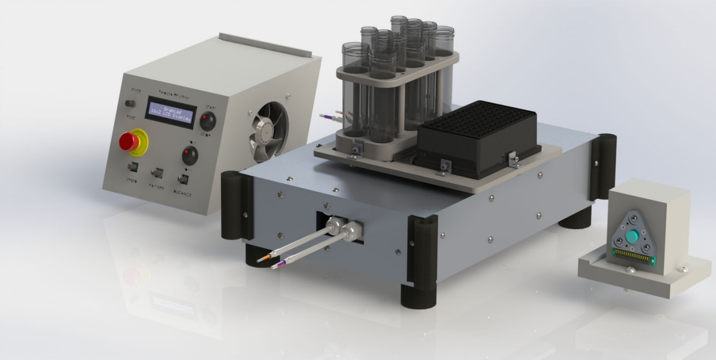
Herbert Wertheim College of Engineering
UNIVERSITY of FLORIDA

REACTOR RHYTHM



A cheap, effective, and easy to use shaker table system

Class 16141, Group 674Y

Alex Lugo, Caitlyn Limpioso, Joshua Kempfert, Marco Moreno, Orlando Travers, Samuel Fetter, Raian Sadman

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Hedgehog Concept

Passions

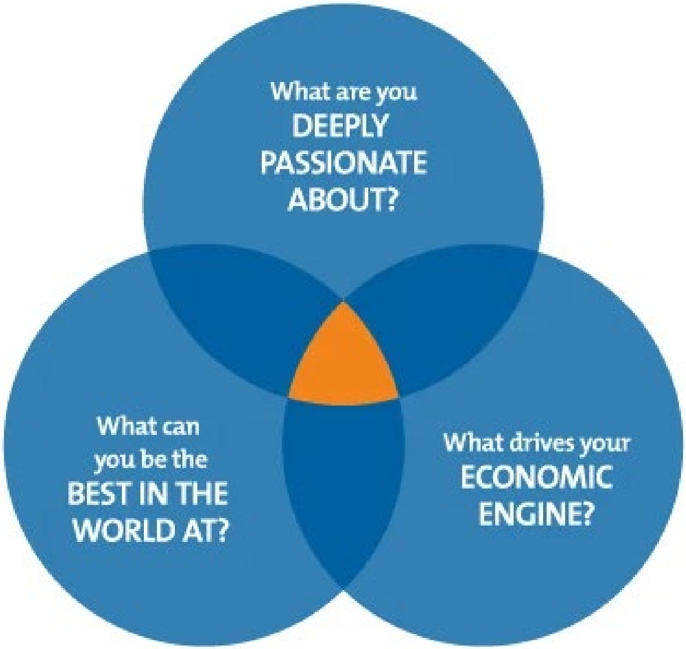
- Ease-of-Use: ReactorRhythm's shaker table should be designed to be very easy to use with an intuitive user interface that a person should be able to learn very quickly

Strengths

- Optimization: ReactorRhythm's shaker table is optimized to occupy the lowest amount of space possible while operating at required parameters.
  - Only taking up about 0.71 cubic feet of space

Economics

- Cost-Effective: ReactorRhythm's shaker table doubles the effectiveness of many predecessors and competitors while staying in a similar price range
  - 1100-1200 rpm capability for the price of around $1,200

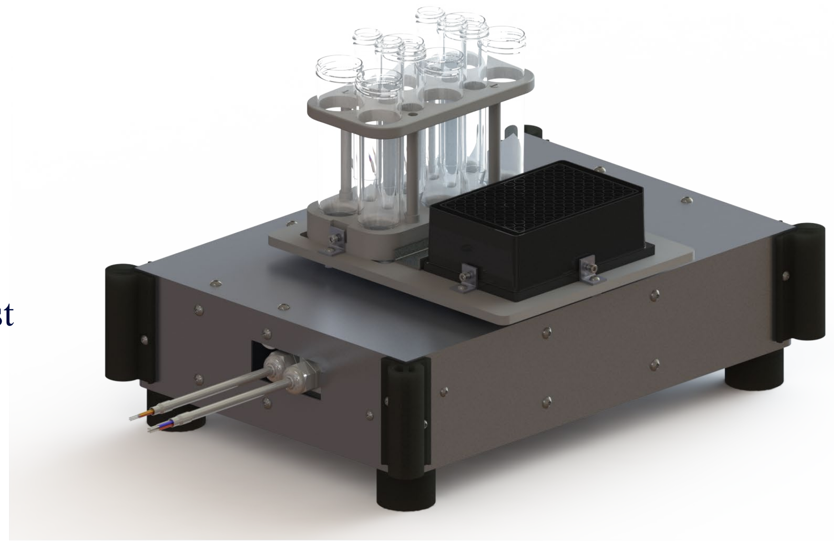


Product Overview and Specifications

Overall dimensions: 14" x 9.75" x 9"

Subsystems

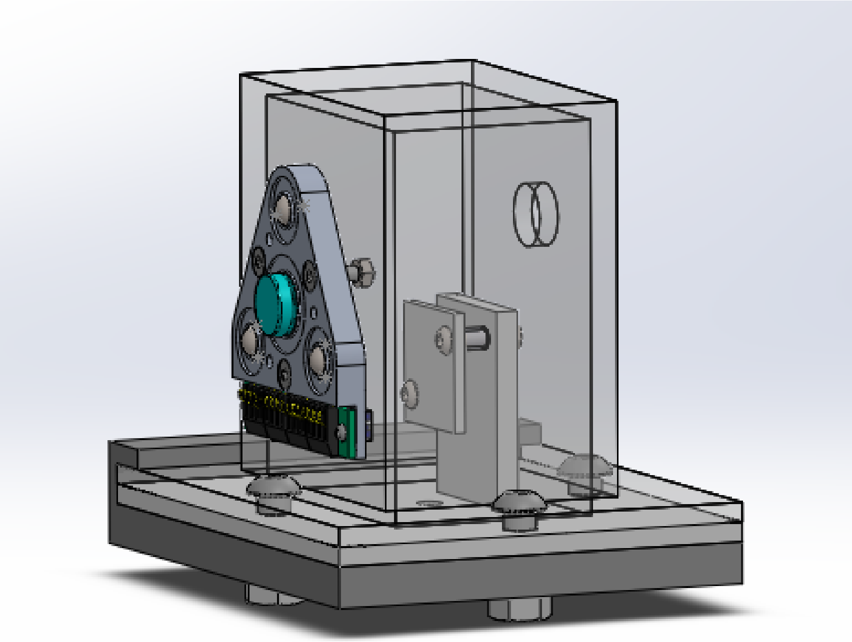
- Shaker Mechanism: Stepper motor driven dual belt-pulley system
  - High power stepper motors provide increased responsiveness, enabling higher speeds
  - Differential position encoders prevent drift and allow for centering
  - Custom rail system with linear plain bearings reduce cost and are operable in extreme and contaminated environments
- Shaker Top Plate: HDPE body to support 6 50 mL & 15 mL test tubes and one 96-well plate.
- Enclosure: 16 GA Aluminum sheet metal with EPDM rubber corner guards in case of drops and rubber feet to grip tabletop



Product Overview and Specifications

Subsystems

- User Interface: 3D printed shell with LCD display and mechanical control.
- OD/FI: LDR sensor package with UV LED PCBs



Previous Design

Improvements on previous design

- More powerful stepper motors
- OD/FI interrogation system
- Tube rack storage added
- Updated User Interface

Source: Bionic Builders Co.

Customer Needs

CN	Metric	Justification
General Requirements		
1	Less than 14" x 9.75" x 7.5" size requirement	Given
2	22.25" deep, 21.75" tall, 23.5" wide	Measured Bioreactor
3	Repeatable zero location ± 0.82 mm	Given
4	Zero debris or turbulent airflow	Stability and enclosure
5	Runs on 120 VAC 60 Hz electrical power	Given
6	Electrical power enters the unit through UI	Ambilocal supplies power to unit
7	Weight requirement of less than 49 lbs	Low mass design with small amounts of materials
8	Less than 125 parts required	Most parts are modular and have no blind mates
9	Common fasteners, electrical components, and plumbing are used	OTS parts are used
10	Enclosure has a top plate and removable side plates making inside easy to clean	Removable enclosure and modular UI

Customer Needs

CN	Metric	Justification
General Requirements		
11	<=0.1mm of corrosion build up per year	Corrosion Resistance
12	Nonporous and nonreactive materials	Steel and approved test tubes are used
13	Shaker table must survive a 75 cm drop test performance evaluation	Enclosures have shock absorbers, but needs to be tested during fall test
14	Shaker table cannot move from initial location due to vibrations	Vibrational movement will need to be tested with current rubber feet
15	User interface exists	Given
16	User interface ambilocal is at least 1 meter long	Given
17	Labels and LCD displaying current status	Given
18	Operates in a BSL-2 Lab Space	Given
19	Noise level must be below 50 decibels from at most 15 cm away from the device	Noise under 50 decibels on average, but occasionally exceeds
20	Product looks like those in background research	Given

Customer Needs

CN	Metric	Justification
General Requirements		
21	5 year life expectancy is required	No loads experienced will cause failure and components are made to last at least 5 years
22	Cost is less than $500 per unit	The cost is the highest amount that would be spent per unit while still ordering many OTS parts that may be carried in lab. The real cost should be in budget.
23	Shaker table must display a double orbital pattern after being sprayed by a water hose	IP-X5 certification will take place at a later date, but enclosures and components should help with waterproofing
Function Requirements		
24	Orbital shaking of 25 mm up to 350 rpm	Given
25	Linear shaking of 25 mm up to 350 rpm	Given
26	Double orbital shaking of 25 mm up to 350 rpm	Given
27	One well plate is towards top of table	Given
28	Tube mounting fits sizes 15 mL and 50 mL	Given
29	Supports one well plate and six conical tubes	Supports one well plate and twelve conical tubes.

