Herbert Wertheim College of Engineering
UNIVERSITY of FLORIDA

EML 4502 FINAL PRESENTATION

25th April, 2023

“Design of shaker table mechanism for a micro-bio reactor"

Team 227B - Benchmark Bio Solutions

Adam Hays, Andrew Graeber, Crae Andrew, Domingo Alegria, Drew Meyerson, Snehal Misra, and Zachary Brown

Meet the Team

Team 227B

Benchmark Bio Solutions

Presentation Agenda

Objective → **Design** → **Prototype** → **Evaluate**

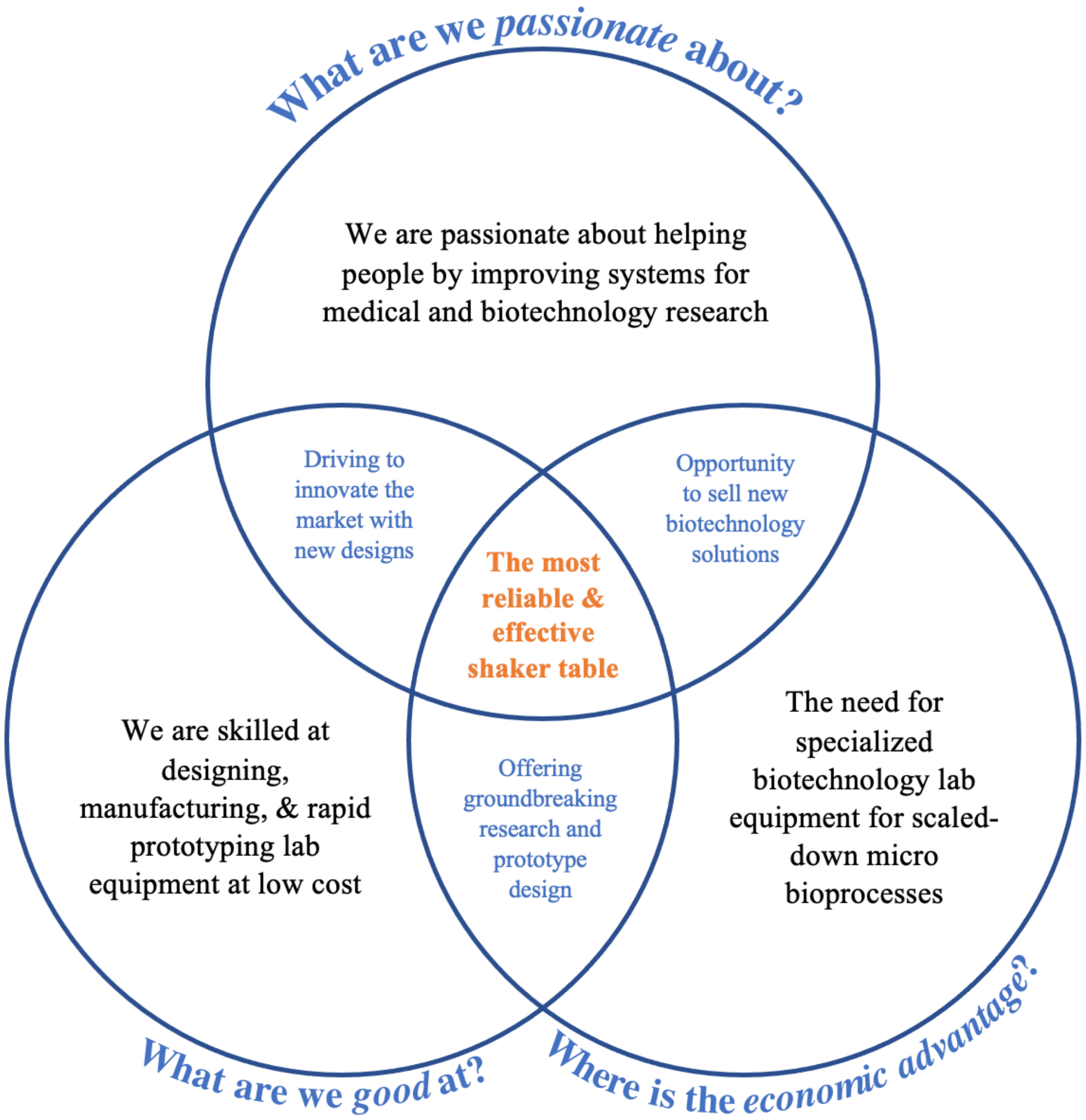
Objective
- Customer needs breakdown
- Our solution and goals

Design
- Prototype evaluation
- Mechanical design
- Electrical system
- Culture integration method
- Software approach

Prototype
- Manufacturing
- Substitute components / interim design changes

Evaluate
- Performance testing
- Delivered needs
- Improvement plan

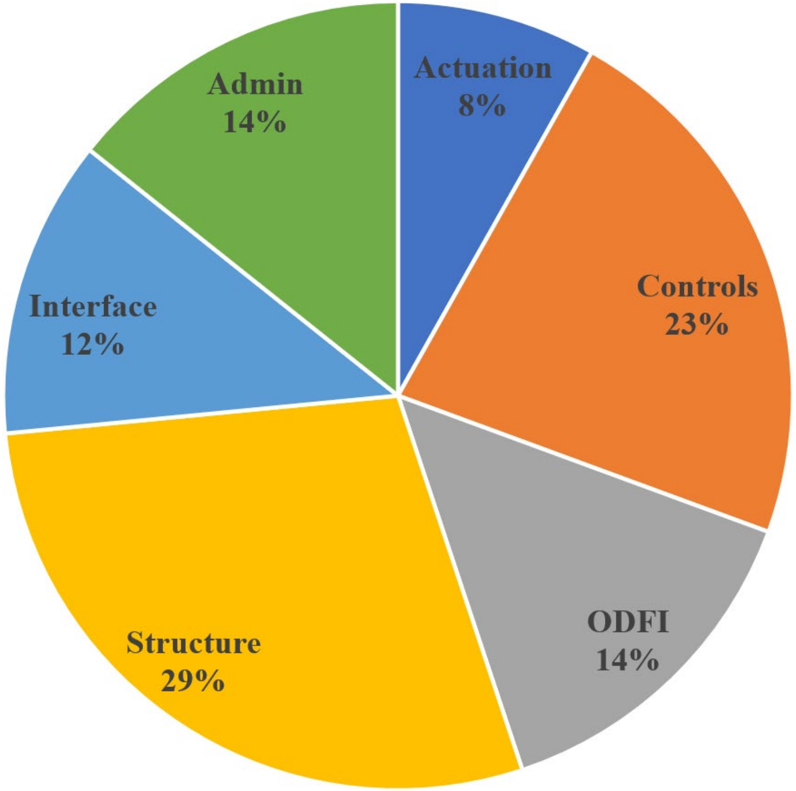
Hedgehog Concept



Customer Requirements

- Given 49 customer needs
  - Categorized and parameterized
- Table movement
  - 3 patterns, up to 350 rpm
  - Quiet
- Robust
  - Temperatures 0 °C to 70 °C
  - IPx5 waterproofing
  - Chemical resistant
  - 2 week endurance testing

- OD/FI Interrogation
  - Wavelength and intensity of light
  - Photoresistor for sensing



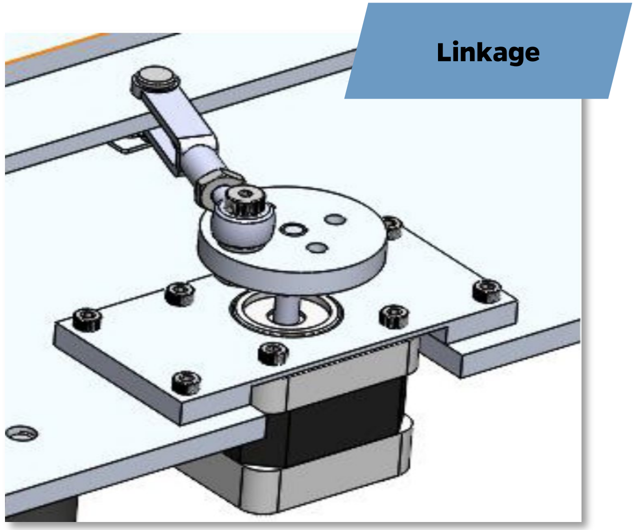
227B’s Focus

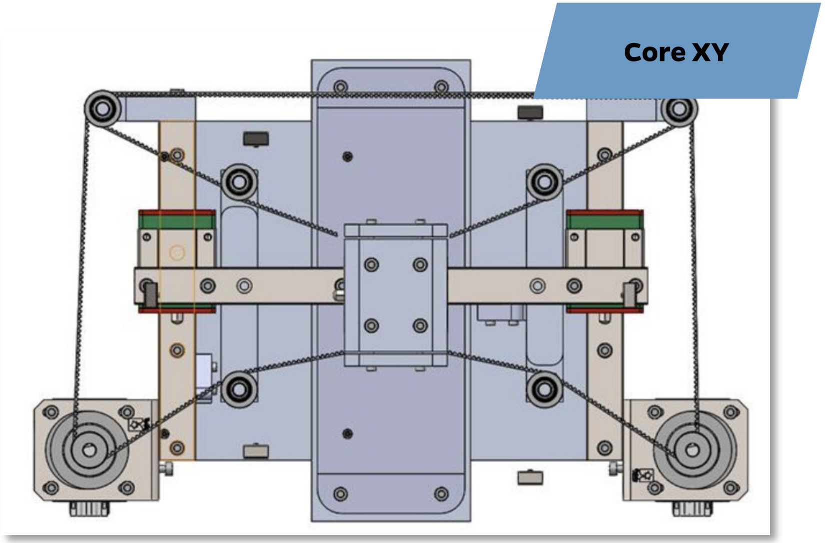
- Our goals / focus
  - Thermal
    - Table must run continuously at its maximum-rated speed for two weeks in its most demanding shaker pattern in an environment maintained at 70 °C and 0 °C
  - Waterproofing
    - All parts that could potentially be water infiltrated / damaged must be IP-X5 certified
  - ODFI Integration
    - Shaker integrated OD/FI interrogation for illumination at proper OD and FI wavelength and intensity
- Concerns
  - Production-scale device cost of no more than $400
    - 542P linkage prototype that our design dramatically improved upon already exceeded this estimate, at $479.92

