Variable Light Box

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BME 472
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Final Product

Functionalities

Figure 1 illustrates the light box in the on state. Complete demonstrations of the light box functionalities may be observed on the corresponding website.

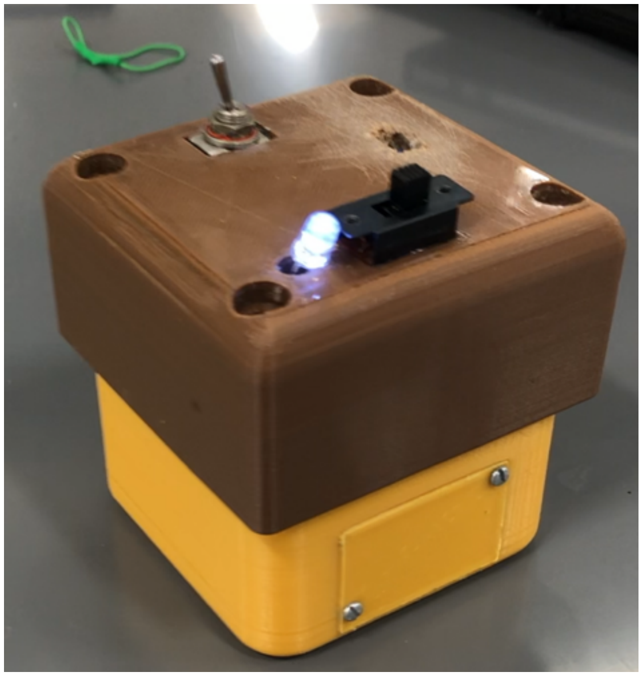


Figure 1. Functional Light Box

Full Assembly

The CAD and manufactured full assembly may be observed in Figure 2 and Figure 3 respectively. No modifications were made in the procedure for assembling the PCB and enclosure components.

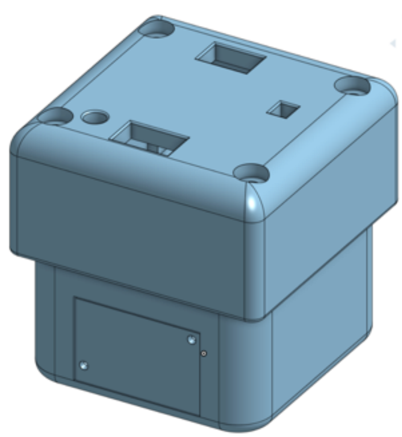


Figure 2. CAD Assembly Design

Figure 3. Manufactured Assembly

<u>Base</u>

There were no significant differences between the manufactured base and the CAD design. Figure 4 illustrates the CAD of the base, and Figure 5 represents the final printed base.

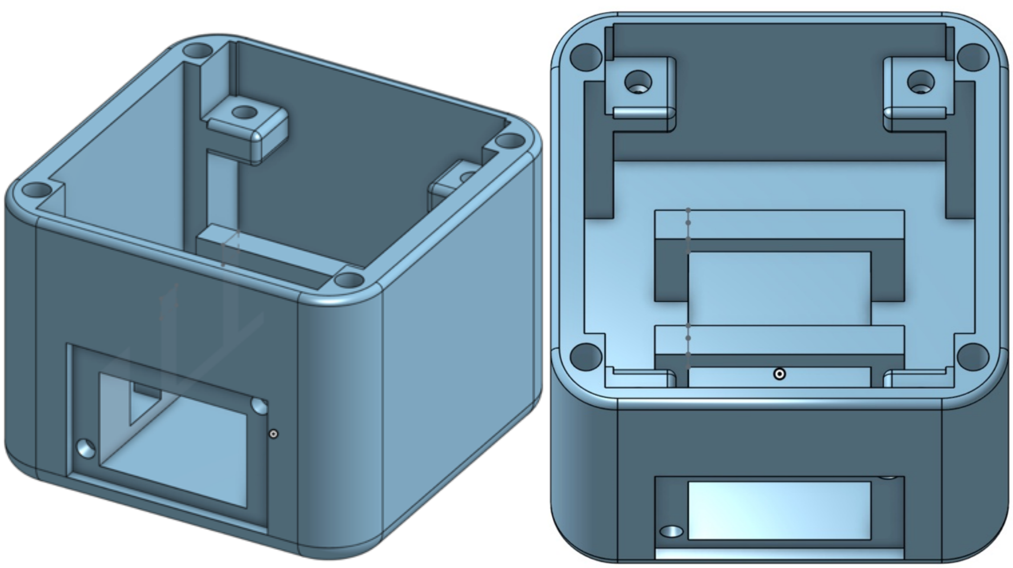


Figure 4. CAD Base Design

Figure 5. Manufactured Base

Lid

The final manufactured lid varied from the CAD lid as the support beam under the potentiometer broke after each print. Furthermore, the hole for the potentiometer was expanded with pliers and files. Figure 6 and Figure 7 illustrate the CAD lid and manufactured lid respectively.

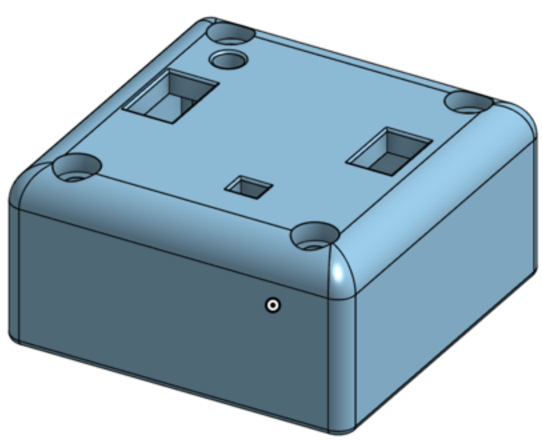


Figure 6. CAD Lid Design

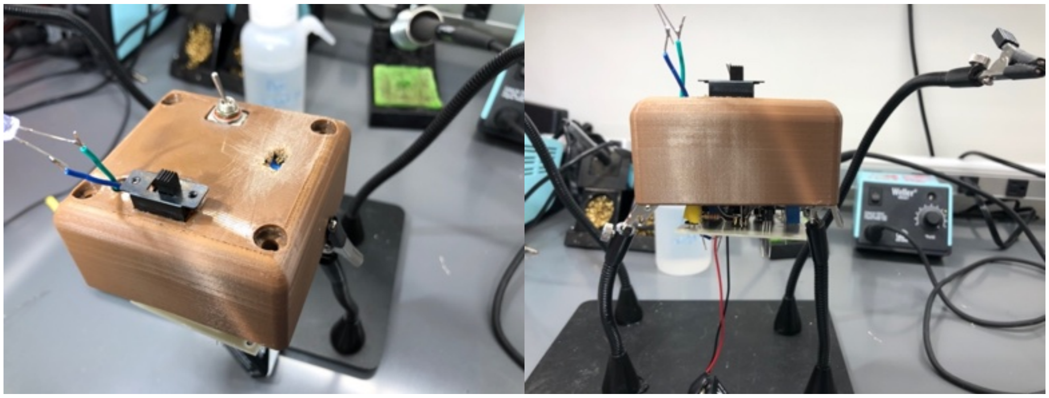


Figure 7. Manufactured Lid

Battery Door

The battery door was minimally sanded on all four sides to remove sharp edges. Otherwise, no significant changes existed between the manufactured battery door and the CAD design. Figure 8 and Figure 9 depict the CAD and manufactured battery door respectively.

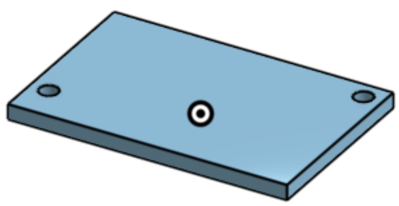


Figure 8. CAD Battery Door Design

Figure 9. Manufactured Battery Door

PCB

The designed PCB varied from the manufactured PCB as te traces for the AND gate did not include connections to the 5V supply or ground. These connections were added. Figure 10 and Figure 11 depict the designed PCB and the manufactured PCB respectively.

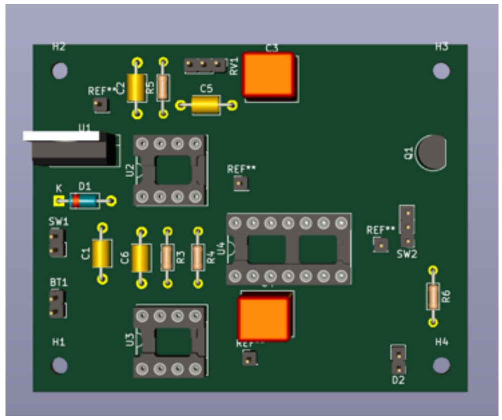


Figure 10. PCB Kicad Design

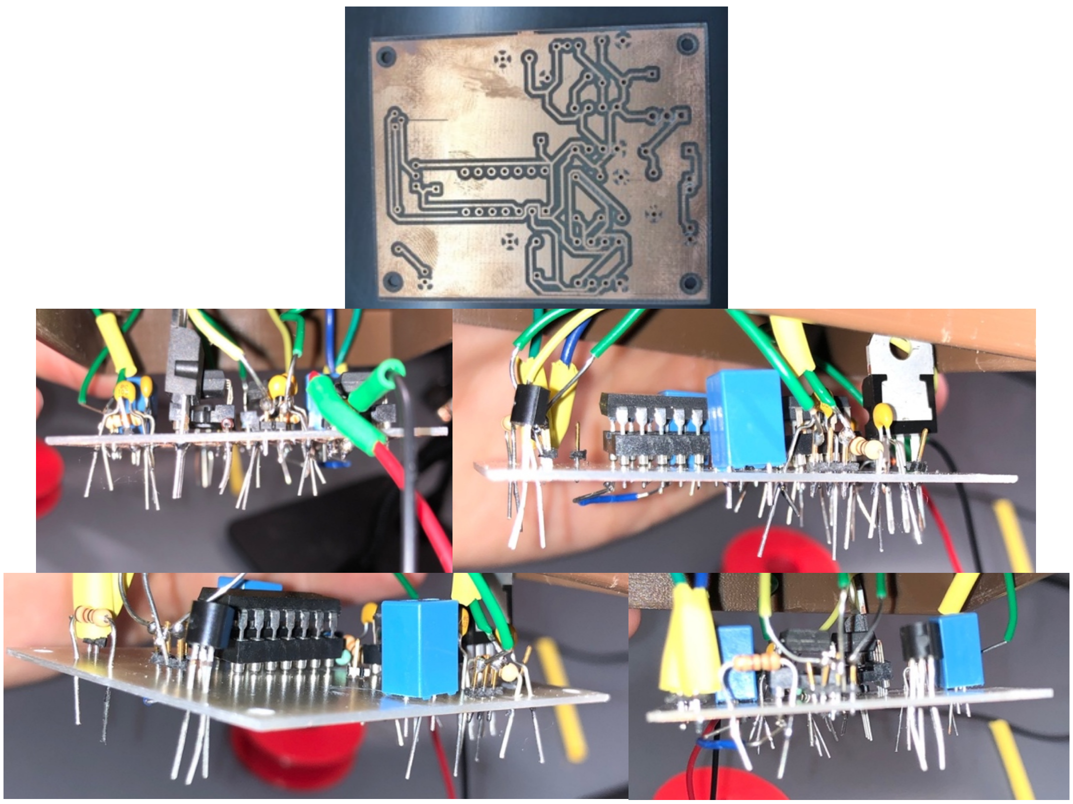


Figure 11. Manufactured PCB Board and Components

User Design Criteria

Designing the variable light box presented the opportunity to hone 3D CAD, EDA, PCB manufacturing, and wholistic design skills as preparation for a project in conjunction with Duke Medicine. Table 1 below illustrates the design criteria and the corresponding testing approach. Additionally, the testing performed for each criterion, ideal response, and statistical analyses are detailed.