Customer Needs

CN	Metric	Justification
General Requirements		
31	Selectable patterns, sizes, and other parameters	User interface accommodates for parameters
32	“Smart” OD feature for different shaking patterns	Arduino program will be able to perform this
33	One emergency shutoff included	On front face of user interface
34	One pause/resume button included	On front face of user interface
35	System indicators for important parameters	Displayed on on/off button and LCD
36	Will run continuously for two weeks at 70° C	Closed-Loop motor to control temp rise in motor
37	Will run continuously for two weeks at 0° C	Within Motor Operating Temperature

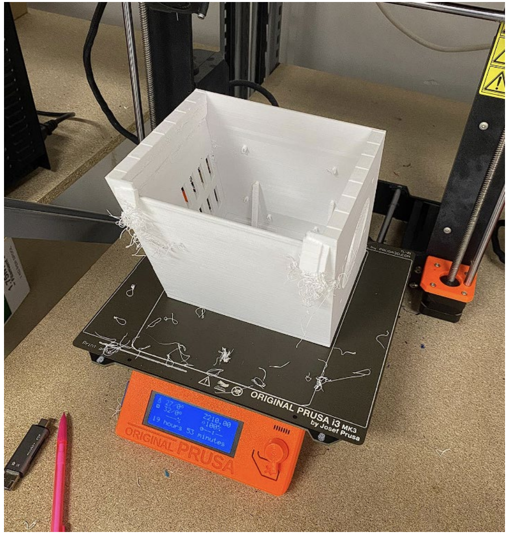
Customer Needs

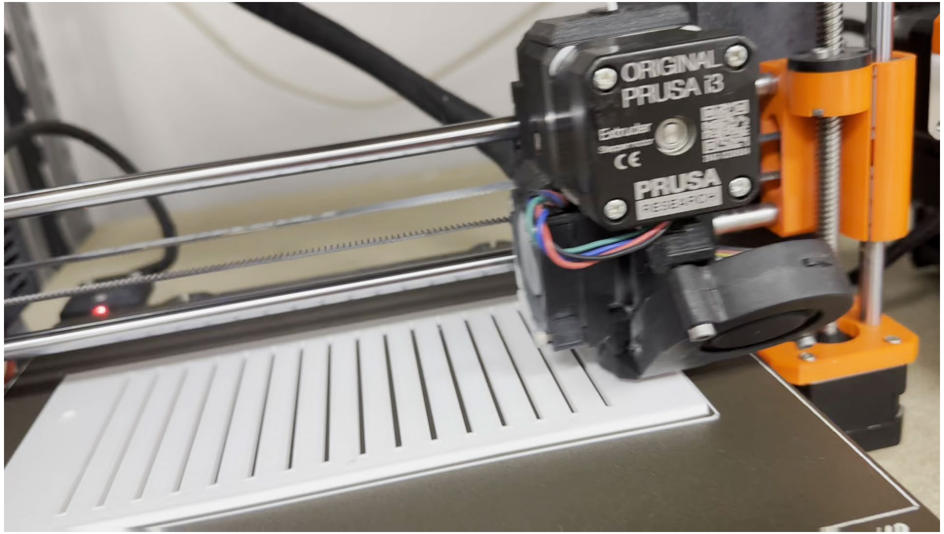
OD/FI Sensing Requirements		
38	Light source emits proper wavelength and light intensity for OD/FI interrogation of wells	UV LEDs will be placed below wells and emit 350nm light to excite Quinine.
39	Light source emits correct wavelength and light intensity for OD/FI interrogation of tubes	UV LEDs will be placed below tubes and emit 350nm light to excite Quinine.
40	Sensor packaged mounted to a NOEL™ fixture	Given
41	Optical sensors able to sense opposing illumination	Using robot arm, sensor can sense visible light emitted from above wells and at the sides of the tubes
42	Light source can emit the same intensity and wavelength of light to each well in various well-plate sizes	UV LEDs placed directly under each well at the same distance from the bottom of the wells.
43	Light source can emit the same intensity and wavelength of light to tubes of varying size	UV LEDs placed directly under each tube. For each tube size, LEDs are the same distance from the bottom of the tubes.
44	Source light and LDR sensor data collection is constant for each well or conical tube	Individual UV LEDs placed under each well or conical tube, and LDR sensor located where it can pick up light from each light source.
45	OD/FI system can perform a requested test type at a requested location	User has the necessary permissions to select the test type and location.
46	OD system is calibrated with an accuracy of measurement higher than ±15%.	OD system is properly calibrated using the provided calibration fluid and calibration process.
47	FI system is calibrated with an accuracy of measurement higher than ±15%.	FI system is properly calibrated using the provided calibration fluid and calibration process.
Nice to Have Requirements		
48	Safety shutoff included for unexpected events.	Programming for automatic shutoff will be accomplished at a later time
49	Terminal velocity fall onto concrete floor.	Enclosures have shock absorbers; negligible damage during drop test

Prototyping

3D Printing

- Due to manufacturing backlog, 3D printing of PLA and PETG parts was utilized.
- Parts of the final design had to accommodate for the use of 3D printing

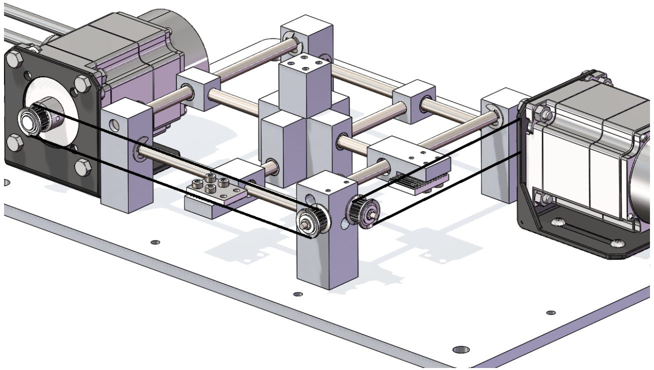




Design Highlights

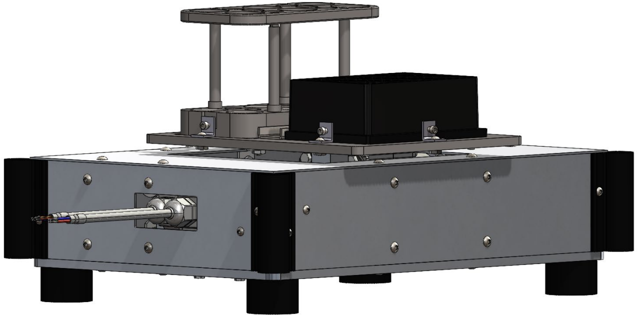
Shaker Mechanism

- Dual stepper motor driven belts
- Plain bearings used over linear ball bearings
  - Cheaper, corrosion resistant, & do not require hardened shafts
  - Downside: Bending moments can cause binding if bearings are insufficiently spaced



- Space bearings with center block to manage bending load caused by payload

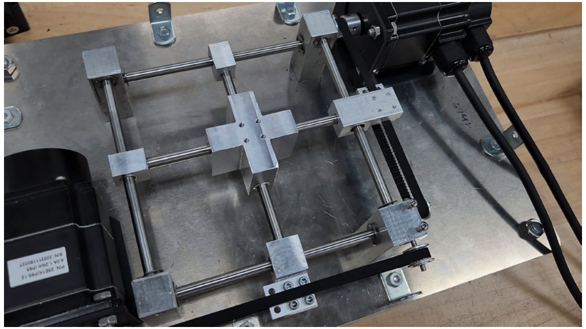
- Repeated parts to reduce # of unique parts