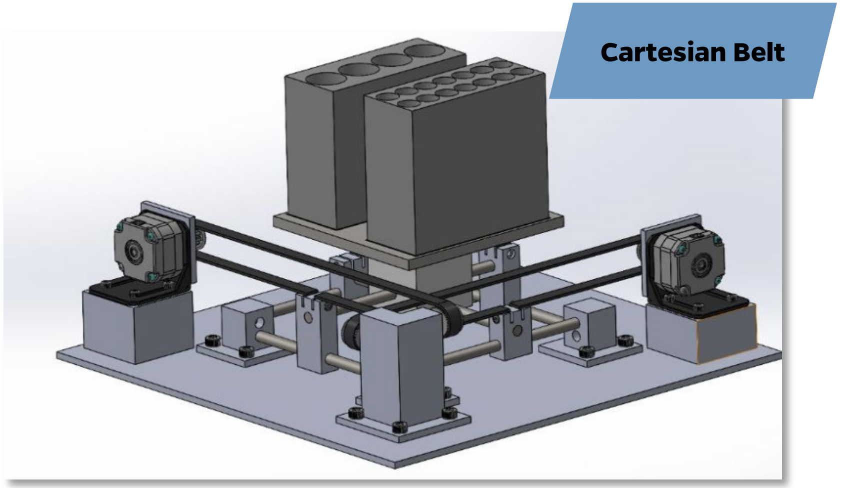
PROTOTYPE EVALUATION

A look at the EML4502 prototypes designed during the Fall 2022 semester

Prototype Evaluation



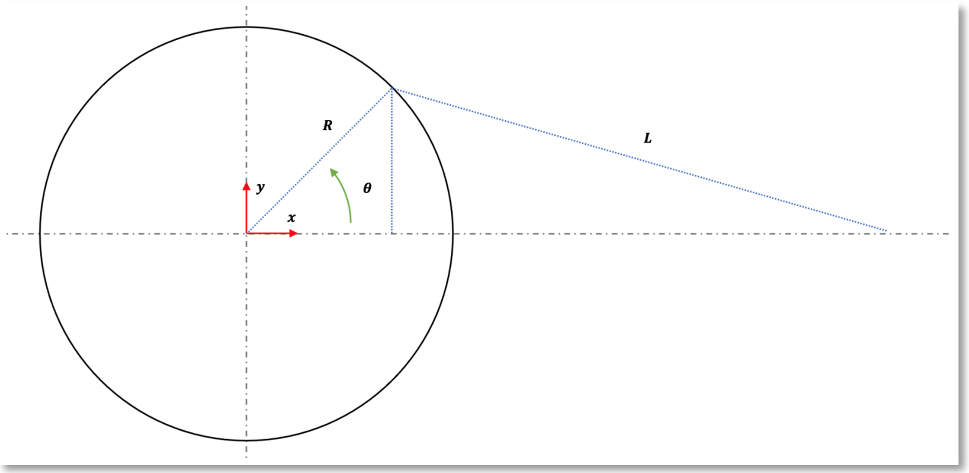




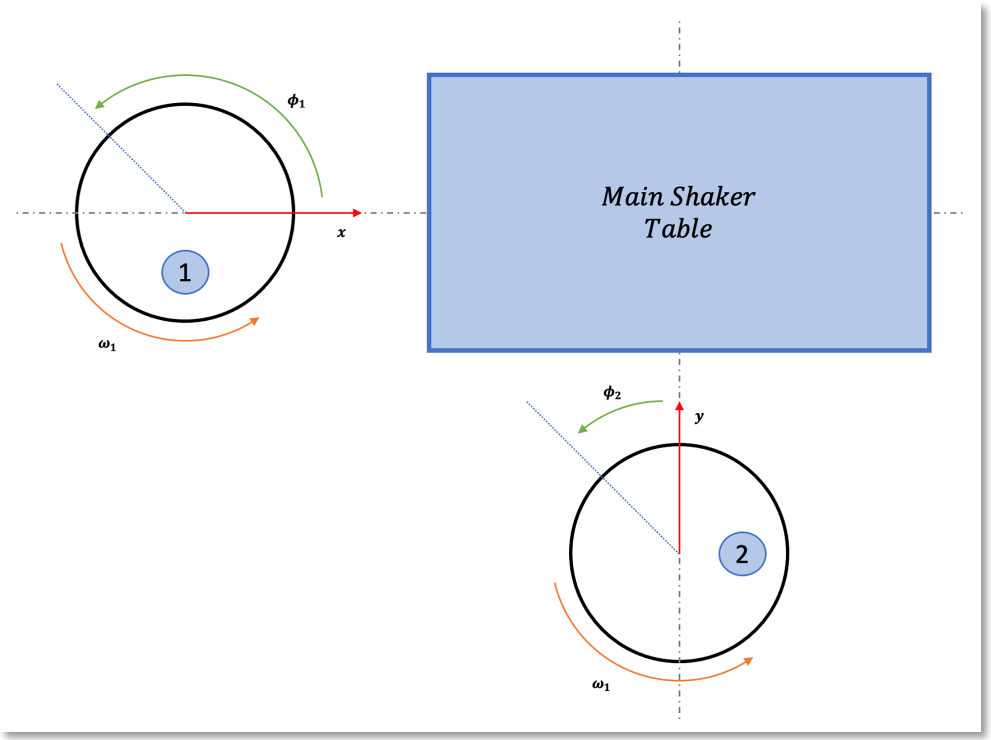
- Linkage Design was chosen
  - Cheapest prototype option
  - Robust mechanical interfaces, good for extreme environments / endurance
  - DC motors integration is more viable
    - Motors spin continuously in a single direction

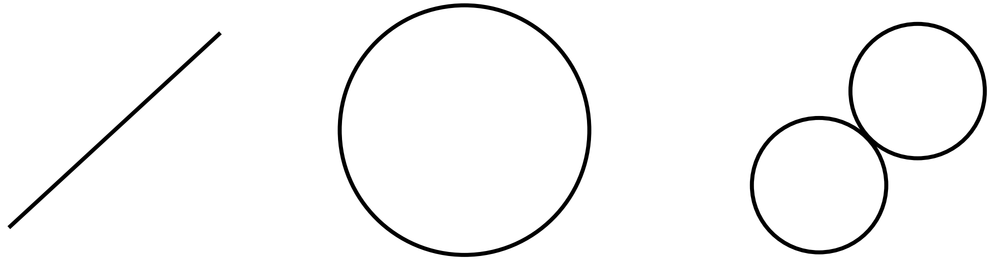
Slider Crank Kinematics

- Common for converting rotational motion to linear motion
- Displacement is a function of the rotation angle, θ
  - $x = Rcos(\theta) + \sqrt{L^2 - R^2\sin^2(\theta)}$
- Slightly more complicated in two dimensions…



2D Linkage Patterns





Linear

Cartesian: $y = x$
Velocity: $\omega_1 = -\omega_2$
Phase: $\phi_1 = \phi_2$

Orbital

Cartesian: $x^2 + y^2 = R^2$
Velocity: $\omega_1 = \omega_2$
Phase: $\phi_1 = \phi_2 + 90°$

Double Orbital

Cartesian: $(x^2 + y^2)^2 = R^2(x^2 - y^2)$
Velocity: $\omega_1 = 2 \cdot \omega_2$
Phase: $\phi_1 = \phi_2 + 90°$

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DESIGN

227B’s design process for this iteration of the shaker table mechanism

Mechanical Design

- Motors
  - Upright, keeps rotation plane of crank in line with shaker table
  - Brushless DC optimal for long life, continuously turning applications
- Waterproofing solution
  - O-Rings and Marine epoxy to seal off electronics
- Thermal management
  - Enclosed motors, need to conduct and convect heat out of pods
  - No 3D printing components! Glass transition temperature is $\sim 60\ ^\circ\mathrm{C}$
  - Other options include heat pipes and cooling plates
- Vibrational considerations

Mechanical – Motors

- Torque Calculations
  - Based on force to accelerate the rotating mass and frictional force of the 3 linear rails used
  - $\tau_{min} = (TTE)(R)(R_f) =$ $0.1495\ Nm$
  - Team 542P was not conservative enough in their estimation
  - Parameters: $\mu = 0.1, W = 30\ N,$ and $R_f = 15\%$

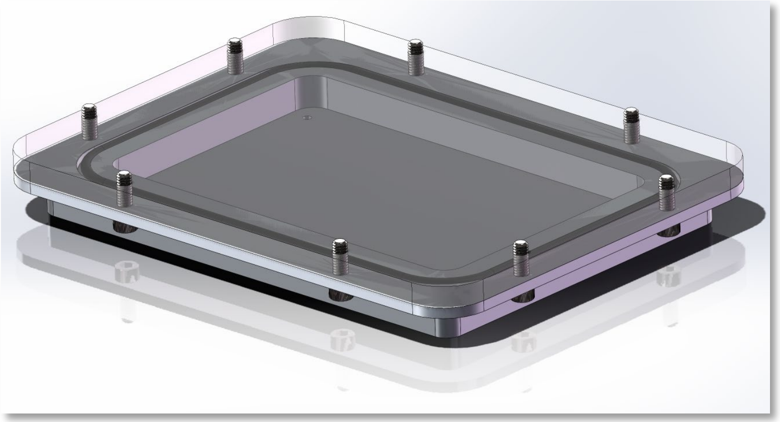
Electrocraft

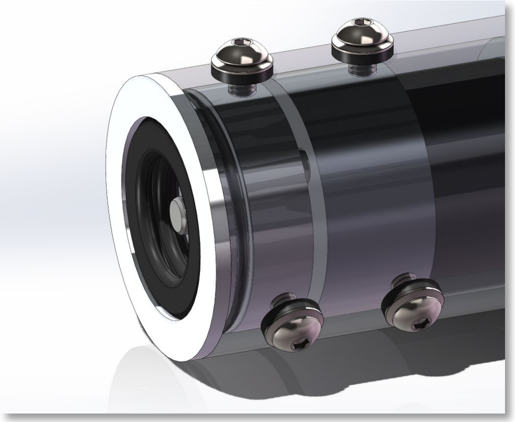
- LRPX32-090V24-110-S010
- Brushless DC Planetary Gearmotor

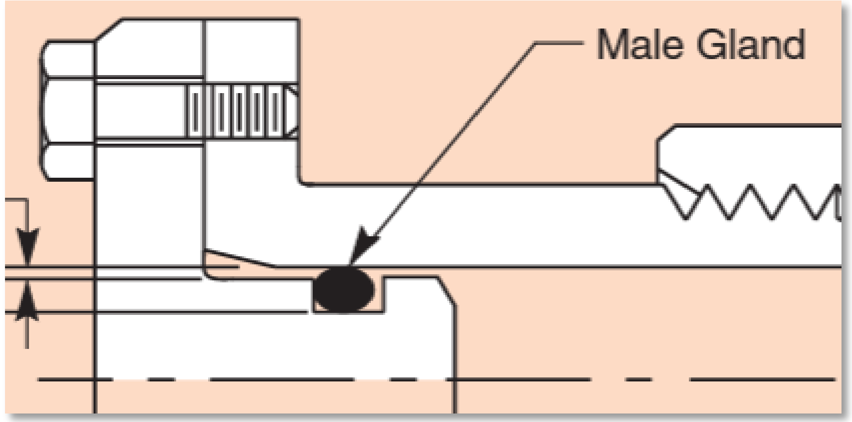
Continuous Running			Peak		
Torque (N-m)	RPM	Current (A)	Torque (N-m)	RPM	Current (A)
0.47	722	5.40	2.34	155	23.5
0.47	722	2.70	2.34	155	11.8
0.47	722	1.35	2.34	155	5.9

Mechanical – Waterproofing

- IPX5 Definition:
  - Protected from water sprayed from any direction around the enclosure
- O-Rings:
  - Parker O-Ring Handbook
  - Male glands, face seals
  - $R \geq 6 \cdot W$
- High Speed Shaft Seals
- Marine Sealant:
  - Used to seal wire pathways
  - Protect hall effect sensors

