indications for Use

The vibration table provides a method of simulating specific loads in a variety of traveling methods: by ship, walking, truck, and train. The vibration table operates with a maximum testing load of 100 kg, a frequency range of 0 to 5 Hz, and an amplitude of up to 25.4 mm. This machine will stably perform in a relative humidity of no higher than 85% and should be installed indoors in a well-ventilated, shaded area away from combustibles or high-temperature sources. Currently, the table tests for constant cyclic rotation. Intended users include only trained personnel.

Summary of Customer Requirements

This project has several upgrades that are to be undertaken. Specifically, Eagle Medical requires a new HMI that allows the operators to select a desired vibration schedule that matches their specifications. They also want user feedback to inform the operator of cycle completion and a USB output to easily download the cycle parameter report. Finally, a new circuit diagram outlining the inner electronics will also be provided. An extensive review of the customer requirements can be seen in Appendix A.

Quality Function Deployment

For this project, Eagle Medical provided several customer requirements as well as several desired engineering specifications. This helped with the creation of the House of Quality (HOQ) in which we expanded upon the preliminary ideas given to incorporate more engineering specifications. To create this HOQ, we had to translate the customer requirements to engineering requirements. Because the original requirements were given to us by an engineering team, many of these were already clear, but some still had to be developed and defined. We generated several specifications in a collaborative setting that could apply to the customer requirements and then evaluated which ones had the highest weights when compared to the customer requirements. Once we weighted the customer requirements and generated the engineering specifications, we applied a simple evaluation system comparing each requirement to each specification as nothing, weak, medium, or strong. Additionally, at the top of the HOQ, we compared which engineering requirements were positively/negatively correlated. On the right side of the HOQ, we weighted our competition against our customer requirements on a 1-5 scale with 1 being the weakest. This helped to reveal where our competition was lacking and how we could improve. Finally, at the bottom of the HOQ, we evaluated the competition's engineering specs and set ideal thresholds that were quantitative and descriptive if the information was available.

The House of Quality as seen in Figure 1 reveals several of the most important requirements for this project. Overall, the top-weighted engineering requirements were the integration of the GUI functionality, control of the vibration motor as a percentage of maximum RPM, and the maximum acceleration that can be obtained. As seen in the upper section of the house of quality, the accelerometer and vibration control specifications are positively correlated, which is helpful for accomplishing these goals. Further comparison between some competitors such as the VibTable [17] and LDS V780 [18] have revealed the need for improvements. These machines lack a modern UI interface and lack an easily accessible data output. The modern UI already matches one of the top engineering specifications, but the addition of an easily accessible USB data output can also help give this product an advantage over the competitors.

Correlation roof	Precise Control	Acceleration	Motor Electronic	Min. Sampling	Power Supply	E-Stop	Max Load	GUI Functionality	GUI Aesthetic	Time to Run
Time to Run a Test on GUI (s)										■
GUI Aesthetic (Human Satsifaction 1-10)									■	+
GUI Functionality (Yes or No)								■	+	+
Max Load Rating (Kg)							■			
E-Stop (Yes or No)						■		-		
Power Supply Variance at Nominal Voltage (V)					■	+				
Minimum Sampling Frequency for Sensors (Hz)				■						-
Motor Electronic Rating (amps)			■		+					
Acceleration Maximum (m/s^2)		■					-			
Precise Control of Vibration Motor (% max RPM)	■	+			+		-	+		+

Relative Weight	Customer Importance	Customer Requirements	Precise Control of Vibration Motor (% max RPM)	Acceleration Maximum (m/s^2)	Motor Electronic Rating (amps)	Minimum Sampling Frequency for Sensors (Hz)	Power Supply Variance at Nominal Voltage (V)	E-Stop (Yes or No)	Max Load Rating (Kg)	GUI Functionality (Yes or No)	S	Time to Run a Test on GUI (s)	1	2	3	4	5	Legend
			Functional Requirements															
		Direction of Improvement	▲	□	▲	□	□	□	▲	▲	□	▲	Customer Competitive Assessment					
13%	9	2-Axis Vibration	●										+		*			VibSource: +
13%	9	Can Retrieve Frequency Data		●						●	○					+	*	LDS V780 *
10%	7	Clean Human Machine Interface	●			○				●	●	●		*	+			
13%	9	Can Choose Vibration Profile	●	●						●	▽						+, *	
6%	4	Announces Finished Testing						▽		●							+, *	
4%	3	Easily Accessible Data Ouput				●				●			+			*		
13%	9	Updated and Reliable Electronics	●	●	●	▽	●	○				○			+		*	
8%	6	Easy to repair	○	○	●		●				▽				+		*	
13%	9	Ability to set Timers on Testing								●		●					+, *	
8%	6	Use old Metal Frame							●				N/A	N/A	N/A	N/A	N/A	
		Sum (Importance x Relationship)	456.34	368	190	80.3	190	43.66	76.056	520	148	241						
		Relative Weight	20%	16%	8%	3%	8%	2%	3%	22%	6%	10%						
		VibSource	5-100	0-14 G	?	?	?	Yes	50	No	?	?						
		LDS V780	0-4000	1088	?	?	?	Yes	20	No	?	?						
		Threshold Ideal	± 3%	18	<20	50	± 1%	Yes	50	Yes	10	20						
		Threshold Not Ideal	± 5%	9.81	<26	12	± 5%	Yes	20	Yes	6	30						
			Technical Competitive Assessment															

Correlations	
Positive	+
Negative	-
No Correlation	

Direction of Improvement	
Maximize	▲
Target	□
Minimize	▼

Relationships		Weight
Strong	●	9
Medium	○	3
Weak	▽	1

Figure 1: House of Quality for the Programmable Vibration Table

Engineering Specifications Table

The house of quality shown in Figure 1 reveals the importance weighting of the engineering specifications. These are reflected in Table 3, where the specifications are listed by order of importance and have additional information including the target goal for each specification, the tolerance levels, risk (H = high, M = medium, L = low), and compliance or how we will measure the specification (I = inspection, T = testing, A = analysis, S = similarity with another product). These engineering specifications went through several changes, the most notable being that the minimum sampling frequency and vibration control were both reduced due to the reduction in project scope. Additionally, more GUI tests were added as this became an extremely important part of this project.

Table 3: Engineering Specifications Table

Spec. #	Parameter Description	Target	Tolerance	Risk	Compliance
1	GUI Aesthetic Satisfaction	10 (User satisfaction)	Max	H	I, T, S
2	Maximum Acceleration	18 (m/s^2)	Min	M	A, T
3	Control of Vibration Motor	% max (RPM/RPM)	± 3%	M	A, T
4	Minimum Sampling Frequency	12 (Hz)	Min	L	A, T
5	Motor Electronic ratings	<20 amps (pass/fail)	N/A	L	I, T
6	Power Supply Variance at Nominal	Nominal voltage (V)	± 5%	L	T
7	Time to Run a Test on GUI	30 (s)	Max	M	T
8	E-stop	Yes	N/A	L	T
9	GUI Functionality	Yes	N/A	H	T, I

- The Graphic User Interface (GUI) will be evaluated based on a 1-10 user satisfaction scale, which can be done by both inspection of the interface and testing. This is high risk due to the complexity of working with an embedded system with custom user input. It will also be compared against similar industrial UIs.
- The acceleration will be measured based on the maximum amount of acceleration output that the table can simulate measured in $\frac{m}{s^2}$, which can be evaluated by analyzing the output of the motors and testing using accelerometers.
- The control of vibration motors will be measured by testing the range in RPM that the table can safely vibrate at by both analyzing the rating of the motors and testing using an accelerometer.
- The minimum sampling frequency to run the motors and gather information will also be measured in Hz and can be confirmed be found by doing testing on the GUI backend.
- The motor electronic ratings will need to be correct for the power source and measured in amps. These will be measured by inspection.
- The power supply variance at nominal is an important metric of power supply reliability. When the power supply is running at a nominal voltage, the power supply needs to output a voltage within 5% of either direction.
- The time to run a test on the GUI should be low and will be an indicator of both the ease of use of the GUI and if any bugs cause freezes in the GUI. We want to keep the time to set up a test to be under 30 seconds.
- The max load rating is measured in kg and will be evaluated by analyzing the material strength and testing.
- The E-Stop is essential for safety and will be measured by running tests on its functionality.
- GUI functionality includes making sure all the buttons work, there are no data leakages, and the output can be correctly saved. This will be done through a series of unit tests.

Project Management

Proposed Design Process

The design process we followed was comprised of 6 phases of mechanical design: product discovery, project planning, product definition, conceptual design, product development, and product support. This design cascade ensures quality in the product by emphasizing the effort in the early phases. In the product discovery phase, the need was established. Extensive background research was performed to explore how other companies tackled vibration testing. Next in the Project Planning phase, a budget was created, relevant advisors were selected, and a Gantt chart was created to act as a guide for keeping the team on track. In the Product Definition phase, there were many meetings with Eagle Medical to discuss customer requirements and how best to convert them into quantifiable metrics. In this phase, it was crucial to understand the underlying problems to create engineering specifications. Then, in the conceptual design phase, the goal was to evaluate different concepts for the new vibration table. After this phase comes Product Development, in which we refined the best concept into the actual vibration table. Also in this phase, we created technical documentation for manufacturing, assembly, and quality control. This phase ends with the release of the Vibration Table to Eagle Medical. The final phase is Product Support, in which we will provide support in manufacturing and assembly.

Key Deliverables and Project Timeline

The key deliverables are summarized in the following table.

Table 4: Key Deliverables and Timeline

Deliverables	Deadline
Indications for Use	1/24/2023
Statement of Work	1/30/2023
Morphology and Concept Sketches	2/6/2023
Pugh Decision Matrix	2/8/2023
Conceptual Model and FMEA	2/15/2023
Conceptual Design Review	2/27/2023
Hazard and Risk Assessment	3/6/2023
Spring Quarter Project Plan	3/21/2023
Test Plan Report	4/25/2023
Expo Poster	6/1/2023
Final Report	6/6/2023

As of June 6, 2023, the key deliverables were submitted on time, with this document being the final deliverable.

Proposed Techniques

The design process will require many of the prototyping and manufacturing equipment available to use on campus. This includes but is not limited to, 3D printing, machining, soldering, and laser cutting. Also provided to us by Eagle Medical is water jet cutting. For prototyping electronics, breadboards, and perforated boards will be used. In the final product, it is a high priority that a PCB will be designed, manufactured, and delivered to us.

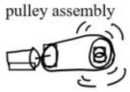
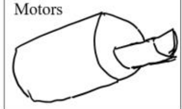
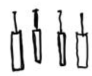
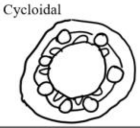
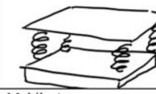
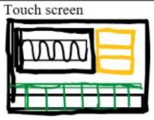
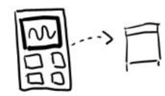
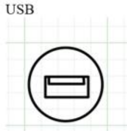
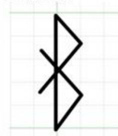
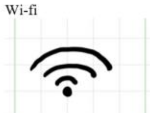
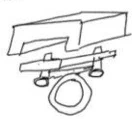
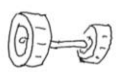
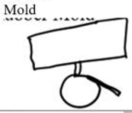
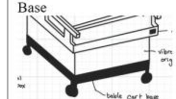
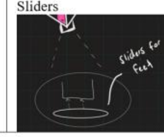
Network Diagram and Critical Path

A network diagram was created to track the project's timeline. – see Appendix B. The critical pathway was found and from this, all the key deliverables were laid out with expected timelines listed in Table 2. The most difficult and time-consuming tasks included the Conceptual Design Review, the Test Plan Report, and the Final Report. Therefore, to ensure the project's completion, some tasks may need to be shortened. Out of the deliverables listed in Table 2, the identified tasks that were targeted to be completed early were the Morphology, Pugh Decision Matrix, and Hazard and Risk Assessment. It was highly favorable to complete the morphology and Pugh Matrix early since these were fundamental deliverables that allowed us to proceed with the rest of the phases earlier.

Morphology

To come up with our conceptual design, we first needed to generate design ideas. The ideas shown below reflect the conceptual design process before we underwent the redesign. To accomplish this task, we brainstormed several ideas and wrote them down. These ideas fell into one of four categories: vibration mechanism, HMI, data logging, and portability. The categories were chosen based on the weights from the House of Quality and the importance to Eagle Medical. All ideas were considered, and at the end of the brainstorming session, we discarded the ones that were completely unfeasible and generated preliminary sketches for the remaining designs. The sketches that were generated can be seen in Table 5, which is representative of the morphology that we generated.

Table 5: Preliminary Sketches of Potential Designs

Morphology						
Product: Programmable Vibration Table with Eagle Medical				Organization Name : Cal Poly San Luis Obispo		
Function	Concept 1	Concept 2	Concept 3	Concept 4	Concept 5	Concept 6
Vibration Mechanism	Eccentric shaft and pulley assembly 	Eccentric Mass Motors 	Linear Actuators 	Cycloidal 	External Tabletop 	
Safe, easy operation (HMI)	Touch screen 	Touch screen with Buttons 	Mouse and Keyboard 	LCD and Purely Buttons 	Mobile App 	
Data Logging	Cloud-based 	USB 	Bluetooth 	Wi-fi 		
Portability	Castor wheels 	3d Printed Mold for Feet 	Rubber removable wheels 	Drilling into Current Rubber Mold 	Cart Base 	Sliders 
Team member: Madhav Asok		Team member: Jonathan Ilagan		Prepared by:		
Team member: Max Lewter		Team member: -----		Checked by:	Approved by:	
The Mechanical Design Process Copyright 2008, McGraw Hill					Designed by Professor David G. Ullman Form # 15.0	

Once the morphology was generated, we then each created an overall conceptual design that included one idea from each of the four categories to evaluate. We chose our combinations based on deliberation with the group and application to the customer's requirements. The first concept is based on the external tabletop, an LCD touchscreen with buttons, a USB port, and caster wheels. This concept adds to the current vibration table design. Instead of having the motors vibrate the whole table, an external tabletop will be added on top of the table. There will be springs that attach the tabletop to the rest of the frame. The DC motor will vibrate causing the springs to change positions on the z-axis. To account for all different axis of vibration the package will go through multiple tests by flipping the package to another side. The HMI will be an LCD touch screen paired with a D-pad and two forward and back buttons for controls. On the HMI, there will be a USB output to export results to a plugged-in USB thumb drive. The advantage of having a touch screen and d-pad is that if one of the features fails tests it can still be run using touch or buttons. Also, using an LCD is a cheap option since they are readily available on the market. The concept is visualized in Figure 2.