Design Highlights

Motor Selection

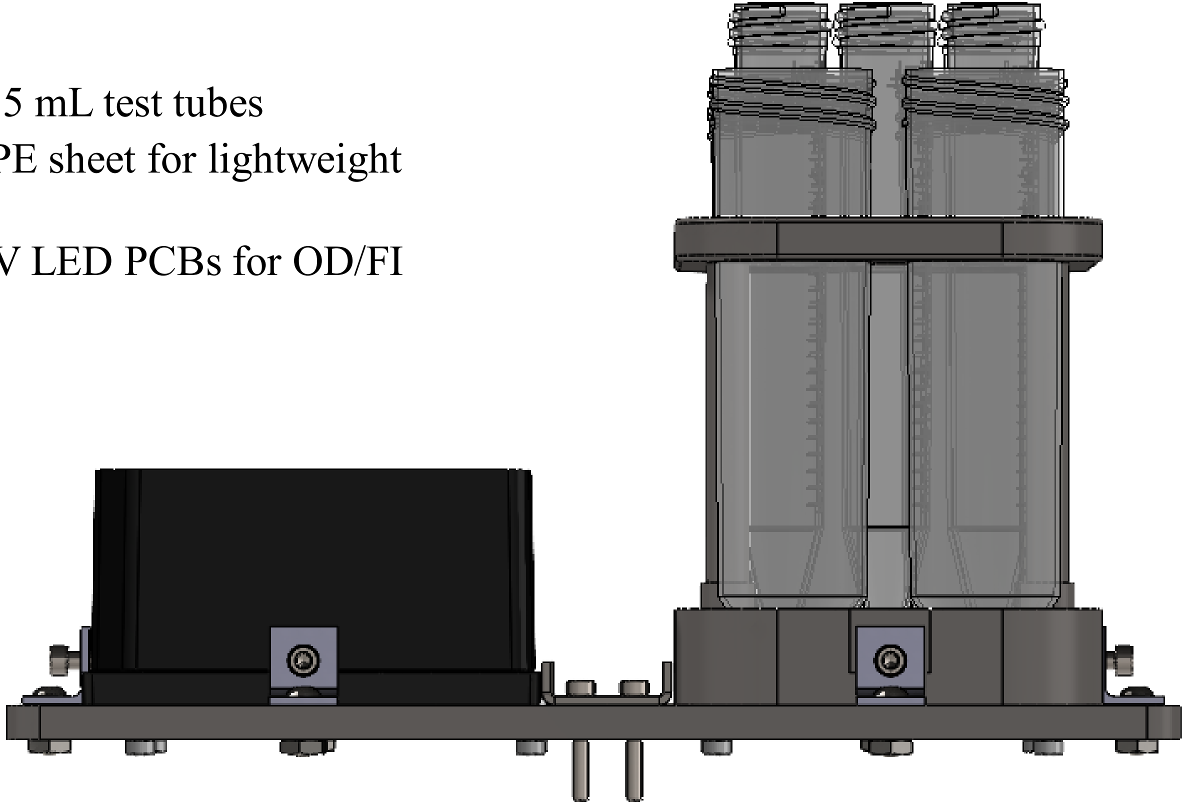
- Stepper Motor: NEMA 23 IP-65
- Built-in Encoder for Positional Accuracy
- Good motor performance due to high torque at low speeds
- No gearbox (wear prevention)
- Overpowered motor to limit skipping steps and internal temperature rise



Design Highlights

Shaker Top Plate

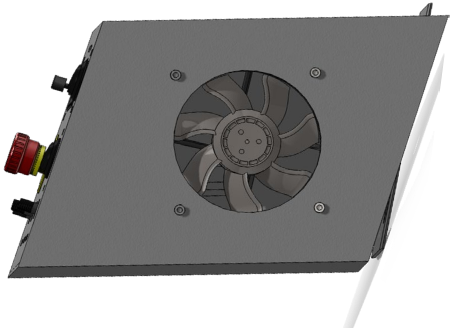
- Holds 6 50 mL and 6 15 mL test tubes
- Made of 1/4” cast HDPE sheet for lightweight but durable properties.
- Includes 2 wells for UV LED PCBs for OD/FI capabilities

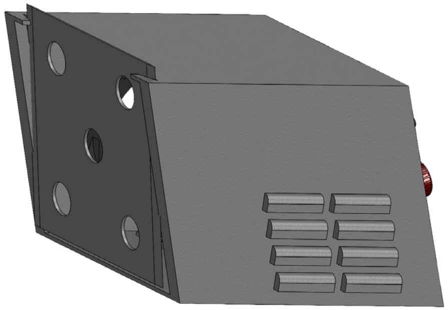


Design Highlights

User Interface

- 3D printed PETG with umbilical cord, cooling fan, and mechanical switches
- Includes emergency switch and pattern, speed, and distance control.
- Singular large fan and venting system included to prevent overheating during high speeds
- New insertable backplate with umbilical cable hole and single larger cooling fan.



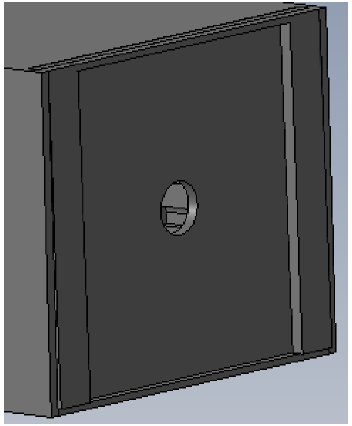


User Interface

- Previous design includes most features present on current user interface
  - This is the winning core X-Y shaker table’s user interface from Fall 2022
  - This includes a power button, pause switch, timer button, an LCD display, and use of a venting system
  - Controllable parameters include 5-option dial switches for the speed, distance, and shaking patterns
- This design does not meet current requirements due to changes in the project or our design

User Interface

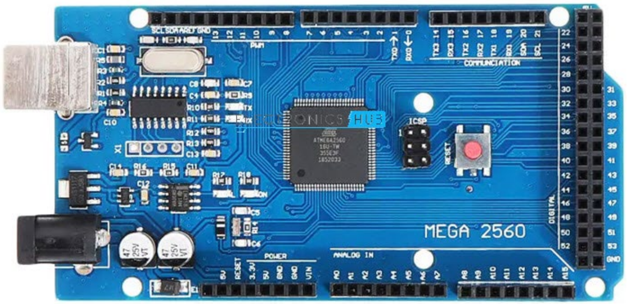
- Most design iterations that occurred during the middle of the semester was UI related
- Back portion of the user-interface used to be completely straight with no slant like with the front of the design
    - This included a rectangular slot for the back plate to fit into
        - The back plate went from one hole in the middle to five to reduce thermal load while printing
        - The back plate is now in a triangular slot due to easier tolerancing
- Design iterations mostly occurred to adapt to 3D printing the structure of the user interface
- Overall dimensions were eventually finalized to 5.25” x 6.25“ x 6.75” to fit on the Prusa 3D printer
    - Changed from old 4.25” x 6.25“ x 4.5”
    - Would have been bigger if not restricted by printer size



Design Highlights

Software/Electronics

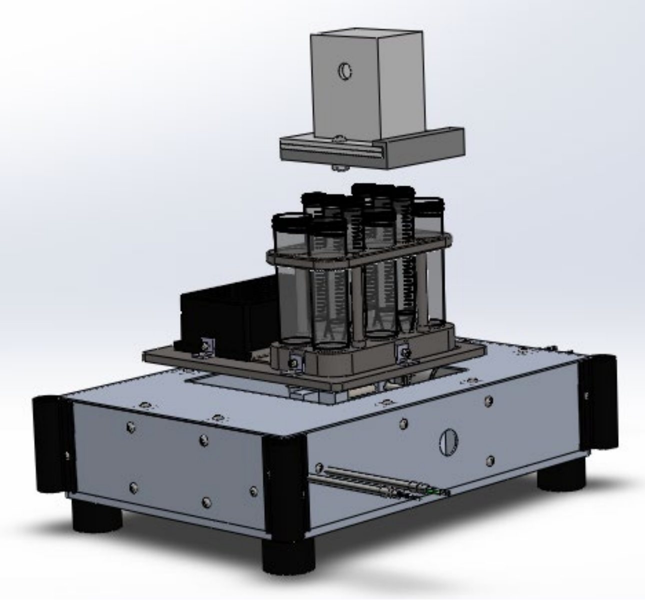
- Arduino code was made to control UI, motors, and motor encoders
  - Calibration now occurs when powered on and with encoder coding unlike other designs using limit switches
  - Proportional controller was implemented for the encoder-based programming for shaking patterns
- No breadboards are used in the current iteration of the design
  - Two perf boards are now used for more “finality” to the design
    - One is attached to the LCD screen due to have so many pins by itself while the other controls every other aspect of the design
- Arduino Mega 2560 is used as a microcontroller
  - Has enough pins and power for the needs of our shaker table

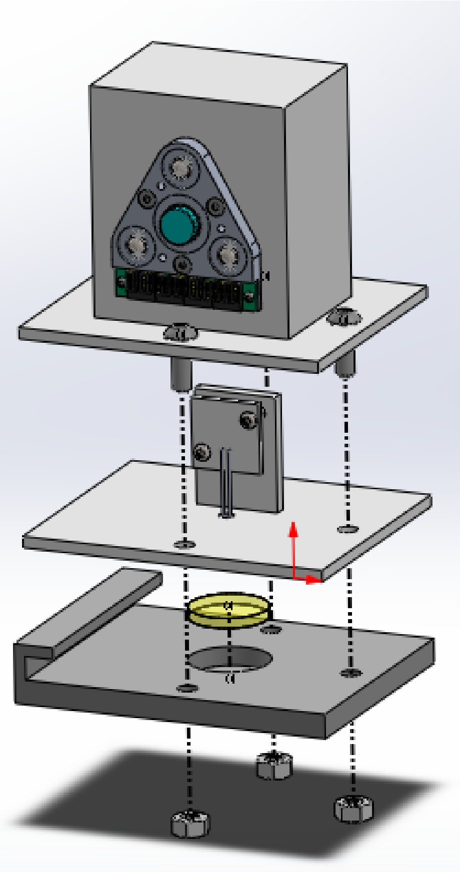


Design Highlights

OD/FI System: Sensor package

- Parts printed from PETG
- Allows for attachment of NOEL mount, LDR PCB, and 450nm longpass filter
- For OD, sensor package is positioned over the tubes and wells while the specific tube/well is uncovered.
- For FI, sensor package is positioned over the wells with a filter inserted and at the sides of the tubes.