Table 1. User Needs / Design Constraints

	Design Component	Design Criteria	Testing Method	Ideal Response	# of Trials	Statistics if Applicable
LightBox	User Interface	Switch to turn device on/off	Visual	Yes, light on	10	N/A
			Compare voltage across LED when on or off	Off < 0.1 V ± 0.1 V; On > 1 V ± 0.1 V	10	2 Sample t-test
		Battery must be replaceable in < 5 min	Measure time to replace battery	< 5 min (300 s) ± 10 s	10	1 Sample t-test
	Durability/Portability	Battery life of at least 4 Hours	Measure current drawn during max brightness continuous mode to estimate battery life based on amp hours for maximum voltage of 9V and minimum voltage threshold	≥ 4 hours ± 10 min	10	1 Sample t-test
		Identify 3 circuit component that are largest power drains	Combine intuition with measured voltage across and current through a component to implement P=iV or datasheet plots to identify power consumed	N/A	10	N/A
		All dimensions must be < 3 in.	Measure enclosure with calipers	< 3 ± 0.1 in in in x, y, and z directions	10	1 Sample t-test
		Weight must be < 0.5 lb	Weigh light box	< 0.5 ± 0.05 lbs	10	1 Sample t-test
		Enclosure must be Sealed	Inspect if parts fell out after being shaken for 5 seconds	No parts fallen out	10	N/A
		Enclosure must survive a 3 ft drop	Drop lightbox from 3 ft in random orientations	No damage sustained	10	N/A
		Must cost less than $20	Sum cost of each part in light box	$ 20 ± 1	1	N/A
		Powered by voltage-regulated, 9V battery, with reverse-polarity protection	Measure output battery voltage	9 ± 0.5 V	1	N/A
			Measure output voltage regulator voltage	5 ± 0.2 V	1	N/A
			Measure output voltage when battery is reverse	0 ± 0.1 V	1	N/A
		Must be safe	Visual inspection of no sharp edges or loose wires	N/A	1	N/A
	Light Functionality	Must switch between continuous and blinking (10 Hz, 50% duty cycle) modes	Measure oscilloscope duty cycle and period	10 ± 0.5 Hz with 50 ± 2 % duty cycle	10	1 Sample t-test
		Rotary knob to linearly modulate brightness of an LED from off (no light) to maximum brightness the circuit may achieve	Visual identification of brightness modulation and PWM frequency change to completely off	Yes, brightness modulated to off state	10	N/A
			Measure resistance across potentiometer and total on time for every 5 seconds for LED	$r^2 > 0.9$ & $r > 0.9$	10	Linear regression
		Max brightness the same in continuous and blinking modes	Measure area under voltage vs. time curve across LED	No statistical significance between the two data sets	10	2 Sample t-test

Circuit Design

The initial circuit design was created in sub circuit components to match the required design constraints. Figure 12 depicts the original sketch for the entire circuit. The first objective was to ensure the circuit was powered by 9V, voltage-regulated, and reverse-polarity protected. The voltage regulator desired converts the 9V input to a 5V output. Furthermore, the diode protects the circuit from reverse current flow should the battery be connected in reverse. In theory, in the incorrect reverse case, the voltage across the diode would be negative and below the threshold, preventing current flow through the circuit. Reverse current flow must be prevented as select circuit components may break under reverse current flow. The presence of the capacitors before the voltage regulator and after the voltage regulator, supports the voltage regulator in the case of sharp changes in current. Should the voltage regulator require a sharp increase in current output, the capacitor connected to the output may support this current flow.

Following the voltage regulation, two 555 timers were needed to create the blinking mode and allow for pulse-width modulation adjustments to alter the brightness of the LED. The 555-timer surrounded in blue establishes a blink mode by manipulation the resistors and capacitors connected to the 555-timer. Furthermore, the 555-timer surrounded by green implements a potentiometer for variable square wave outputs that will result in variable currents through the LED and therefore brightness. Knowing the blink frequency should be 10 Hz with a 50 % duty cycle, the frequency of the wave to modulate brightness was made to be relatively larger to ensure the brightness modulation wave does not alter the frequency of the blink when compounding the two waveforms. The final block of the circuit is surrounded in orange. This constitutes a switch to determine what mode the circuit is in, and AND gate to combine the logic of the two 555 timers when in the blinking mode, and transistor to ensure the power going to the LED is constant between the continuous and blinking modes, as well as a resistor to take the additional voltage beyond the LED's threshold voltage.

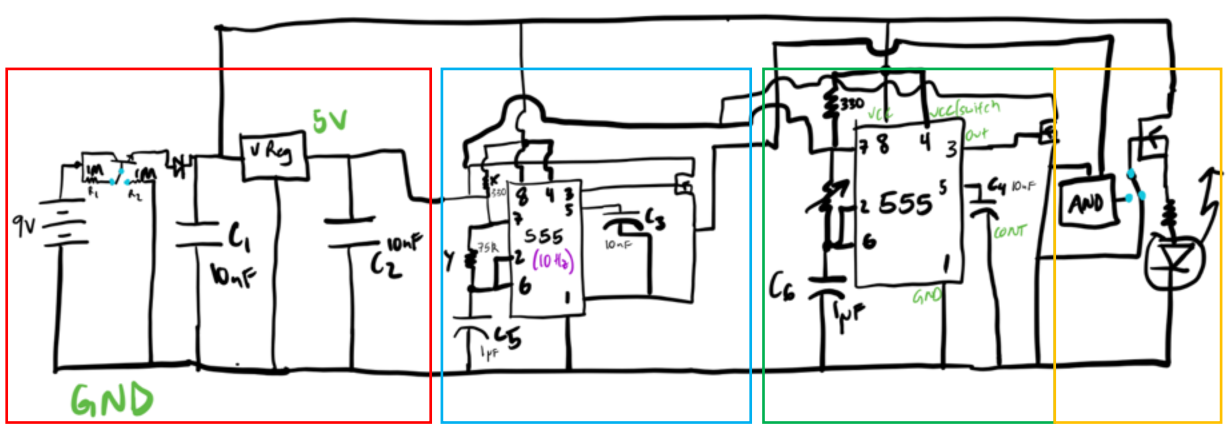


Figure 12. Initial Circuit Sketch

The resistance and capacitance values were determined using the online 555-timer calculator (https://ohmslawcalculator.com/555-astable-calculator). The kicad schematic for the first circuit iteration may be observed in Figure 13.

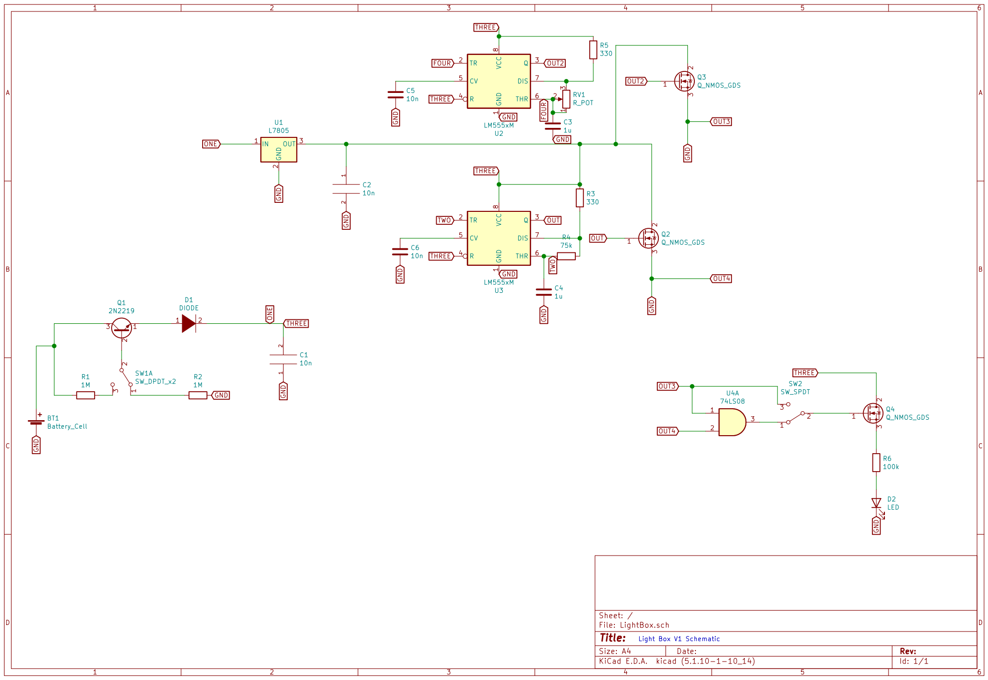


Figure 13. First Light Box Iteration Schematic

While the core overarching logic behind the circuit was maintained, the second iteration of the circuit design may be observed in the sketch in Figure 14 depicting the removal of unnecessary components. The transistor switch configuration was simplified to a basic SPST switch as the 9V supply was not a large enough voltage supply to warrant the extra components to not switch the load directly. Furthermore, the transistors after the 555-timers were removed as redundant. Additionally, the 555-timers were powered by the 5V from the voltage regulator output rather than the 9V battery supply.

