Phoebe Dijour
BME 473

Variable Light Box Design Report

This project contains:

- A light with a continuous and blinking mode, controlled by a switch
- A rotary knob to modulate brightness in both modes
- An on/off switch
- An easily replaceable battery with a life of > 4 hours
- A portable, durable, safe enclosure
- An affordable design

User Needs

Table 1a: Light Functionality

User Need	Test	Marginal Value
Switch turns device on/off	Visual identification of LED turning on and off	Yes
Rotary knob linearly modulates brightness of LED from off to maximum brightness	Measure voltage across the resistor directly before the LED at minimum and maximum brightness, since voltage is proportional to current, which is proportional to LED brightness	Min and max brightness voltages are statistically different ($p < 0.05$)
Switch to toggle from continuous to a 2Hz blinking mode (50% duty cycle)	2Hz: Count the number of blinks in 10 seconds 50% duty cycle: Use oscilloscope to measure time between timer blinks at output of DPDT	Frequency = 2Hz (±0.1Hz) Duty cycle = 50% (±3%)
Max brightness is the same in continuous and blinking modes	Measure voltage across the resistor directly preceding the LED at maximum brightness in continuous and blinking modes	Continuous and blinking voltages are statistically equivalent ($p > 0.05$)

Table 1b: Battery Design

User Need	Test	Marginal Value
Powered using voltage-regulated, 9V battery	Power circuit with 9V battery to determine	Yes
Battery is replaceable in under 5 min	Time how long it takes to remove and replace the battery	< 5 minutes (±0.2 min)
Battery life ≥ 4 hours	Measure the amount of current drawn from the battery on the power supply while the box is in the brightest continuous and blinking modes and calculate the time for 9V to run out of 500 mAh	≥ 4 hours (±0.2 hours)

Table 1c: Box Design

User Need	Test	Marginal Value
Single-sided printed circuit board	Visual identification of single-sided printed circuit board	Yes
Weight ≤ 0.5 lbs	Measure weight of circuit board on scale	≤ 0.5 lbs (±0.02 lbs)
All dimensions ≤ 3 in	Measure length, width, and height using calipers	≤ 3 in (±0.1 in)
Enclosure is "sealed" / air gaps minimized	Visual identification of enclosure sealed with no parts falling out	Yes
≤ \$20 to duplicate unit	Add the prices of all components together to determine the total price	≤ \$20 (±\$0.50)
Survive 3 ft drop	Visual identification of secure mounting of all internal components, fillet corners/edges, few protruding switches and knobs Official test by Dr. Palmeri: drop box from 3-foot height and visually identify if components remain secure	Yes
Safe	Visual identification of no protruding or sharp edges and no external components that are hot to the touch	Yes