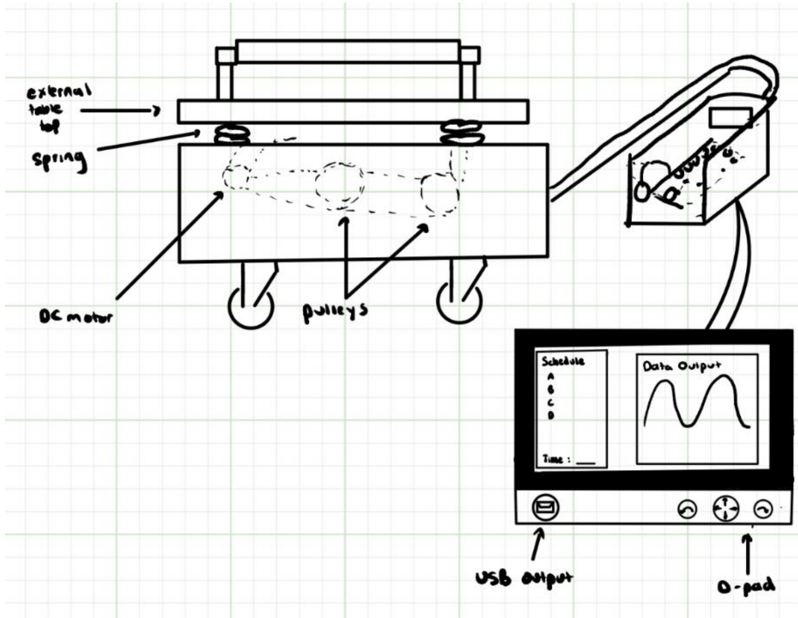


Figure 2: Preliminary Conceptual Design 1

The second concept uses the same full-table vibration mechanism, an HMI with a mouse and keyboard, Wi-Fi-based data logging, and a cart base for transportation. It would be relatively easy to upgrade the motors, but quantifying the vibration amplitude would be more difficult. Also, this design would require an extremely high-power motor, since this design vibrates the entire table causing a loss of vibration amplitude. Both the control box and the vibration table are mounted on a base with lockable wheels for easy transportation. To aid in transporting the table, there is a handle on the back of the machine. On the control box, a monitor arm and a keyboard and mouse arm can be mounted on the side which makes this design space conscious. Data can be saved and transmitted over Wi-Fi through a Windows PC placed inside the control box. This concept is visualized in Figure 3.

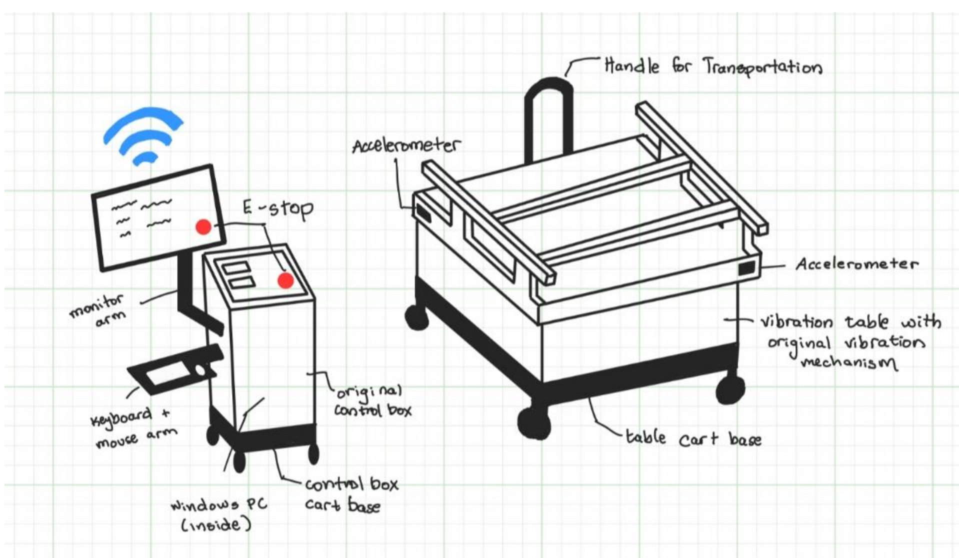


Figure 3: Preliminary Conceptual Design 2

The third concept involves using an LCD screen controlled by buttons, linear actuators to vibrate the table, a USB output to collect data, and removable slides to easily move the table. This concept is visualized in Figure 4. The LCD screen would take up most of the available space on the control monitor (light blue). There would be four arrow keys (green), an enter button (dark blue), a back button (grey), a keypad with numbers 0-9 (orange), and an emergency stop button (red). There is also a USB output to allow the operator to easily export and transport the resulting data. The linear actuators would be placed at each of the four corners and vibrate in the z-direction. They would be like the current design in the sense that they would shake the whole table. The advantage of this concept is that an LCD screen with buttons would be cheaper and easier to implement than a touch screen. Additionally, having sliders to place under the table would be simple and effective. Finally, linear actuators are a common motor type and can be easily sourced as well as easily installed. Some potential disadvantages would be that the current motor placement would shake the entire table and not just the top and the user control is not very modern.

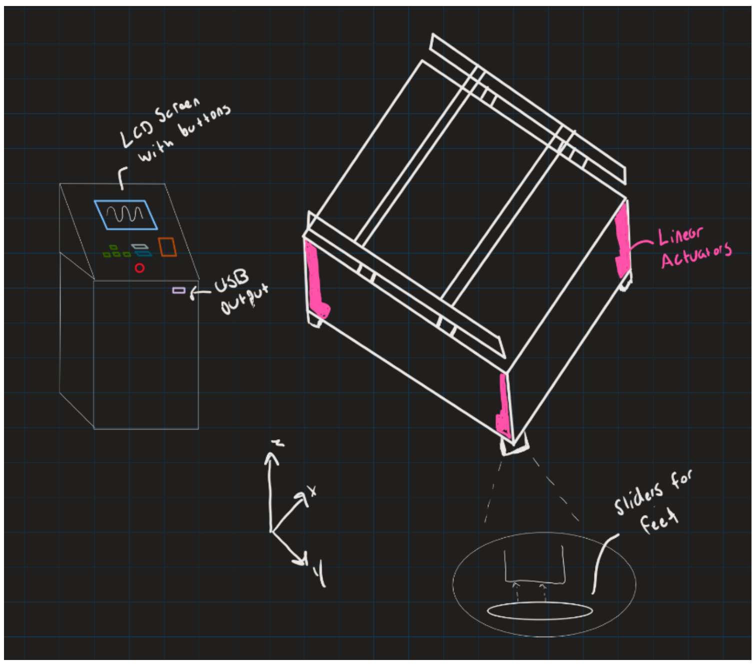


Figure 4: Preliminary Conceptual Design 3

Concept Evaluation

Pugh Matrix

Note: As of 6/6/2023, the Pugh now outdated due to the project rescope, but many of the core ideas are similar. It would not be useful to undergo this again, thus, we are leaving this as is.

To evaluate the three concepts that we came up with, a Pugh Matrix was used for quantitative analysis. To do so, a set of criteria was created to compare each component to a specific baseline. We decided to use an LDS V780 Vibration Table as our baseline since it is one of the most popular vibration tables on the market and has many features that Eagle desired, like programmable vibration cycles.

The criteria were loosely based on the previous House of Quality and the customer requirements. As we came to understand the project more, the specifics of the criteria changed slightly, which is why the criteria are not perfectly adapted from the House of Quality. We feel that these updated criteria, while not all quantitative, are more useful criteria to build a better product. The criteria include cost, method of vibration control, feasibility, user interface, data output, durability, serviceability, ease of use, and portability. After the criteria were evaluated, they were also assigned weights to highlight which were the most important criteria in this design.

Each member had to fill out the Pugh Matrix, scoring how well each concept did for every criterion against the baseline. To score, each concept's method of addressing each criterion was assigned a value from 1 to 4, with 1 being poor and 4 being excellent. After this process, we came together and discussed our results to create a Pugh Matrix that we all agreed upon. These results can be seen in the following figures.

Concept 1: External Tabletop, Touch screen with Buttons, USB Output, Castor Wheels

Concept 2: Eccentric Shaft and Pulley Assembly (original mechanism for the table), Mouse, and Keyboard, Wi-fi, Cart Base

Concept 3: Linear Actuator Motors, LCD Screen with Buttons, USB Output, Sliders

Decision Matrix

		Baseline		Concept 1		Concept 2		Concept 3	
CRITERIA	WEIGHTAGE	RATING	TOTAL	RATING	TOTAL	RATING	TOTAL	RATING	TOTAL
COST	20%	1	5.00%	4	20.00%	4	20.00%	4	20.00%
VIBRATION CONTROL	15%	4	15.00%	4	15.00%	2	7.50%	4	15.00%
FEASABILITY	15%	4	15.00%	4	15.00%	4	15.00%	4	15.00%
H-M INTERFACE	15%	2	7.50%	4	15.00%	4	15.00%	2	7.50%
DATA OUTPUT	5%	2	2.50%	3	3.75%	3	3.75%	3	3.75%
DURABILITY	8%	4	8.00%	3	6.00%	4	8.00%	4	8.00%
SERVICABILITY	9%	3	6.75%	4	9.00%	2	4.50%	3	6.75%
EASE OF USE	8%	3	6.00%	4	8.00%	4	8.00%	3	6.00%
PORTABILITY	5%	1	1.25%	4	5.00%	4	5.00%	4	5.00%
		3	0.00%	4	0.00%	3	0.00%	4	0.00%
	max		TOTAL Baseline		TOTAL Concept 1		TOTAL Concept 2		TOTAL Concept 3
	100%		67.00%		96.75%		86.75%		87.00%

Figure 5: Pugh Matrix filled out by Jonathan Ilagan

Decision Matrix

CRITERIA	WEIGHTAGE	Baseline RATING	Baseline TOTAL	Concept 1 RATING	Concept 1 TOTAL	Concept 2 RATING	Concept 2 TOTAL	Concept 3 RATING	Concept 3 TOTAL
COST	20%	1	5.00%	4	20.00%	4	20.00%	4	20.00%
VIBRATION CONTROL	15%	4	15.00%	4	15.00%	3	11.25%	3	11.25%
FEASABILITY	15%	2	7.50%	1	3.75%	2	7.50%	3	11.25%
H-M INTERFACE	15%	2	7.50%	4	15.00%	3	11.25%	2	7.50%
DATA OUTPUT	5%	2	2.50%	2	2.50%	2	2.50%	2	2.50%
DURABILITY	8%	3	6.00%	4	8.00%	4	8.00%	3	6.00%
SERVICABILITY	9%	3	6.75%	3	6.75%	1	2.25%	2	4.50%
EASE OF USE	8%	3	6.00%	4	8.00%	4	8.00%	4	8.00%
PORTABILITY	5%	1	1.25%	2	2.50%	4	5.00%	3	3.75%

max	TOTAL Baseline	TOTAL Concept 1	TOTAL Concept 2	TOTAL Concept 3
100%	57.50%	81.50%	75.75%	74.75%

Figure 6: Pugh Matrix filled out by Max Lewter

Decision Matrix

CRITERIA	WEIGHTAGE	Baseline RATING	Baseline TOTAL	Concept 1 RATING	Concept 1 TOTAL	Concept 2 RATING	Concept 2 TOTAL	Concept 3 RATING	Concept 3 TOTAL
COST	20%	1	5.00%	4	20.00%	3.5	17.50%	4	20.00%
VIBRATION CONTROL	15%	4	15.00%	4	15.00%	3	11.25%	3	11.25%
FEASABILITY	15%	2	7.50%	3	11.25%	4	15.00%	4	15.00%
H-M INTERFACE	15%	2	7.50%	4	15.00%	3	11.25%	2	7.50%
DATA OUTPUT	5%	2	2.50%	3	3.75%	1	1.25%	3	3.75%
DURABILITY	8%	4	8.00%	4	8.00%	2	4.00%	3	6.00%
SERVICABILITY	9%	3	6.75%	4	9.00%	2	4.50%	4	9.00%
EASE OF USE	8%	3	6.00%	3	6.00%	4	8.00%	4	8.00%
PORTABILITY	5%	1	1.25%	4	5.00%	4	5.00%	3	3.75%

max	TOTAL Baseline	TOTAL Concept 1	TOTAL Concept 2	TOTAL Concept 3
100%	59.50%	93.00%	77.75%	84.25%

Figure 7: Pugh Matrix filled out by Madhav Asok

Decision Matrix

CRITERIA	WEIGHTAGE	Baseline RATING	Baseline TOTAL	Concept 1 RATING	Concept 1 TOTAL	Concept 2 RATING	Concept 2 TOTAL	Concept 3 RATING	Concept 3 TOTAL
COST	20%	1	5.00%	4	20.00%	4	20.00%	4	20.00%
VIBRATION CONTROL	15%	4	15.00%	4	15.00%	3	11.25%	3	11.25%
FEASABILITY	15%	2	7.50%	2	7.50%	3.5	13.13%	4	15.00%
H-M INTERFACE	15%	2	7.50%	4	15.00%	3	11.25%	2	7.50%
DATA OUTPUT	5%	2	2.50%	3	3.75%	2	2.50%	3	3.75%
DURABILITY	8%	4	8.00%	3	6.00%	4	8.00%	3	6.00%
SERVICABILITY	9%	3	6.75%	4	9.00%	2	4.50%	4	9.00%
EASE OF USE	8%	3	6.00%	4	8.00%	4	8.00%	4	8.00%
PORTABILITY	5%	1	1.25%	4	5.00%	4	5.00%	3	3.75%

max	TOTAL Baseline	TOTAL Concept 1	TOTAL Concept 2	TOTAL Concept 3
100%	59.50%	89.25%	83.63%	84.25%

Figure 8: Pugh Matrix filled out by All Team Members

Our Weighted Decision Matrix results show that Concept 1 scored the best. Across all criteria, it outcompeted or matched the baseline device. Also, this concept scored higher in vibration control since the tabletop is external, making it significantly easier to validate vibration. The human-machine interface scored the highest here as well since this concept perfectly fits Eagle-Medical's explicit customer requirements. One thing that we learned from this chart is that the data output does not need to have only 1 option, there can be multiple modes of data output to increase ease of use and reliability. Therefore, the following concept will be selected to move forward: External tabletop, Touch screen with Buttons, Castor Wheels, and multiple data outputs. The multiple data outputs will be USB, Cloud, and Wi-fi. This configuration scored lower in feasibility, but after discussion with Eagle Medical, we came to the agreement that this would be the highest quality product and the most desirable pathway.