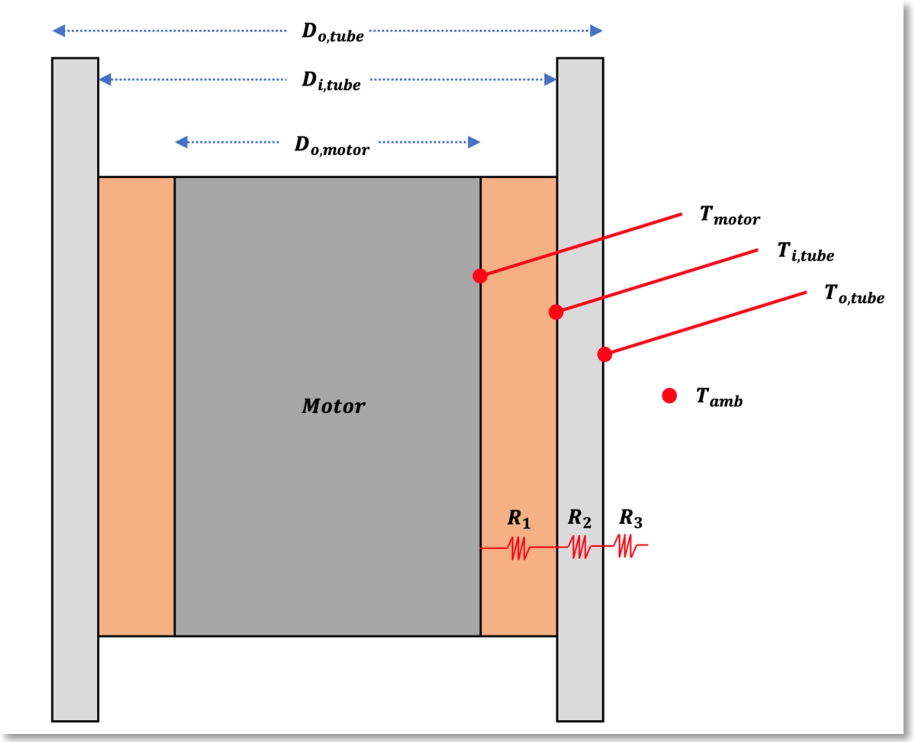






- Thermal Calculations
  - Steady state, check operating current against max current before burnout
  - $\dot{Q}_{out} = \frac{T_{motor} - T_{amb}}{\sum R} = I_{max} V$
- Thermal Resistances
  - $R = \frac{\ln\left(\frac{D_i}{D_o}\right)}{2\pi L K}$
  - Heat sink specified for flow rate
  - $R = \left(\frac{N}{R_h}\right)^{-1}$

System	Low Temperature	High Temperature
Electrocraft Motor	−40 ℃	100 ℃
Microbio Reactor	0 ℃	70 ℃



Mechanical – Thermal Management

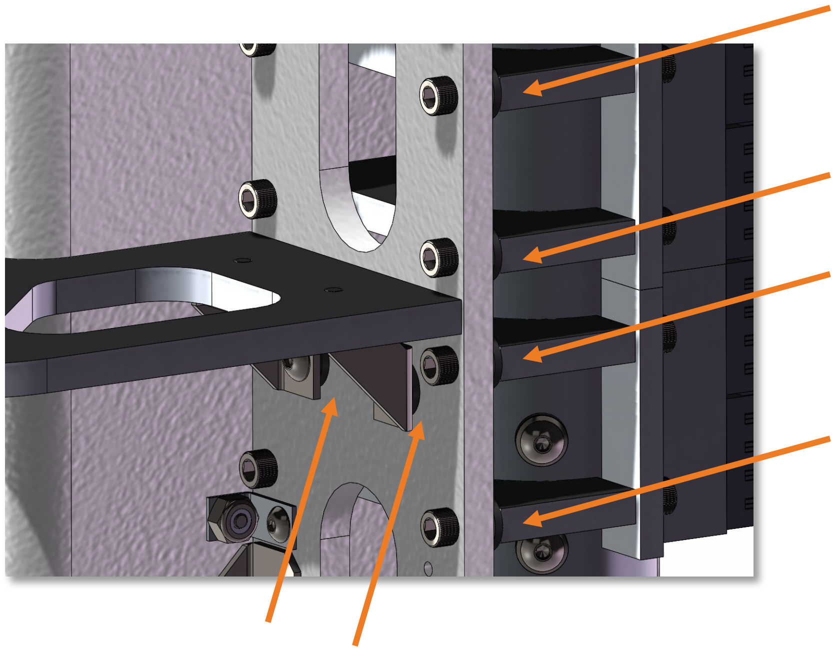
- Heat sinks
  - Stack heat sinks in parallel
  - $R_h = 4.7 \ \frac{K}{W}$
- Forced convection
  - Rated for 200 LFM
  - IPX5 Rated fans deliver 2.1 cfm or 397 LFM
  - R_h will be lower
  - Comps show ratings of $R_h = 1.0 \ \frac{K}{W}$ at flow rates of 400 LFM

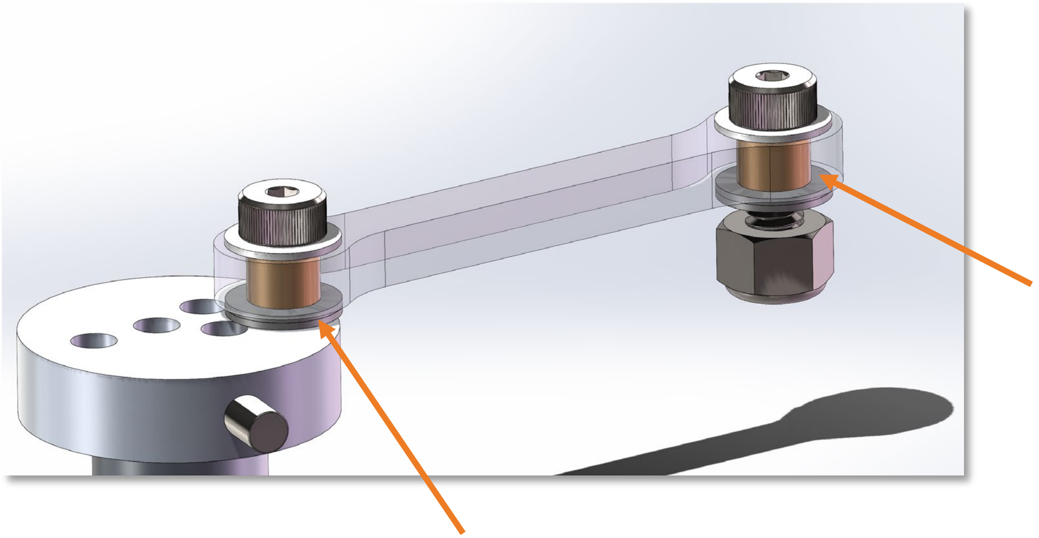
Parameter	Value
R_1	$0.00743 \ \frac{K}{W}$
R_2	$0.00209 \ \frac{K}{W}$
R_h	$4.7 \ \frac{K}{W}$
N	8
R_3	$0.5875 \ \frac{K}{W}$
I_{max}	$2.094\ A$ – $9.292\ A$*

* Higher max current is calculated from a 1.0 K/W thermal resistance on the heat sinks

Mechanical – Structure

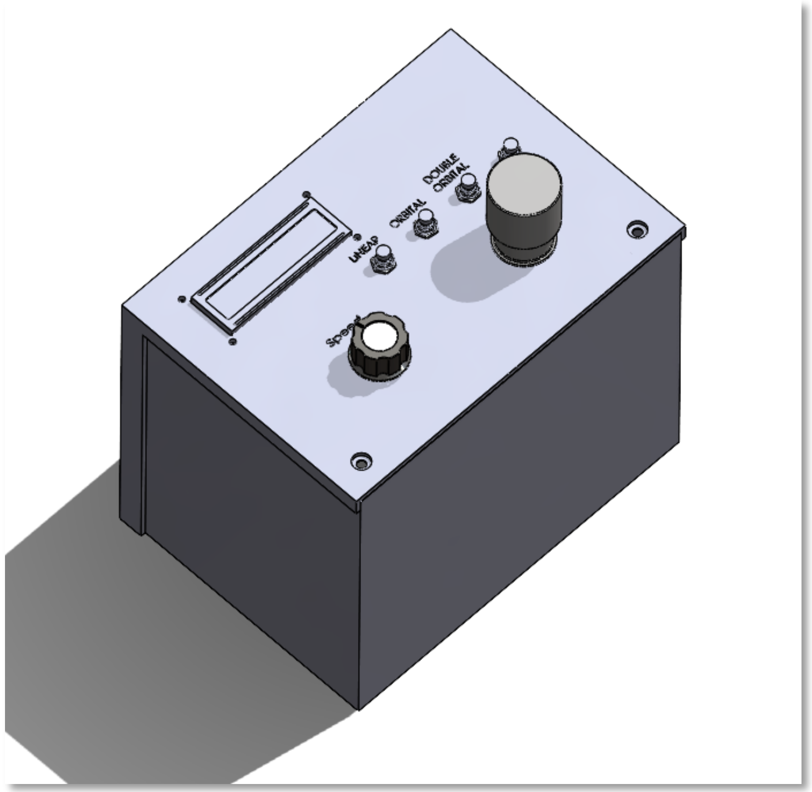
- Vibrations
  - Cantilevered motor housings with offset spinning masses will cause vibrations
  - Rubber washers dampen structural connections
- Reducing Friction
  - Ball bearing driven linear rails guide motion
  - Brass PTFE lubricated bushings reduce wear at linkage bar – shoulder screw interface