Mechanical Drawings, 3D Renderings, and Pictures

Full Assembly

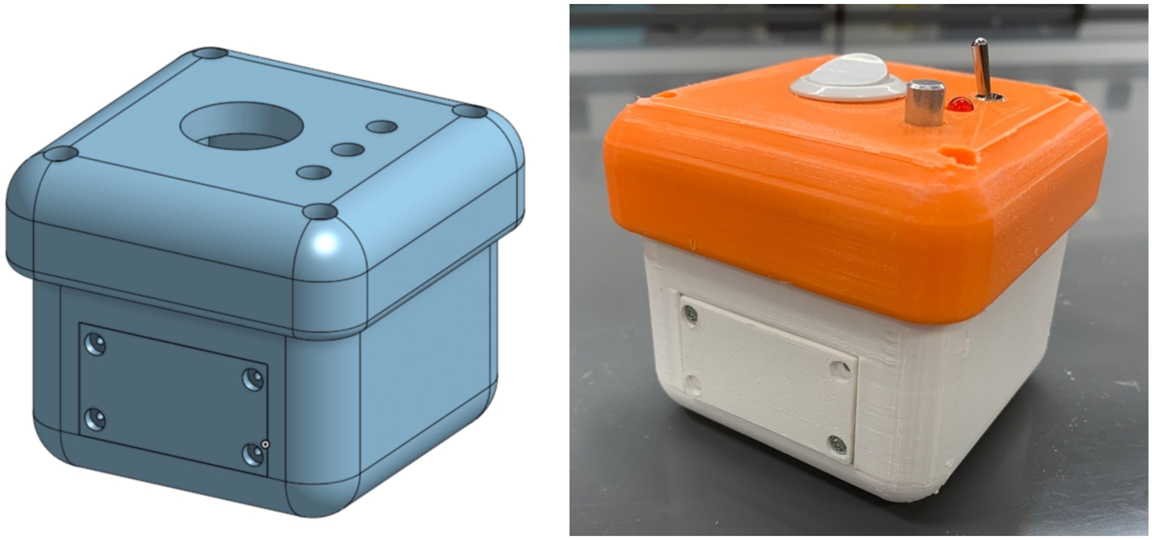

Figure 1a: CAD and real isometric views of full assembly

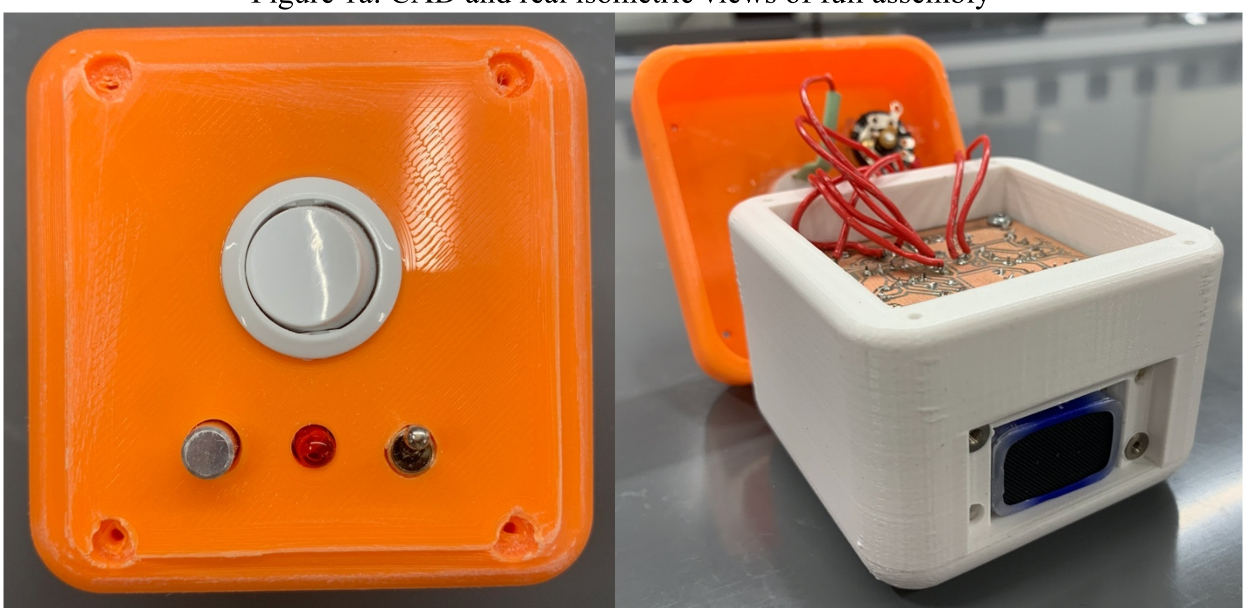

Figure 1b: Top and exploded views of full assembly

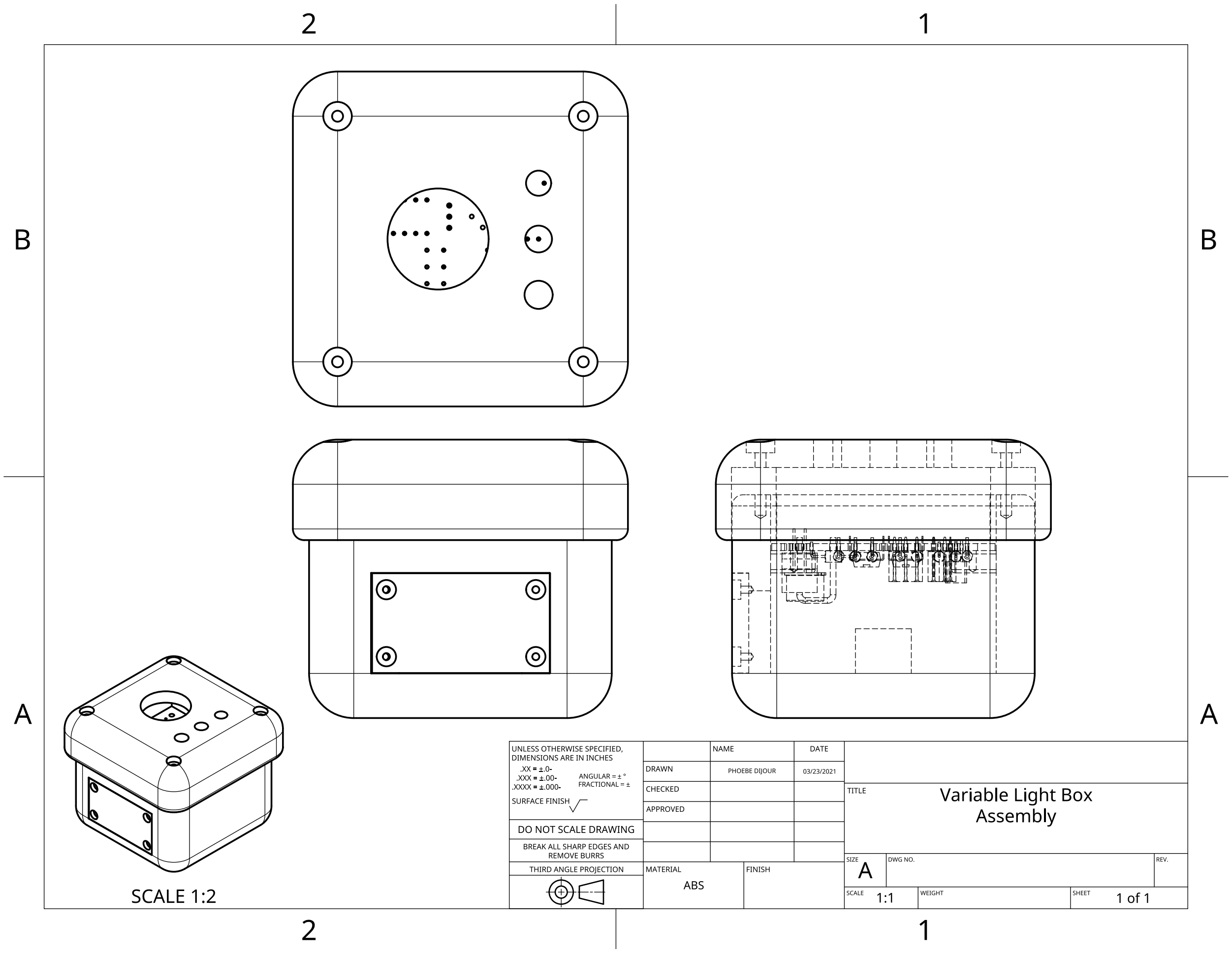

Figure 1c: Mechanical drawing of full assembly

There were several deviations in the final assembly from the CAD design. Primarily, the CAD design accounted for several screws to secure the lid to the base, with screw holes in the lid and holes for screw inserts in the base. However, these were not used in the final assembly because the lid fit snugly on the base and did not require screws to keep it in secure. Moreover, four screw holes were designed to be in the battery lid, but only two were used in the final assembly to save time while replacing the battery. Finally, the screw holes were manually increased using a hand drill to insert M2 female threads for the battery lid mounting holes and PCB mounting holes.