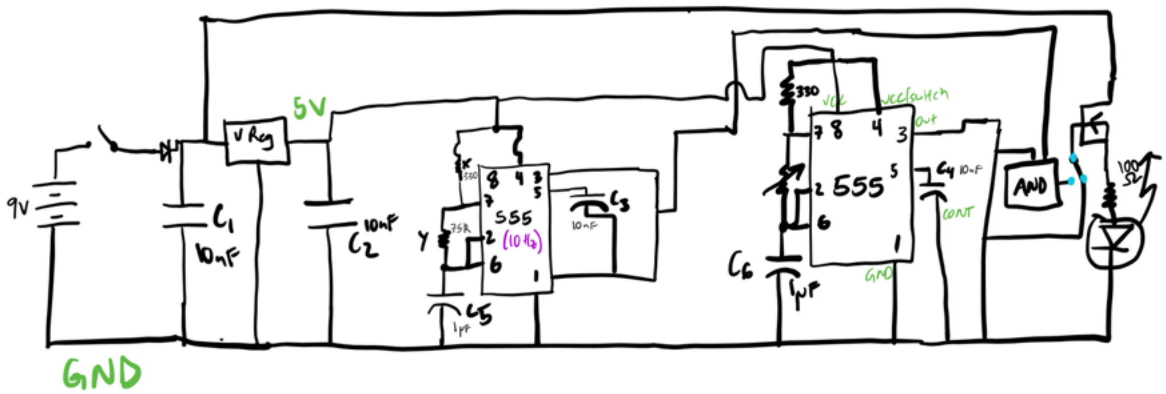


Figure 14. Second Iteration Circuit Sketch

Breadboarding Circuit & Testing Component Functionality

Entering the breadboarding process, all circuit components were tentatively established except for the potentiometer. As the circuit was built the 9V output of the battery and 5V output of the 7805-voltage regulator were checked using as oscilloscope as observed in Figure 15.

Figure 15. Confirmation of Battery and Voltage Regulator Output

Furthermore, quick checks were performed on the two 555 timers to ensure they are behaving as desired. Figure 16 depicts the functional blinking voltage output as well as the variable voltage output from the brightness modulating waveform.

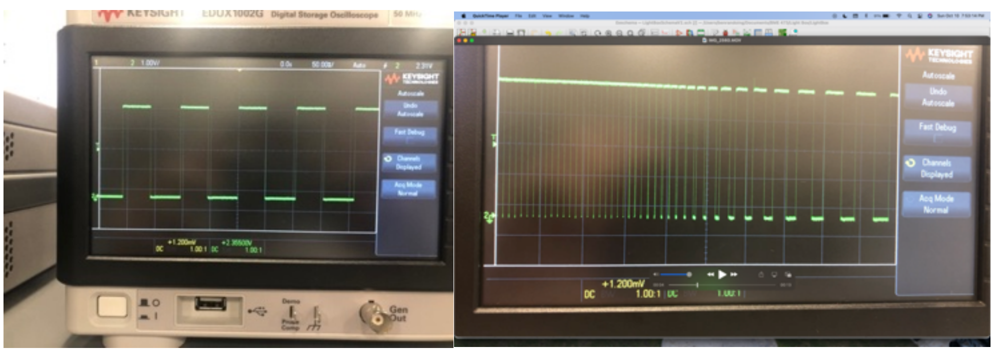


Figure 16. 555 Timer Waveform Outputs for Blinking and Brightness Modulation

Similarly, The AND gate was subject to an investigation of proper functionality as observed in Figure 17.

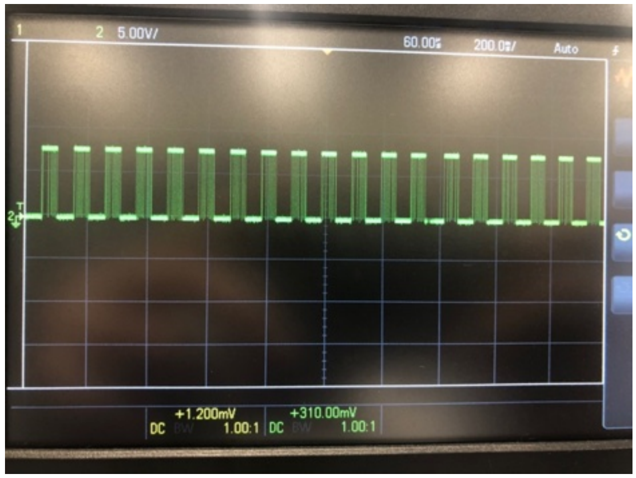


Figure 17. AND Gate Output from Breadboard Design

The circuit was built and potentiometer of 100 kΩ, 200kΩ, and 20kΩ were tested. The larger two potentiometers were influencing the blinking frequency at larger resistances; therefore, the 20 kΩ potentiometer was selected for the final circuit design. Additionally, the 75 kΩ resistor was replaced with a 68 kΩ resistor. The chesterfield design space did not have 75 kΩ resistors easily accessible and combining multiple resistors would be inefficient provided the limited space within the final light box. The final circuit schematic is illustrated in Figure 18.

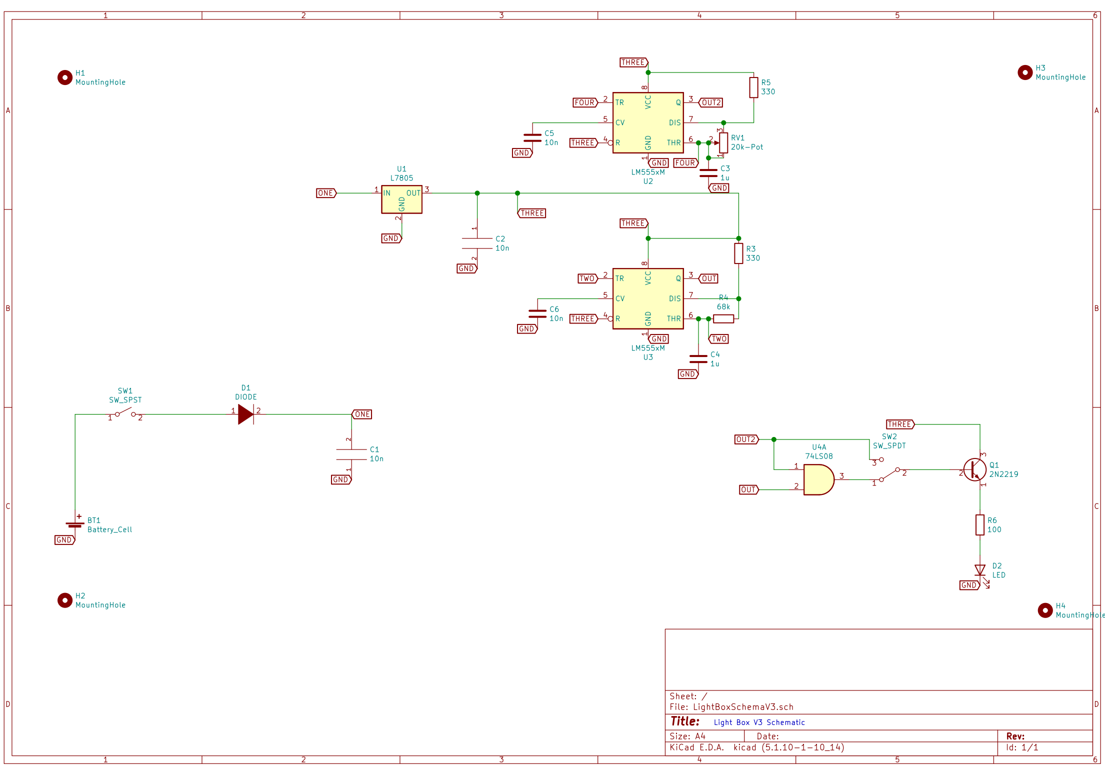


Figure 18. Final Circuit Design Kicad Schematic

Upon completion of the breadboard circuit, the functionality of the final product was tested visually. Two primary factors were identified in terms of circuit design limitations. First, in the blinking mode, the 50 % duty cycle was achieved by having the resistor between pins 6 and 7 be significantly greater than that between pins 7 and 8. This produces a duty cycle of approximately but not exactly 50 %. This first limitation is compounded by the limitation surrounding frequency. The light box and PCB are limited in size, therefore, extreme measures to ensure a frequency of exactly 10 Hz would result in inefficient combinations of multiple resistors and capacitors. To avoid such inefficiency, the circuit design reaches as close to a blink of 10 Hz as possible. Furthermore, limitations existed with respect to the modulation of brightness of the circuit. With the current 555 timer configuration, it is theoretically not possible to have a duty cycle below 50 %. Therefore, changes in the resistance between pins 6 and 7 may change the duty cycle and frequency to dim the LED, but the brightness will not dim to nothing. Theoretically, a NOT gate could be implemented to invert the 555-timer output; however, the resultant voltage was too minor to elicit any LED brightness. Furthermore, the adjustment of the potentiometer would alter not only the duty cycle but also the frequency of the 555-timer output at small resistances. This prevented linear modulations of the brightness of the LED. One potential alternative to alleviate the limitations regarding brightness modulation would be to have a diode in parallel with the resistor between pins 6 and 7. This would short said resistor during the charging phase of the oscillation. Thus, the charging phase behavior would be dictated by the resistor between pins 7 and 8. Such heightened control over manipulating the circuit behavior may allow for more precise linear modulation of the LED brightness.

PCB Design

Footprints for each circuit component to be soldered directly to the PCB were selected by measuring the component with calipers and selecting a THT through hole footprint as close as possible to the actual size of the component. However, the battery, LED, switches, and potentiometer were given footprints of header pins as the circuit components will be housed near the exterior of the light box for user manipulation. Additionally, the 555 timers and AND gate were provided footprints of either 8 or 14 pin buffers to avoid unnecessary soldering during assembly. Table 2 details the final footprints for each circuit component. Additional, single header pins were connected to the output of the 7805-voltage regulator, both 555 timers, and the AND gate to enhance the ease of functional testing upon fabrication of the light box.