Conceptual Model

System Block Diagram

We created an initial conceptual model of the block diagram outlining the flow of information in the circuit system – see Figure 11. Additionally, the system block diagram shows all of the subsystems involved in this project, as well as the critical components necessary. The creation of this block diagram involved extensive research into motor control loops, HMI control, and PLC/microcontroller research.

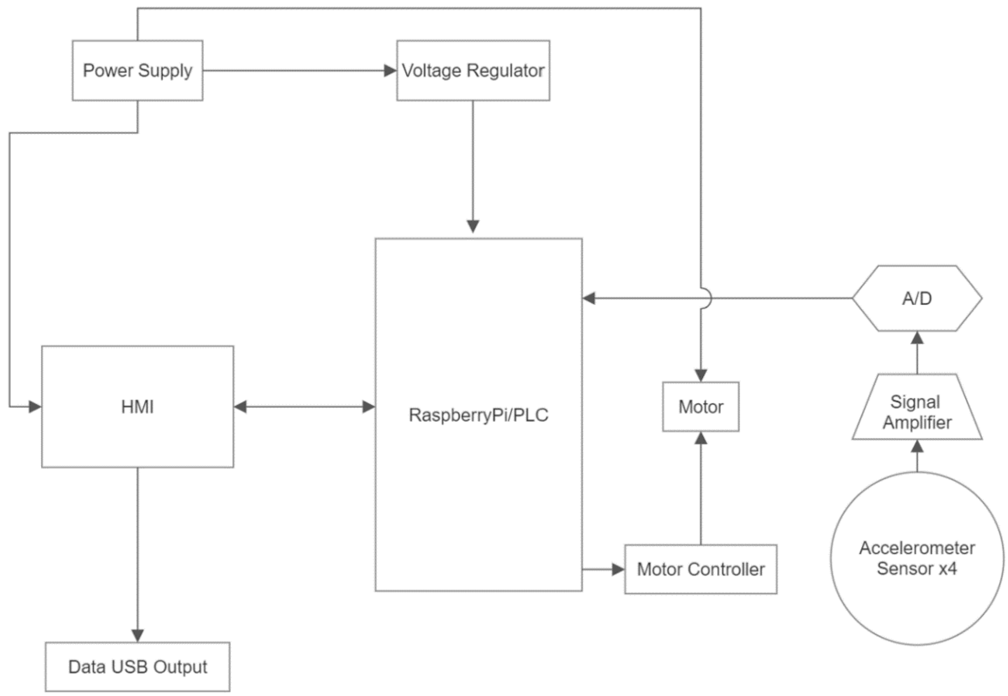


Figure 9: Overall System Block Diagram <update me!>

We learned that the PLC/Microcontroller will act as the brain of this machine, and all inputs and outputs will flow through it. This means that the microcontroller will receive data from the sensor, user inputs from the HMI, and power supply information. The microcontroller will process this information and send commands to the motor controller, which will regulate the motor's speed and direction.

In our research, we also learned about how to control a motor by extending the power supply to it and using the microcontroller to send pulse width modulated (PWM) signals. These signals can be interpreted by the motor controller (essentially a transistor) to drive the motor. By varying the duty cycle of the PWM signal, we can adjust the motor's speed and torque, which is crucial for creating different vibration patterns on the vibration table. After doing an in-depth analysis of the types of microcontrollers such as PLC, Raspberry Pi, and Arduino, we have decided to use Arduinos for prototyping. They are ideal for rapid testing and come with many built-in libraries to support motor drivers.

Furthermore, we discovered that the HMI will also have a small computer on it to run the graphics and receive touch input. The HMI will display important information to the user, such as the vibration level, testing progress, and any warnings or errors. When the user interacts with the HMI by touching buttons or adjusting sliders, the HMI's computer will send this input to the microcontroller for further instructions. This ensures that the system is responsive to the user's commands and provides an intuitive and user-friendly interface.

Overall, the research into motor control loops, HMI control, and PLC/microcontroller research was crucial for creating an effective block diagram as shown in Figure 11 that outlines the flow of information and control for the vibration table testing system. By understanding how each component interacts with the others and how data flows between them, we can create a well-functioning system that meets the needs of our client.

Human Machine Interface Mockup

The human-machine interface will be used by the user to control the vibration table. It is essential that this interface is clear, accurate, and displays all necessary information. This conceptual model comes with a decision tree, which outlines the flow of steps that an operator needs to follow when using the table.

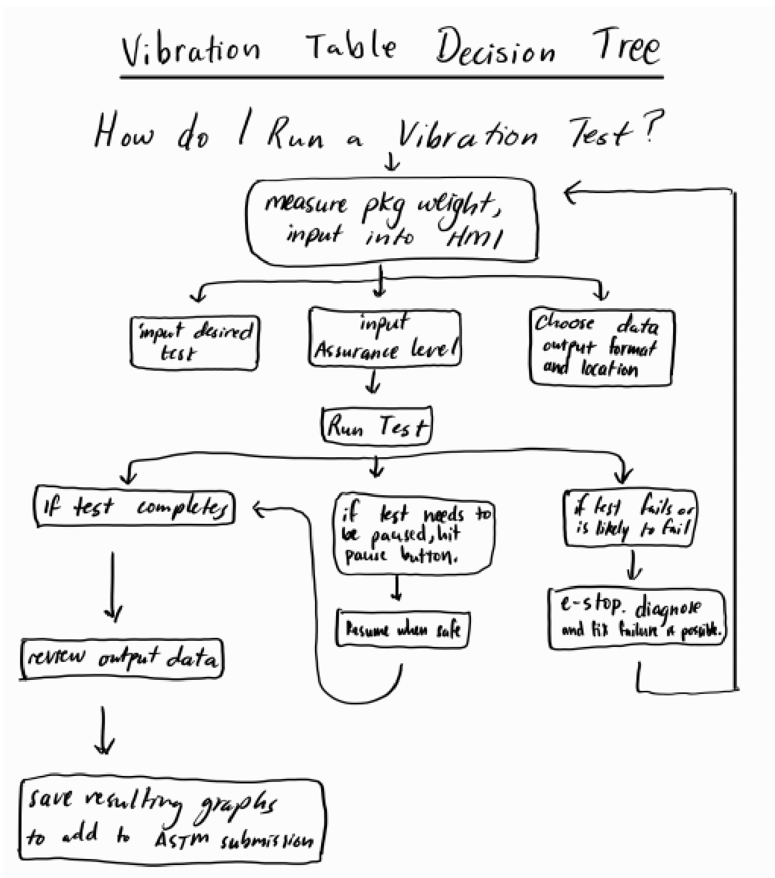


Figure 10: Decision Tree for Running a Vibration Test

Creating the decision tree allowed us to identify the explicit functions that the human-machine interface will need. Then, the decision tree was converted into a user interface in Figure 13, as well as a representation of potentially how this user interface would like in practice in Figure 14.

Figure 11: User Interface for Vibration Table

Figure 12: Human Machine Interface for Vibration Table

Making this part of the conceptual model taught us how to convey the flow of operations clearly to the user, and to see all of the necessary information that needs to be shown. The final step of this part of the conceptual model is a view of what the full human-machine interface looks like in real life. This revealed how the user will physically interact with the HMI plus the indicators we can have alongside the screen. For example, it should be important that the HMI communicates whether the machine is on standby, is currently running a test, or a problem has occurred. This is seen from the lights alongside the screen in the final HMI mockup.

Concluding the Conceptual Model

The conceptual model is composed of two parts: the system block diagram, and a graphical representation of the Human Machine Interface. The system block diagram outlined the critical components and flow of information through the system. The HMI mockup provided us with an idea of how to present the information required to run a vibration test.

FMEA

The FMEA is a failure mode and effect analysis. The purpose of this analysis is to predict any potential points of failure, rate the severity of such failures, and how easy it is to identify errors. This is a guide to determine what areas require attention in the design and build process as well as can help in the troubleshooting process once building has begun.

Function Affected	Potential Failure Mode	Potential Effect(s) of Failure	OCC	DET	SEV	RPN	Cause of Failure	Recommended Actions	Responsible Person	Taken Actions
Vibration Mechanism	Motor stops running	Test fails, no data generated	3	1	10	30	Electrical failure, overdriven	Ensure inputs to motor are properly spec'd, implement safety features to ensure a clean stop	Madhav Asok	
	Table-Top Mechanical Connection failure	Test fails and table-top is damaged	2	1	10	20	Material failure, overstress, or to much weight	Document lifetime of table, run wetests for weight	Madhav Asok	
	Motor overheats	Test fails, unusable data	4	3	7	84	Motor gets used to much, poor ventilation	Develop cooling methods for the motor, implement lifecycle management	Jonathan Ilagan	
Human Machine Interface	No generated output	No data output	2	1	7	14	Bugs in UI, faulty connection to arduino	Create an extensive testing lib (100% coverage)	Madhav Asok	
	Doesn't run	No data output, no test running	2	1	7	14	Bugs in UI, faulty connection to PCB	Create an automatic reset system	Max Lewter	
	New schedules don't show up in menu	Cannot run vibration test	2	1	7	14	Bugs in UI	Test adding schedules	Jonathan Ilagan	
	Buttons don't detect inputs	Cannot run vibration test	2	1	7	14	Faulty connection to PCB or arduino	Test connections after subjecting the board to movement tests	Madhav Asok	
Power Delivery	Faulty mechanical connection	Possible fire	2	5	10	100	Poor soldering, poor connections made	Completely power off machine.	Jonathan Ilagan	
	Voltage spike	Electronic parts are destroyed	2	10	8	160	Transformer failure, faulty power supply	Ensure power supply has high reliability	Max Lewter	
Data Logging	False data output	Package incorrectly passes or fails	4	7	10	280	Faulty code, Edge case missed in testing	Create a test suite, possibly implement a random check at specified time intervals to ensure proper readings	Madhav Asok	

Figure 13: Failure Mode and Effect Analysis for Vibration Table. OCC = Occurrence, a score of likely this failure can happen. DET = Detection, a score of how detectable this failure can happen. SEV = Severity, a score of how severe the resulting failure would be. RPN = Risk Priority Number, a metric of the previous scores to show which failures are most important.

This FMEA shows that for the vibration mechanism, the highest priority is to prevent the motor from overheating. As an example, the first row shows that the vibration mechanism may fail due to a motor failure. If the motor fails, the vibration test fails, and no data is generated. The occurrence of this failure mode would be rare, which is why it scored a 3. The detection of this failure mode would be easy to predict, so it scored 1. The severity of this failure results in complete failure of the table, so the severity scores a 10. The cause of this failure could be due to a faulty connection or if it was overvolted. The recommended action to prevent this failure is to ensure that the inputs entering the motor are within the specifications and to implement an emergency stop button.

For the HMI, there was no identified failure to focus on since all modes have the same priority. The power delivery has the most risk since we will work with relatively high voltages to drive the table. If there is a power delivery failure, the table would become non-functional and also become a fire or electrical hazard. It is critical that the electrical connections are stable, and that the power delivery can handle voltage spikes or sudden drops.

Detailed Design

The following graphic illustrates the full scope of the vibration table project. The original vibration table as well as its vibration mechanism are re-used, with a complete overhaul of the controls and power delivery. The vibration patterns are controlled via a microcontroller connected to a UI on a nearby computer. The UI has control over the duration, and number of cycles, as well as the start and stop buttons. The control box houses the new microcontroller and power supply. There is a physical emergency stop placed on the control box, as well as indicators to show the status of the vibration table: on, off, in progress, and on standby.

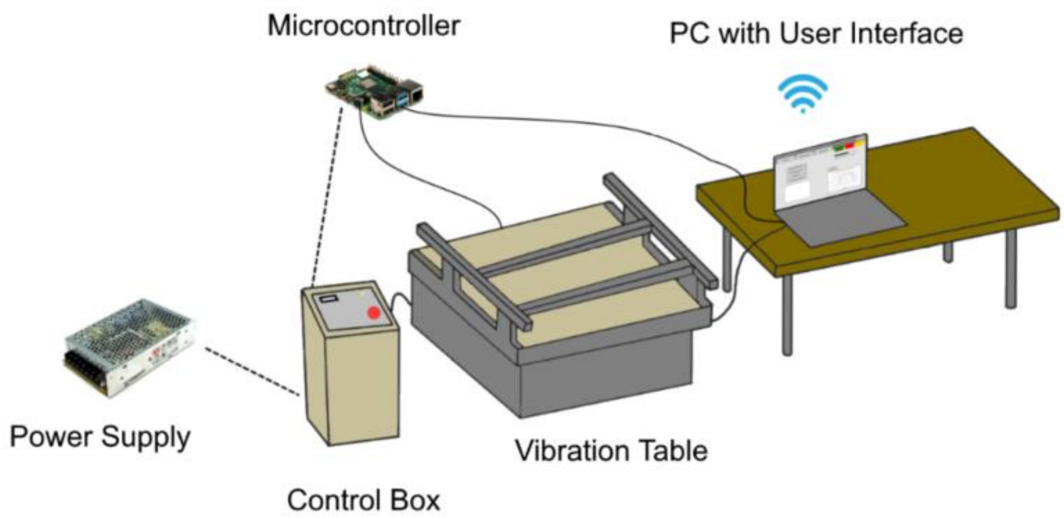


Figure 14: An Overall Design of the Prototype

Control Box

The control box came with the original vibration table and housed all the electronic components. It is made of steel, and it is constructed well enough to withstand typical use and movement. All the original electronics were removed and discarded. Inside the control box, we placed a MELIFE motor 58V motor driver, an Arduino mega, an EAGLEWELL power supply, an Emergency-Stop button, and an indicator light.