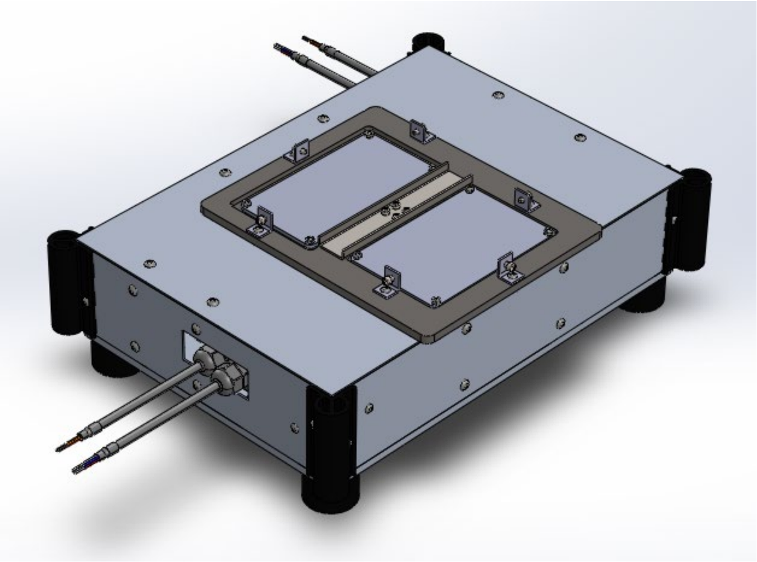




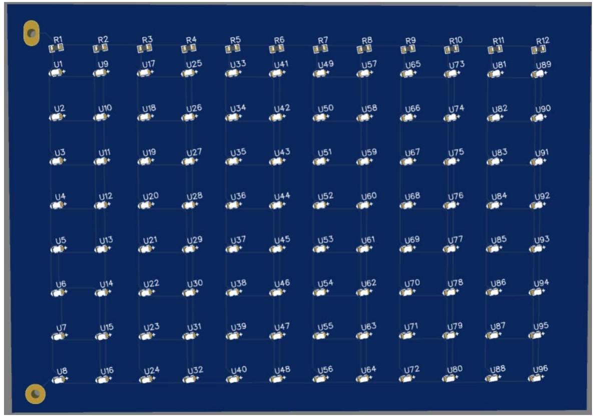
Design Highlights

OD/FI System

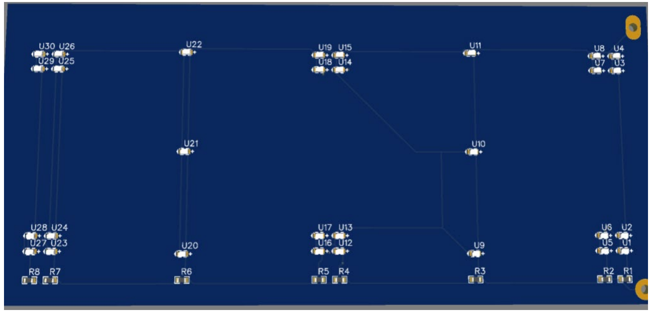
- Ultraviolet LEDs with a Peak wavelength of 370 nm and a Luminous Intensity of 4 Mw/sr.
- Custom PCBs placed under the wells and tube rack.



Well Plate Set Up

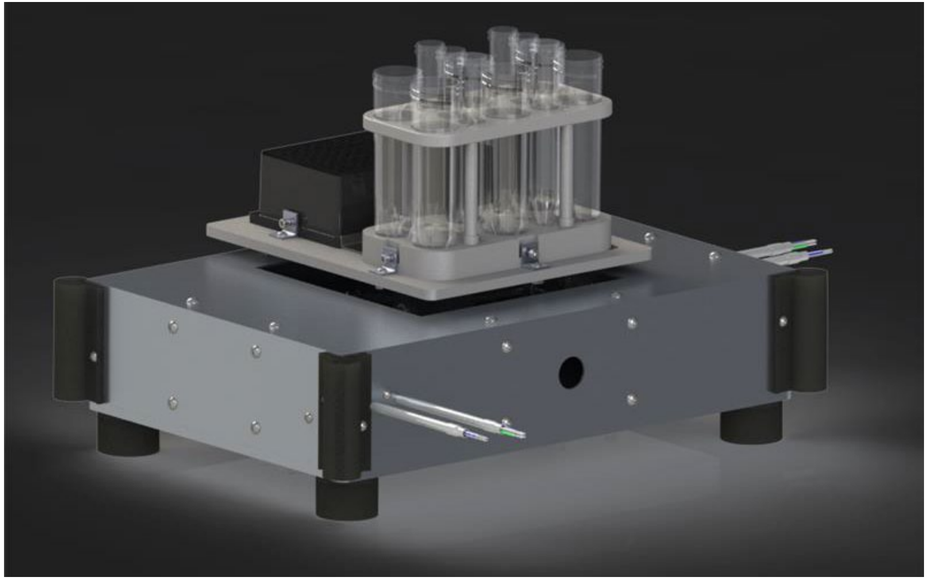


Test Tube Set Up



Design Analyses & Addressing Customer Needs

- *Shaker Mechanism*
- *Shaker Top Plate*
- *OD/FI*



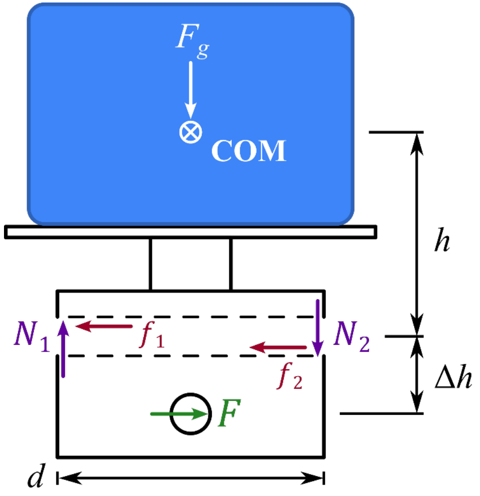
Shaker Mechanism

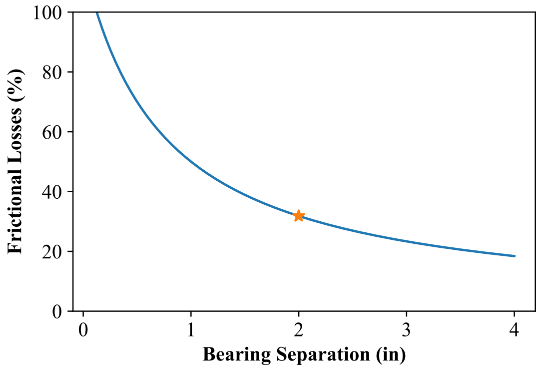
Kinetics Analysis

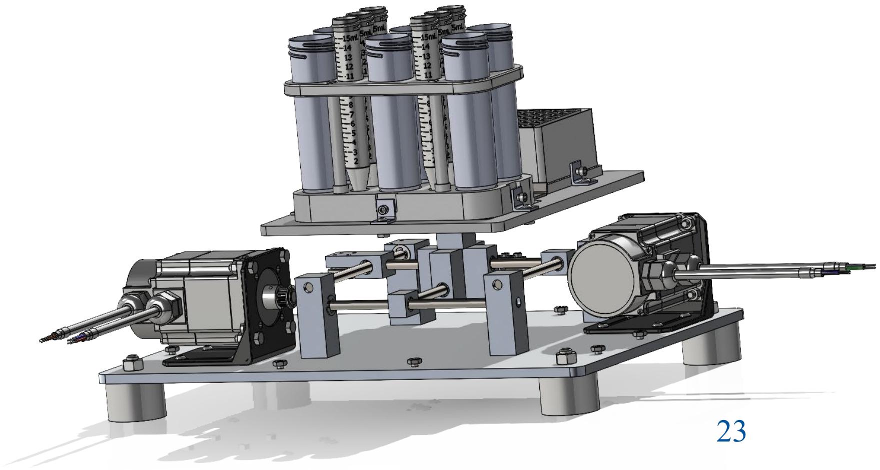
$$\sum F_y = N_1 - N_2 - mg = 0 \rightarrow N_1 = N_2 + mg$$

$$\sum M_{COM} = -N_1 \frac{d}{2} - N_2 \frac{d}{2} - f_1 h - f_2 h + F(h + \Delta h) = 0, f_1 = \mu N_1, f_2 = \mu N_2$$