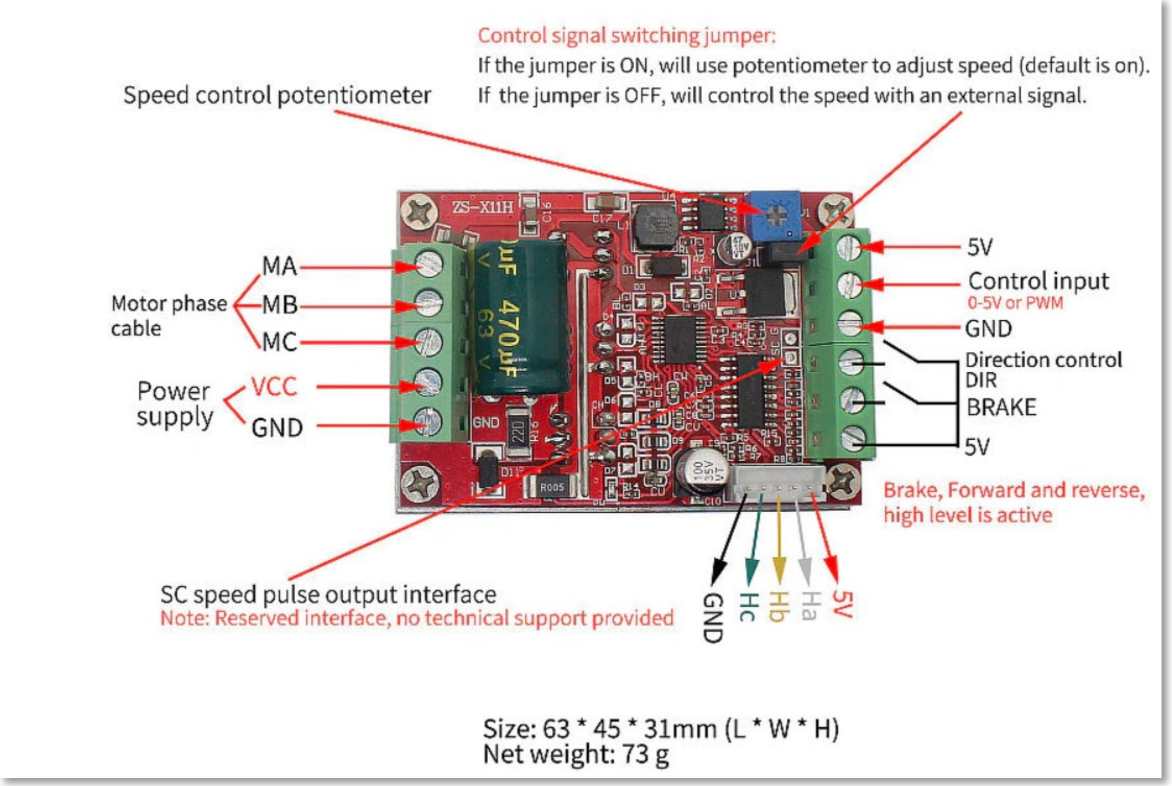
Electrical Design

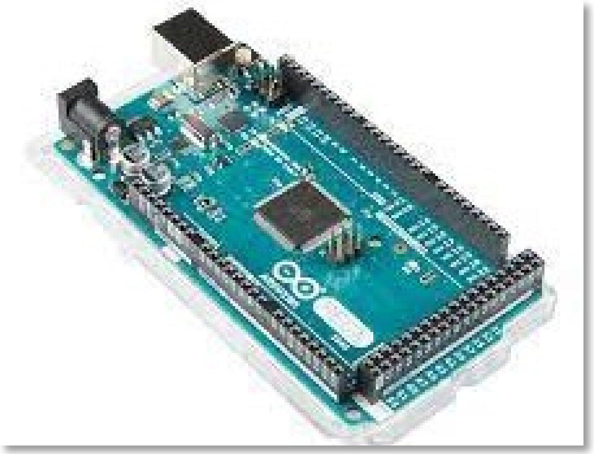
- Motor function components:
  - Microcontroller- Arduino Mega chosen for versatility and familiarity
  - Motor controller- Two 3-Phase BLDC Motor driver with 20A max current
  - Encoders- 5V Hall encoder for position feedback
  - Hall effect sensors- 5V Hall effect switches for zeroing
- User interface components:
  - 4 Push buttons for pattern selection
  - 10-turn potentiometer for precise velocity tuning
  - LCD for user feedback and status
- ODFI components
  - UV and Visible LED
  - Photoresistor for measurement
- Power Calculations:
  - Total power consumption ~ 560 W
  - 24V-720W AC-DC converter



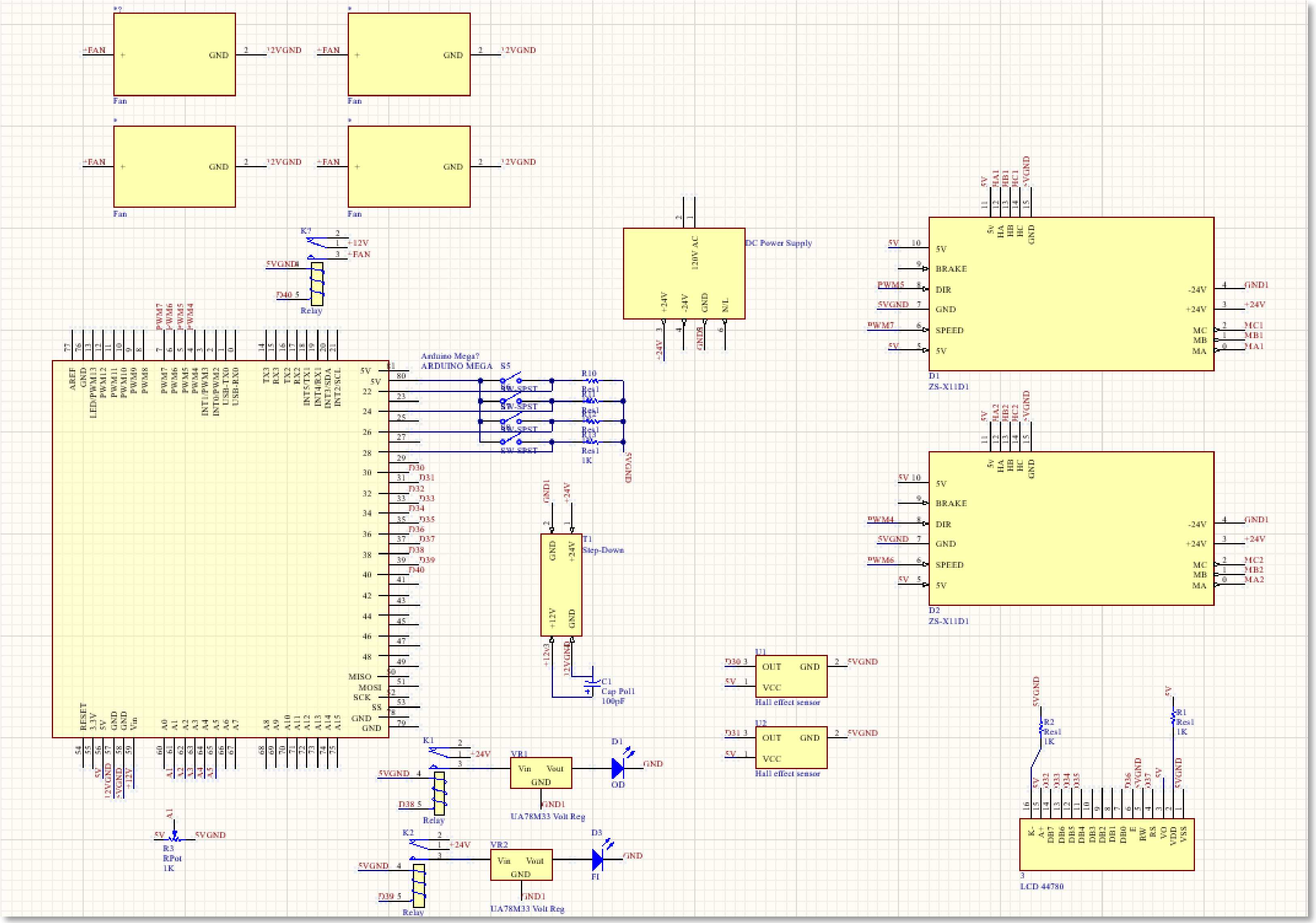
Circuit Functionality

- Four integrated circuits controlled by a microcontroller through relays and step-downs.
  - 24V Motor circuit-Motors, Motor controllers
  - 12V Fan circuit- 12V fans
  - 5V Arduino circuit- Logic, user interphase, and sensor measurement
  - OD/FI circuit- LEDs and photoresistor

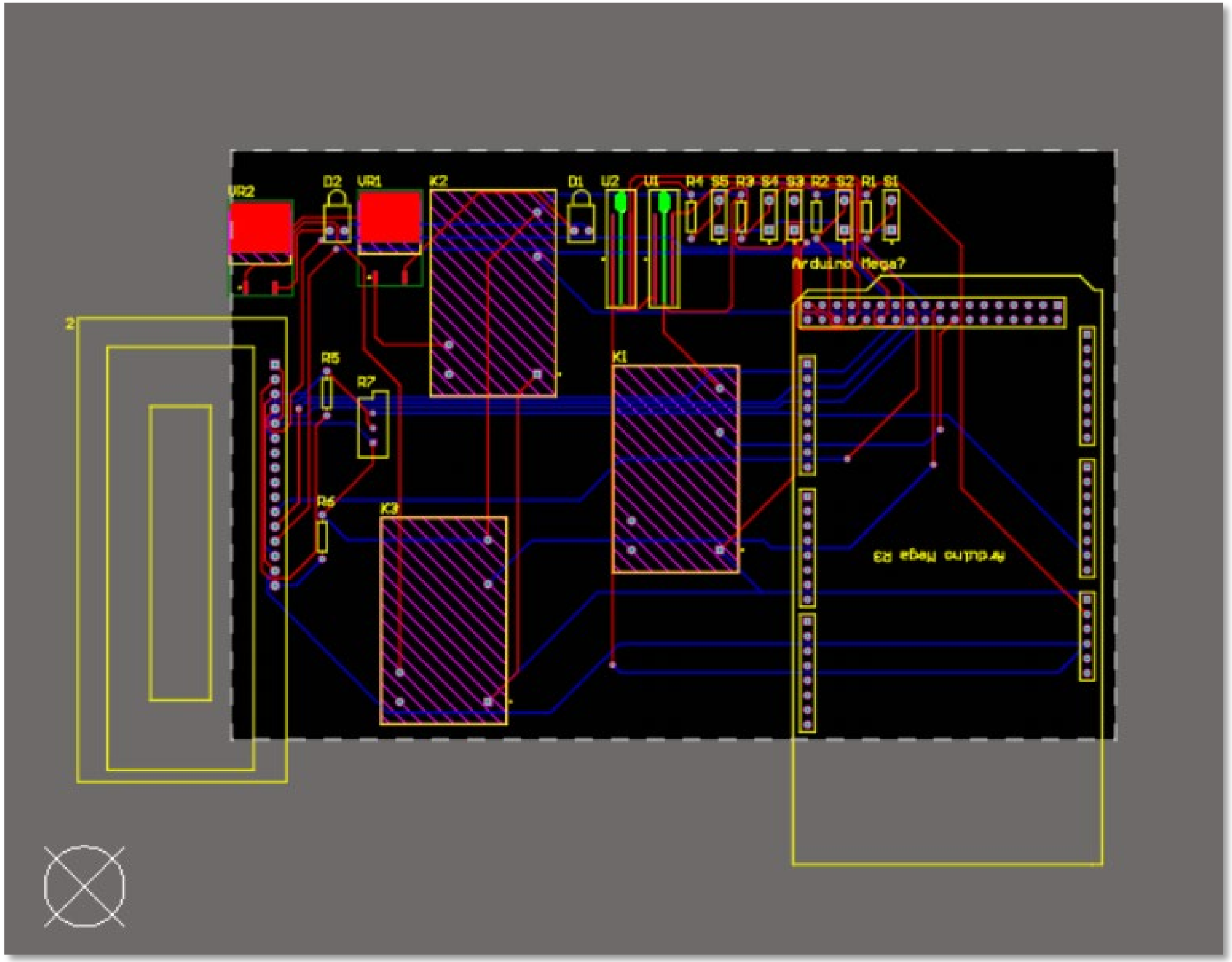




Electrical – Diagram



PCB design


VR2
D2
VR1
K2
D1
U2
U1
R4
S5
R3
S4
S3
R2
S2
R1
S1
Arduino Mega?
R5
R7
K1
R6
K3

Culture Interrogation

- Why do we need this?

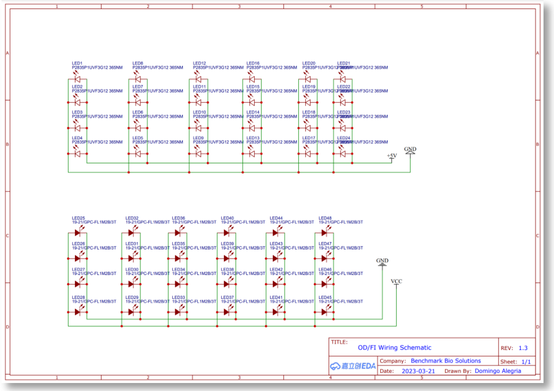
Customer Need	Requirement Text
38	Shaker integrated OD/FI interrogation for illumination at proper OD and FI wavelength and intensity of fluid aliquots in the wells.
39	Shaker integrated OD/FI interrogation for illumination at proper OD and FI wavelength and intensity of fluid aliquots in the conical tubes.
41	Shaker integrated OD/FI interrogation with access for optical sensors opposing illumination sources.
44	An aliquot of fluid interrogated by the OD/FI system must return the same, correct OD and FI value regardless of which well or conical tube it is located in.
45	OD/FI system must be programmable where the user can select test type and test location.
46	OD system must measure sample turbidity within ± 15% of calibration fluid values over a range from 0% to 100%. Higher accuracy is preferred.
47	FI system must measure sample vitality to within ± 15% of calibration fluid values over a range from 0% to 100%. Higher accuracy is preferred.