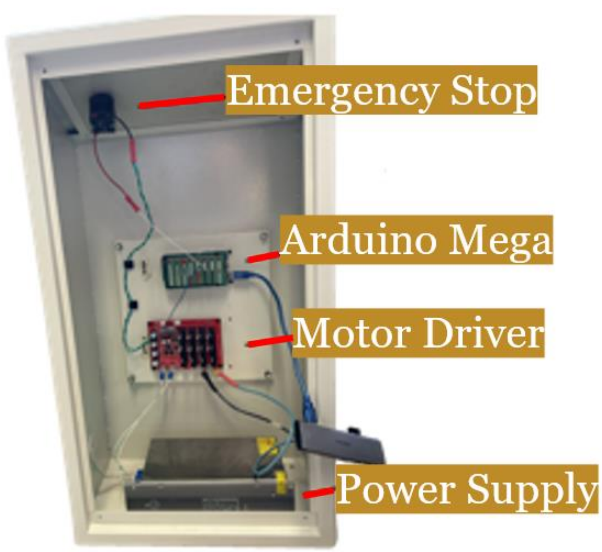


Figure 15: Fully Assembled Control Box

The following graphic shows the wiring diagram used inside the control box. The names next to each connection correspond to the labels on the Arduino, E-Stop, motor driver, and power supply.

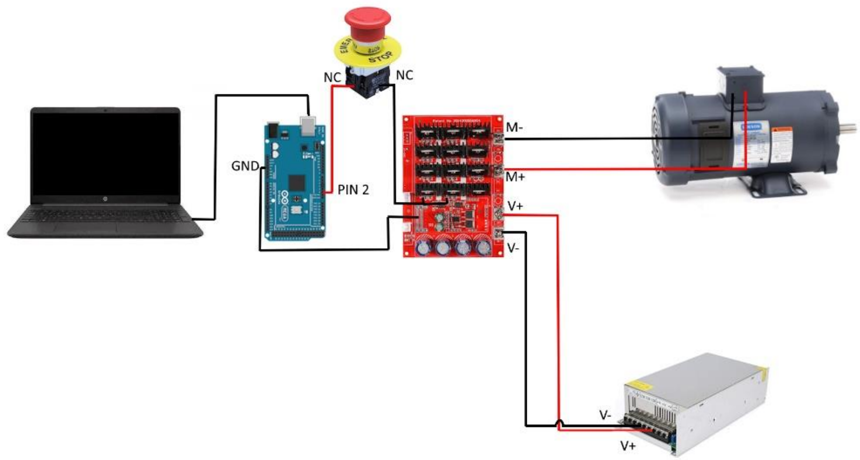


Figure 16. Wiring Diagram for Vibration Table Electronics

Vibration Table

In the U.S., it is difficult to source power supplies that can drive the original 200V motor that the vibration table was equipped with. Therefore, the motor was replaced with a 48V 18A motor. This motor was rated for similar torque and power ratings. However, the dimensions of the motor did not perfectly match the original motor, so new holes had to be drilled through the rails of the vibration table. The vibration mechanism remained the same as the original vibration table.

The following image shows all the changes we made to the vibration table. Note that this image was taken prior to placing the outer body and tabletop back on, as these components cannot be seen otherwise.

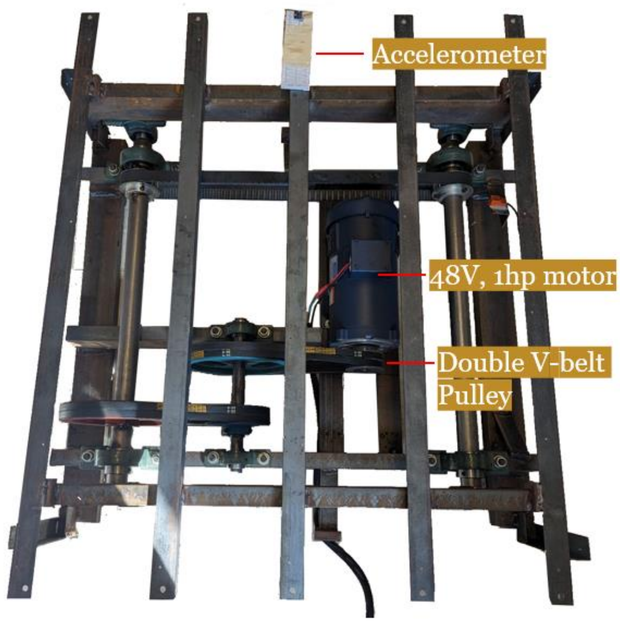


Figure 17: Vibration Table without External Covers

User Interface

The following graphic shows the final state of the User Interface. It was designed with minimalism, and modernism in mind as this was important to Eagle Medical. The purpose of this user interface is to allow the operator to program a vibration schedule and send the job to the vibration table. The interface also includes a stop button and handles accelerometer data collection in the background. Also, there is a progress bar that shows how far along the test is.

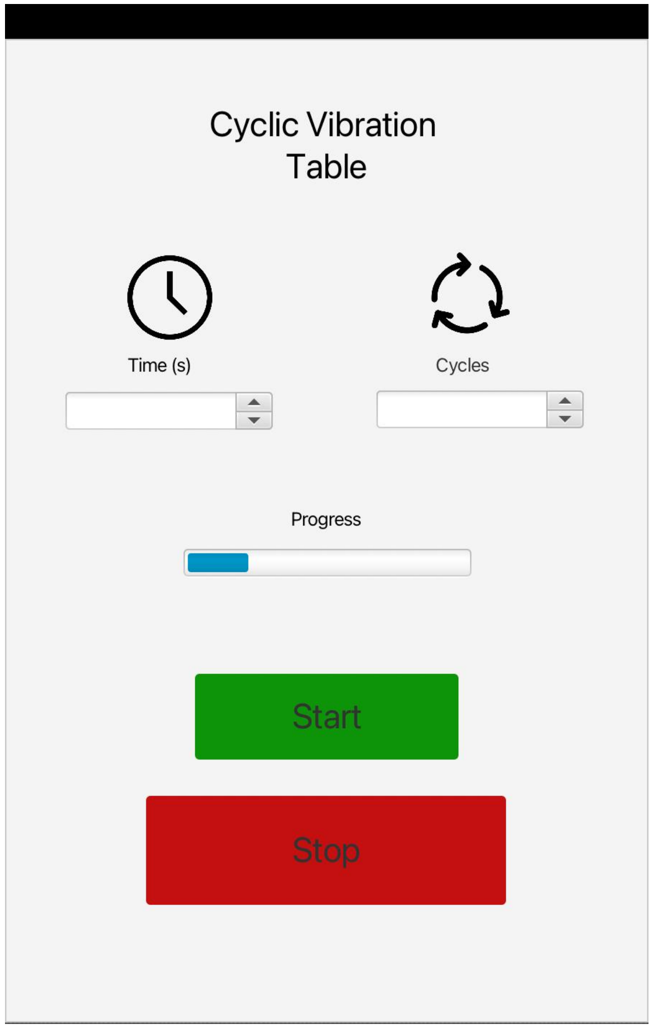


Figure 18. User Interface

The front end of the user interface was programmed using JavaFX. Scene Builder. This allowed us to build the UI with drag-and-drop features. The backend was programmed using Java and used serial communication libraries to communicate with Arduino. Serial communication was used to send vibration control to the table and receive accelerometer data.

Accelerometer Data

To quantify the vibration data, we selected a HiLetGo accelerometer. This sensor had the proper sensitivity range we desired, was easily sourced, and was easy to prototype with since it was designed for use with an Arduino. The accelerometer was placed in various locations on the table, including on the side, in the middle of the table, and in the middle of a package.

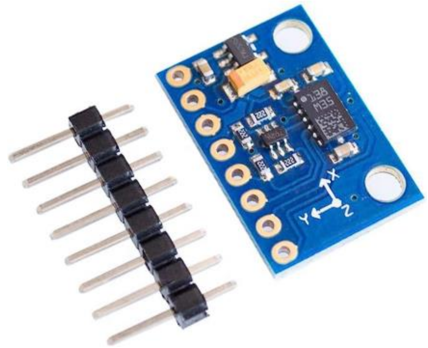


Figure 19. Accelerometer

The accelerometer sends a 3-dimensions of vibration over time data. The user interface collects the vibration data and saves it to a .csv file. Then, the file is processed using a Python script for analysis. The goal of the analysis is to create a graph of the power spectral density and quantify the total vibration intensity with a metric called Grms. To find this value, we computed the power spectral density, took the integral under the curve, then took the square root of this value.

Design Hazard Checklist

Once the detailed design was put together, we were able to create a Design Hazard Checklist – see Table 6. This checklist identifies the possible hazards of this design. For any identified hazards, the hazard was described, and the planned corrective action was outlined in Table 7.

Table 6: Design Hazard Checklist

Y	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing, or similar action, including pinch points and sheer points?
Y	2. Can any part of the design undergo high acceleration/decelerations?
Y	3. Will the system have any large moving masses or large forces?
N	4. Will the system produce a projectile?
N	5. Would it be possible for the system to fall under gravity creating injury?
N	6. Will a user be exposed to overhanging weights as part of the design?
N	7. Will the system have any sharp edges?
N	8. Will any part of the electrical systems not be grounded?
Y	9. Will there be any large batteries or electrical voltage in the system above 40 V?
N	10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights, or pressurized fluids?
N	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
N	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
N	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
Y	14. Can the system generate high levels of noise?
N	15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
Y	16. Is it possible for the system to be used in an unsafe manner?
N	17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

Table 7: Identified Hazards and Proposed Corrective Actions

Description of Hazard	Planned Corrective Action	Planned Date	Actual
Vibrating table and large motor.	External tabletop to reduce overall vibrations, warning labels, and visual signal if the machine is in operation or not.	5/4/2023	5/15/2023
The tabletop will undergo high acceleration and high deceleration in normal operation.	Visual signal to show whether the machine is in progress. Place the table far away from high-traffic areas.	5/6/2023	5/15/2023
The system will have large forces exerted by the vibration motor.	Visual signal to show whether the machine is in progress. Placement in an out-of-the-way location.	5/5/2023	5/30/2023
The system will have large voltages from the main voltage and transformer.	Isolate the power supply, and operational lights on PCB.	5/5/2023	5/5/2023
The vibration system will produce high levels of noise in normal operation.	Vibration dampening feet so that the noise is minimized. Testing will occur to measure the dB of normal usage to assess the need for PPE.	5/5/2023	N.A.
The system could be used unsafely if the weight limit is exceeded and/or if the IFU is not properly followed.	Implement clear instructions and warning labels.	5/15/2023	6/6/2023

Tables 6 and 7 identified the risks that are involved in the design and implementation of the retrofit vibration table. The hazards include the vibration mechanism, high accelerations, large forces, high voltages, auditory hazards, and potential misuse. These hazards will be taken into consideration in the design of the vibration table, and planned dates were assigned as deadlines for when the corrective actions should be physically put into place.

With the detailed design in mind, we were able to create the proposed bill of materials in Table 8. This table lists the item description, product number, purpose, associated task, quantity, and cost.

Table 8: Final Bill of Materials

Item Description	Product Number	Purpose	Procurement Source	Quantity	Unit Price	Total Price	Purchasing Link
Wirefy Heat Shrink Tubing	Wirefy-DWT-200-B-R	For strong electrical /mechanical connections	Amazon	1	$ 13.99	$ 13.99	Wirefy Heat Shrink T
MELIFE Motor Driver	5598340	To control the motor	Amazon	1	$ 18.99	$ 18.99	https://www.amazo
Arduino Mega	2560 R3	To control the motor driver	Amazon	1	$ 48.20	$ 48.20	Amazon.com: ARDU
Electronics-Salon Screw Terminal for Arduino	MD-D1236-1	Stabilizes electrical connections to the MEGA	Amazon	1	$ 32.00	$ 32.00	Electronics-Salon Sc
HiLetgo Accelerometer	3-01-0122	Speed Testing	Amazon	1	$ 9.99	$ 9.99	HiLetgo 3pcs GY-521
mxuteuk Emergancy Stop	HB2-ES545	Stop the motor	Amazon	1	$ 11.99	$ 11.99	mxuteuk 2pcs 22mn
Power Supply	B09BKNFBTT	Powers the table	Amazon	1	$ 109.96	$ 109.96	EAGWELL 48V 1200
Motor	109102	Drives the vibration	MRO Supply	1	$ 604.81	$ 604.81	https://www.mrosu
Pulley	B08CBGVHRJ	Drives the vibration	Amazon	1	$ 36.97	$ 36.97	2AK30-5/8 Fixed Bo
Adhesive Cable Clips	B08ZJF9W33	Organizes Wires	Amazon	1	$ 7.85	$ 7.85	Amazon.com: 60 PC
KECO Cable Sleeve	Da1/2inblack100ft	Protects Motor Wires	Amazon	1	$ 15.99	$ 15.99	https://www.amazo
Fasteners for Control Box	B0BKZWWTJY	Lock PSU + electronics in place	Amazon	1	$ 26.77	$ 26.77	Amazon.com: 1625
Neodymium Magnet	5862K173	fasten accelerometer to chassis	McMaster	3	$ 5.16	$ 15.48	Neodymium Magne
12 Voltage Regulator	dkplnt 20A 240W	steps down the power supply voltage. Can be used for an additional fan or lights	Amazon	1	$ 24.99	$ 24.99	https://www.amazo
Arduino Wire	B08KDFQ4JT	Connects the control box to the external computer	Amazon	1	$ 7.99	$ 7.99	Amazon.com: 3M A
Green Indicator Light	2779K14-2779K142	Indicates the table is getting power	McMaster	1	$ 9.18	$ 9.18	Panel Light, Quick-D
Insulated Wire	18	Accelerometer Wire	Amazon	1	$ 15.99	$ 15.99	TUOFENG 20 awg W
					Total Price	$ 1,011.14	(before tax /shipping)

The most important purchases are the motor driver, microcontroller, and power supply since these parts are responsible for the critical functions of the vibration table. The other components support the critical functions. It is worth noting the significant decrease in the cost. Since the scope of the project has changed and we are able to reuse the whole table, the cost has gone down.

Parts Selection

The main driving constraint was the motor. As we had decided to replace the previous motor, we needed to find a motor that would output the same torque, with less voltage and more current. Additionally, the geometry of the motor had to fit in the location of the current vibration motor. After careful measurements, we decided on the MRO 48V DC motor, since it met our torque and geometry requirements. With the motor selected, it became easier to select the right driver board, power supply, and pulleys. The driver board and power supply were selected from reputable brands that output the correct voltages and currents. The pulley was purchased to replace the previous pulley and fit on the new motor.

Materials Selection

For the current functional prototype, there were no raw materials used, so we cannot discuss materials selection.

Prototype Manufacturing Process Instructions

In this section, we will outline the steps to manufacture the functional prototype. This project has three main parts: the vibration table, the circuit for motor control, and the software for the GUI. As such, this section will address the prototyping for each of these three areas separately.