Proportion of motor force lost to friction: $\delta = \mu \frac{h + \Delta h}{d/2 + \mu h}$







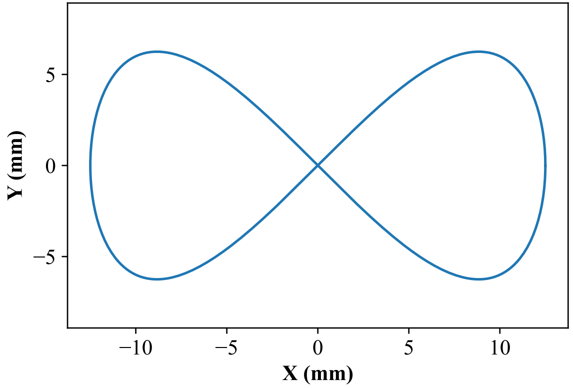
Shaker Mechanism

Kinematic Analysis:

Linear: $(x, y) = (\frac{D}{2}\sin 2\pi f t, 0)$

Orbital: $(x, y) = (\frac{D}{2}\cos 2\pi f t, \frac{D}{2}\sin 2\pi f t)$

Double orbital: $(x, y) = (\frac{D}{2}\cos 2\pi f t, \frac{D}{4}\sin 4\pi f t)$



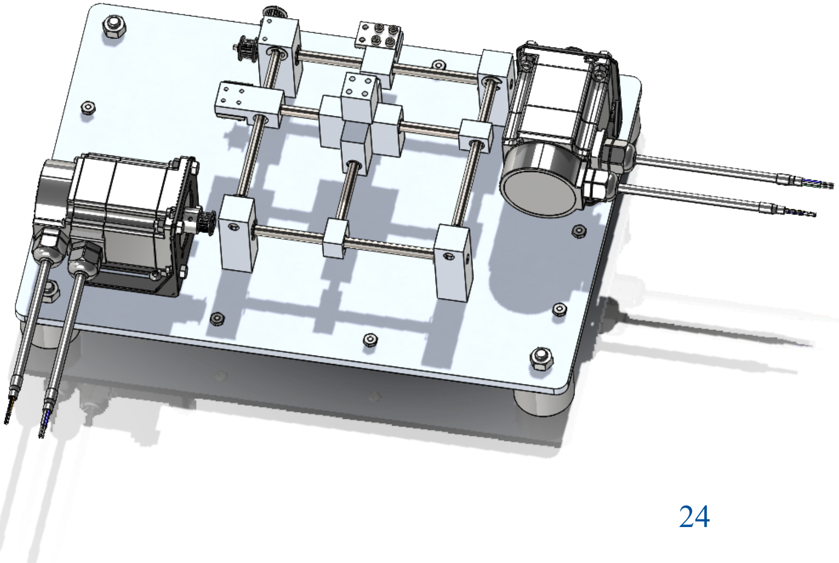
$\ddot{x}_{\max} = 2D(\pi f)^2$, $a = \ddot{y}_{\max} = 4D(\pi f)^2$, $\ddot{y}_{\max} > \ddot{x}_{\max}$

$T = \frac{D_p}{2}F$, $F = m_m a$, $T = \frac{D_p}{2}m_m a = 2DD_p m_m(\pi f)^2$

$T = 2(0.025\text{ m})(0.01273\text{ m})(0.5\text{ kg})(\pi \times 5.83\bar{3}\text{ Hz})^2 = 0.107\text{ N}\cdot\text{m}$

$\dot{y}_{\max} = \pi D f$, $y = \frac{D_p}{2}\theta \rightarrow \theta = \frac{2}{D_p}y$

$\omega_{max} = 2\frac{D}{D_p}\pi f = 2\frac{0.025\text{ m}}{0.01273}\pi(5.83\bar{3}\text{ Hz}) = 72.0\frac{\text{rad}}{\text{s}} = 687\text{ RPM}$

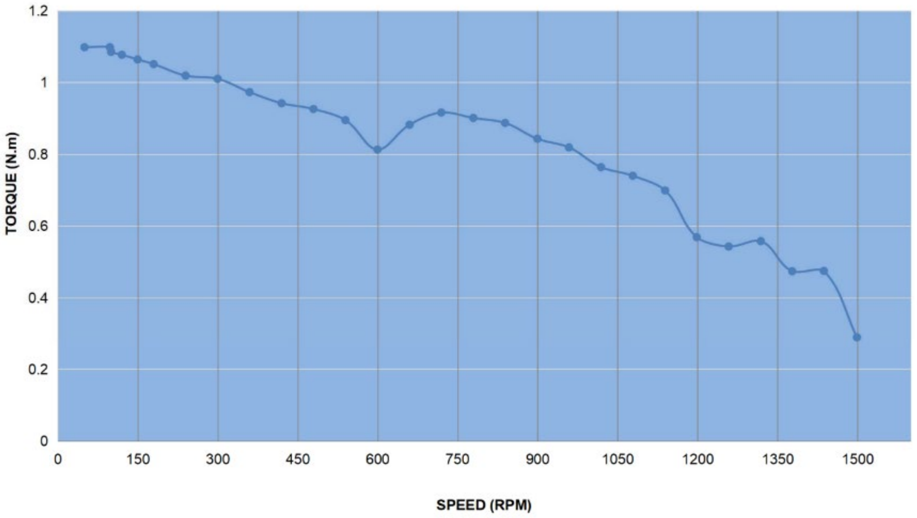


Shaker Mechanism

Kinematic Analysis

$$a = 4(0.025\text{ m})(\pi \times 5.83\bar{3}\text{ Hz})^2 = 33.6\frac{\text{m}}{\text{s}^2}$$

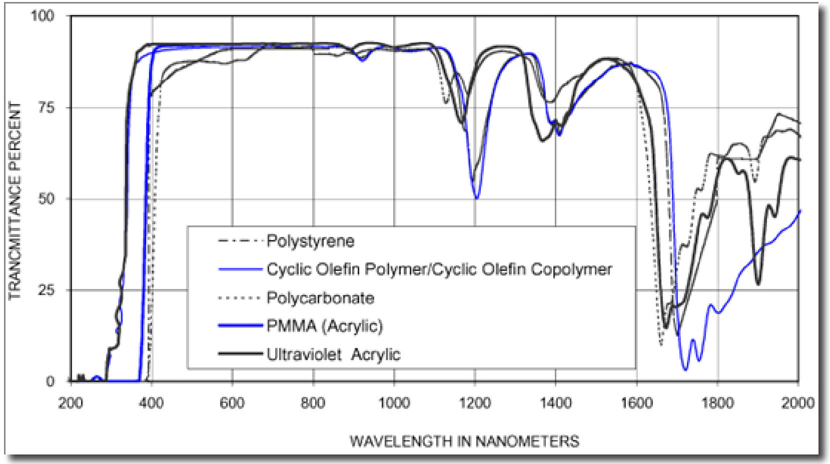
$$T_{max} > T = 0.107\text{ N}\cdot\text{m @ }\omega = 700\text{ RPM}$$

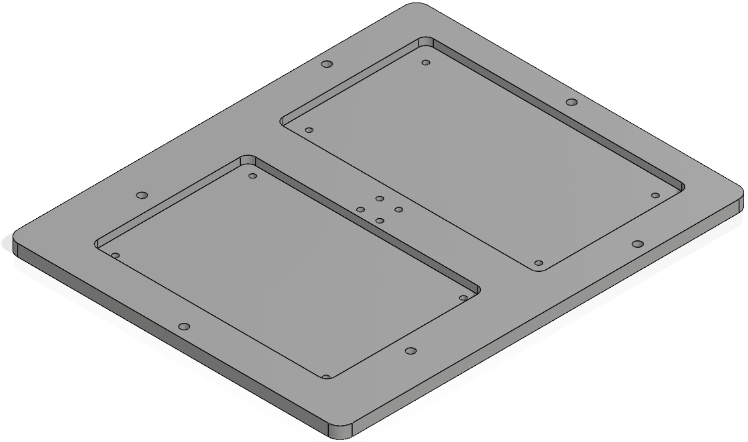


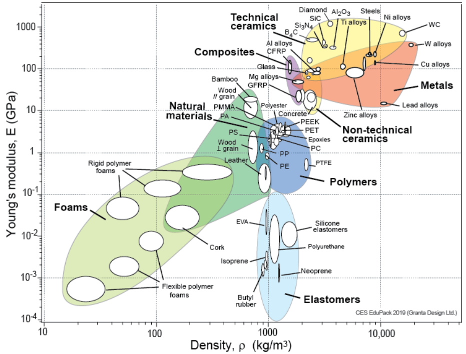
Excess torque accounts for mechanical losses, finite-actuation time, and limits internal temperature rise

Shaker Top Plate

- Due to OD/FI requirement of using a maximum wavelength of 350 nm, the previous acrylic plate design could not be used.
- A lightweight, durable, and high melting point material was desired to meet all customer needs.
- The material must also be machinable to allow for the tube rack and well plate to be secured.
- HDPE was selected as it meets all requirements and is inexpensive, with cutouts for LED arrays to allow for OD/FI ability.