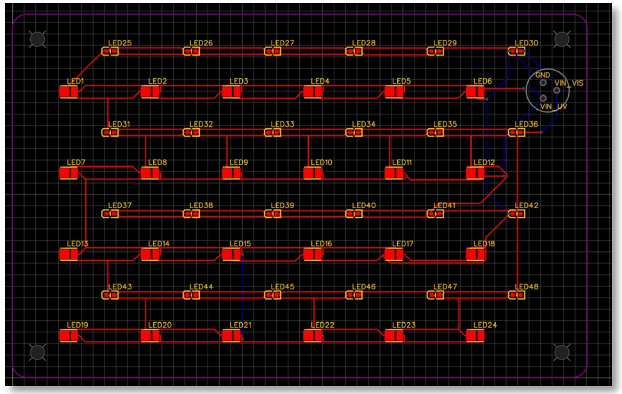
- Optical Density (OD)
  - Visible light (560 nm) illuminates samples obscured by cell culture growth
  - The light is then measured and recorded with LDR
- Fluorescent Intensity (FI)
  - Ultraviolet light (370 nm) excites quinine in samples
  - Resulting quinine fluorescence emission (450 nm) is measured and recorded with LDR

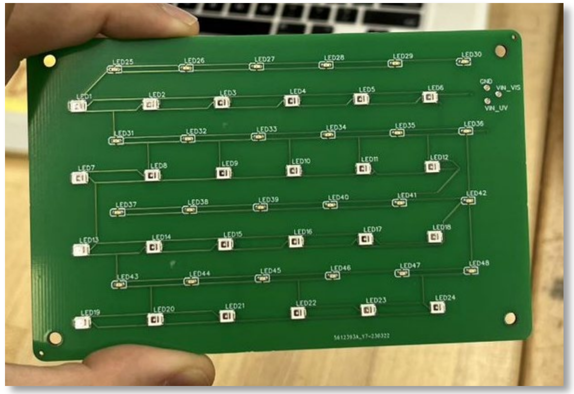
OD/FI – Implementation

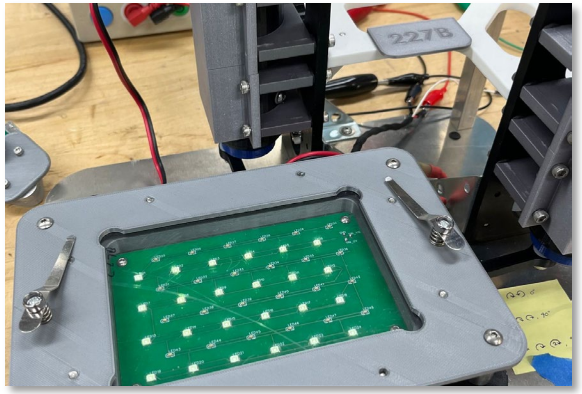
- LED PCB Design Process

Wiring Diagram → PCB Design → PCB → Shaker Table Integration



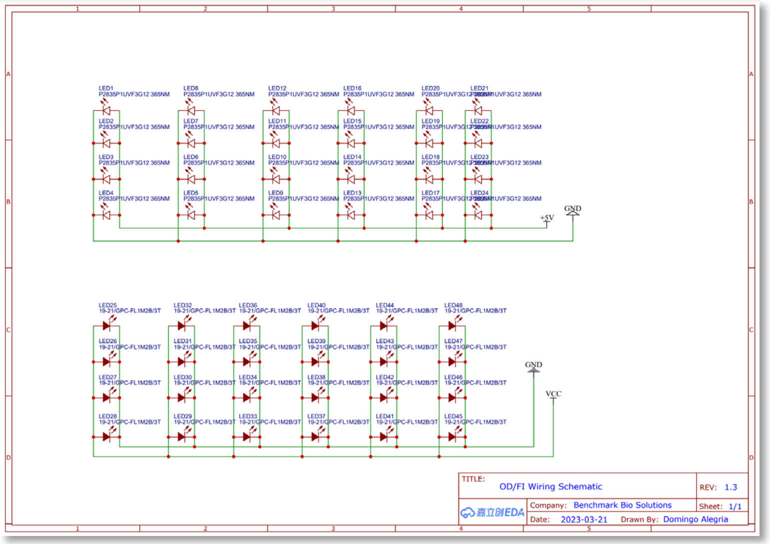




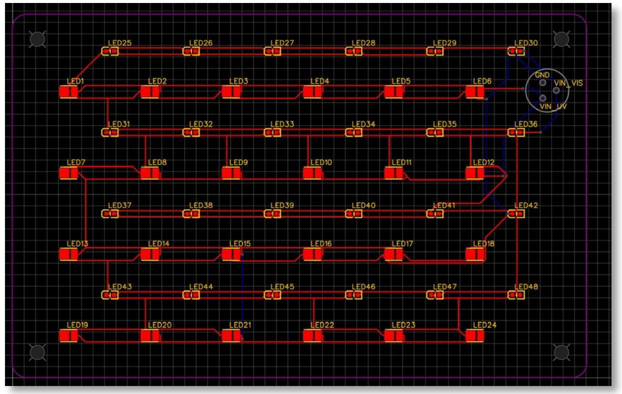


OD/FI – Implementation

- PCB Wiring Diagram
  - 5V Input Voltage
  - 24 LEDs per circuit
  - Visible LED Matrix
  - Ultraviolet LED Matrix



- PCB Design
  - Visible and UV LED Loops wired separately
  - LED placement for well plate and test tube illumination
  - Allows user to switch between Visible & UV LEDs

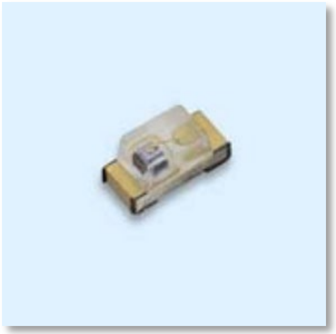


OD/FI – Implementation

- Sensing Equipment
  - Use of LDR to sense light for OD/FI
  - Spectral Range of 400 – 700 nm
  - Spectral Peak at 520 nm
- LEDs
  - Outsourced LED & PCB Manufacturing

Parameter	Visible LED	Ultraviolet LED	Unit
Forward Voltage	2.05	3.30	V
Forward Current	25	150	mA
Dominant Wavelength	560	370	nm

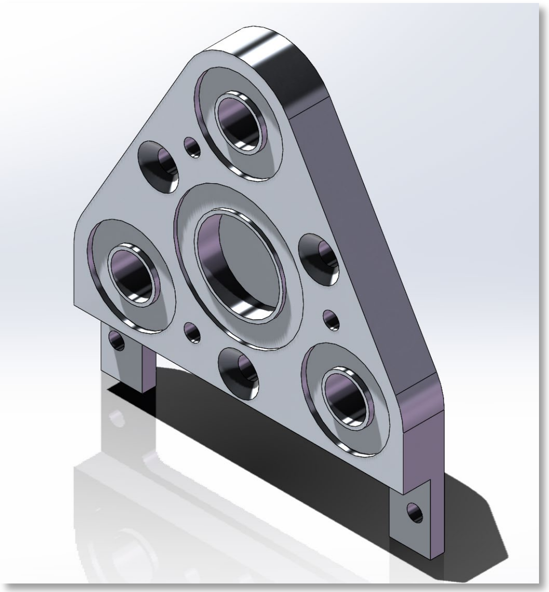

LDR


Visible LED

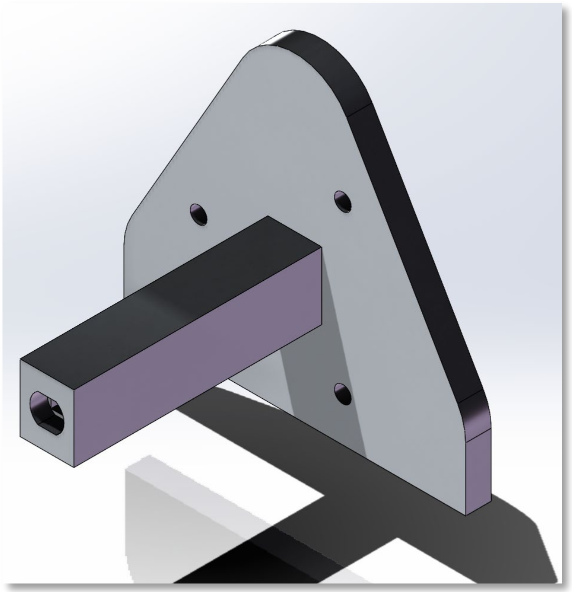

UV LED

OD/FI – Implementation

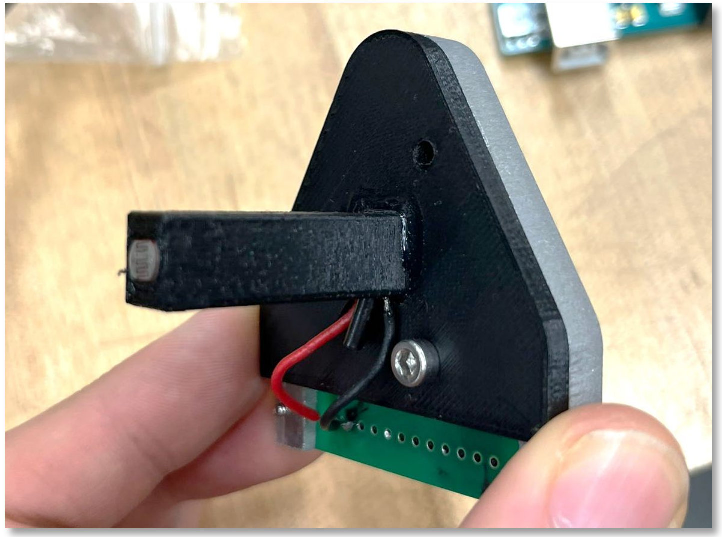
- OD/FI Sensing
  - Robotic arm used for positioning
  - NOEL Mount Provided by lab
  - LDR Housing design
    - Connect LDR to NOEL mount
    - Interface with Test Tube viewing window
  - LDR sensing controlled with Arduino/Breadboard