Installing the New Motor

1. Remove the bolts and nuts used to secure the previous motor and remove the motor.

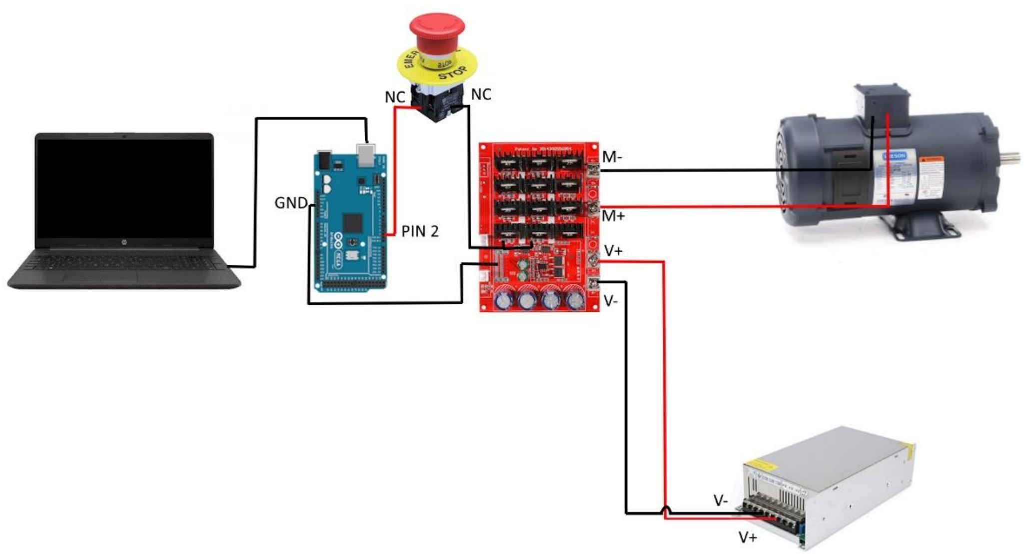
Figure 20. Old Motor with Mounting Bracket

Figure 21. Location of Old Motor. Note the plane that the pulley system is on

2. Lock the pulley onto the new motor with the set screws and a hex key.
3. Place the new motor in the location of the old motor such that the pulley is in the same location as before.
4. Mark 4x new holes on the rails of the vibration table for mounting the new motor.
5. Remove the motor and set aside.
6. Drill new holes with a 1/4th-inch drill bit.
7. Place the new motor on the rails of the vibration table at the position found in step 3.

8. Pass a bolt from under the table through the newly drilled hole and the motor's mounting bracket.
9. Lock the nut with a locking washer and a nut. Repeat this process for the remaining 3 newly drilled holes.
10. Stretch the belt over the pulley.
11. Take the motor wires and use a butt crimp to connect a 4 ft of 12-gauge copper wire to the positive and negative wires.
12. Add heat shrinking tube to the butt crimp connections and then slide wires into a cable sheath to protect both wires.
13. Using cable organizers, route the motor wires along the underside of the vibration table to prevent excess rubbing.
14. The motor is now fully installed.

Wiring the Arduino, Motor Controller, and Power Supply



It is highly recommended to follow the wiring diagram in Figure 18. For convenience, this figure is reprinted in this section.

1. First, prepare the MELIFE motor driver, and solder wires onto the PWM input diodes as seen in the following figure.

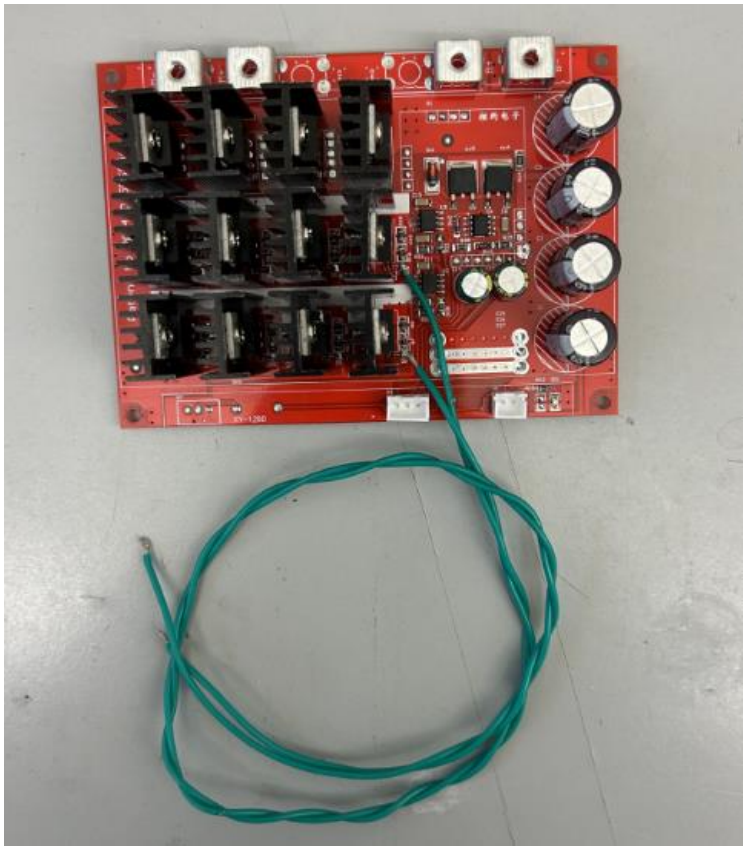


Figure 22. Soldered connections to the PWM inputs on Motor Driver

2. Then, solder a wire to the motor controller ground. See the following figure.

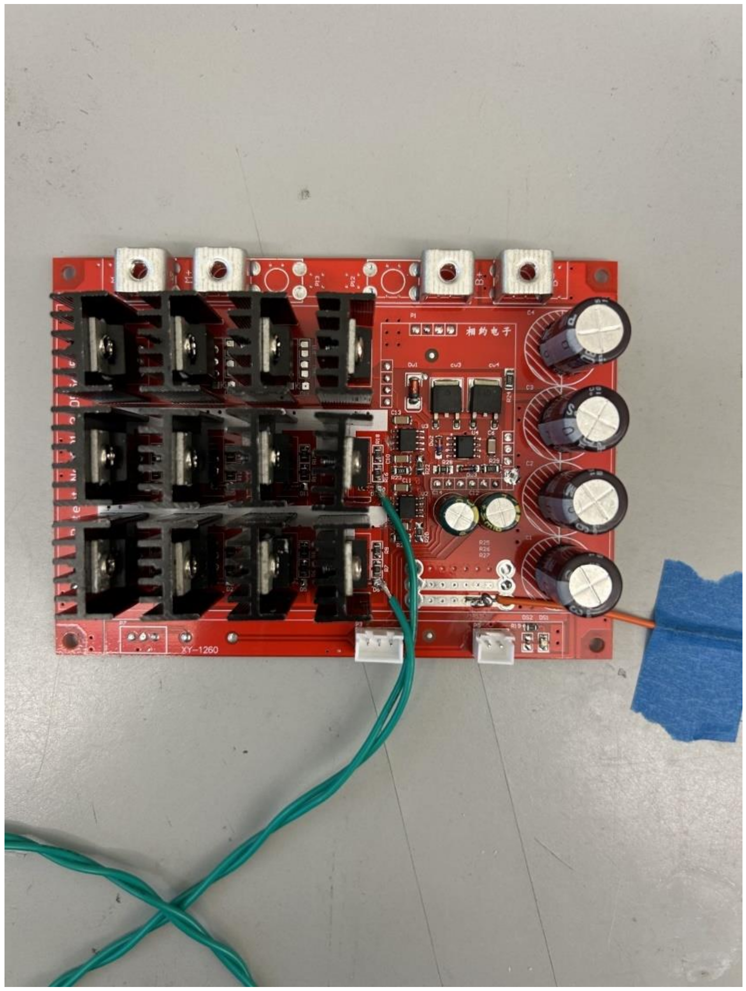


Figure 23. Soldering connection to motor controller ground

3. Then, wire the PWM signal into one of the NC terminals at the emergency stop.
4. Connect a wire from the other NC terminal to Pin 2 on the Arduino Mega.
5. Connect the newly soldered wire from the ground of the driver board to the ground of the Arduino Mega.

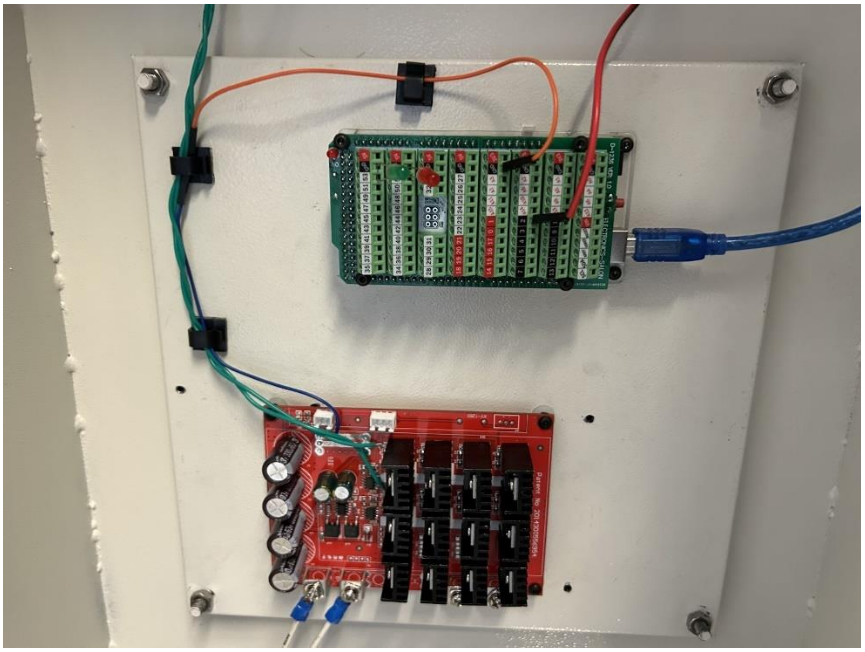


Figure 24. Completed Motor controller to Arduino Circuit

6. Connect the Arduino to a laptop with the Arduino cable. This connection will power the board and allow for the uploading of the code.
7. Now to wire the power supply. Using crimp connections, screw the V+ on the power supply into V+ on the board, and V- on the power supply to B- on the board.
8. Now to wire the motor. Using crimp connections, screw the red motor wire onto M+, and the black motor wire onto M-. The circuit is now built.

Assembling the Control Box

1. Drill the required mounting holes for the Motor control unit, Arduino Mega, and power supply.
2. Place the power supply at the bottom of the control box, and secure it with M3 bolts and nuts.
3. Place the power input terminal in the hole on the side of the control box, and secure it with 2x M3 bolts and nuts.
4. Place the Arduino mega in its location, and secure it with M3 bolts and M3 washers.
5. Place the motor driver board, and secure it with M3 bolts and M3 washers.
6. Connect the power supply to the input terminal, the motor driver, and the motor according to the wiring diagram.
7. Secure the E-Stop to the face of the control box and lock the face onto the control box with M3 hardware.

Figure 25. The face of the Control Box Installed on the Control Box

8. Wire the E-Stop according to the wiring diagram, making sure to use the Normally Closed (NC) terminals.
9. The control box is fully assembled.

Prototyping for the GUI and Backend

The GUI was built as a Java program using JavaFX. This library is used primarily in building graphical interfaces and can be connected to sensors to output their values. Firstly, we used SceneBuilder to create an FXML file that outlines the front-facing aspects of the GUI. Secondly, we generate a controller that will control the backend of the GUI and give functionality to the buttons. For the sake of this prototype, we just implement the start and stop buttons as well as the graph so that we can read accelerometer data. The pseudocode for both can be found in Appendix D.

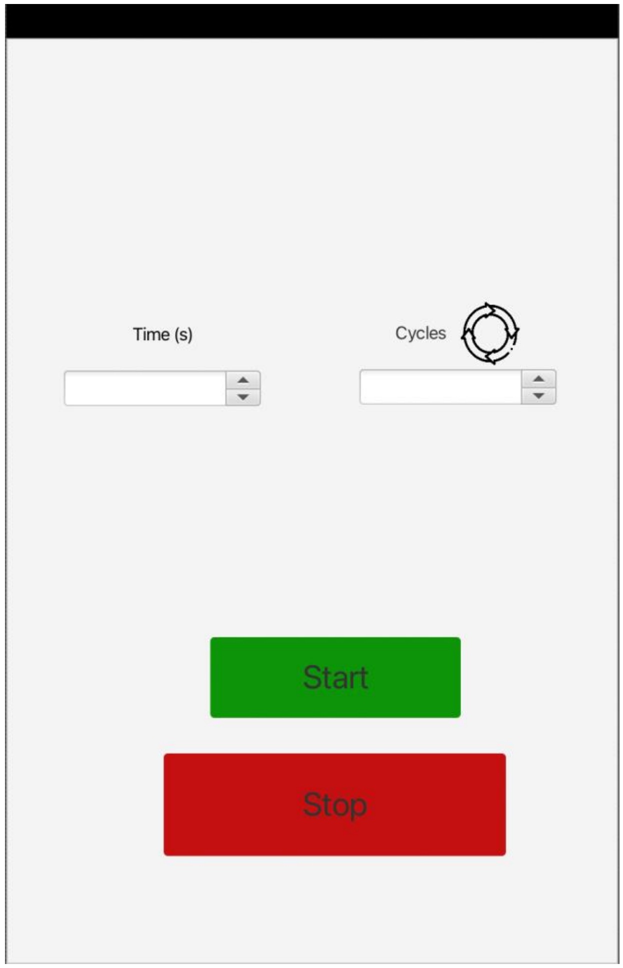


Figure 26: Prototype GUI Developed Using JavaFX and Associated Libraries

Test Plans

Summary Table

The following table summarizes the testing plans that will be used to analyze the performance and safety of the vibration table. The tests were divided into the following subsections: electrical, thermal, mechanical, and software. The table also includes the sample size, facilities, and equipment needed for the testing. The sample size is set to 1 for most tests since there is only 1 prototype being manufactured.