Base

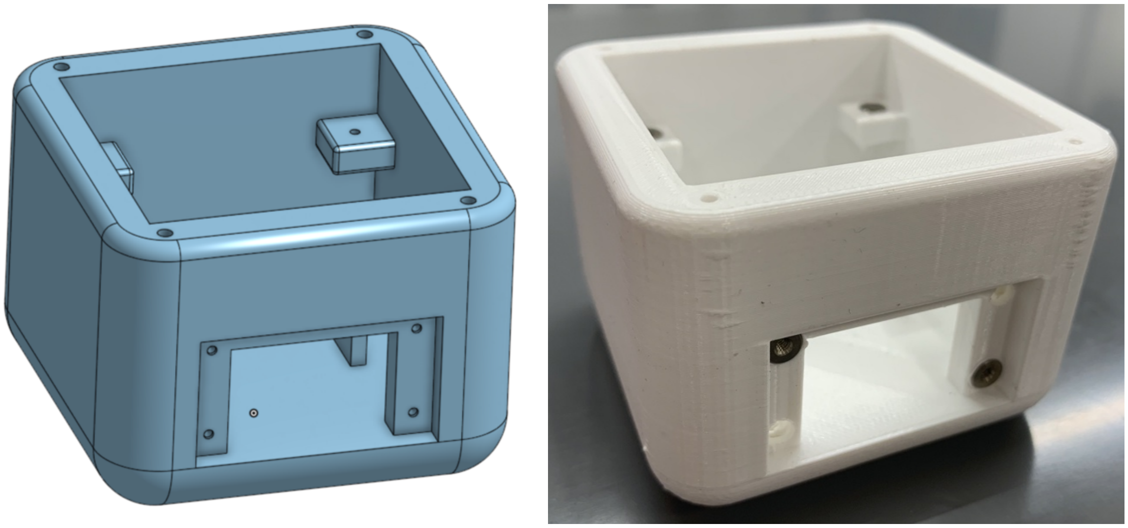

Figure 2a: CAD and real isometric views of base without lid

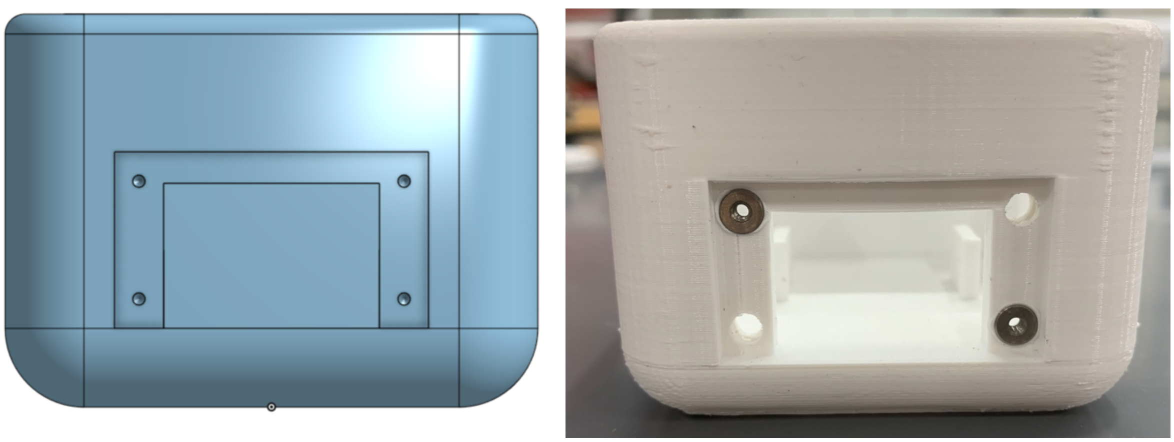

Figure 2b: CAD and real front views of base

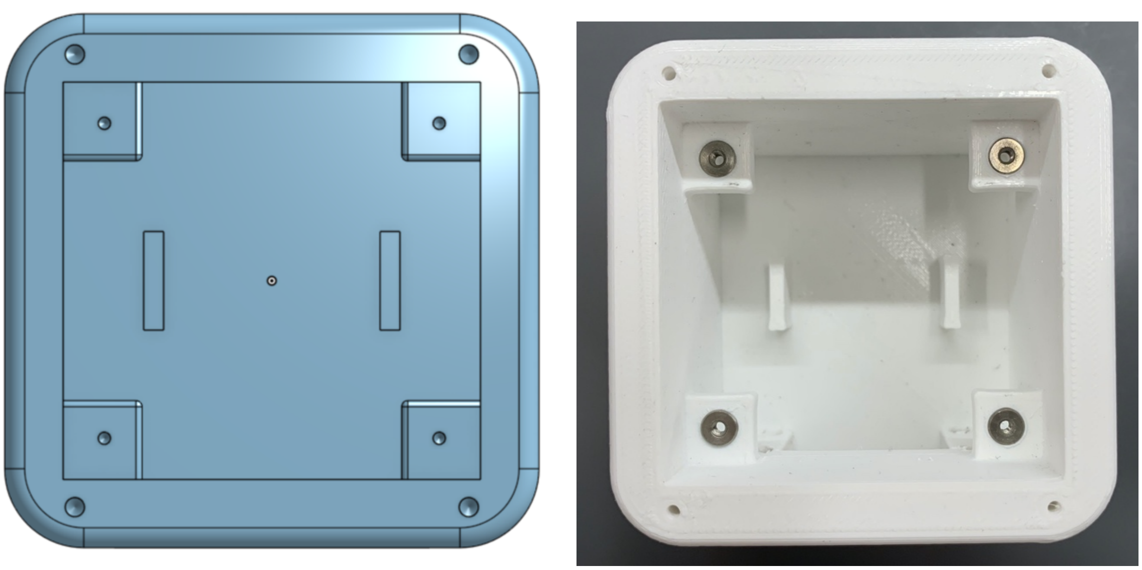

Figure 2c: CAD and real top view of base

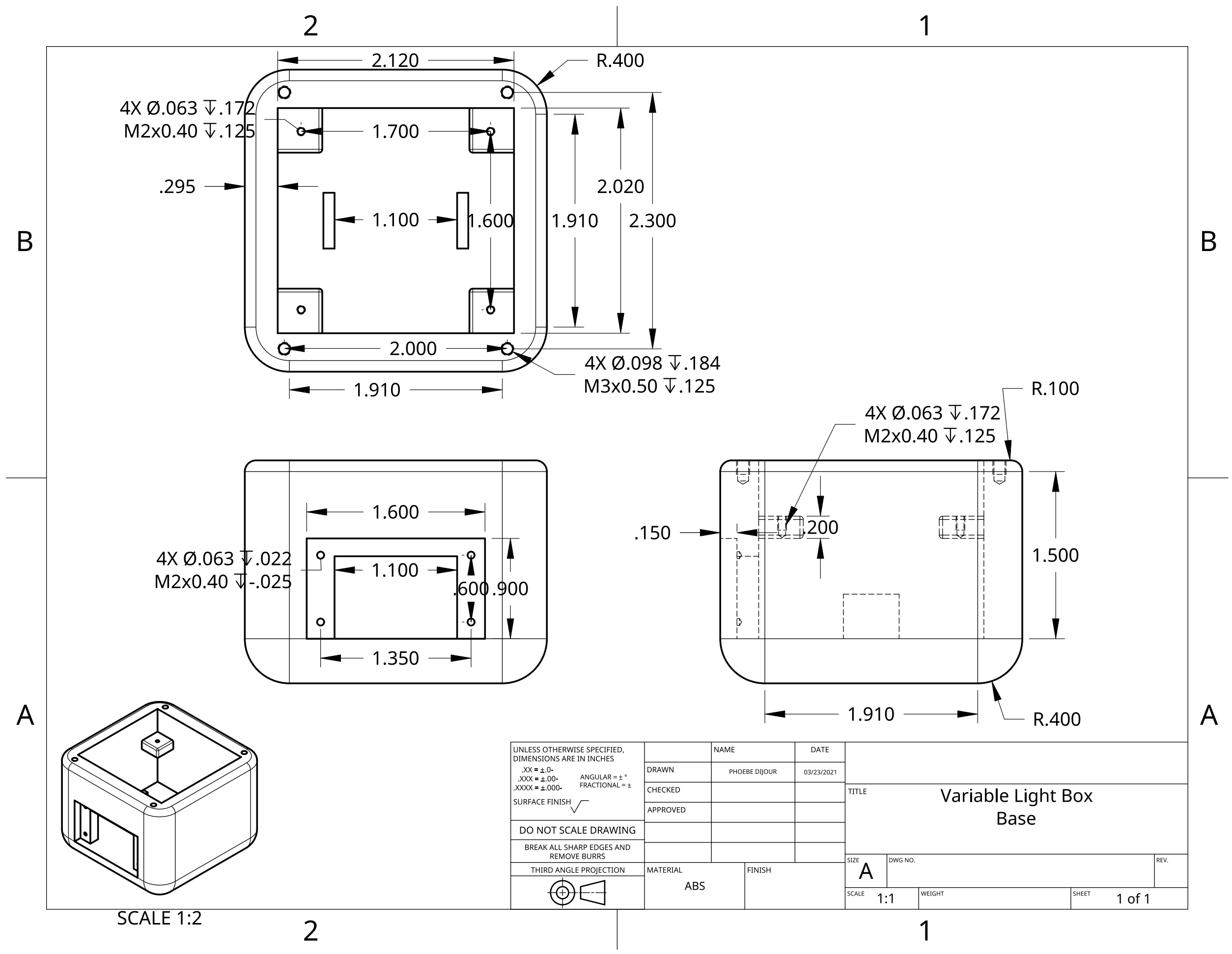

Figure 2d: Mechanical drawing of base

Lid

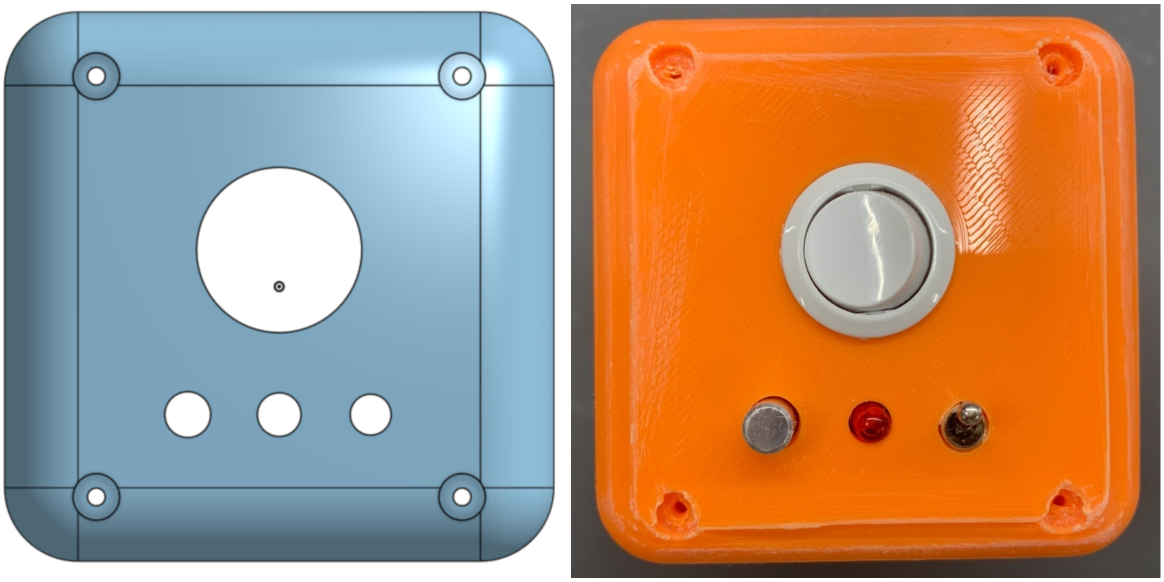

Figure 3a: CAD and real top views of lid

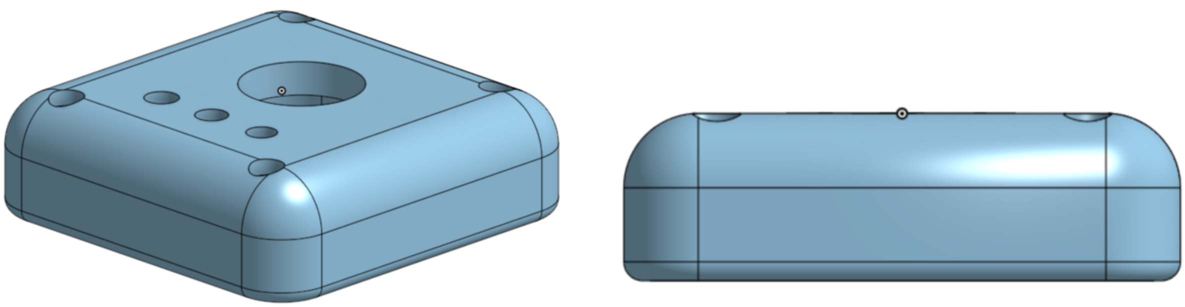

Figure 3b: CAD isometric and side views of lid

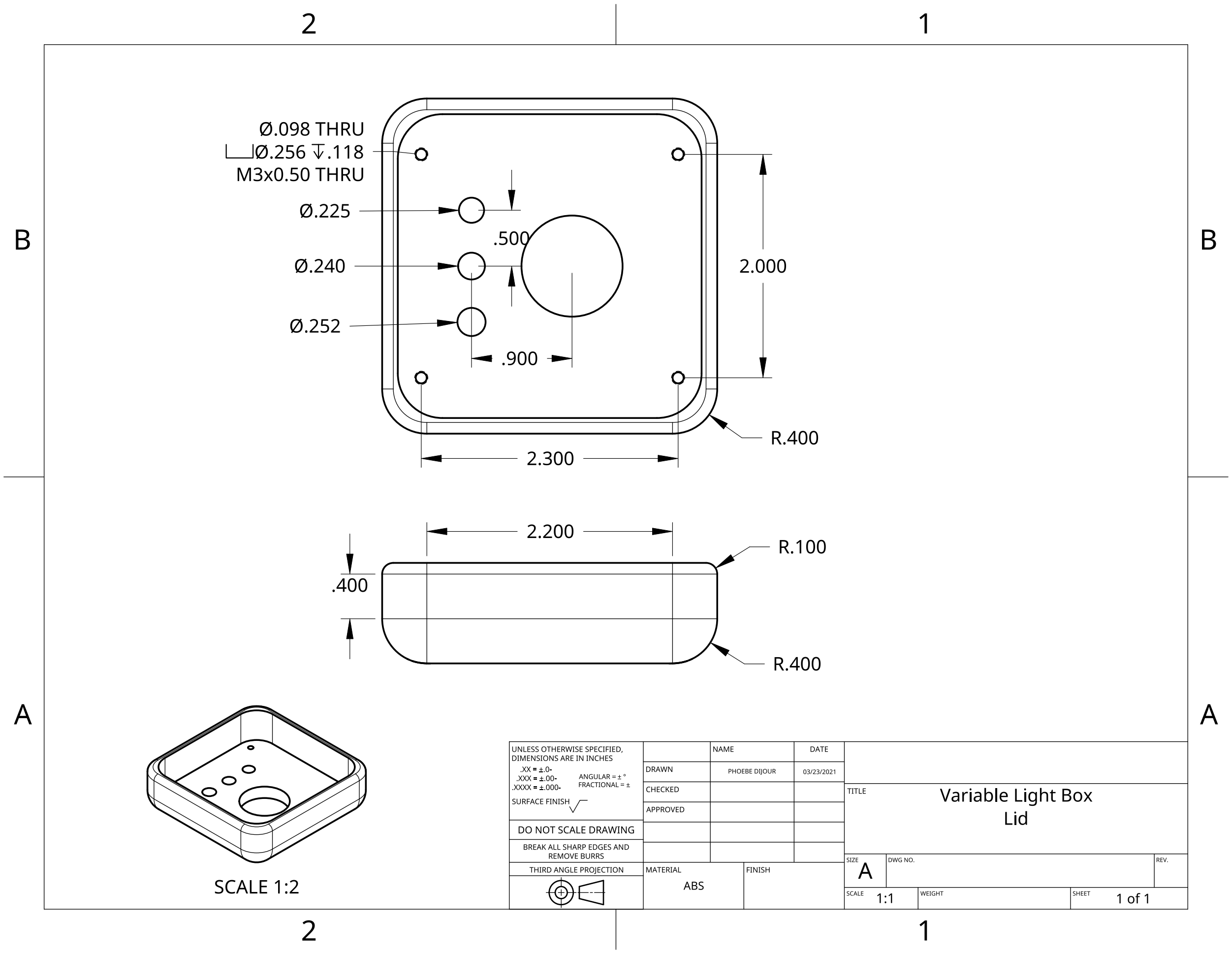

Figure 3c: Mechanical drawing of lid

Battery Lid

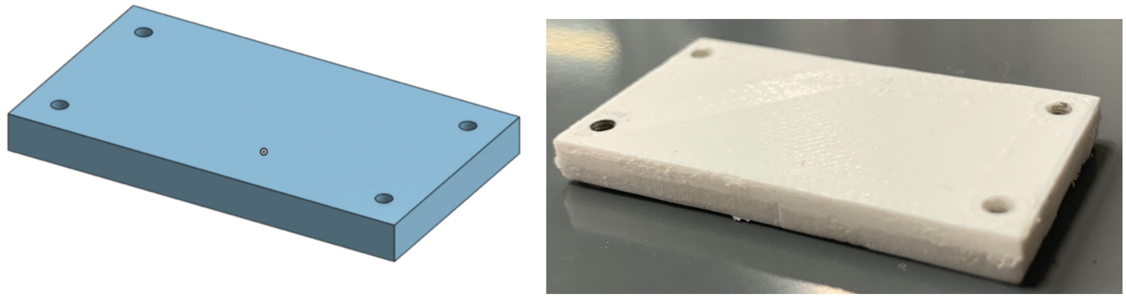

Figure 4a: CAD and real isometric views of battery lid