NOEL Mount

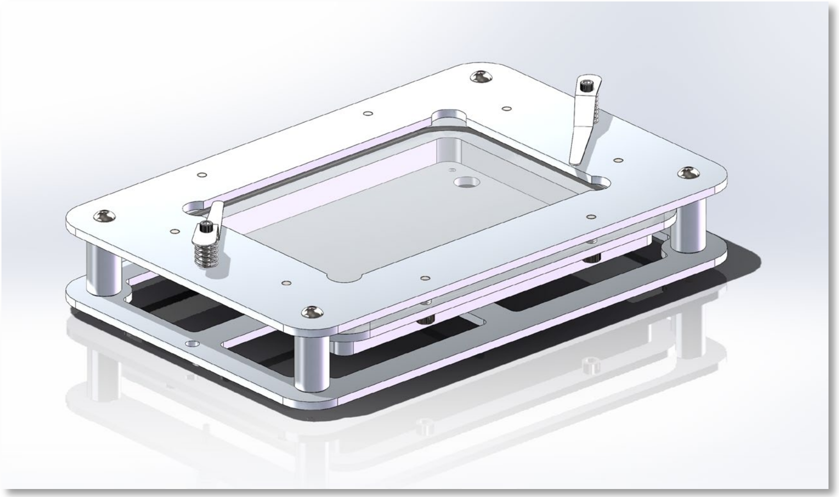


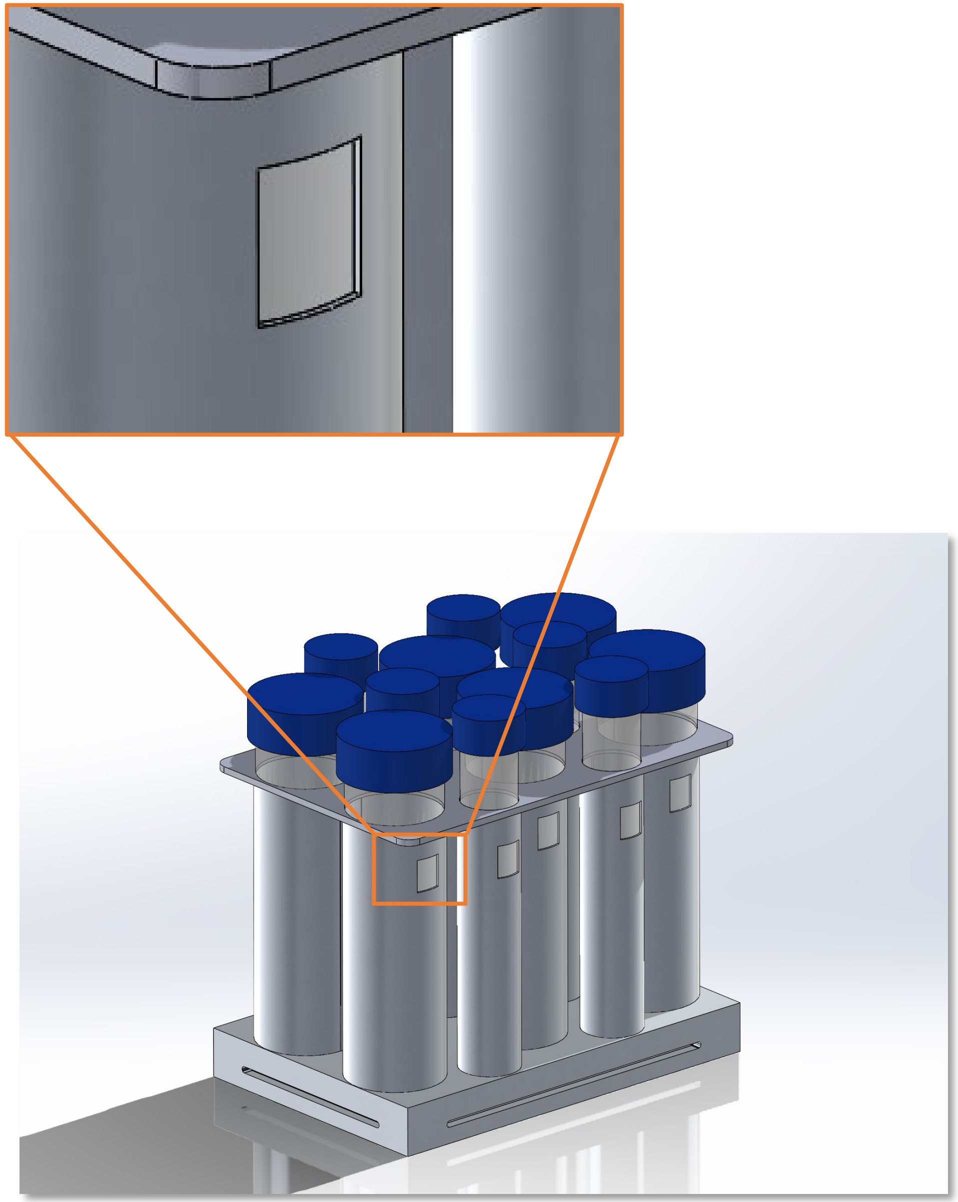
LDR Housing



ODFI – Implementation

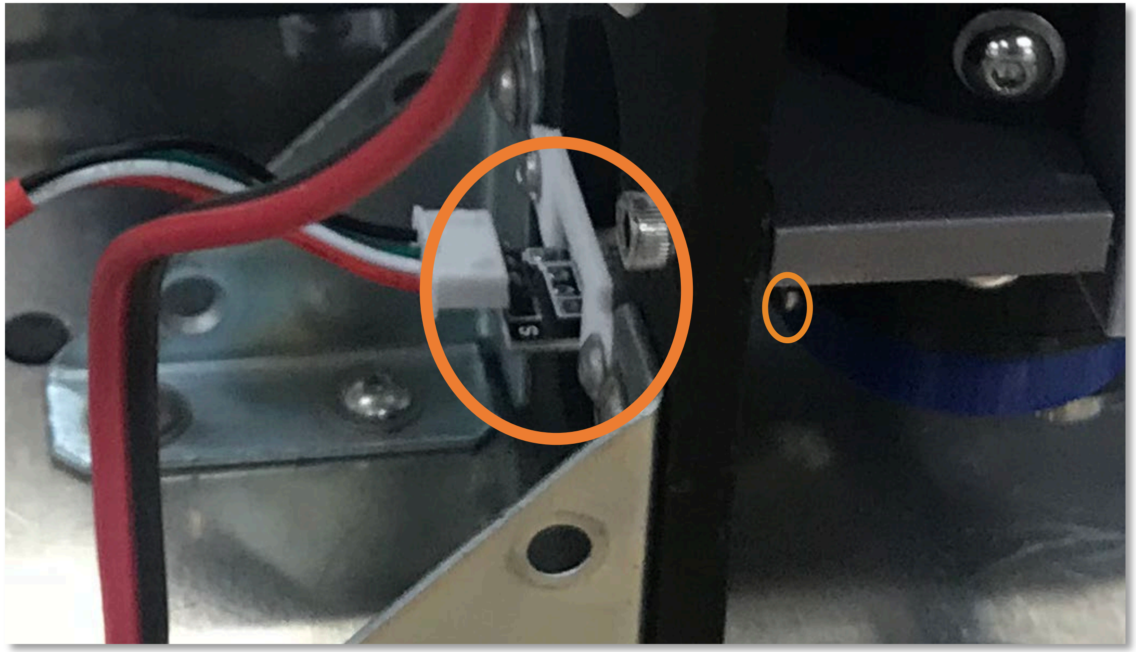
- Designed Test Tube & Well Plate Mount
- Optical Density (OD)
  - Clear top test tubes / well plate
- Fluorescent Intensity (FI)
  - Side view port through test tube





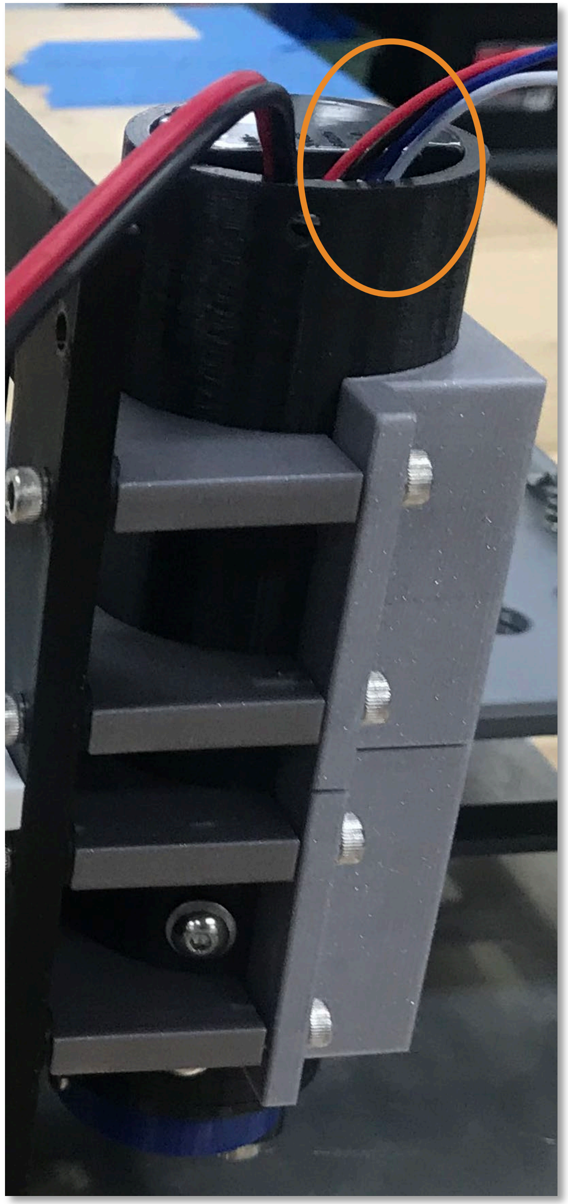
Software Design

- Hub initialization
  - Hall effect sensors detects the magnets and sets the motors starting positions at the Hall effect sensor.
  - Motor steps until hall effect sensor is triggered by the magnet.



Software Design

- Motor Speed Control
  - Potentiometer sets target velocities in RPM.
  - Interrupts track encoder's pulses measuring the hub's position and velocity.



Software Design

- UI control
  - LCD shows system status, selected pattern, and RPM.
  - A button for each pattern, when selected the pattern will be displayed.
  - OD/FI measurement is taken when table is stopped and continues to pattern selection. Measurement is skipped if the start/stop button is held.

Software Design - Flowchart

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PROTOTYPING & MANUFACTURING

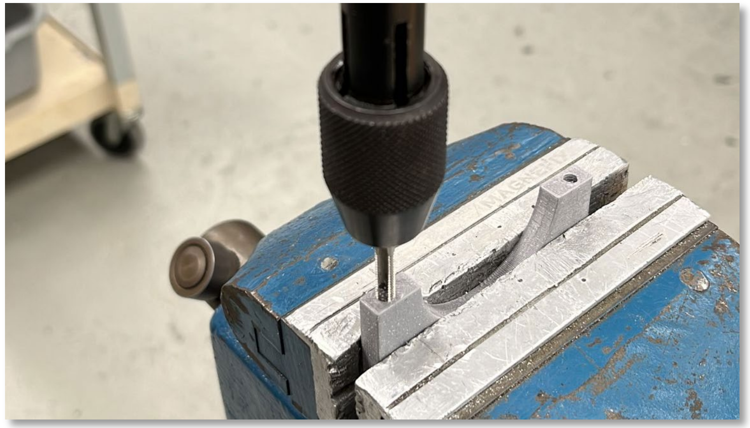
Realization of the shaker table design, prototyping changes, and manufacturing updates

POWERING THE NEW ENGINEER TO TRANSFORM THE FUTURE

Manufacturing

- Required processes
  - Most parts waterjet, then post-processed
    - Tapping holes
    - Breaking edges
  - Mill & lathe operations (motor housings and hubs)
  - CNC machining was used to cut o-ring grooves

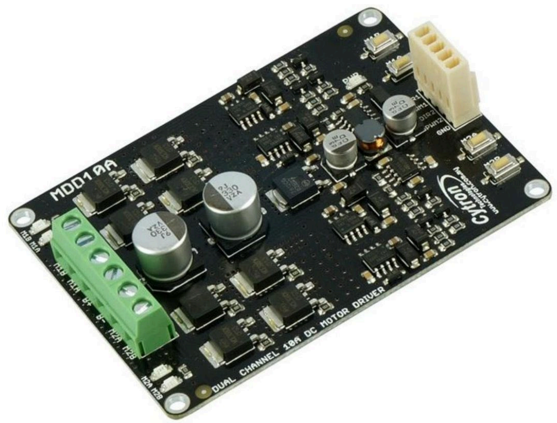
- 3D printing
  - Intended for rapid prototyping
    - Strength & heat tolerance is not needed (UI Box)
  - Was performed in lab using PLA and PETG