Table 9: Summary Table of Test Plans

Specification	Test	Test Type	Sample Size	Facilities	Equipment
GUI Aesthetic Satisfaction	UI Survey	Survey rating the UI from 1 to 10	15	EMPS/Cal Poly	-
Acceleration	Acceleration Test	Test the maximum accelerations	1	Vibrations Laboratory	Accelerometer Arduino
Vibration Control	Vibration Control Test	Tests for how well we can control the table	1	Vibrations Laboratory	RPM Meter
Minimum Sampling Frequency	Electronics Testing	Frequency analysis to ensure proper data collection	1	N.A.	Microcontroller
Motor Electronic Rating	Current Test	Ensure the motor runs at the proper current	1	Project Room @ Room Temp	Electric Multimeter
Power Supply Variance at Nominal	Voltage Test	Ensure the power supply runs at a safe voltage	1	Project Room @ Room Temp	Electric Multimeter
GUI Functionality	Component Unit Testing	Software functionality	-	N.A	Compatible IDE (Eclipse, IntelliJ)
GUI Functionality	Sensor Connectivity	Software functionality	-	N.A	Compatible IDE (Eclipse, IntelliJ)
Time to Run Test	Timing Test	Time to run the test	-	N.A.	timer
E-Stop Testing	E-Stop Electronics Testing	Ensures safe stopping	1	N.A.	N.A.

Description of Test Plans

UI Aesthetic Satisfaction (Max)

This test will be done by creating a survey to then be filled out by random users. The users will be provided the instructions to run the machine and the users will click through the UI. They will then rate the UI on aesthetics with questions about the color, button layouts, ease of use, and efficiency all on a scale from 1 to 10.

The expected result is a survey collection of at least 20 subjects with ratings that can be used to improve UI design. Data analysis will include an average and standard deviation.

Acceleration Test (Max)

This test will be used to validate the motor control software and implementation. The required equipment will be an accelerometer, and the facility used will be Cal Poly's vibration laboratory.

The expected outcome will be an acceleration time graph, showing changing speeds corresponding to the input signal from the software. No training is required. The steps are as follows:

1) Secure the accelerometer to the center of the vibration table testing area.
2) Run a random vibration cycle for approximately 3 minutes.
3) After the test is complete, use the accelerometer data to create a speed-time graph.
4) Compare the actual speed vs. time graph to the input signal.

Data will include a maximum acceleration value.

Vibration Control Testing (Jonathan)

The vibration control testing ensures that we can control the motor accurately and precisely. This metric will be measured in RPM. We will first measure the maximum RPM. Then we will input various intensities into the motor control circuit, measure RPM, and compare theoretical and experimental RPMS.

1) Input maximum intensity from the UI. Begin vibration schedule.
2) Use an RPM meter to measure maximum RPM. Point the RPM meter at the protruding bolt on the main vibration shaft. Note: Take an average of 3 measurements for all proceeding RPM recordings.
3) Input 25% intensity and measure RPM.
4) Input 50% intensity and measure RPM.
5) Input 75% intensity and measure RPM.

Expected Results:

- RPM at 25, 50, 75, and 100% intensities
- The standard deviation of RPM
- Comparison between theoretical and actual intensities

Minimum Sampling Frequency (Madhav)

To ensure accurate data, the sampling frequency must be twice as high as the highest frequency of vibration. The minimum sampling frequency must therefore be 12 Hz.

1) Power on the GUI and the motor control circuit.
2) Record accelerometer data for 5 min.
3) Measure the sampling frequency across the 5 min.

Expected Results: sampling frequency is greater than 12 Hz, pass or fail.

Motor Wire Temperature Testing (Jonathan)

Motor wire temperature testing will substitute current testing. As the motor pulls over 18A of current, it was difficult to find instrumentation equipment for this range. However, the temperature of the wire will show that the wire is properly specified for the current because if it is too small, the wire will heat up. Failure to address motor wire temperatures may result in the critical failure of the motor. The equipment required for this test is a thermocouple and insulated gloves. The facility does not matter. To run the test, the operator must be trained in using a thermocouple correctly because misuse may damage the vibration table or the multimeter. The expected results of this test are current readings at various motor speeds over time. The steps for this test are the following:

1) Power off the vibration table.
2) Place the thermocouple on the motor wire, about 6 inches away from the driver board.
3) Power the vibration table at a low speed and monitor the temperature.
4) Increase the motor speed to maximum and monitor the temperature.
    a. If the temperature reaches 35C, immediately turn off the machine and stop the test.
5) Power off the motor after 30min

Expected Results: Motor wiring does not heat up over 5C.

Power Supply Voltage Testing (Jonathan)

The power supply must output a regulated voltage that does not fluctuate in time. Failure in power delivery results in a risk of damage to the components. The equipment required is a digital multimeter and insulated gloves. The facility does not matter.

1) Power off vibration table
2) Place the multimeter in series with a power supply with alligator clips.
3) Power on the table.
4) Measure output voltage over the course of 1 hr.
5) Power off the table.

Expected Results: The power supply should output an average voltage of 48V +/- 5%

Emergency Stop Testing (Madhav)

This test will ensure the functionality of the emergency stops placed throughout the system. No requirements or materials are needed beyond the vibration table and its computer. To perform the test, follow these steps:

1) Power on the table and increase the motor speed to maximum.
2) Press the physical emergency stop on the control box and ensure that the table stops vibrating.
3) Repeat step 1.
4) Press the electronic emergency stop on the computer and ensure that the table stops vibrating.

The expected results of this test will be that the motor stops whenever the emergency stop is pressed. Pass or fail for ten trials.

Component Unit Testing (Madhav)

In software development, unit testing is an industry-wide method used to test individual components of code. Essentially, a method or function in the code would be tested by calling the function, providing an expected value, and running the function to determine if it matches the expected value. The tests will be run using JUnit Testing, which is a methodology that is used to test front-end code.

Testing Data and Analysis

GUI Aesthetic Satisfaction Results

The GUI aesthetic satisfaction test was performed by providing a prototype of the GUI for ten new users to rate the usability, simplicity, and color choice on a scale of 1-10. The ratings were then averaged out and recorded in the following table.

Table 10: GUI Aesthetic Satisfaction Table Results (Scale from 1 to 10)

Attribute	Rating
Usability	10
Simplicity	10
Color choice	10

The survey results demonstrated a successful design of the UI for the user experience. The survey yielded perfect results for its usability, simplicity, and color choice making it an effective tool in displaying motor control settings.

Acceleration Test Results

The acceleration test was performed by attaching an accelerometer to the vibration mechanism and recording the results. The graphical user interface (GUI) application can receive data at a rate of 50 Hz, which surpasses the minimum requirement of 12 Hz stated in the test specifications. Figure 29 displays the raw data obtained from running the machine for 160 seconds, where the following schedule was applied in a pattern (note, all percentages are percentages of max motor speed): 25%, slow down, 50%, slow down, 75%, slow down, 50%, slow down, 25%, slow down, etc.

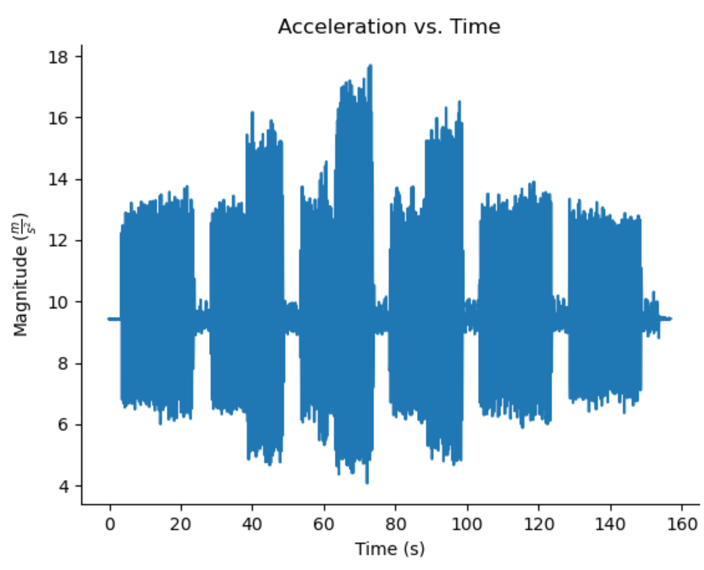


Figure 27: Accelerometer magnitude data recorded for 160 seconds, where the vibration table was switching between 25%, 50%, and 75% of maximum speed.

The observed results align with our expectations, as evident from the distinct divisions observed in the acceleration data at 25%, 50%, and 75%. The maximum frequency the table can reach is 5 Hz; hence, when applying the Fourier transform to this data, we anticipate the peaks to fall within this range. Figure 30 illustrates the Fourier Transform of the recorded data.

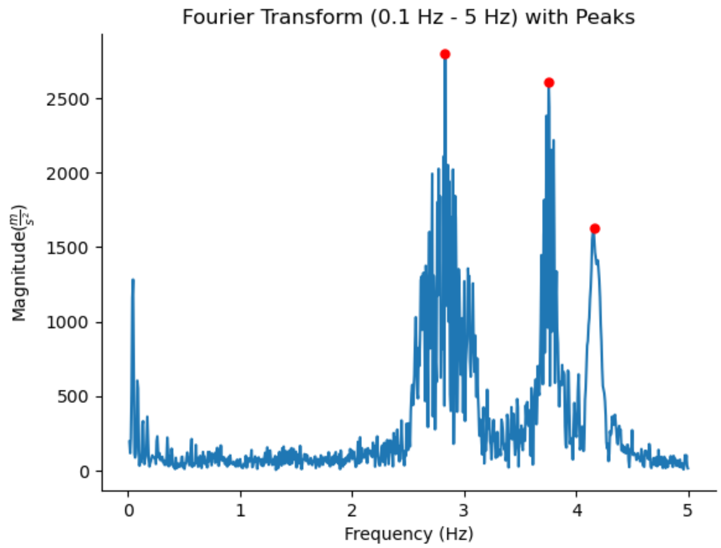


Figure 28: Fourier transforms of accelerometer magnitude data recorded for 160 seconds, where the vibration table was switching between 25%, 50%, and 75% of maximum speed.

This data substantiates our anticipated hypothesis, revealing a peak at the expected frequency of 2.83, 3.75, and an additional smaller peak at 4.13 Hz. To mitigate the influence of the gravitational constant, the DC offset was removed. Additionally, higher-frequency noise was deemed insignificant and eliminated from the analysis (a comprehensive image can be found in Appendix E). This data was further analyzed to create a power spectral density plot and to extract key components such as the area under the curve and peak power.

Control of Vibration Motor Results

To collect the vibration control data, we recorded a bolt attached to one rail of the vibration table and sent the vibration controls through our user interfaces. The maximum RPM was found first since this value could not be theoretically determined. Then, the RPM at various intensities was recorded. The theoretical RPM is calculated as the intensity percentage times the maximum RPM.

Table 11. RPM measurements

Intensity	Theoretical RPM (based on max)	Actual RPM
25%	63	65
50%	126	123
75%	189	190
100%	N.A.	252

We were able to control the vibration table to produce expected RPM values. This test was a pass because we are within the error range.

Minimum Sampling Frequency Results

The minimum sampling frequency is a value returned through the accelerometer programming. The target of this test would be any value above 12Hz since this is over twice the highest expected frequency of the vibration table. The actual sampling frequency was 38Hz, so this test passed.

Table 12. Sampling Frequency Results

Target Sampling Frequency	Actual Sampling Frequency
12Hz	38Hz

Motor Wire Temperature Results

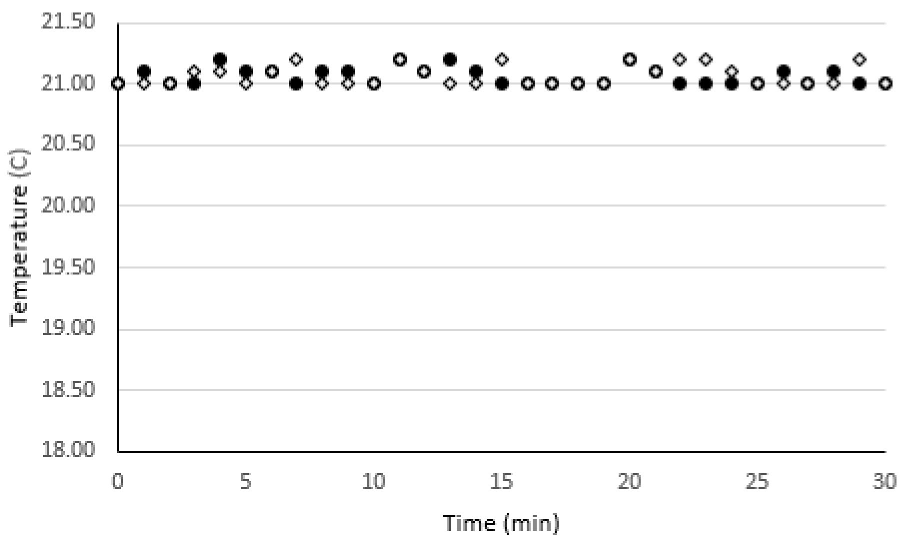


Figure 29. Temperature over Time Graph for Room Temperature and Motor Wire

Table 13. Average Motor Wire Temperature vs. Room Temperature

Average Room Temperature	Average Motor Wire Temperature
21.06 ± 0.07	21.06 ± 0.08

Since there was no significant difference between the temperature of the wire and the room temperature, no heating was observed. Therefore, the vibration table passed the test. To interpret the results, this means that the gauge of wire was properly selected for the currents passing through it.

Power Supply Variance Results

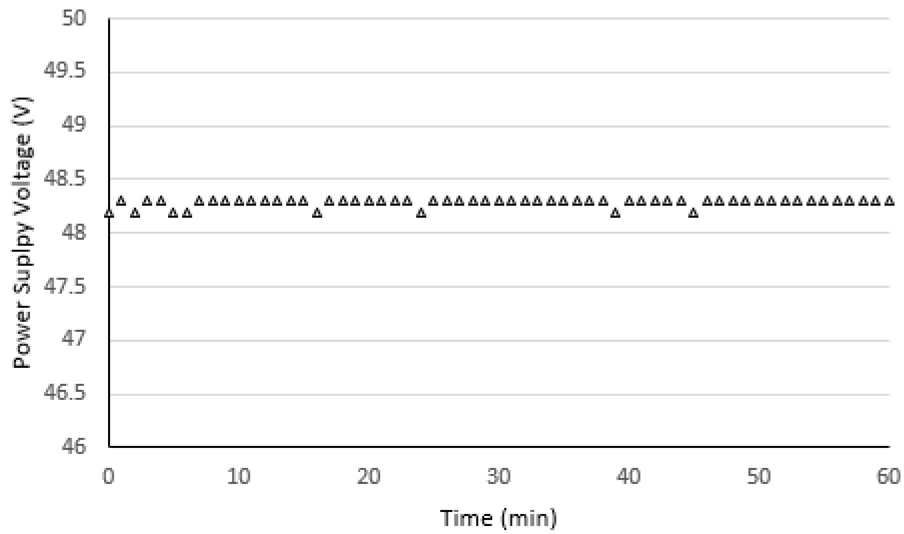


Figure 30. Power Supply Voltage over Time

The average voltage for this test was 48.30 ± 0.022V. This is within our tolerance of the power supply, and the variance is seen to be very small. Therefore, this power supply is reliable, and we should not expect voltage spikes from it.