Table 2. Bill of Materials for the Light Box PCB

Reference	Quantity	Value	Footprint
BT1	1	Battery_Cell	Connector_PinHeader_2.00mm:PinHeader_1x02_P2.00mm_Vertical
C1 C2 C5 C6	4	10n	Capacitor_THT:C_Axial_L3.8mm_D2.6mm_P7.50mm_Horizontal
C3 C4	2	1u	Capacitor_THT:C_Rect_L7.5mm_W6.5mm_P5.00mm
D1	1	DIODE	Diode_THT:D_DO-35_SOD27_P7.62mm_Horizontal
D2	1	LED	Connector_PinHeader_2.00mm:PinHeader_1x02_P2.00mm_Vertical
H1 H2 H3 H4	4	MountingHole	MountingHole:MountingHole_2.5mm
Q1	1	2N2219	Package_TO_SOT_THT:TO-92
R3 R5	2	330	Resistor_THT:R_Axial_DIN0204_L3.6mm_D1.6mm_P7.62mm_Horizontal
R4	1	68k	Resistor_THT:R_Axial_DIN0204_L3.6mm_D1.6mm_P7.62mm_Horizontal
R6	1	100	Resistor_THT:R_Axial_DIN0204_L3.6mm_D1.6mm_P7.62mm_Horizontal
RV1	1	20k-Pot	Connector_PinHeader_2.00mm:PinHeader_1x03_P2.00mm_Vertical
SW1	1	SW_SPST	Connector_PinHeader_2.00mm:PinHeader_1x02_P2.00mm_Vertical
SW2	1	SW_SPDT	Connector_PinHeader_2.00mm:PinHeader_1x03_P2.00mm_Vertical
U1	1	L7805	Package_TO_SOT_THT:TO-220-3_Vertical
U2 U3	2	LM555xM	Package_DIP:DIP-8_W7.62mm_Socket
U4	1	74LS08	Package_DIP:DIP-14_W7.62mm_Socket

The PCB board was created with trace widths of 20 mils and clearances of 32 mils. The final PCB board may be observed in Figure 19.

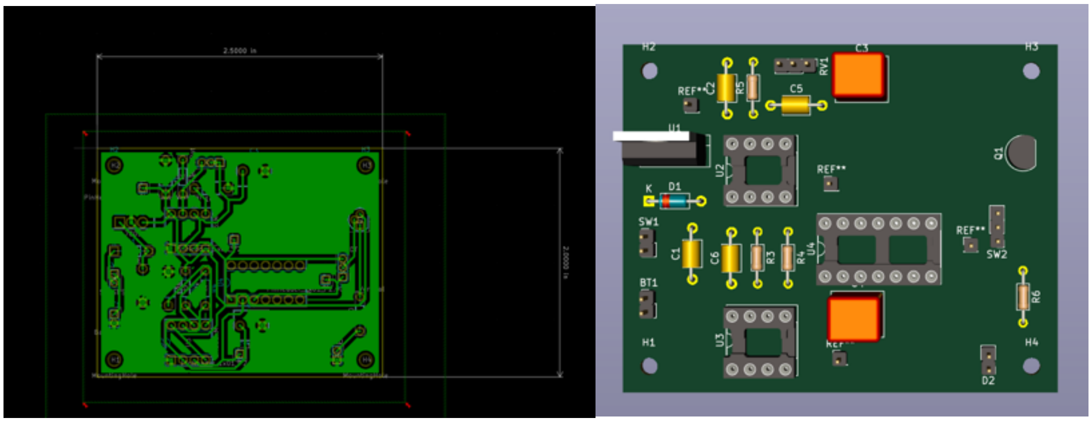


Figure 19. Final PCB Design

The milled PCB without added circuitry may be observed in Figure 20. A multimeter was implemented to identify shorts, and a blade was used to separated shorted traces. There were no key differences in the manufactured PCB in the light box and the final design.

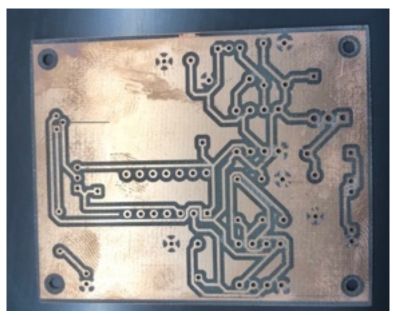


Figure 20. Final PCB without Added Components

3D Enclosure Design

The 3D enclosure was built with 3 components: a bottom, top, and battery door. These components may be observed in Appendix A. The bottom component housed the PCB as well as the battery. Holes were implemented for securing the lid to the bottom, attaching the battery door, and securing te PCB within the bottom. For the battery door and securing the PCB, steel pan head slotted screws were implemented. Two screws were used for the battery door, and four screws were used to mount each corner of the PCB. The specific screws as observed in Figure 21 were connected to the heat-set inserts as also depicted in Figure 21.

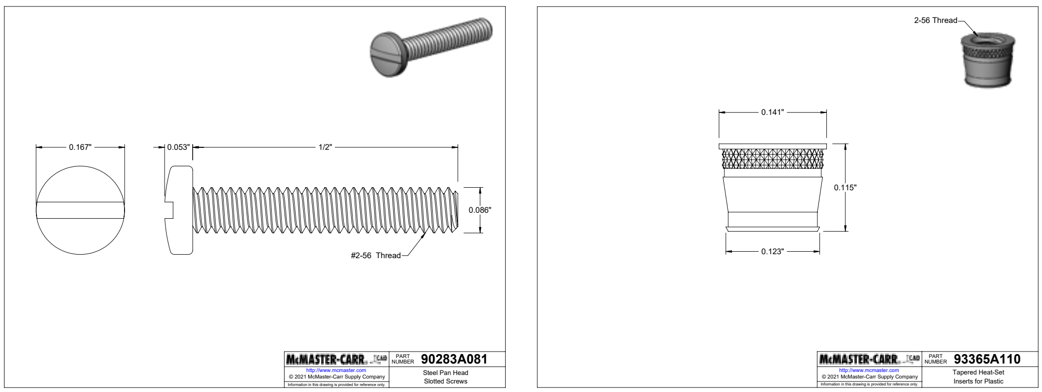


Figure 21. Screw and Heat-Set Inserts to Mount PCB and Secure Battery Door

To connect the lid to the bottom of the light box, Phillips pan head steel screws were implemented with heat-set inserts as depicted in Figure 22 .

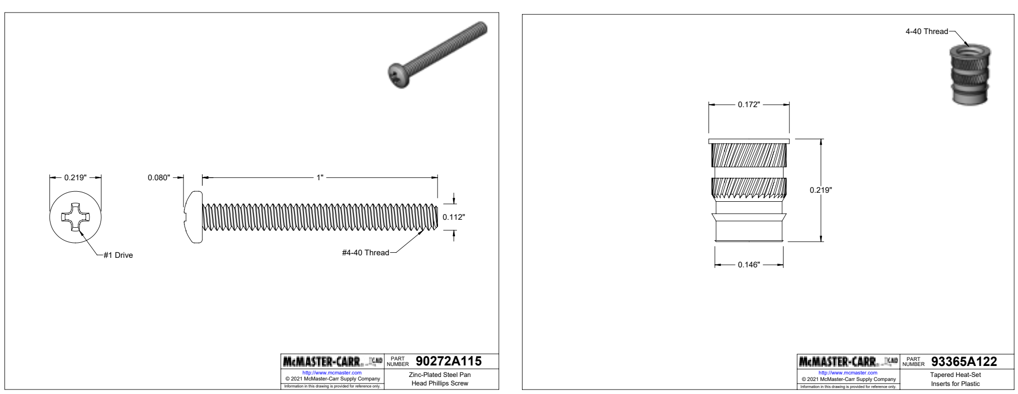


Figure 22. Screw and Heat-Set Inserts to Mount the Lid to the Bottom

Multiple print iterations were conducted to adjust the ratio of each component as the 3D printers demonstrated mild imprecision. Additionally, the enclosure was sanded slightly to remove sharp edges and to allow for a slightly looser PCB design. The top featured holes for the LED, potentiometer, and both switches to protrude for user interaction. There are supporting brackets for the LED and potentiometer to sit in the light box more securely. In the final iteration of the enclosure, the support beam beneath the potentiometer as part of the lid broke multiple times despite attempts to super glue the PLA back onto the lid. The cumulative key differences between the final CAD design and the manufactured light box were the absence of the potentiometer support beam and a combination of filing and sanding of the hole in the lid for the potentiometer to ensure the component could fit.

Final Product Testing

Detailed testing was performed with statistical analyses to determine whether the final circuit, PCB, and enclosure design met the design constraints in Table 1.

On/Off Switch

First, to ensure the light box could be turned on and off with a switch, a visual analysis was performed. 10 trials were conducted of turning on the switch to observe the LED illuminate. The ideal result would be a "yes" confirmation of the LED illuminating. All 10 trials resulted in "yes" results.

Additionally, the voltage across the LED was measured in 10 trials to determine if there existed a significant difference between the LED voltage during the on and off states. Furthermore, the ideal voltage during the off and on states were $< 0.1 \pm 0.1$ V and $> 1.0 \pm 0.1$ V respectively. Table 3 depicts the results of the on and off voltages across the LED using a multimeter as observed in Figure 23. Two one-tailed t-tests were performed to determine if the on or off voltages were statistically lower or greater than the ideal values, depicting the voltages are within the desire ranges. The t-tests for the on and off voltage comparisons to ideal quantities resulted in p-values of < 0.01 and < 0.01 respectively. Therefore, the on/off switch modulated the voltage across the LED to be within the ideal ranges for both the on and off states. A two-tailed t-test was implemented to determine if there was statistical significance between the voltage across the LED in the on and off state. This test resulted in a p-value < 0.01, supporting the ideal result of there being a significant difference between the on and off voltage states across the LED. Additionally, the voltage for the on and off states align with the ideal values with 95% confidence. Similarly, the 95% confidence intervals for. Both voltage states do not overlap, supporting the voltages during both states as different.

Table 3. LED Voltage Quantities in On and Off States

Trial	Voltage Across ON LED (V)	Voltage Across OFF LED (V)
1	1.572	0.0024
2	1.571	0.0021
3	1.564	0.0021
4	1.573	0.0022
5	1.573	0.0023
6	1.572	0.0021
7	1.569	0.0021
8	1.574	0.002
9	1.572	0.0022
10	1.575	0.0023
Avg ± Std	1.571 ± 0.0029	0.0022 ± 0.00012
Avg ± 95% CI	1.571 ± 0.0018	0.0022 ± 0.000072

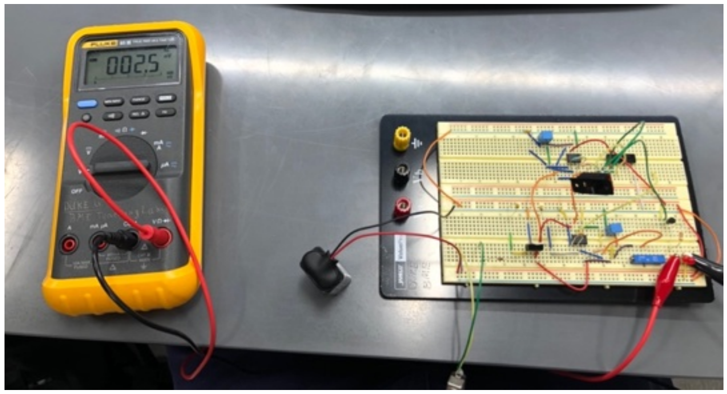


Figure 23. Multimeter Measurement of LED Voltage

Battery Replaceable

To replace the battery, two screw must be removed from the battery door with a flat head screwdriver. Then the battery must be removed, and the battery pulled out. A new battery should be attached to the battery socket before screwing the battery door back into place. Ideally, the time to replace te battery should be less than 5 (300 seconds) minutes ± 10 seconds. A video example of a battery replacement may be observed on the corresponding online portfolio. Nonetheless, images during the battery removal are illustrated in Figure 24.