Prototyping Redesign

- Servocity Motors
  - 12V brushed motors
  - Stall torque of 5.4 kg-cm
  - No-load speed of 1620 RPM
- Electrical Changes
  - Downsized power supply
  - Fewer Integrated circuits
  - Brushed motor controller
- 3D printed parts
  - Not eligible for most tests due to material hazards

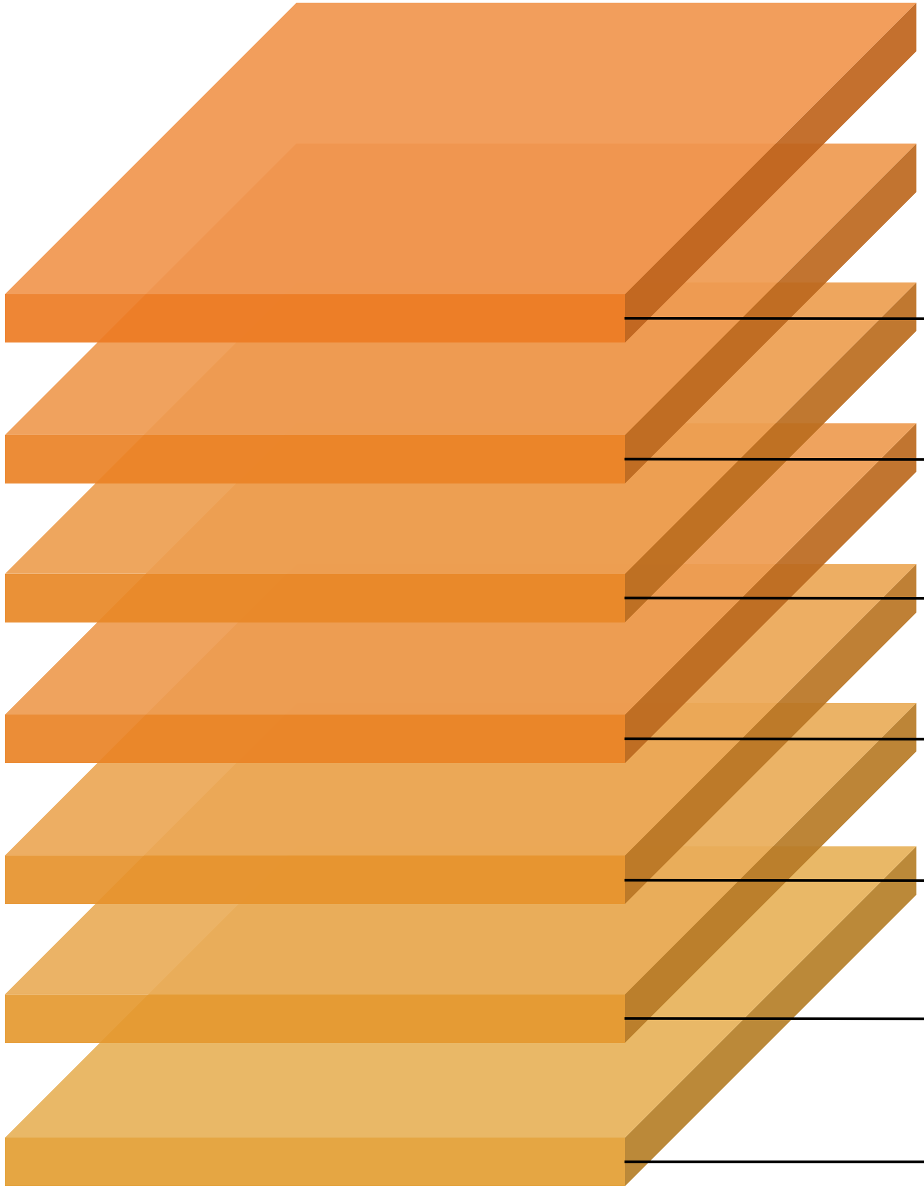
FIRST TECH CHALLENGE LEGAL



PERFORMANCE EVALUATION

Testing the capabilities of the shaker table prototype to assess customer needs

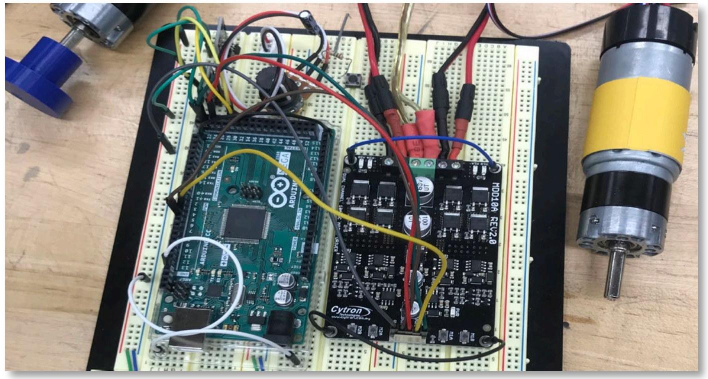
Testing Plan



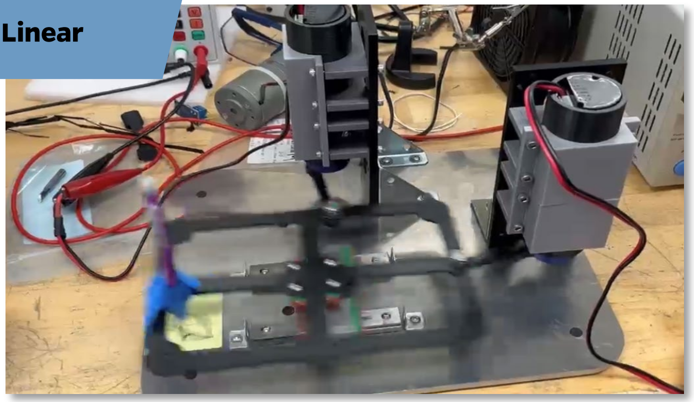
- Pattern Functionality
- IPX5 Water Infiltration
- OD/FI Calibration and Sensing
- Hot/Cold Temperature Resilience
- Speed Overclocking
- Acoustic Emittance
- Drop Survivability

Pattern Functionality

- No controllers
  - For prototyping
  - Voltage “controls” speed, polarity controls direction
- Controllers
  - Motor controllers and control algorithms in place

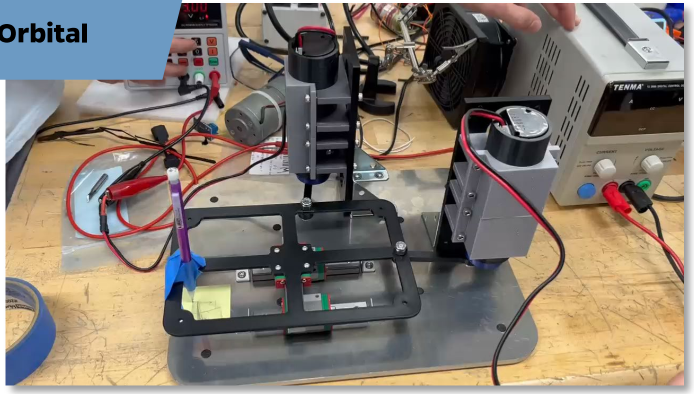


Linear



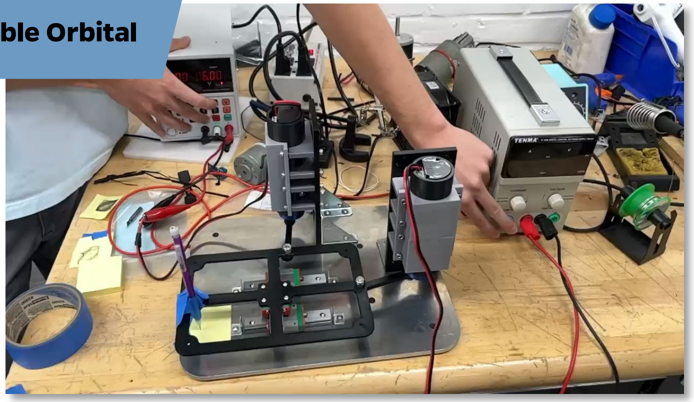
Image

Orbital



Video

Double Orbital



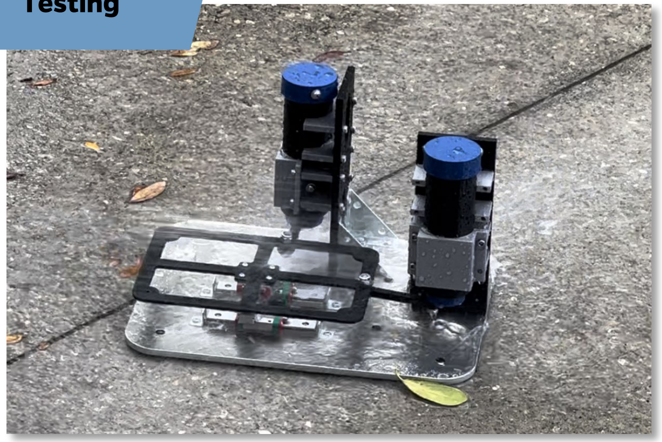
Video

IPX5 Waterproofing

- Adhesive water contact indicator tape was placed along sealed critical compartments
- Spray test
  - Water hose delivered ~12.5 LPM of water at ~30 kN/m^2 for 4 minutes.
- Failure at cap seal locations
  - Looser tolerances on 3D printed parts
  - No tight seals/o-rings in critical compartments due to manufacturing delays
- Pass
  - Critical compartments sealed by rubber washers