Time to Run Test Results

The time to open the application, type in the desired time and cycles, and start the test was recorded ten times on ten random users who have not used the application prior. The results yielded the following times: 7.1, 3.2, 6.4, 4.0, 4.5, 9.2, 3.3, 6.8, 3.1, 5.0 which averaged out to 5.2 seconds.

Emergency Stop Results

The emergency stop test was a pass/fail test to ensure the E-stop worked correctly by shorting the PWM signal to the motor control. The E-stop was tested ten times and had a 100% success rate in shorting the signal and stopping the motor. The motor would resume once the E-stop was reversed.

GUI Functionality Results

The GUI functionality was determined by running the GUI under several use cases and considering edge cases to spot any bugs. Regarding stopping and starting the GUI during tests, after completion, there were no apparent bugs. The minimum time of tests was set to 15 seconds to account for the 10-second ramp-up time and from user tests, no time under 15 seconds could be inputted.

Instructions for Use

The following is an operator's manual for using the vibration table to run a cyclic vibration test on a package. The first step is to install the required software. Then, we will cover how to assess the connections and make sure that everything is wired properly. The following section goes over how to run your first vibration schedule using the user interface. Finally, the last section covers how to analyze the vibration data collected by the accelerometer.

Installing the User Interface

1. Download the User Interface Installer executable file from the following link: mdhvsk/seniorProject (github.com).
2. Run the installer.
3. Plug the Arduino cable into the desired PC (Windows only).
4. Open the Vibration Table User Interface and ensure that the Arduino is being recognized by the UI.
5. If needed, update Arduino Port in the MainController.java file to the current port used
6. Proceed to the next section.

Ensuring the Cables are Properly Connected

1. Unscrew the bolts holding the back of the control box in place.
2. Inside the control box, check to make sure no connections have come loose. Specifically, ensure that the motor controller's soldered connections are secure since these may come loose in transit.
    a. If any wires are loose, refer to the manufacturing process above and the wiring diagram to re-connect.
3. Ensure that the Arduino is plugged into the PC.
4. Plug the power cord into the side of the control box.
5. Plug the power cord into a 110V socket **IMPORTANT: be completely sure that the socket outputs 110-120V, as any higher may damage the power supply.
6. Proceed to the next section.

Running your First Vibration Schedule

1. Ensure that the package fits the vibration table. The area of the package must fit within the $1m^2$ testable surface area.
2. Secure the package using the package-locking mechanism on the vibration table.

Figure 31. Example of a Package Secured During Vibration Testing

3. In the user interface, input the desired pulse time, and desired number of cycles.
4. Standby the Emergency Stop on the control box.
5. Press the start button and observe the vibration test to ensure the table moves properly at the beginning.
    a. If the vibration table stalls or performs unexpectedly, immediately press the emergency stop button. If safe, unplug the power to the control box.
6. Once the vibration test is complete, we are ready to analyze the vibration data. Proceed to the next section.

Using the UI to Analyze Vibration Data

1. Once the vibration table completes its desired number of cycles, all the vibration data will have been saved to a .csv file. Press the plot button.
2. The plot button should begin to analyze the data. It may take a couple of minutes if the vibration test had many cycles.
3. Once the analysis is complete, the UI will show the power spectral density and the Grms of the vibration test. These values can then be used to validate the package's test cycle.

Discussion and Conclusion

The purpose of this document is to record all the work management aspects of this project: the retrofitting of the Programmable Vibration Table. This included a complete overhaul of the electrical design and control, an overhaul of the vibration mechanism, and the integration of a new

Human Machine Interface. The goals of this project are to increase the safety of the machine, add a display system to visualize sensor data and make vibration testing easy and efficient. This document contains a summary of our background research and patent search. Also found in this document is the conversion of customer requirements into engineering specifications, as well as the anticipated timeline for key deliverables. In addition to the above sections, we have also included our documented process for conceptual modeling and evaluation, followed by our failure analysis. Finally, we have included sections for detailed design and prototype manufacturing to discuss how we plan on making our project idea as well as a section called test plan for testing.

There are some future considerations that we would recommend improving upon for this project. We would recommend focusing on creating a more streamlined UI experience that would allow for more flexibility in deciding vibration schedules and for more integration with the plotting of accelerometer data. Currently, the motor control is hard coded for the desired vibration schedule of 25-50-75% intensity. Going forward, this schedule should be able to be edited from the GUI and vibration schedules should be saved for further use. This would involve a dedicated software team familiar with the web design framework to improve the java and python scripts. We would also recommend water jetting vent holes in the control box for better temperature control of the power supply and controllers. Another upgrade could be to install leveling castor wheels at the base to make it easier to transport.

The Cal Poly team working on this project learned many new skills including basic motor control, UI design, electrical design, how to implement safety precautions, etc. We also learned how to undergo a redesign and pivot when a project specification was unable to be met. After two quarters of work, the result was a functional vibration table that could take user input and generate the required acceleration graphs to get useful results. We would like to extend our thanks to Eagle Medical for making this project possible and for their help along the way.

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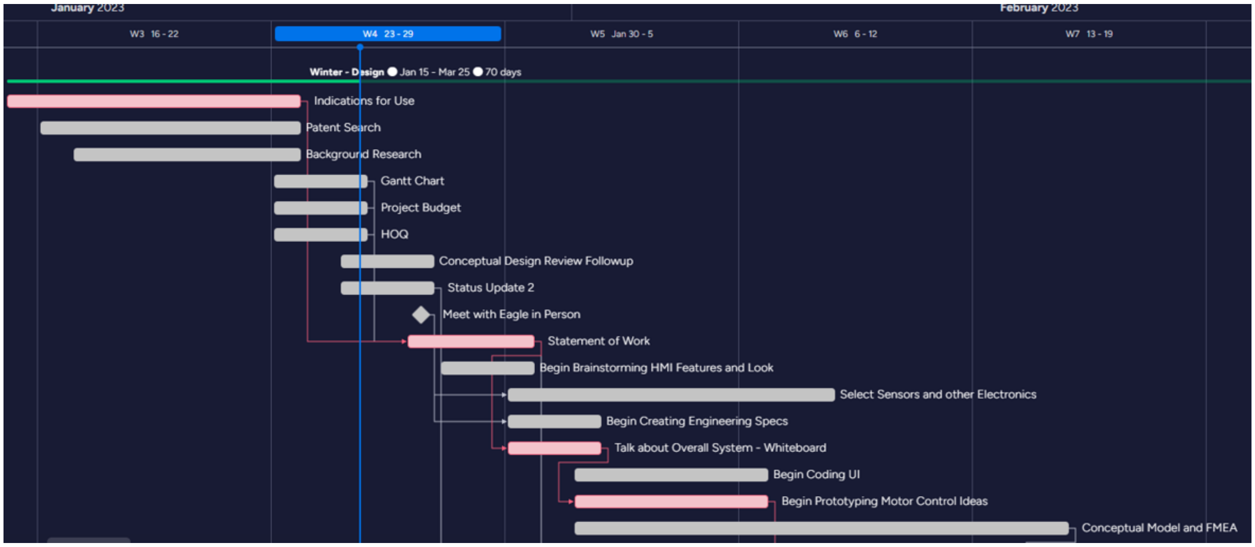
Appendix A – Customer Needs and Wants

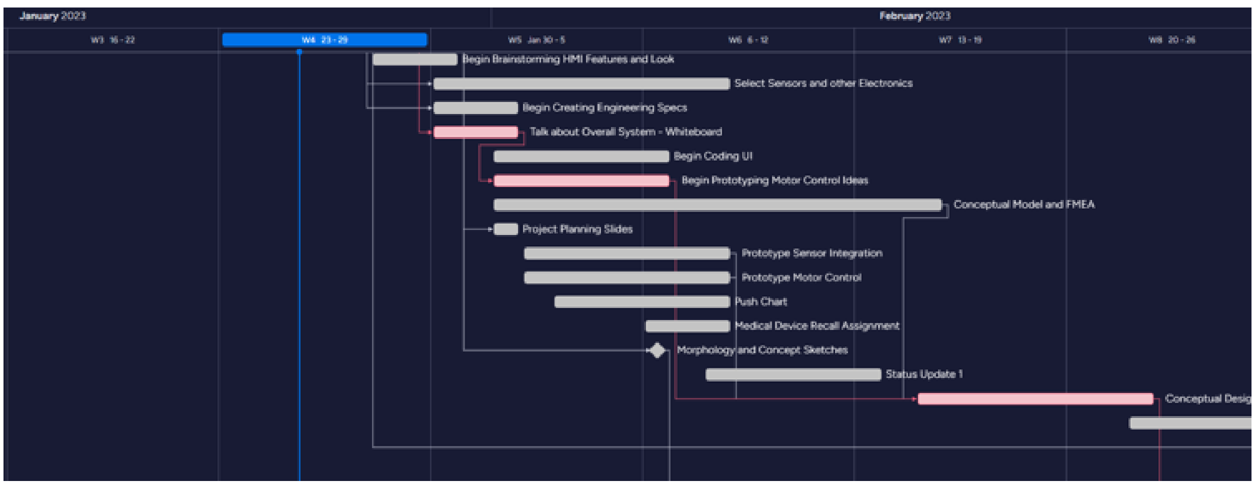
Updated the Customer Requirements based on the change of scope.

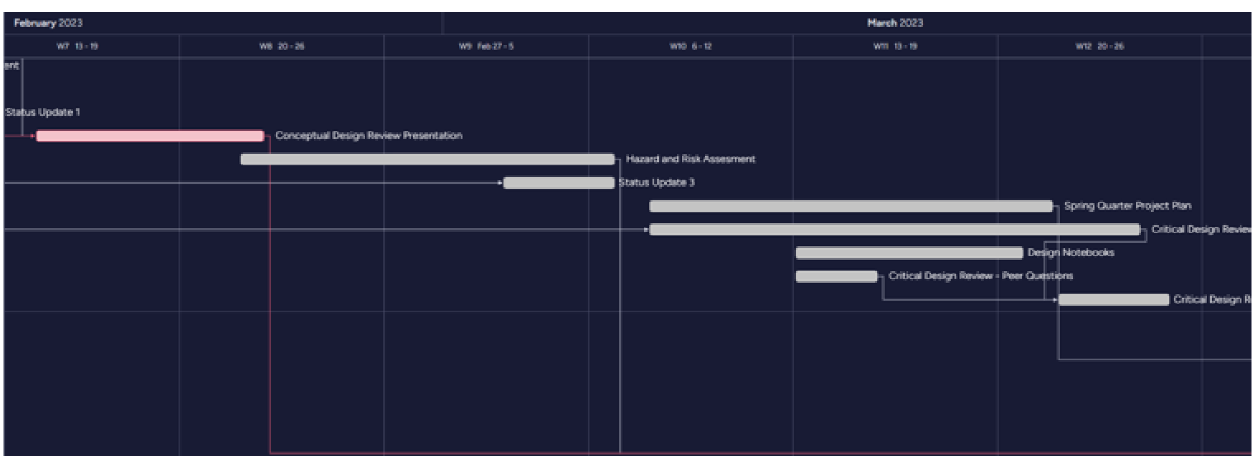
Table 14: Customer Needs and Wants for Vibration Table

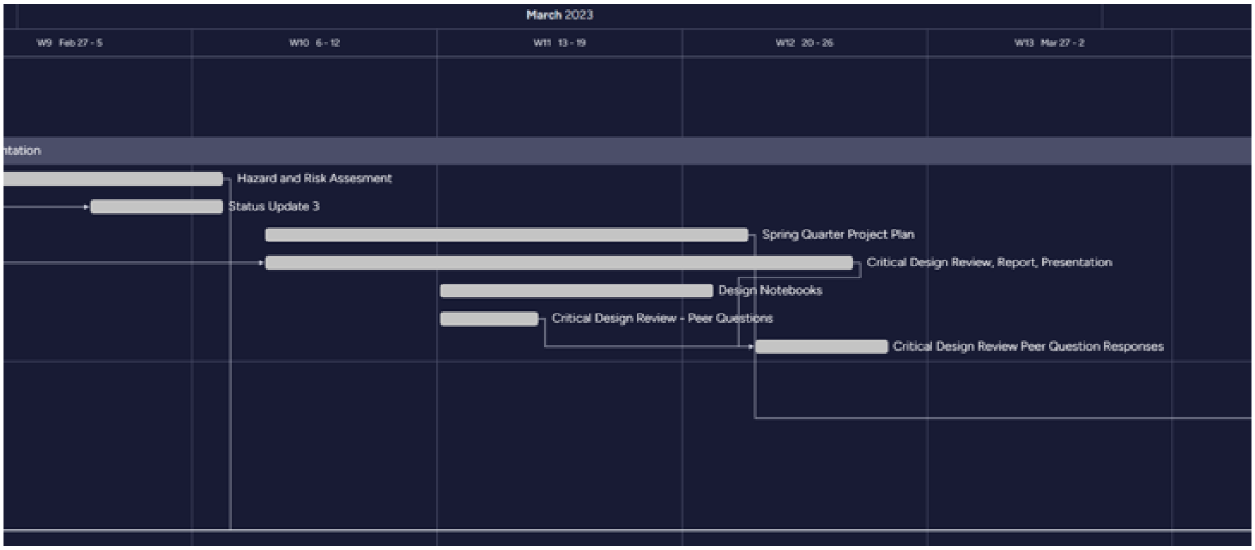
Customer Requirements	
Needs	Wants
Vibration According to Given Standards	Modern HMI
Outputs Frequency Data	Circuit Diagram
Programmable Vibration Schedules	Easy to Repair
Microcontroller Integration	Salvage as Much as Possible
Easily Accessible Data Output	
Updated and Reliable Electronics	
A Usable HMI	