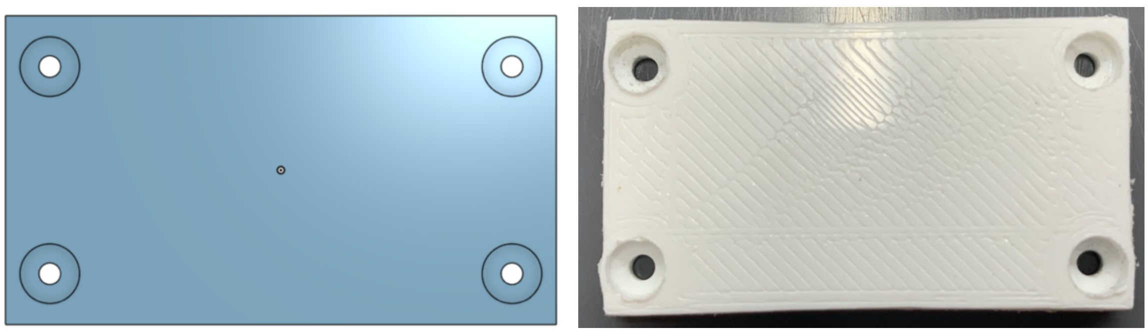

Figure 4b: CAD and real side views of battery lid

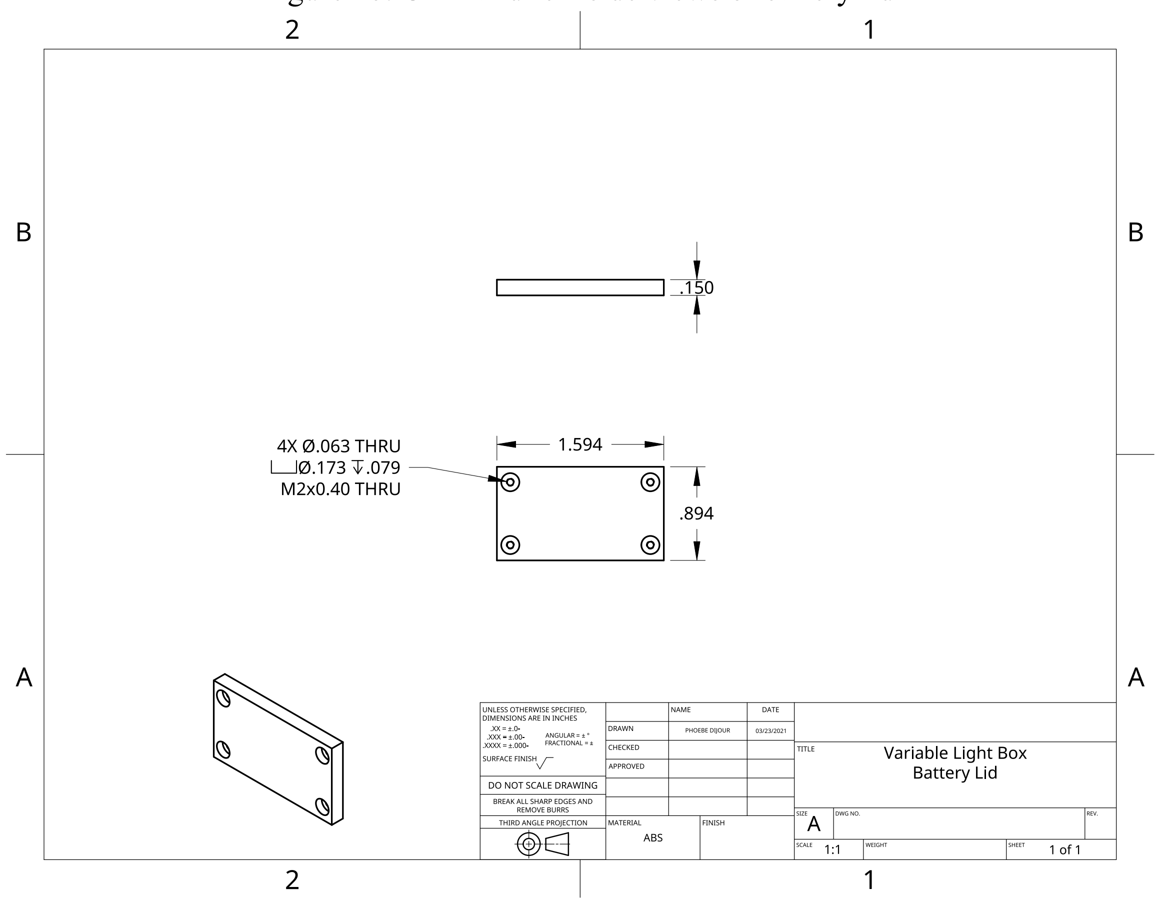

Figure 4c: Mechanical drawing of battery lid

Circuit Schematic

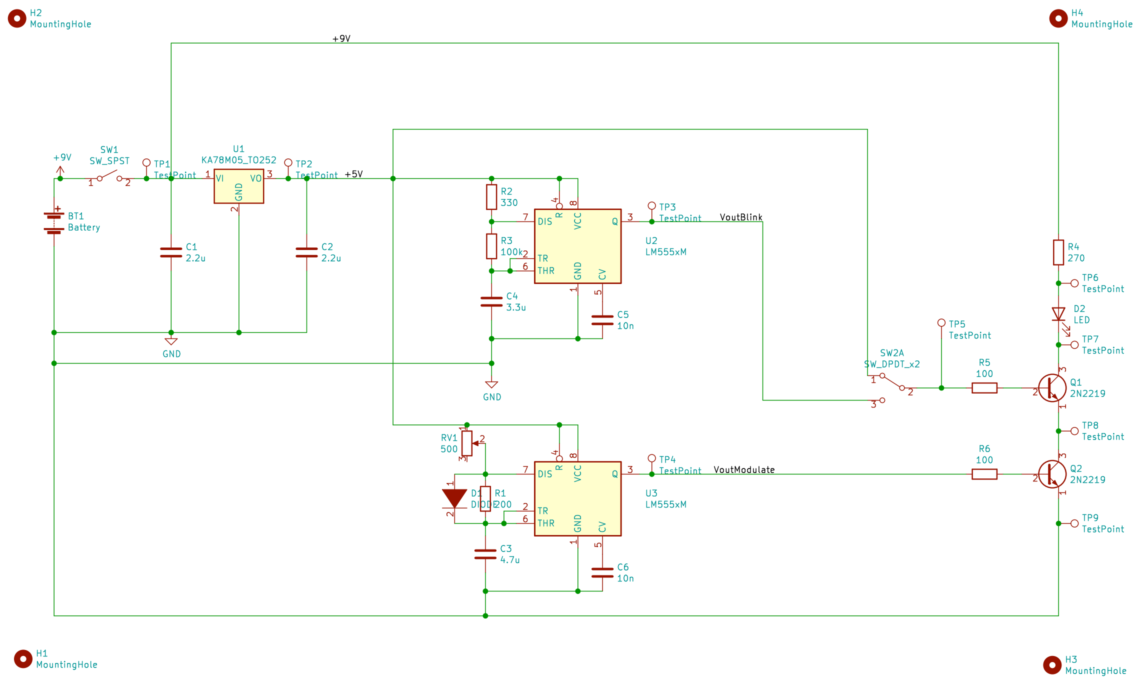

Figure 5a: Circuit Schematic, generated in KiCad

PCB Layout

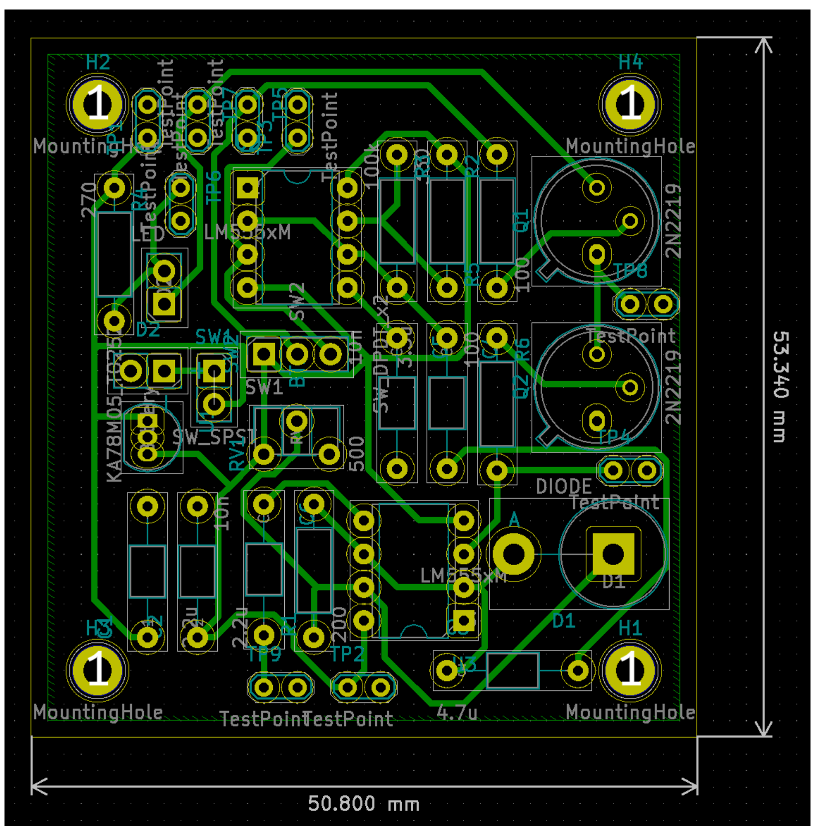

Figure 5b: PCB layout, generated in KiCad

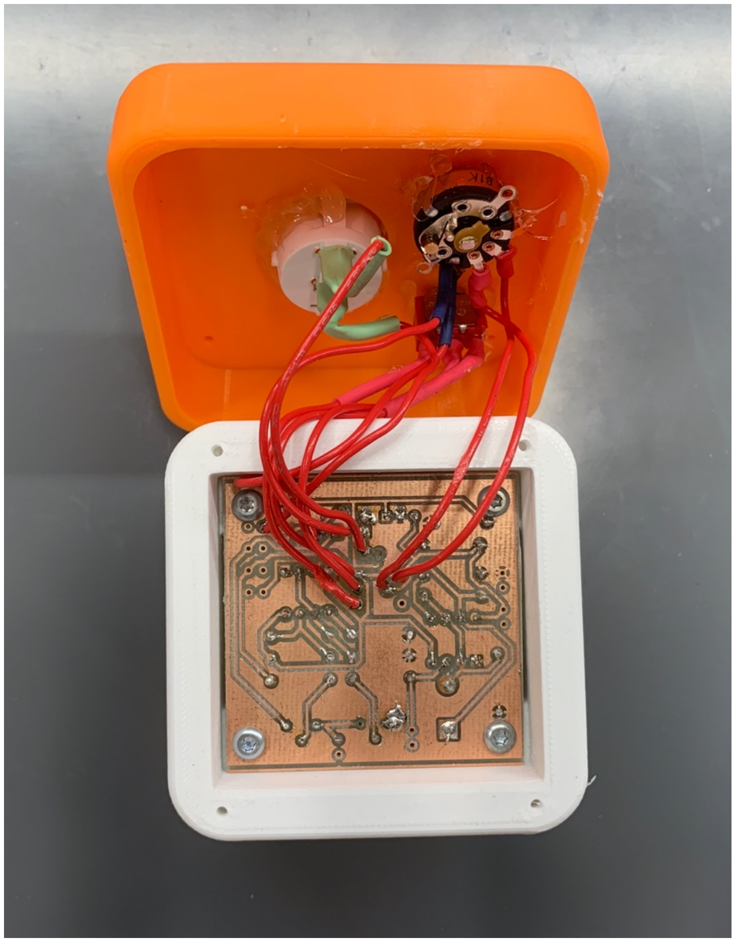
Figure 5c: PCB inside of box

There were several deviations in the final PCB from what was designed in KiCad. Primarily, a 1k Ohm potentiometer was used in the final enclosure instead of a 500 Ohm potentiometer in order to improve the rotary knob user interface. In addition, the PCB was slightly trimmed so that it could more easily fit into the enclosure.