Figure 24. Battery Removal Process

Table 4 depicts the results of 10 battery removal trials. A one-sample t-test demonstrated the battery removal time was significantly lower than the ideal value of 300 seconds with a p value of < 0.01. Additionally, the battery removal time is proved to be within the ideal range with 95 % confidence. Therefore, the design constraint was met.

Table 4. Battery Replacement Time

Trial	Battery Replacement Time (s)
1	145
2	202
3	123
4	131
5	97
6	118
7	104
8	128
9	113
10	73
Avg ± Std	123 ± 34
Avg ± 95% CI	123 ± 21

Battery Life

To quantify the battery life of the circuit. The circuit draw required by the circuit was measured by the function generator as a 9V supply was provided to the circuit. Provided the 9V battery is a 550 mAh battery, the maximum bound of the battery life may be identified by 550 mAh divided by the current draw. The current draw was taken during the continuous mode as the theoretical current required during this mode would be greater to accommodate continuous illumination of the LED. This was confirmed in Table 5, which features the current draw during the continuous and blinking modes and the calculated battery life of the circuit. A one-tailed t-test was implemented to identify if the maximum battery life was statistically greater than the ideal value of > 4 hours ± 10 minutes. The p-value of < 0.01 indicates the maximum battery life of the circuit meets the design constraint. Additionally, the battery lifetime during the continuous mode was proven to meet the ideal design constraint with 95% confidence. However, as the battery is used, the voltage supply with decrease from 9V until the battery reaches a threshold where it is essentially dead. This is due to the voltage decreasing below the point where the voltage regulator will register a source. Therefore, the 550 mAh is the upper bound of the current able to be supplied by the battery. Nonetheless, the battery life is predicted to be double the ideal battery life with 95% confidence; therefore, the design constraint was met. Figure 25 depicts an example current reading from the function generator.

Table 5. Current Draw and Maximum Battery Life of Circuit

Trials	Current Drawn Continuous (A)	Battery Life (h)	Current Drawn Blink (A)
1	0.065	8.5	0.04
2	0.059	9.3	0.038
3	0.061	9.0	0.039
4	0.066	8.3	0.045
5	0.063	8.7	0.039
6	0.067	8.2	0.038
7	0.058	9.5	0.043
8	0.065	8.5	0.038
9	0.059	9.3	0.045
10	0.065	8.5	0.042
Avg ± Std	0.063 ± 0.003	8.8 ± 0.5	0.041 ± 0.003
Avg ± 95% CI	0.063 ± 0.002	8.8 ± 0.2	0.041 ± 0.002

Figure 25. Function Generator Current Draw

<u>3 Components with Largest Power Drain</u>

The three components that consumed the most power in the circuit were identified with a combination of theoretical knowledge and circuit analysis. With a fully charged battery, the 7805-voltage regulator will dissipate a theoretical 4V. this was identified in practice to be 3.2 V. Furthermore, the voltage across the series resistor to the LED was implemented to identify the current through te LED and resistor using Ohm's Law. Power was then calculated as P = i*V for each component. Table 6 depicts the three circuit components with the largest power consumption.

Table 6. Components with Largest Power Consumption

Component	Voltage Drop (V)	Calculated Current (A)	Power (W)
7805 Voltage Regulator	3.21	0.037	0.12
LED	1.59	0.0121	0.0193
100 Ω Resistor in Series with LED	1.21	0.0121	0.0146

Box Dimensions

The maximum length, width, and height of the light box were measured using calipers as observed in Figure 26. Table 7 illustrates ten trials for each measurement. Three separate on-sample t-tests indicated the measurements were significantly lower than the ideal value of 3 inches with p-values of < 0.01. Additionally, the measurements were proven to be less than 3 inches with 95% confidence.

Table 7. Measurements of Light Box Enclosure

Trial	Length	Width	Height
1	2.98	2.98	2.98
2	2.98	2.98	2.98
3	2.97	2.98	2.98
4	2.98	2.98	2.98
5	2.98	2.97	2.98
6	2.98	2.98	2.98
7	2.98	2.98	2.98
8	2.98	2.98	2.98
9	2.98	2.98	2.99
10	2.98	2.98	2.98
Avg ± Std	2.98 ± 0.003	2.98 ± 0.003	2.98 ± 0.003
Avg ± 95% CI	2.98 ± 0.002	2.98 ± 0.002	2.98 ± 0.002

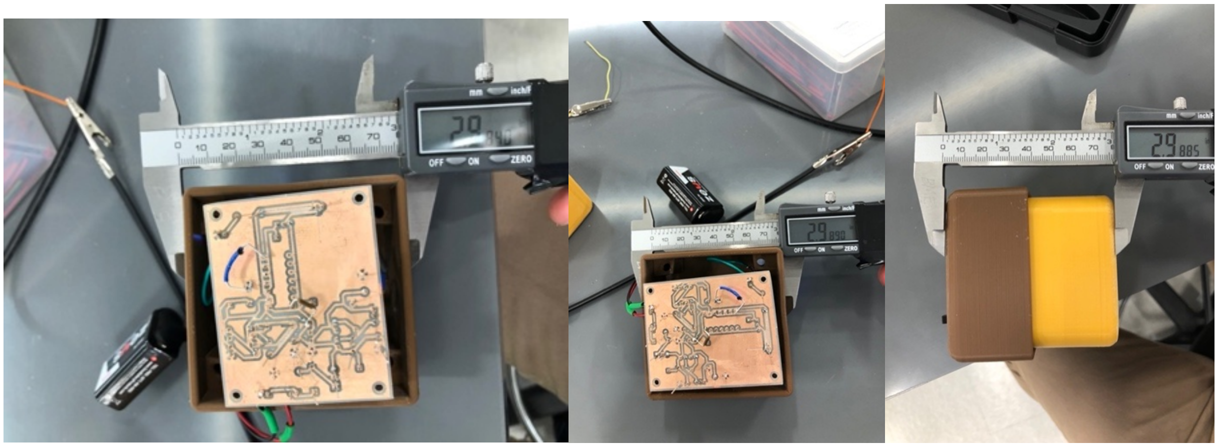


Figure 26 Measurements of Light Box

<u>Box Weight</u>

The light box was weighed once completed as observed in Figure 27.

Figure 27. Completed Lightbox Weight

Table 8 depicts ten trials of weighing the light box. A one-sample t-test proved the light box weighed was significantly lower than the ideal weight limit of 0.5 ± 0.05 lbs with a p-value of < 0.01. Additionally, the weight of the light box was proven to be below the ideal value with 95% confidence.

Table 8. Light Box Weight

Trial	Light Box Weight (lbs)
1	0.436
2	0.435
3	0.436
4	0.438
5	0.435
6	0.429
7	0.432
8	0.433
9	0.435
10	0.436
Avg ± Std	0.435 ± 0.003
Avg ± 95% CI	0.435 ± 0.002

Sealed Enclosure

The light box was proven to be sealed through visual analysis as observed in Figure 1. Components on the top of the lid were superglued to prevent hazardous movement. This supergluing acted as a form of sealant by reducing the openings in the lid. Additionally, no parts became loose, and the functionality of the light box was not compromised after shaking the box for 10 seconds.

Single-Sided PCB

The PCB was proven to be single sided by visual analysis.

3 ft Drop Test

A drop test was performed ten times at 3 ft. There functionality of the box was not compromised after any test. Additionally, the PLA enclosure did not sustain catastrophic failure after the drop tests.

Total Cost

Price estimations were made based on online market prices as of 10/28/2021 for circuit components. Table 9 lists the final components and corresponding prices for the light box. Prices are estimated as the primary objective of the price limit was to prevent using a microcontroller.

Table 9. Estimated Prices of Components

Part	Quantity	Price per Item	Price
PCB	1	10	10
9V	1	4	4
Switch	2	0.67	1.34
Resistors	4	0.1	0.4
Capacitors	5	0.1	0.5
Diode	1	0.1	0.1
LED	1	0.5	0.5
Potentiometer	1	1	1
BJT Transistor	1	0.5	0.5
3D Print PLA		1	1
		Total Cost	19.34

Powered by 9V, Voltage Regulated, Reverse-Polarity Protected

The 9V battery output confirmation may be observed in Figure 15. Similarly, the 5V output from the voltage regulator is illustrated by an oscilloscope in Figure 15. Booth of these values were identified by measuring the voltage output from the battery as well as the output from the 7805-voltage regulator with an oscilloscope. To confirm the diode in series with the 9V battery provides reverse-polarity protection, the battery was connected with a reversed polarity. Figure 28 and Figure 29 demonstrate the LED not turning on with the reverse battery.

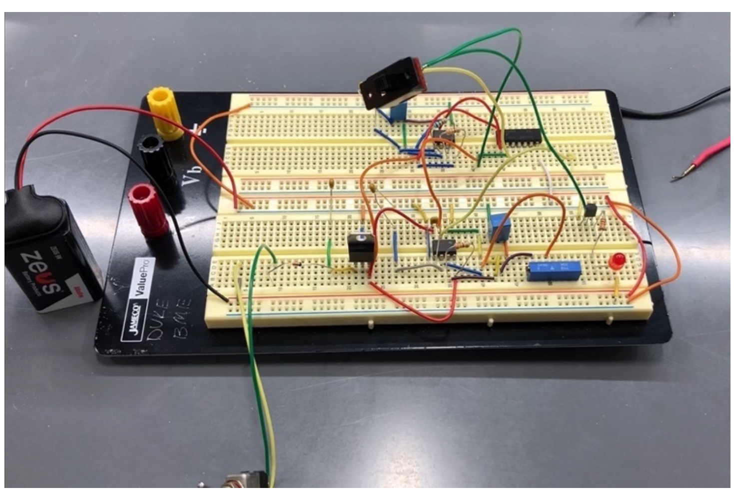


Figure 28. LED Output with Reverse 9V Battery Polarity

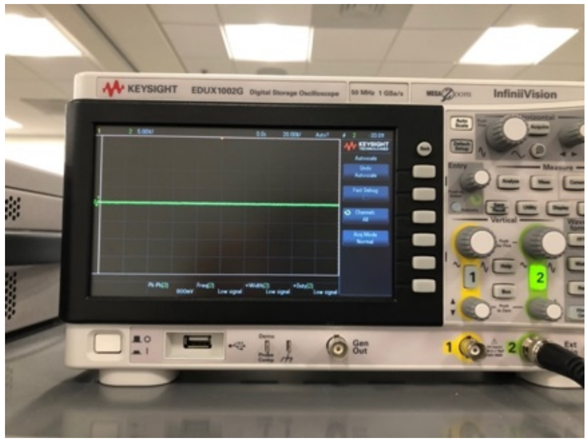


Figure 29. Voltage Across LED with Reversed Battery Polarity

<u>Safety</u>

To ensure the light box is safe, the box features filets as was filed after fabrication, reducing rough edges from the 3D print. Visual and tactile inspection proved there to be no sharp corners or edges. Furthermore, the final light box was inspected for protruding wires, solder, or electrical components to ensure there is no shock hazard. Additional visual inspection proved there to not be any hazardous potential contact between the hardware and the PCB as the hardware was surrounded by PLA. Heat shrink was implemented for components not fixed to the PCB to reduce exposed circuit connections as depicted in Figure 30.