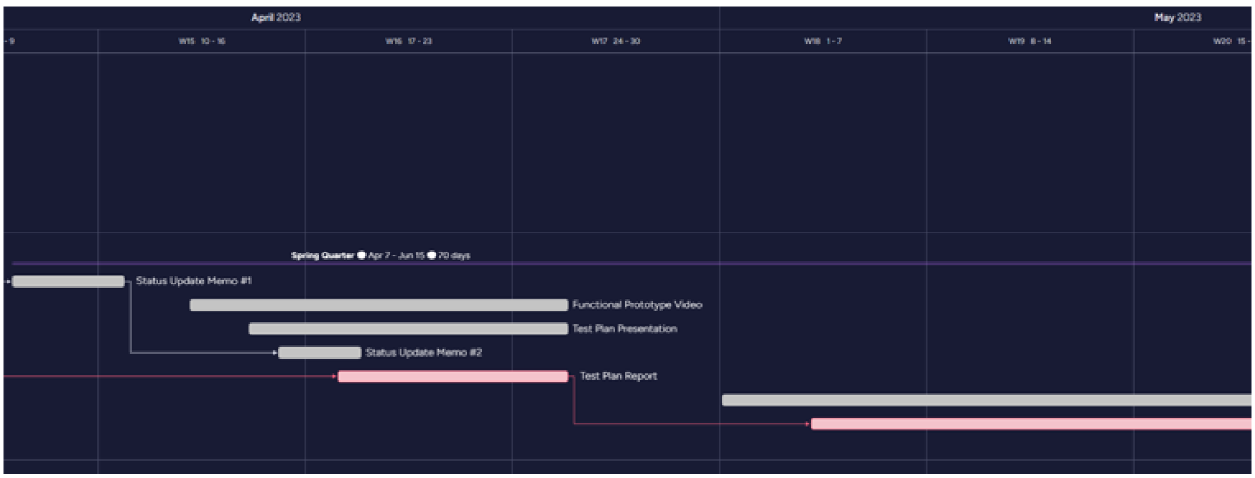
Appendix B– Gantt Chart








March 2023
W9 Feb 27 - 5
W10 6 - 12
W11 13 - 19
W12 20 - 26
W13 Mar 27 - 2
ntation
Hazard and Risk Assesment
Status Update 3
Spring Quarter Project Plan
Critical Design Review, Report, Presentation
Design Notebooks
Critical Design Review - Peer Questions
Critical Design Review Peer Question Responses


April 2023
May 2023
W15 10 - 16
W16 17 - 23
W17 24 - 30
W18 1 - 7
W19 8 - 14
Spring Quarter Apr 7 - Jun 15 70 days
Status Update Memo #1
Functional Prototype Video
Test Plan Presentation
Status Update Memo #2
Test Plan Report


Spring Quarter Apr 7 - Jun 15 70 days
Expo Poster - 1st Draft
Final Report
Expo Poster - Final

Appendix C– Desired Motor Control Profile

Removed the previous Power Density Spectrum plots and added a new one that Eagle Medical gave to show more accurately what they want.

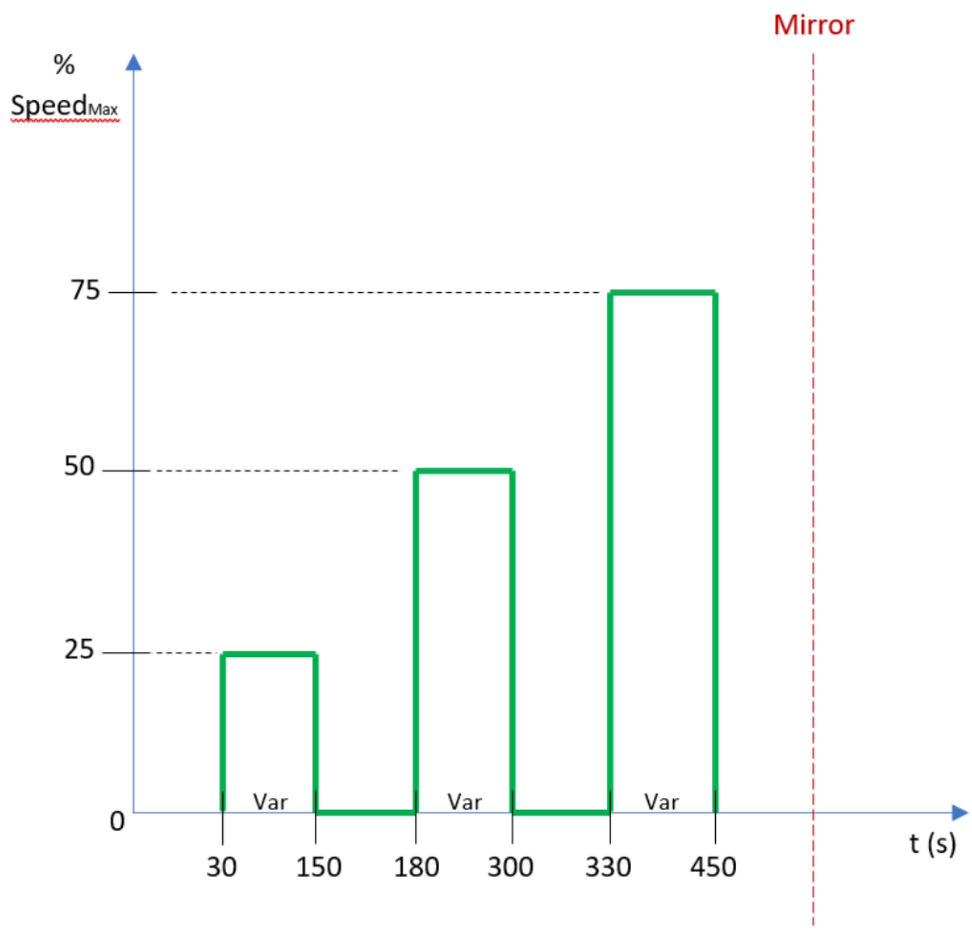


Figure C1: A Basic Chart Outlining the New Desired Motor Control. %Speed Max Represents the Speed of the Motor and Var Represents an Adjustable Variable for Length of Time at Each State.

Appendix D– Code Simplification for GUI

Code Simplification for GUI Controllers and Classes:

AccelerationData:

- **x**, **y**, **z**, **time** are variables to store acceleration data.
- **toCsvStrings()** method returns an array of strings representing the data.

ArduinoUtils:

- **findArduinoPort()** method searches for an Arduino port and returns it.

MainController:

- **stopFlag**, **comPort**, **time**, **intensity** are variables used in the controller.
- **initialize()** method initializes GUI components and sets initial values.
- **handle_btnStart(event)** method finds the Arduino port, opens it, reads data, and writes it to a CSV file.
- **handle_btnStop(event)** method stops data reading and closes the port.
- **handle_btnChart(event)** method loads a chart for data visualization.
- **handleMotorStart(arduinoPort)** method sends motor control commands to the Arduino.

Note: The simplified version removes exception handling and some implementation details for readability purposes.

DataController:

Manages data for two charts: **fourierChart** and **timeChart**. It has a method called **initialize()** which handles initialization tasks.

The **parseData()** method is responsible for reading data from a file and updating the series in the charts. It performs the following steps:

1. It creates an empty list called **rawAccelerationData** to store the data.
2. It opens the specified file using a **FileReader**.
3. It creates a **CSVReader** to read the CSV data from the file.
4. It loops through each line in the CSV file.
5. For each line, it creates an **AccelerationData** object by parsing the values from the line.
6. The **AccelerationData** object is added to the **rawAccelerationData** list.
7. After reading all the data, the CSV reader is closed.
8. The method then loops through each **AccelerationData** object in **rawAccelerationData**.
9. For each object, it extracts the time, x, y, and z values and adds them to the corresponding series (**xSeriesTime**, **ySeriesTime**, **zSeriesTime**).
10. It calculates the magnitude of the acceleration vector using the Euclidean distance formula.
11. The magnitude value is added to the **magSeriesTime**.
12. The length of **rawAccelerationData** is printed.
13. Finally, the **magSeriesTime** is added to the **timeChart**.

Overall, the **DataController** class handles the parsing of CSV data, calculates acceleration magnitudes, and updates the charts with the data.

Pseudocode for GUI FXML:

```
AnchorPane:
    MenuBar:
        Menu:
            MenuItem: Exit
        Menu:
            MenuItem: Delete
        Menu:
            MenuItem: About
    SplitPane:
        AnchorPane:
            Text: Select Your Schedule
            MenuButton:
                MenuItem: Preset1
                MenuItem: Custom
        AnchorPane:
            SplitPane:
                AnchorPane:
                    LineChart:
                        CategoryAxis
                        NumberAxis
                AnchorPane:
                    ProgressBar: progress
            Button: Start
            Button: Stop
```

Appendix E- Complete Graphs of Accelerometer Data

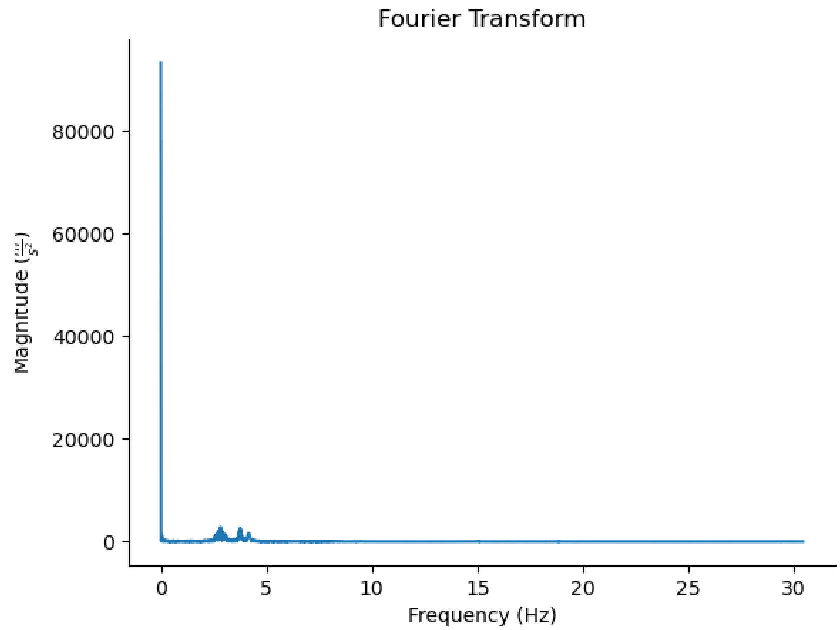


Figure E1: Fourier transform of accelerometer magnitude data recorded for 160 seconds, where the vibration table was switching between 25%, 50%, and 75% of maximum speed. This graph includes the DC offset.

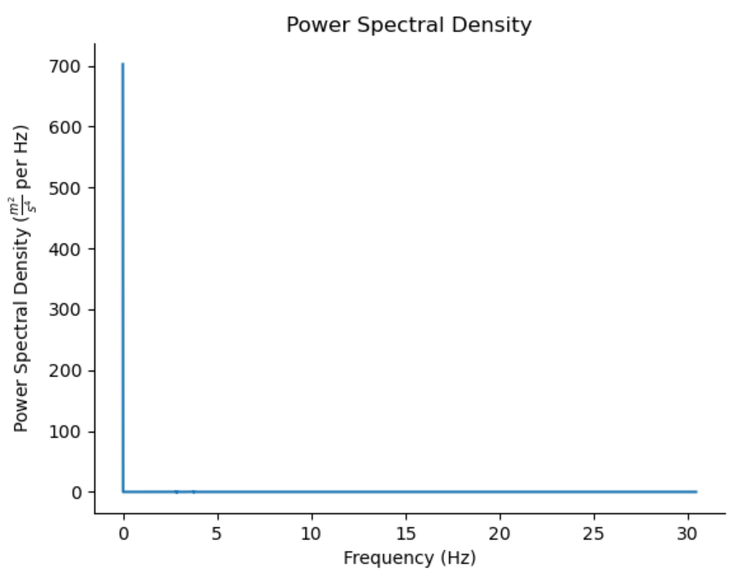


Figure E2: Power spectral density plot of accelerometer magnitude data recorded for 160 seconds, where the vibration table was switching between 25%, 50%, and 75% of maximum speed.

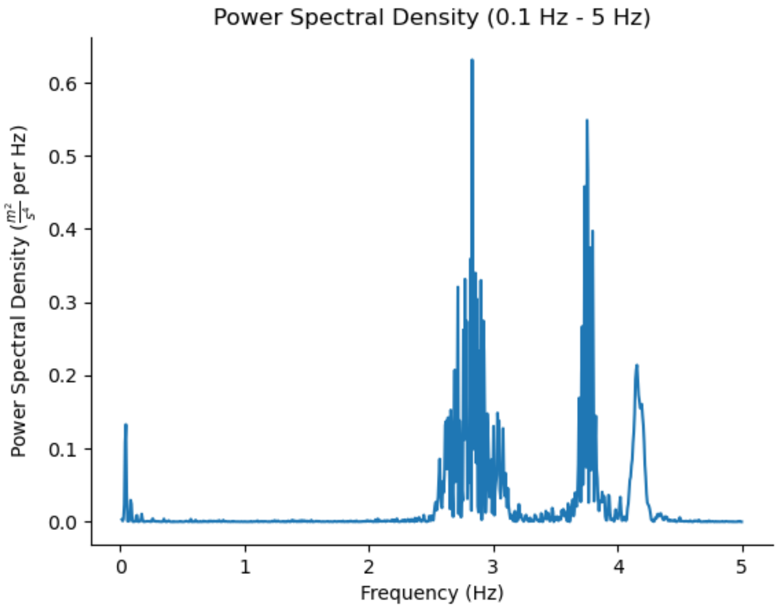


Figure E3: Power spectral density plot of accelerometer magnitude data recorded for 160 seconds, where the vibration table was switching between 25%, 50%, and 75% of maximum speed. This graph cuts off the DC offset and focuses on the operational range of the vibration table (up to 5 Hz).

Peak Frequencies

Frequency	Fourier Transform Magnitude
2.83	2795.59
3.75	2606.37
4.16	1628.1

Key Values

Label	Value
0 Hz Fourier Magnitude	93259.458 ($\frac{m}{s^2}$)
Area Under the PSD Curve	0.125 ($\frac{m^2}{s^4}$) per Hz

Figure E4: Important values from the above graphs for a test that was recorded for 160 seconds, where the vibration table was switching between 25%, 50%, and 75% of maximum speed.