Test procedures and testing / analysis data for specifications
Green marginal values indicate "passing" criteria; all tests were passed. All values are reported as mean ± confidence interval. An alpha of 0.05 was used for all confidence interval calculations. All tests were performed on a functional breadboard because the PCB stopped working.

Table 2: Testing Summary Data for Light Functionality

User Need	Test	Trials	Ideal Value	Marginal Value
Switch turns device on/off	Visual identification of LED turning on and off	5	Yes	Yes
(1) Rotary knob linearly modulates brightness of LED from off to maximum brightness	Measure voltage across the resistor directly before the LED at minimum and maximum brightness	5	Min and max brightness voltages are statistically different ($p < 0.001$)	p = 1.816E–14
(2) Switch to toggle from continuous to a 2Hz blinking mode (50% duty cycle)	2 Hz: Count the number of blinks in 10 seconds 50% duty cycle: Use oscilloscope to measure time between timer blinks at output of DPDT	5 5	Frequency = 2Hz (±0.1Hz) Duty cycle = 50% (±3%)	1.980 ± 0.039Hz 48.788 ± 0.312%
(3) Max brightness is the same in continuous and blinking modes	Measure voltage across the resistor directly preceding the LED at maximum brightness in continuous and blinking modes	5	Continuous and blinking voltages are statistically equivalent ($p > 0.05$)	p = 0.694

(1) To test for brightness modulation, an oscilloscope was used to measure voltage across the resistor directly preceding the LED at minimum and maximum brightness levels because voltage is proportional to current, which is proportional to current. The mean minimum voltage was found to be 0.0 ± 0.0 V, while the mean maximum voltage was found to be 5.424 ± 0.003 V. A two-tail one-sample t-test was conducted to compare the voltages between the minimum and maximum brightness settings. The null hypothesis was that there is no difference between the minimum and maximum voltages. The t-test gave a p-value of 6.403E–14, which is less than 0.001, so the null hypothesis is rejected. This indicates that the two sets of data are statistically different, so the rotary knob significantly modulates the brightness of the LED.