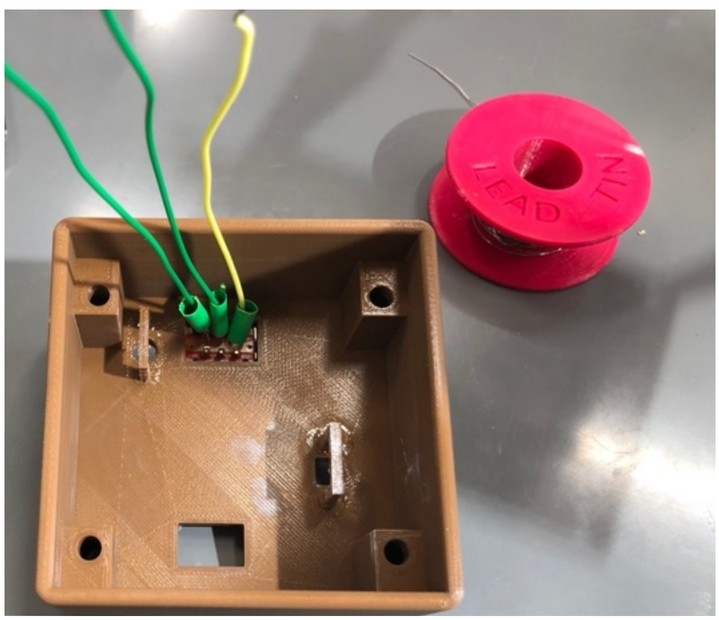


Figure 30. Example of Heat Shrink Implementation around Solder Connections

Switch between Continuous and Blinking Mode

The switch to change the LED mode between the continuous and blinking modes was analyzed visually. Similar to the on/off switch, a “yes” indicated the LED changed modes immediately upon changing the switch configuration. After ten trials, all instances resulted in “yes: ratings for the functionality of the switch, thus, achieving the ideal performance of the switch.

10 Hz (50 % DC) Blinking Mode

Duty Cycle was measured automatically on the oscilloscope. Similarly, the oscilloscope displayed the period of the square wave for the blinking mode. This period was inverted to frequency. The oscilloscope output may be observed in Figure 31. Additionally, Table 10, Displays the measured period, calculated frequency, and measured duty cycle of the blinking waveform.

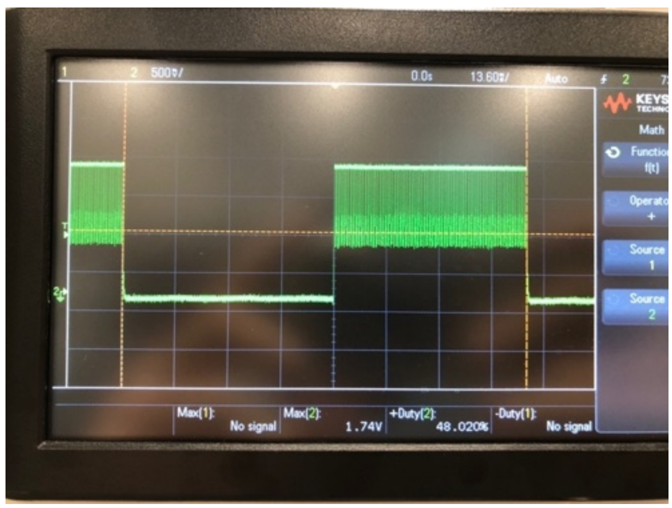


Figure 31. Example Oscilloscope Duty Cycle Output

Table 10. Blink Waveform Characteristics

Trial	Period (ms)	Frequency (Hz)	DC (%)
1	104.7	9.55	48.08
2	104.7	9.55	48.09
3	106.0	9.43	48.07
4	104.7	9.55	48.08
5	106.0	9.43	48.08
6	103.3	9.67	48.08
7	104.7	9.55	48.07
8	104.7	9.55	48.02
9	104.7	9.55	48.09
10	103.3	9.67	48.08
Avg ± Std	104.7 ± 0.90	9.55 ± 0.08	48.07 ± 0.02
Avg ± 95% CI	104.7 ± 0.56	9.55 ± 0.05	48.07 ± 0.01

Provided an ideal frequency of 10 ± 0.5 Hz and an ideal duty cycle of 50 ± 2%, one-sample t-tests were performed to compare the collected data with the ideal metrics. The t-test for frequency featured a p-value of 0.06 for a one-tailed comparison to the lower bound of 9.5. This indicates the null that mean frequency is not significantly below the lower end of the ideal frequency threshold maintained. Therefore, the performance specification is met. Furthermore, a one-tailed t-test compared the duty cycle data to the lower bound of 48%. The resultant p-value was 0.185 indicating the null that the mean of the duty cycle measurements is not significantly lower than the bottom threshold of the ideal duty cycle is maintained. Furthermore, the frequency and duty cycle of the LED blink were proven to be within the acceptable marginal value range with 95% confidence.

Rotary Knob to Linearly Modulate Brightness to Off

To test if the rotary knob potentiometer modulates the brightness of the LED linearly, the total time of high voltage signal in the square waveform voltage within a 5 second interval was calculated for multiple resistance values. Since current through the LED and thus brightness are approximately directly correlated to the voltage across the LED, a linear increase in the time in which the voltage is a high state would result in an approximately linear increase in brightness. The total time off a high voltage state in five second was measured by first identifying the period of the waveform as observed in Figure 32. Then, by identifying the quantity of periods in 5 seconds and percentage of each period in which the signal is in a high voltage state, the total time of which the LED is on in 5 seconds may be identified as portrayed in Table 11.

Table 11. Calculation Results for Total High State Voltage in 5 Seconds

Resistance (kΩ)	Duty Cycle (%)	Frequency (kHz)	Total # of Periods	Time On per 1 Period (s)	Total Time On per 5 seconds (s)
0.004	77.39	3.36	16800	0.000230	3.86
0.785	59.36	581.23	2906150	1.02E-06	2.96
1.423	57.77	388.9	1944500	1.48E-06	2.88
2.992	57.76	238.84	1194200	2.41E-06	2.88
4.93	50.175	133.53	667650	3.75E-06	2.50
7.06	49.58	95.1	475500	5.21E-06	2.47
9.53	49.22	70.81	354050	6.95E-06	2.46
11.85	48.99	57.14	285700	8.57E-06	2.44
13.2	48.83	51.46	257300	9.48E-06	2.44
14.98	48.78	45.23	226150	1.07E-05	2.43
16.34	48.7	41.65	208250	1.16E-05	2.43
18.09	48.65	37.54	187700	1.29E-05	2.43
19.28	48.54	35.27	176350	1.37E-05	2.42

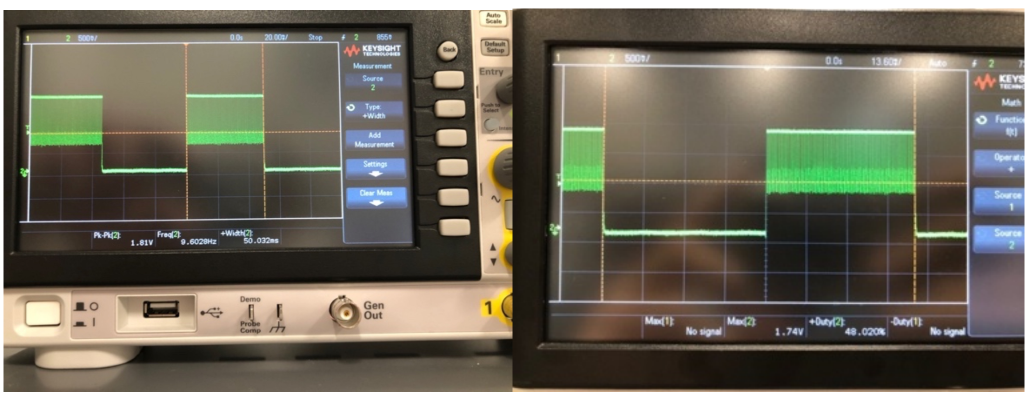


Figure 32. Example Duty Cycle and Frequency Measurements by Oscilloscope

A linear regression with a correlation coefficient absolute value greater than 0.9 and $r^2 > 0.9$ would indicate there is high confidence in a relatively large linear correlation to support the potentiometer linearly modulates the brightness. A linear regression between resistance of the potentiometer and the total high state time in a 5 second window demonstrated an r value of 0.72 with an r^2 of 0.52. This indicates there is poor confidence in the linearity of the relationship between resistance and LED brightness. Figure 33 illustrates the tested relationship to identify linearity between the adjustment of the rotary knob and the brightness of the LED.

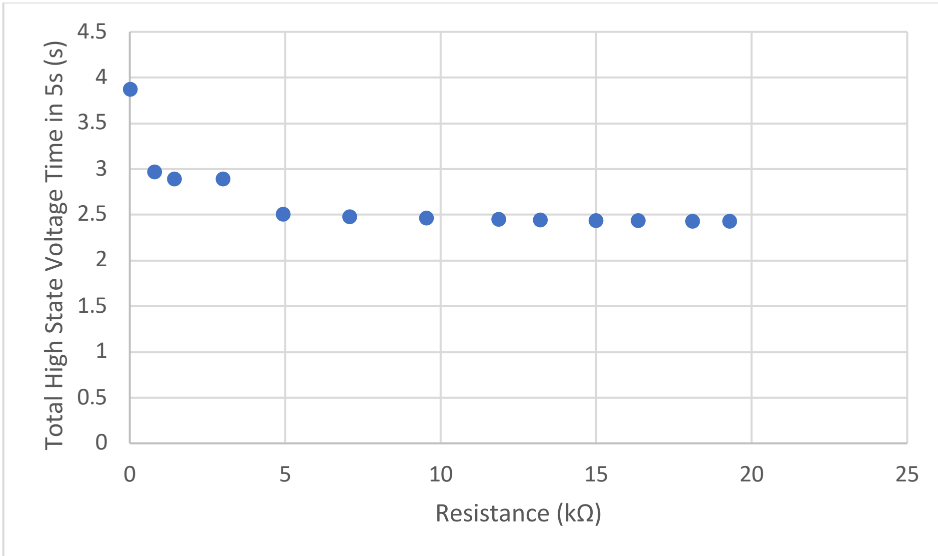


Figure 33. Relationship to Identify Linearity of Brightness Modulation

When creating the circuit, the LED was visually tested to observe if the LED went to a completely off state. This test failed as mentioned in the breadboarding section above. The configuration of the 555-timer prevented reaching a duty cycle below 50 %, which without a NOT gate would not theoretically allow for full dimming of the LED.