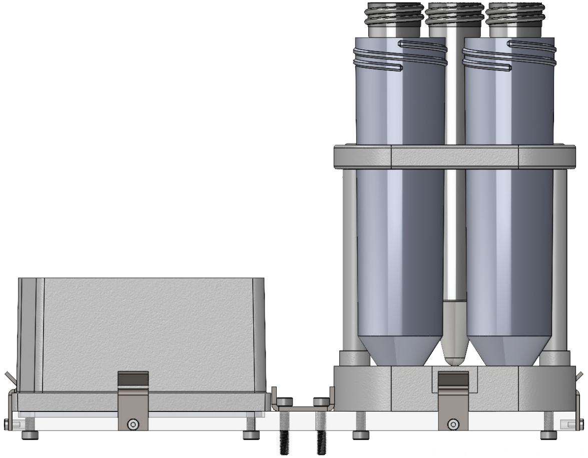


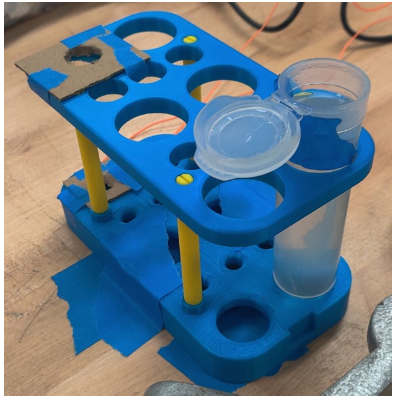


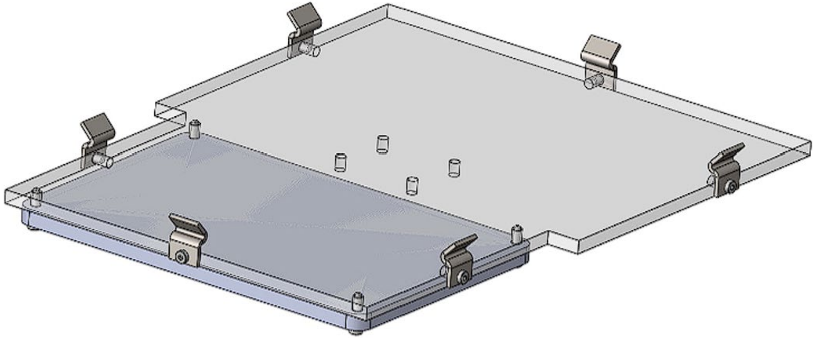


Shaker Top Plate

- Previous design used sheet metal edge clips to secure tube rack and well plate.
- Feedback from manufacturing TAs was that these components performed poorly and were difficult to manufacture, leading to threaded 90-degree brackets being used.
- Tube rack was adjusted to allow OD/FI sensor to reach all tubes.

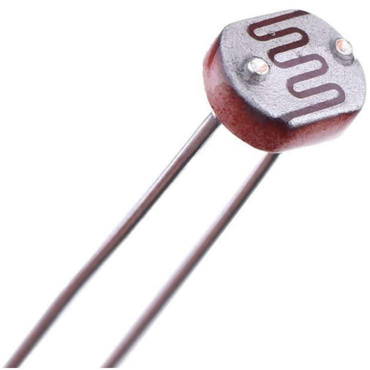


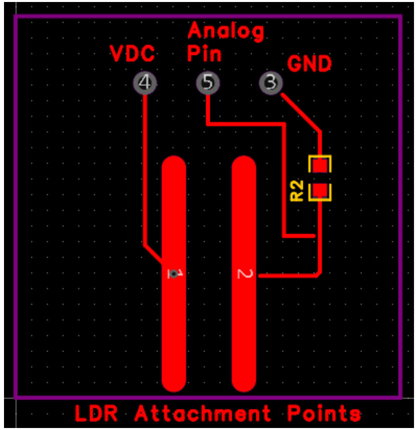




OD/FI

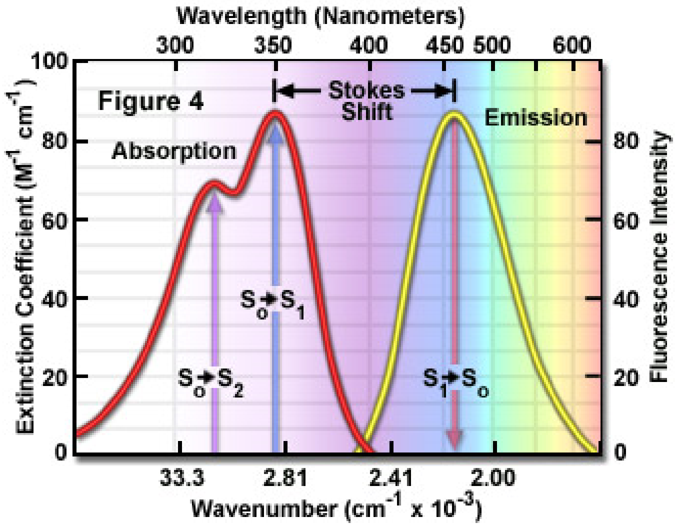
- In designing the LDR PCB, the resistor used in the voltage divider was important to consider.
- To optimize the sensitivity of the LDR, the resistor used was based on the resistance sensed from the LDR under produced under testing conditions.
- Adjustments were made based on calibration results as well.
- As a result, 150KΩ resistor was used for the LDR PCB.

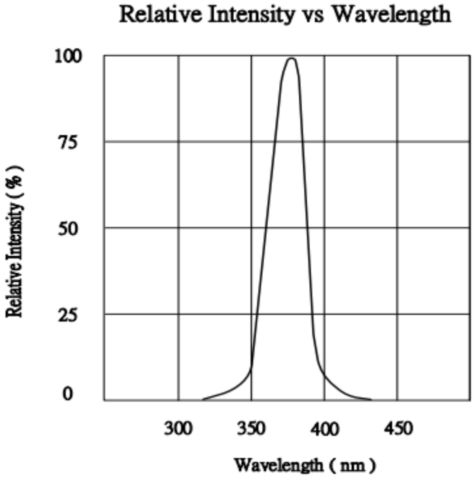




OD/FI

- An LDR sensor with a spectral range of around 400-700 nm was used to detect the fluorescence emission from the quinine. To block the UV excitation light and allow only the fluorescence emission to be detected, an emission filter with a transmission maximum at around 450 nm was used.



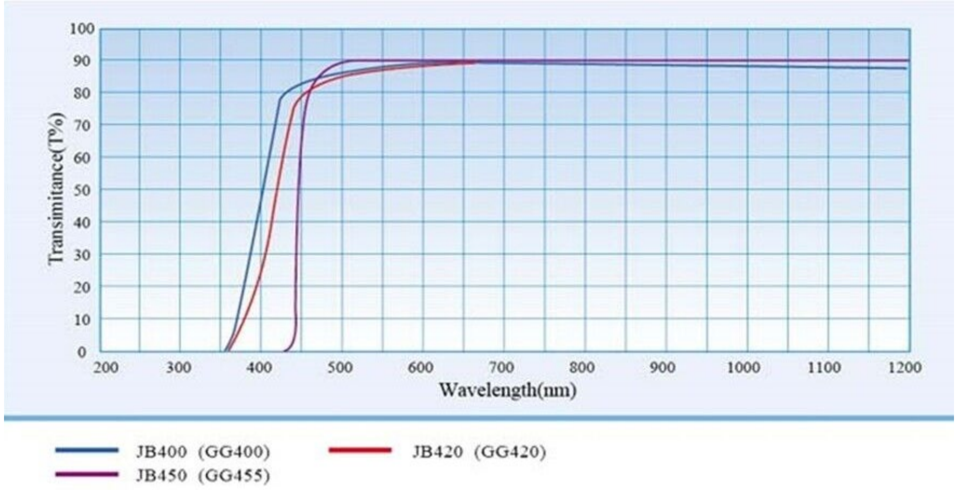


OD/FI

$I = \frac{P}{\pi r^2}$ where *I* represents the irradiance (W/m^2), *P* is the total power output of the UV LED array in watts, and *r* is the radius of the test tube in meters.