Before

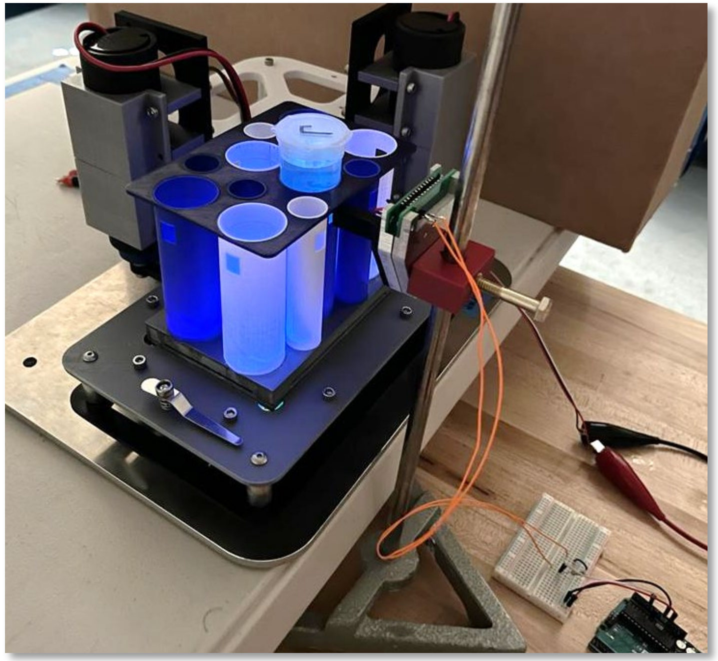
Testing



After

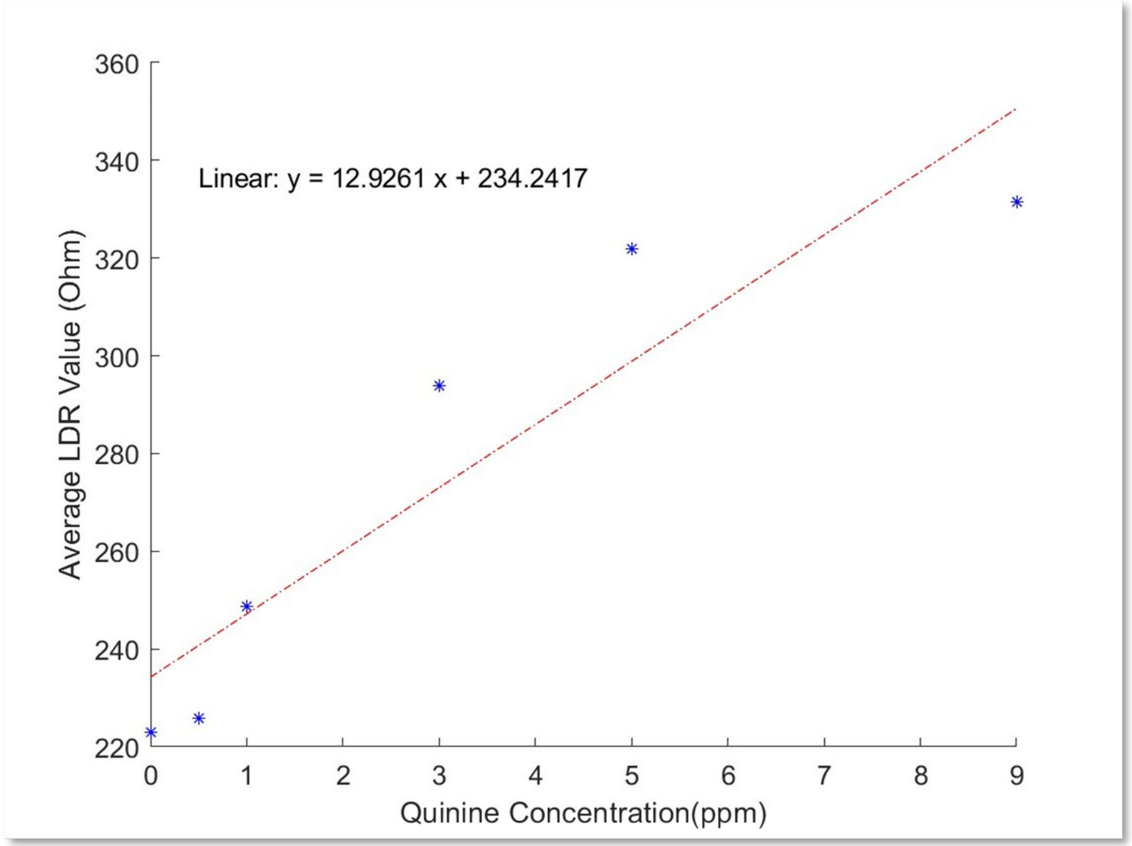
OD/FI Sensing

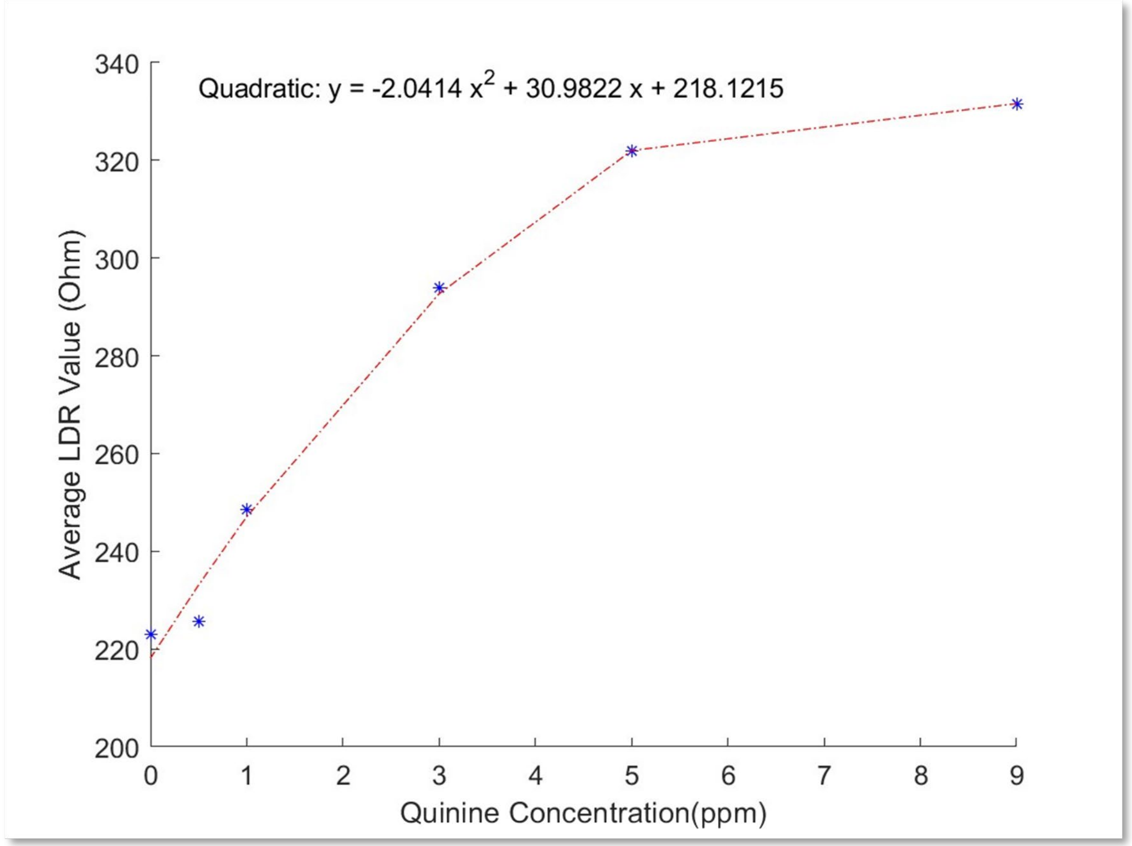
- Preparing Chemical Samples
  - Milk
    - OD Testing
    - Whole Milk diluted with distilled water
    - Concentrations ranging from 0 – 0.2% Milk by volume
  - Quinine
    - FI Testing
    - Dissolve in 0.05 M Sulfuric Acid (H_2SO_4)
    - Concentrations ranging from 0 - 9 ppm of Quinine in H_2SO_4



OD/FI Sensing

- Creating calibration curves for OD and FI LDR measurements
- Unknown sample testing





Temperature Resilience - Hot

- Hot temperature testing
  - Not Tested

Customer Need	Requirement Text
36	In the mode with the control/display unit detached, the shaker can run continuously at its maximum-rated speed for two weeks in its most demanding shaker pattern in an environment maintained at 70 °C (158 °F) [running at 120 °C (250 °F) is preferred, but not required].

- Procedure
  - Oven set to >70°C
  - The shaker maintain at least 350 RPM throughout the test
- Manufacturing Delays
- Prediction:
  - As is: 3d parts and motors will **Fail**
  - As designed: **Pass**

Temperature Resilience – Cold

- Cold temperature testing
  - Not Tested

Customer Need	Requirement Text
37	In the mode with the control/display unit detached, the shaker can run continuously at its maximum-rated speed for two weeks in its most demanding shaker pattern in an environment maintained at 0 °C (32 °F).

- Procedure
  - Freezer set to 4°C
  - Table inside for 90 minutes
  - Demonstrate double orbital at 6 rpm
- Prediction:
  - As is: **Pass***
  - As designed: **Pass**

*based on temperature considerations

Speed Overclocking

- Designed
  - Minimum speed requirement: 350 RPM
  - Linear and orbital patterns: 700 RPM
  - Double orbital pattern: 350 RPM
    - One motor moves twice as fast as the other, pattern speed is based off slowest motor.
- Prototype
  - Servocity motors: 1500 RPM
  - Linear and Orbital patterns: 1500 RPM
  - Double orbital pattern: 750 RPM

Customer Need	Requirement Text
24 - 26	Capable of uniformly shaking well plates and tube racks with the three orbital patterns: i. Adjustable and infinitely variable revolution speeds reaching 350 rpm (up to 1,200 rpm nice to have but not required). ii. Adjustable orbits up to 25 mm on the diameter.

- Not formally tested
- Prediction :
  - As is: **Pass**
  - As designed: **Pass**

Acoustic Emittance

- Procedure
  - Measured at distance of 15 cm
  - Cannot exceed 50 dB
- Prototype performance
  - Testing with the power supplies concluded the prototype is quiet
  - Bearings will dampen some vibrations and sound

Customer Need	Requirement Text
19	Unit noise cannot exceed 50 decibels (dBA weighting) measured 15 cm in every direction from the device.

- Not formally tested
- Prediction :
  - As is: **Pass**
  - As designed: **Pass**

Drop Survivability

- Drop
  - Table falls from a height of 75 cm onto concrete floor
- Pass/Fail
  - Unlikely due to 3D printed parts and weight of metal parts
    - Large shock forces induced by drop
    - Aluminum parts likely to deform
  - Lab equipment with bio-cultures
  - Researchers unlikely to drop

Customer Need	Requirement Text
13	Shaker must survive falling from a 75-cm-tall lab bench onto a concrete floor without damage (i.e., it functions after being accidentally knocked off a lab bench). It is acceptable for the cowling enclosure to be physically damaged / dented by the fall if this part is easily replaced.

- Not tested
- Prediction :
  - As is: **Fail**
  - As designed: **Fail**

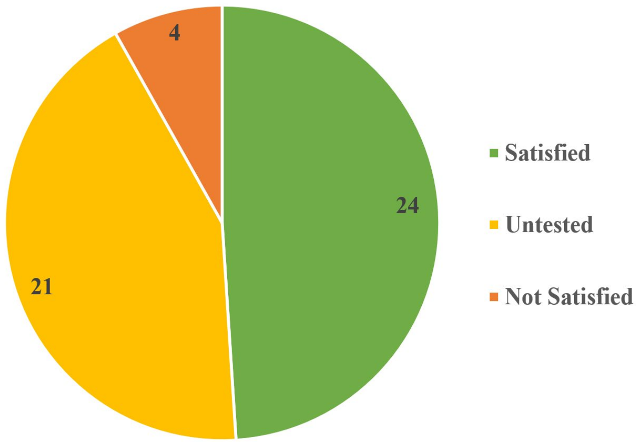
Herbert Wertheim College of Engineering
UNIVERSITY *of* FLORIDA

REVIEW OF DELIVERABLES

Which customer needs were satisfied, and a future improvement plan for our product

Customer Needs Review

Need Category		Satisfied	Untested	Not Satisfied
Actuation	(4)	3	1	0
Admin	(7)	2	4	1
Control	(11)	5	5	1
Interface	(6)	3	2	1
OD/FI	(7)	1	5	1
Structure	(14)	10	4	0



Unsatisfied Needs:

1. Cost ($400)
2. Fluorescent intensity accuracy (15%)
3. Supports test tubes and well plates simultaneously
4. Safety auto-shut down

Improvement Plan

- Cost
  - Budget was $400
  - Prototype ~$750
  - Final Design ~$2,000
- Manufacturing
  - Metal/machined parts take a long time to manufacture
  - Substitute for OTS brackets, etc
  - Higher tolerances needed for thermal and waterproofing testing
- Electrical
  - Custom PCB
  - Simplified design, less room for human error
  - Reduce form factor, improve performance, and reduce cost
- ODFI
  - Higher intensity LEDs, more sensitive LDR
  - Replace acrylic lens with a UV transparent material

Questions?