Max Brightness between Modes

To quantify the maximum brightness of the blinking mode, the area under a single high state of the oscilloscope voltage waveform was calculated from oscilloscope measurements depicted in Figure 34.

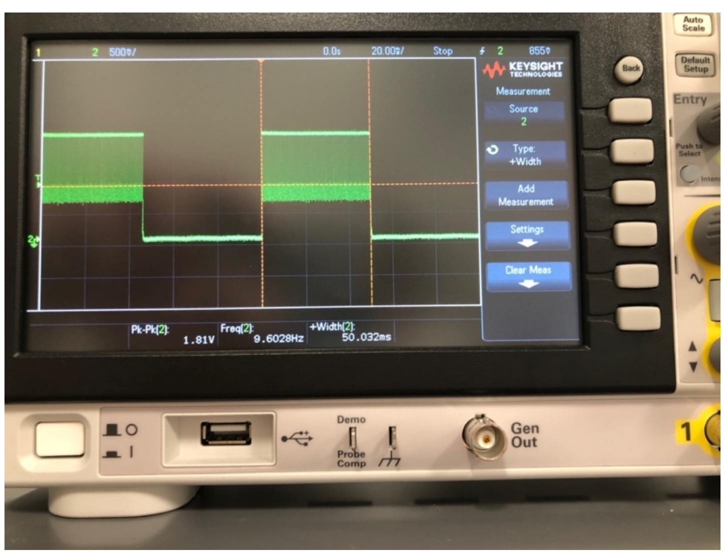


Figure 34. Oscilloscope Measurement to Calculate Area Under Voltage Waveform

This was compared to the area under the continuous voltage state for the same time window. The ideal outcome would be no statistical significance between the two sample sets to support the maximum amplitude is consistent across both modes. Table 12 depicts the calculated area for the blinking and continuous modes.

Table 12. Calculations of Area Under Voltage Waveform for Continuous and Blinking Modes

Trial	Blinking Amplitude (V)	Blinking Window (ms)	Blink Area (V•ms)	Cont Amplitude (V)	Cont Window (ms)	Cont Area (V•ms)
1	1.81	50.032	90.6	1.62	50.032	81.1
2	1.87	49.956	93.4	1.68	49.956	83.9
3	1.83	50.04	91.6	1.7	50.04	85.1
4	1.81	50.048	90.6	1.65	50.048	82.6
5	1.89	50.044	94.6	1.72	50.044	86.1
6	1.87	50.028	93.6	1.63	50.028	81.5
7	1.83	50.028	91.6	1.71	50.028	85.5
8	1.85	50.044	92.6	1.65	50.044	82.6
9	1.87	50.036	93.6	1.68	50.036	84.1
10	1.85	50.044	92.6	1.69	50.044	84.6
Avg ± Std	1.84 ± 0.02	50.03 ± 0.03	92.4 ± 1.3	1.67 ± 0.03	50.03 ± 0.03	83.7± 1.6
Avg ± 95% CI	1.84 ± 0.016	50.03 ± 0.015	92.4 ± 0.79	1.67 ± 0.019	50.03 ± 0.015	83.7 ± 1.0

A two-sampled, two-tailed t-test proved there to be a significant difference between the maximum brightness of the LED during the continuous and blinking modes with a p-value of < 0.01. This difference is difficult to discern visually as the 10 Hz blinking rate is relatively quick. Additionally, the area of the continuous mode voltage waveform is characterized by a 95 % confidence interval that does not overlap with that of the blink area. The blink modality featured a greater area under the voltage curve. Since the BJT transistor is sensitive to slightly larger currents that may result at te base from the compounded AND gate current from both 555-timer outputs, the resultant voltage amplitude across the LED was slightly larger. While the two brightnesses vary statistically, visual analysis would support the current state of the light box as sufficient as the maximum brigtnesses of the two modes appear to be equivalent.

Discussion

Successes

The final design was successful with respect to achieving the ideal blinking frequency. Furthermore, the PCB was assembled through soldering successfully.

The hole in the lid for the on/off switch worked very well as the switch fit snuggly into the hole.

Failures

There were many areas for improvement in the final design. The battery containment mechanism made it difficult to remove the battery as the battery must slide out. If this were to be redesigned, a hard-shell battery compartment could be placed at te bottom of te light box to minimize movement of wires wen replacing te battery.

The PCB should have been placed lower inside the box to have allowed for more room for wires. Furthermore, I would consider connecting the battery to the bottom of its designated pins in the PCB to prevent having to cross the wires over the PCB inside the light box.

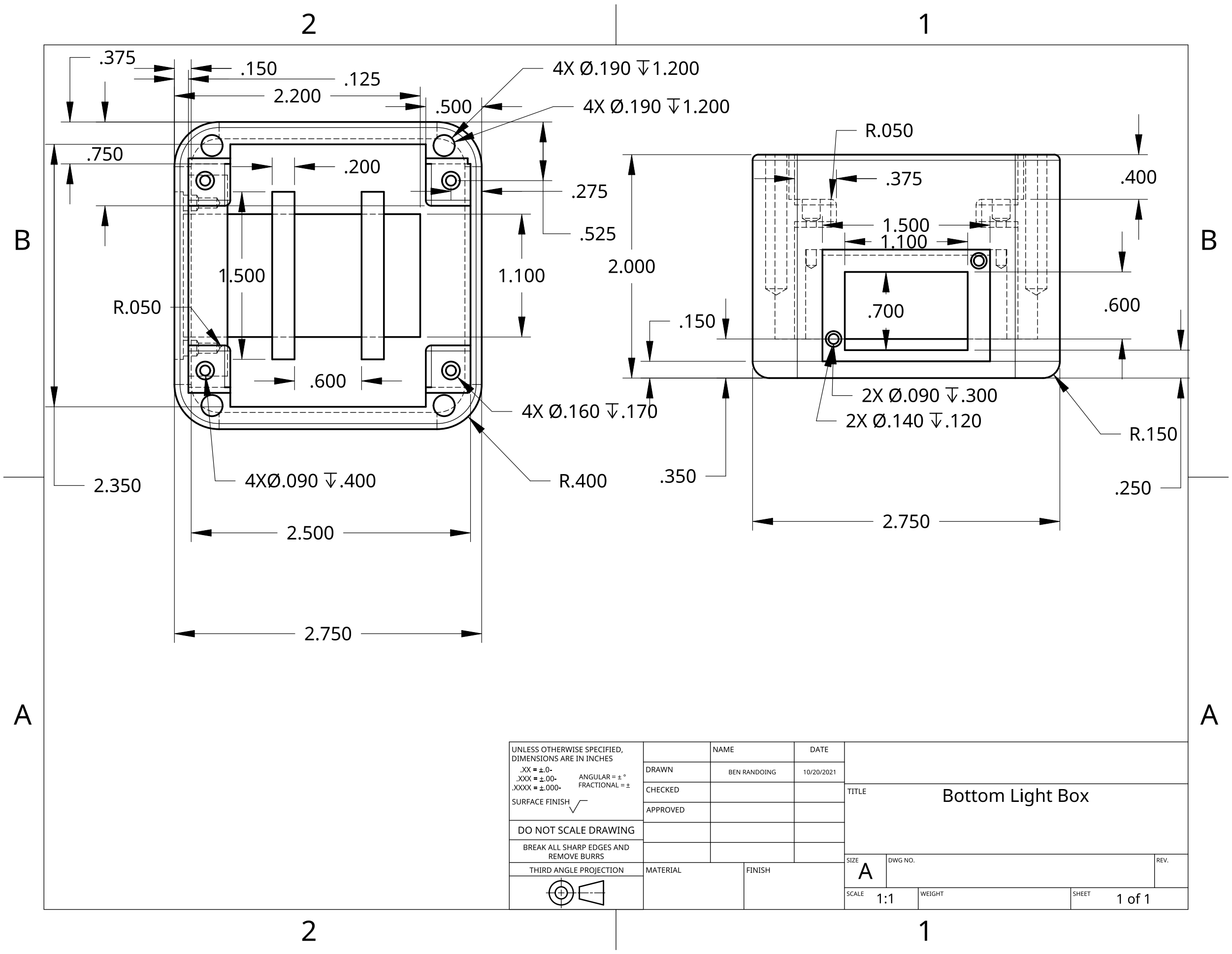
The light box lid features beams to support components. However, the final print featured these components breaking. An alternative design to support the components would be to design the lid to have a hole with a small slit as part of the hole. This ensures there is a support beam for components without having the beam move into the interior of the box where it is easy to break.

The final PCB design should have been smaller. This would have allowed for greater flexibility when making the enclosure. Similarly, I would have made the design in an unconventional way where the lid does not have to cover the bottom. This would increase the space for protective material and would allow for more room to add wires. The final design had long wires inside the box due to the supergluing of components to the lid. This faulty assembly method resulted in the PCB and lid being conjoined. Thus, it was difficult to alter the interior of the box after completion. I would consider adding male-female wires to the PCB and stringing these to the top of the light box before securing the LED and other exterior components to the box.