The absorption coefficient, *Φ*, and quantum yield of quinine ϵ at 365 nm, were defined as 3691 cm^{-1}/M and 0.546 respectively. The LDR sensor has a linear response range of 0 to 150 volts. To generate a fluorescence signal of 30 volts or 20% of the dynamic range at the surface of the test tube with a radius of 1 cm, the power output of the UV LED array must be:

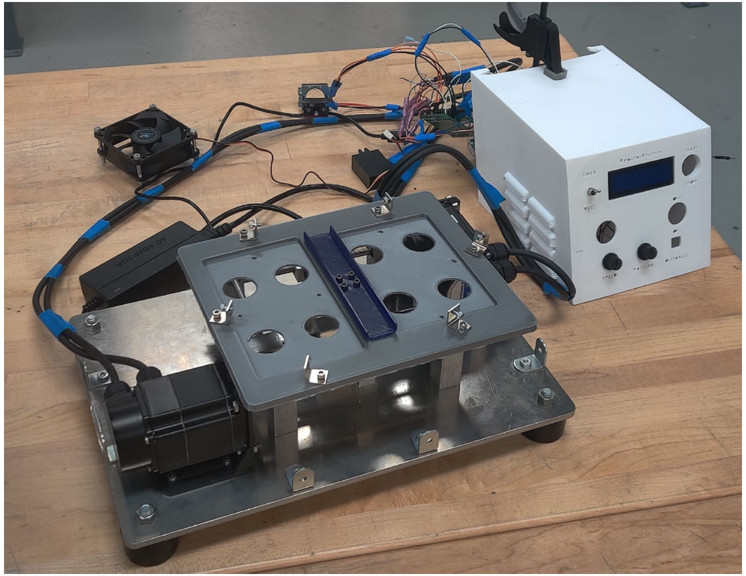
$$P = \frac{(30\ \text{V} \cdot \pi \cdot r^2)}{(I \cdot \Phi \cdot \epsilon \cdot \Lambda)} = 0.23\ \text{mW}$$



Therefore, the UV LED array should be capable of delivering at least 0.23 milliwatts of power to each test tube in order to achieve a fluorescence signal of 30 volts at the surface of the test tube.

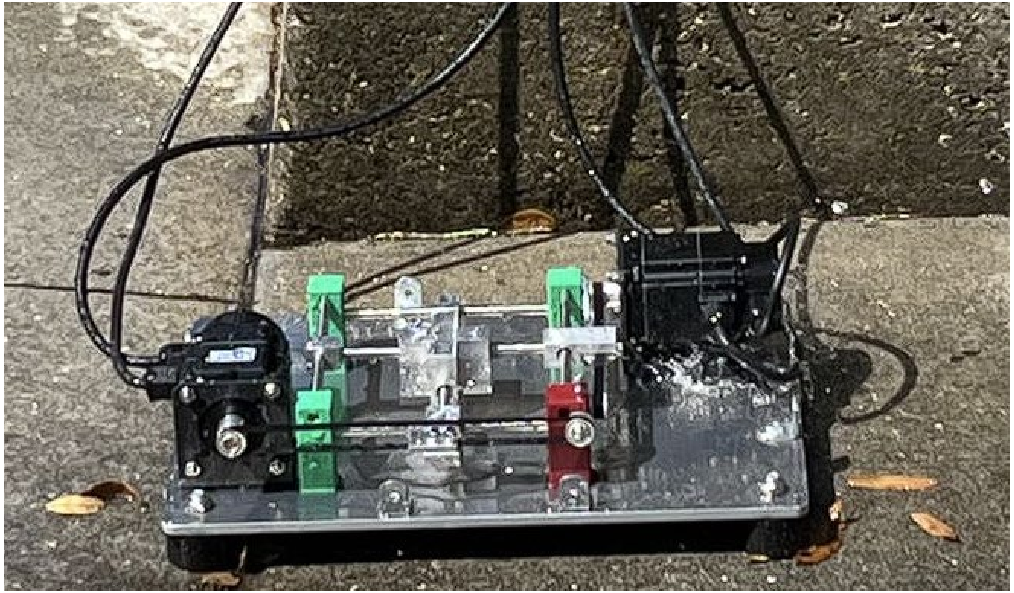
Testing

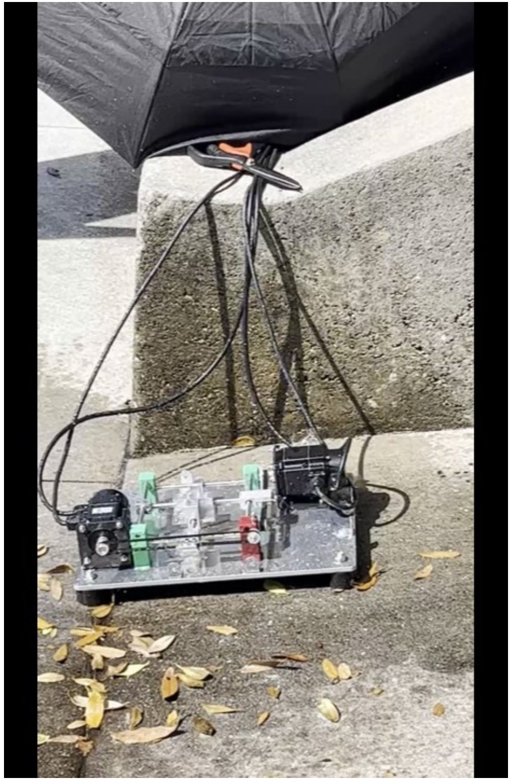
- Motor Demonstration – The initial deadline was missed due to being unable to drive the motor with the Pololu motor driver.
- After replacing motor drivers, motor capabilities were exhibited when completing the IPX5 test.



Testing

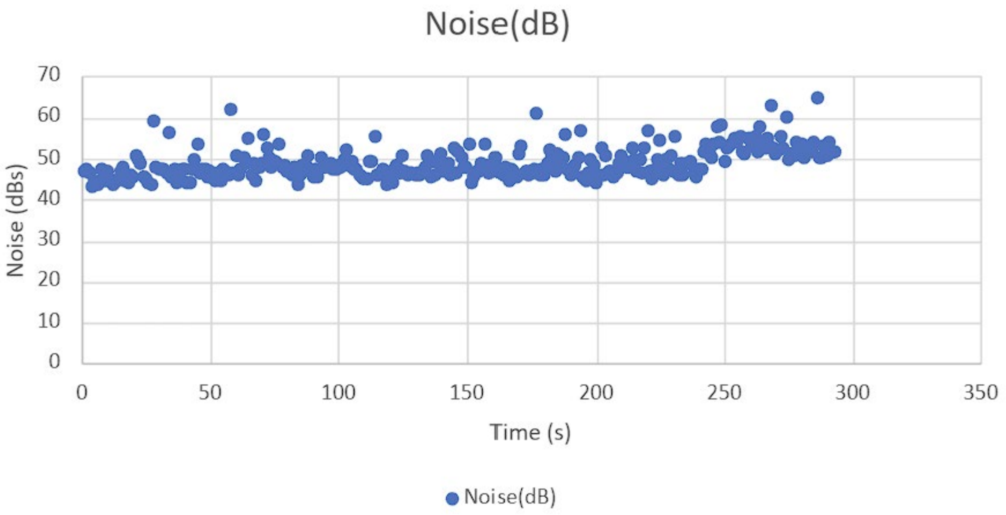
- IPX5 Waterproof Test – Verified integrity of waterproof motors and met motor demonstration requirements
  - Test involved spraying shaker table with hose and determining whether it was still functional after getting sprayed

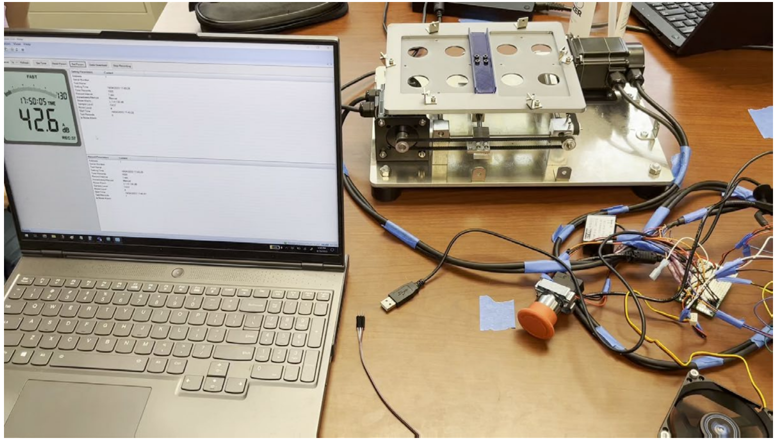




Testing

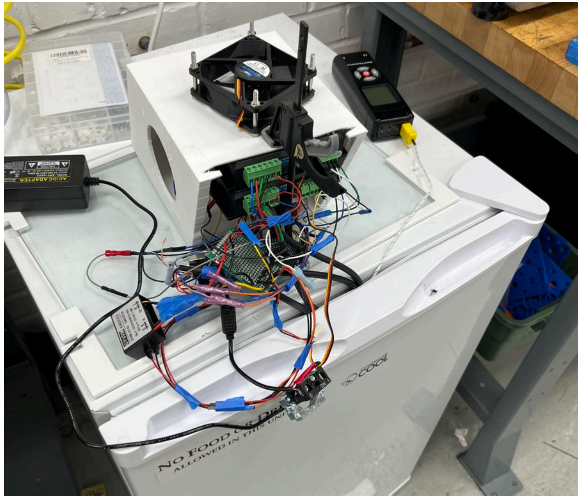
- Acoustic Test – Under 50 dB on average 15 cm away in each direction for all shaker patterns.
    - Test was done with a microphone for five minutes with the microphone direction changing every minute





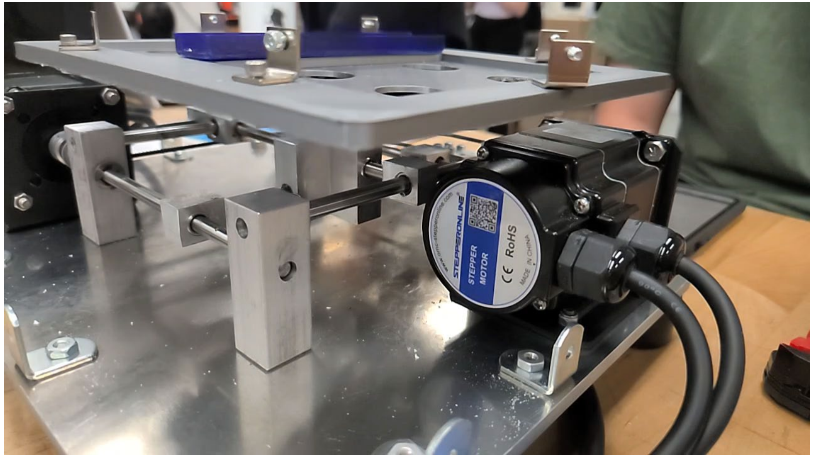
Testing

- Cold Soak Testing – Testing at 4° C was done at a motor control speed of 0.1 Hz while in a mini-fridge
    - Speed testing at this low speed was done after 90 minutes without moving in the fridge and again after another 10 minutes while moving inside



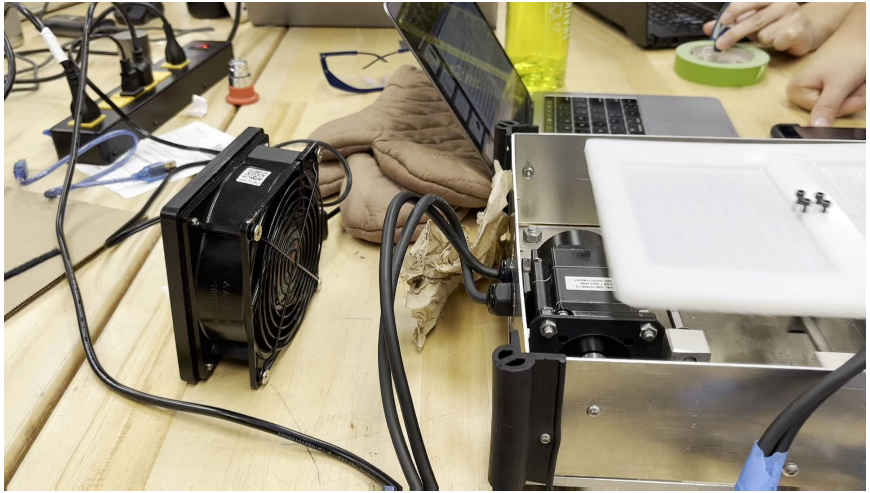
Testing

- Overclock and High Temperature Testing – Shaker table was able to run at 10 Hz (600 rpm) for 10 minutes at room temperature
  - Actual speed is about 582 rpm using 960 FPS video (1/32 real-time)
  - This is not our theoretical maximum speed, but one where all the shaking patterns are still slightly visible. The speed should be able to double and run with slight tweaks to the proportional controller



Testing

- It was then run in the oven with the same settings at 70º C for 100 minutes
- Rapid cooling testing was performed afterwards by testing if the same settings would function after being taken out of the oven and being put immediately in front of a fan

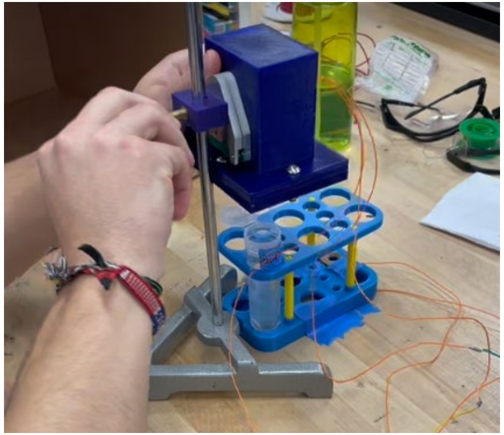


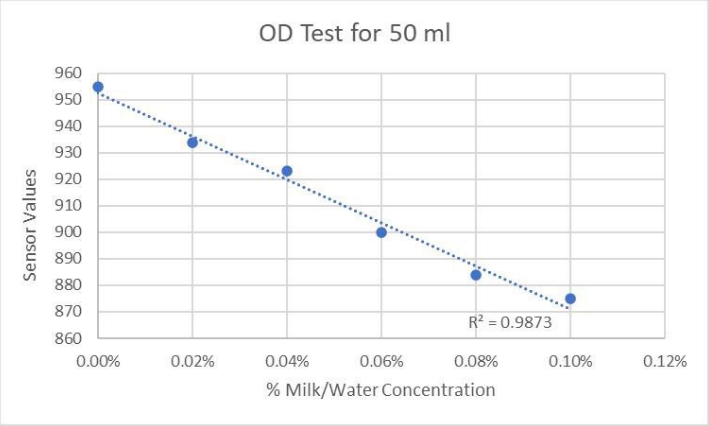
Testing

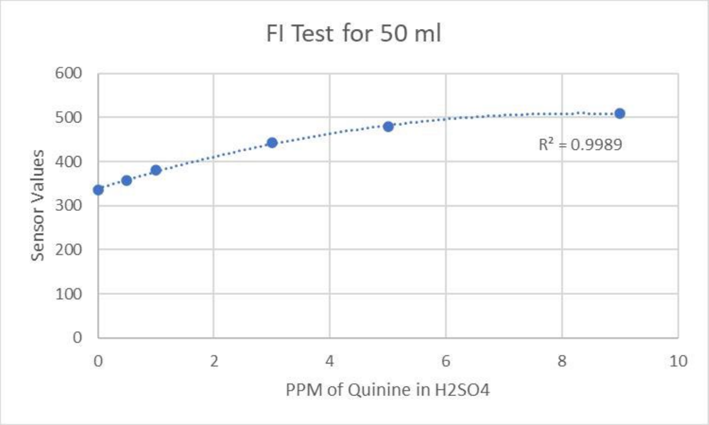
- Drop Test – Shaker table was dropped from a height of 75 cm to see if function could still be sustained after a drop
    - All three shaking patterns were shown to function due to minimal damage to shaker table

Testing

- OD/FI Calibration and Demonstration – Sensed OD and FI for selected solutions of varying concentrations
    - Successfully tested OD and FI for 50ml and 15ml tubes
- 0% to 0.1% milk/water solutions were used to calibrate for OD
- 0 PPM to 9 PPM quinine in 0.05 M H2SO4 were used to calibrate for FI







Cost Analysis

Prototype Run:

- The cost of parts for our prototype run is: $1032.49

Production Run:

- The total cost of a potential production run is about $1,252.79.
- $294.89 was saved due to part bulk pricing
- Manufacturing and Assembly costs calculated from estimated times and labor costs.

Production Run Cost	
Category	Cost
OTS Parts	$722.33
Raw Materials	$58.26
Manufacturing	$448.56
Assembly	$25.52
Total	$1,254.68

Assembly Time

- Assembly time was determined using Boothroyd & Dewhurst Handling & Insertion charts
- Times were calculated for assembling the shaker mechanism, enclosure, shaker top plate, and other necessary steps

Assembly Time	
Subassembly	Time (min)
Shaker Mechanism	12
Enclosure	9
Shaker Top Plate	5
Other	1
Total	27

Summary

Why ReactorRhythm?

- **Easy to Assemble**
- **Low Production Cost**
- **Durable & Long-lasting**
- **Minimal Manufacturing**

Conclusion

Thank you sponsors!

Questions?