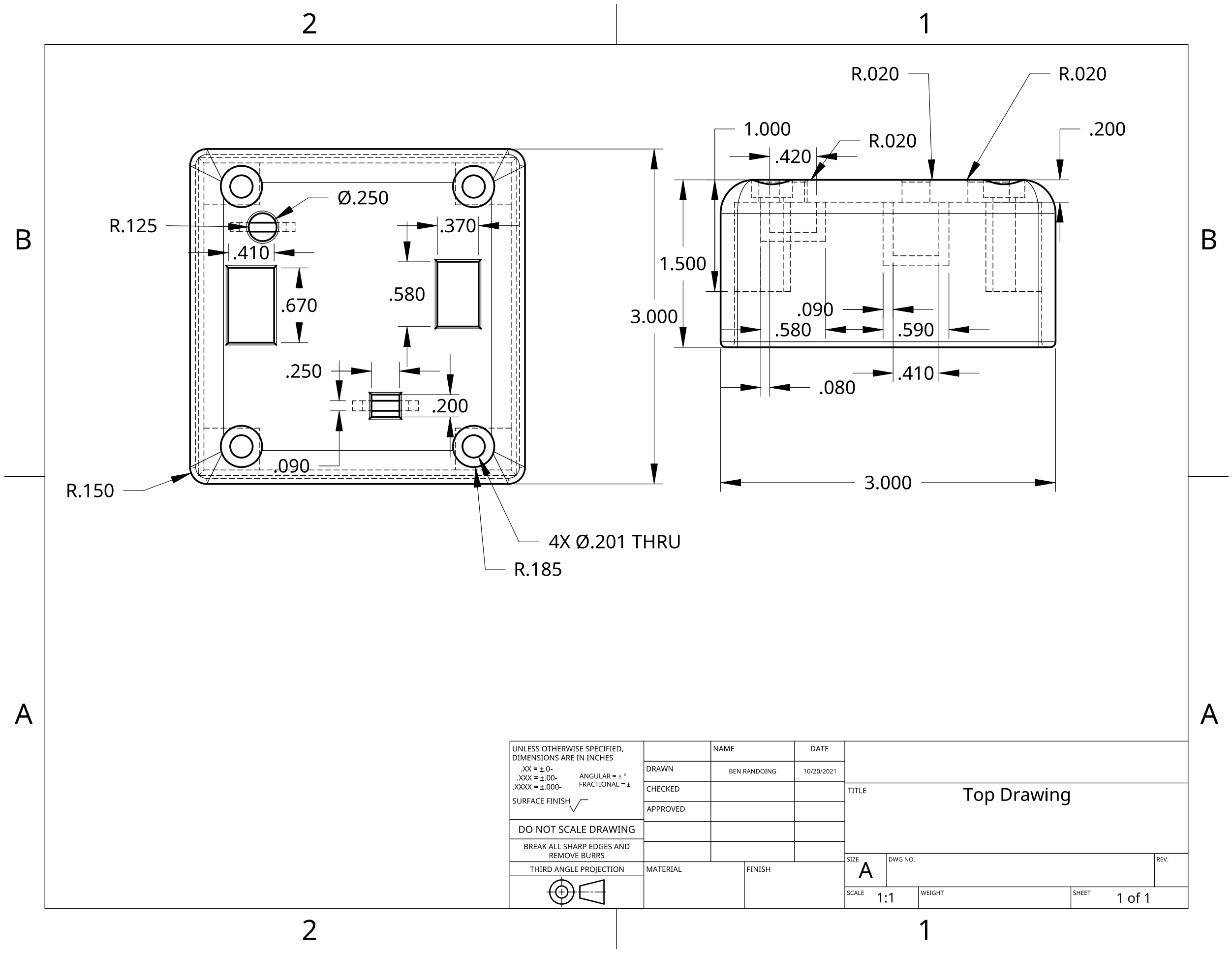
Appendix

Appendix A: Enclosure Engineering Drawings

Bottom



Lid



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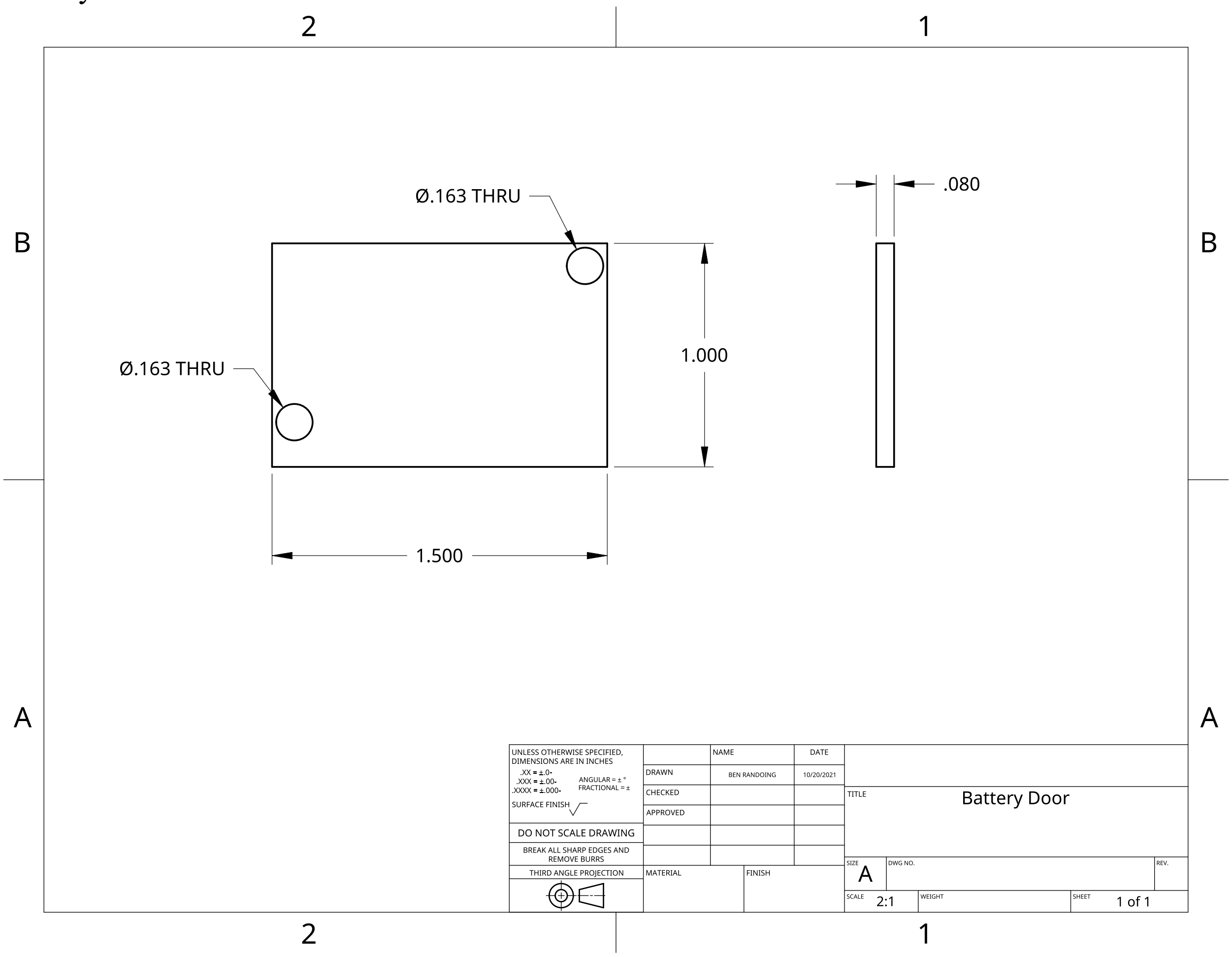
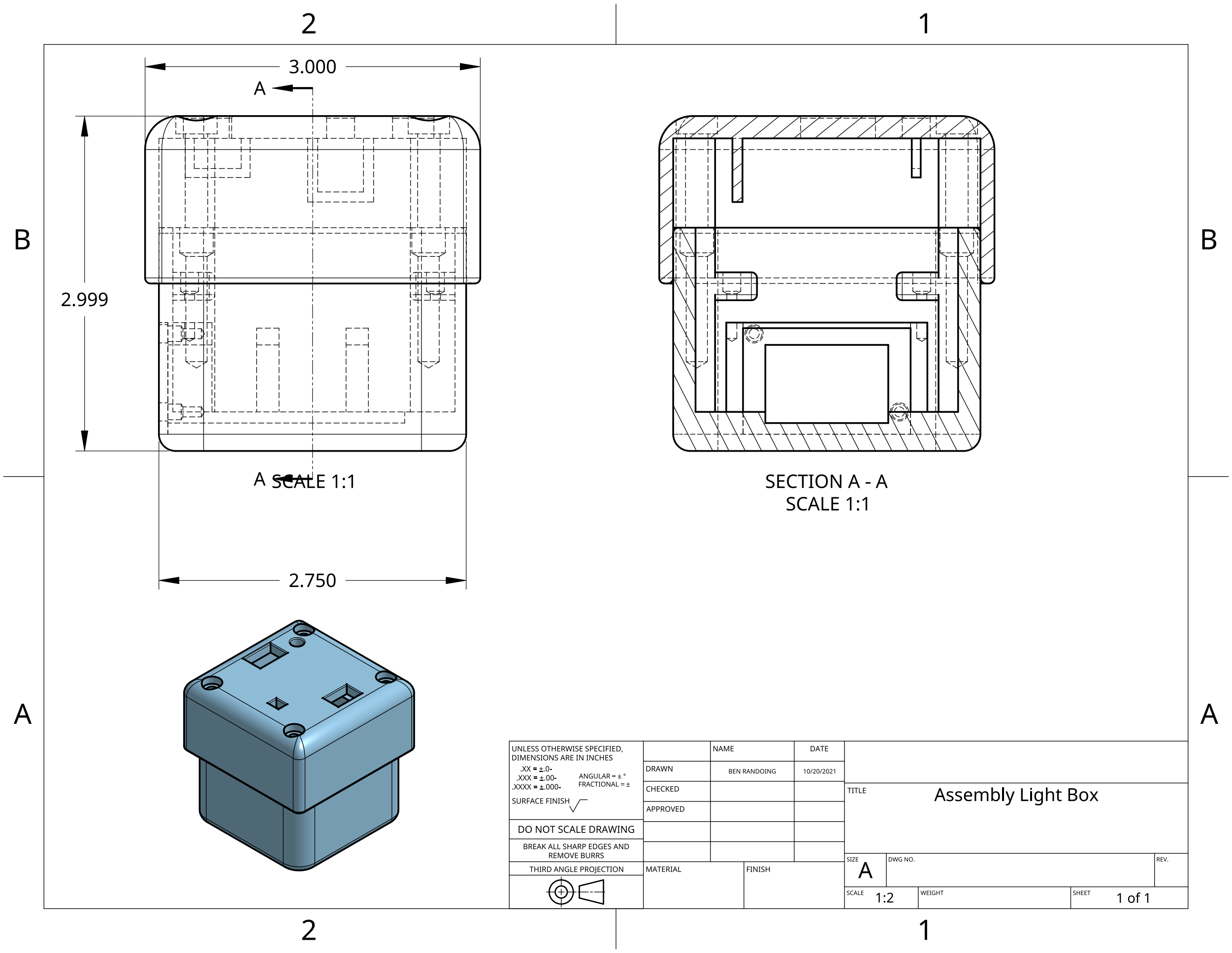
Battery Door



Assembly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