To test if the potentiometer linearly modulates the brightness, the voltage was measured at various degrees of rotary knob rotation with an ammeter, and voltage versus knob rotation was plotted in Figure 6a below. It is important to note that the ammeter gave different maximum voltage value than the oscilloscope, likely due to tolerance levels. The voltage to rotation relationship appears relatively linear but makes a very large from 0V at 0 degrees to 3.08V at 30 degrees. The R^2 value for the linear line of best fit is

0.7197, which is not very high and suggests that the knob does not perfectly linearly modulate the brightness of the LED. However, to the eye, the brightness does appear to increase as the knob continues to rotate, despite the relationship not being linear. Therefore, this test is considered "passed."

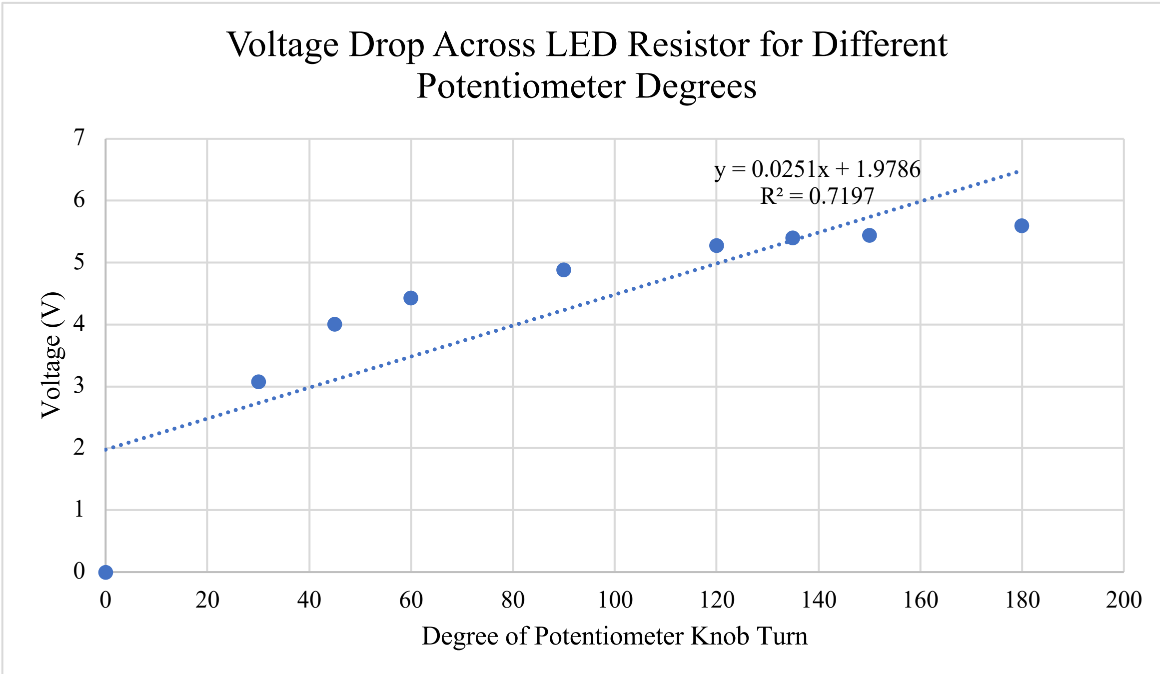

Figure 6a: Voltage drop across 270 Ohm resistor preceding LED across various degrees of potentiometer rotation

(2) To test if the light blinks at a 2Hz frequency, the number of blinks in 10 seconds was counted, giving a mean value of 1.980 ± 0.039Hz. To test the duty cycle, the oscilloscope was used to measure the time between timer blinks at the output of the DPDT switch, which gave a mean value of 48.788 ± 0.312%. Both of these values with their 95% confidence intervals were within the marginal values, sot the test was considered passed. Images of 555 timer outputs for the blinking and brightness modulation circuits can be seen in Figure 6b below.

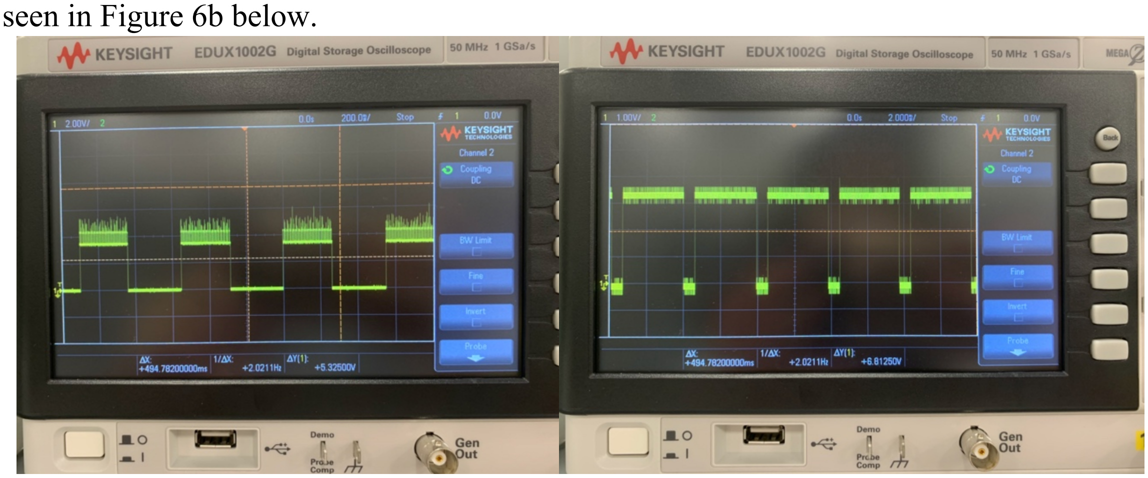

Figure 6b: Oscilloscope images of 2Hz 50% duty cycle blinking LED (left) and maximum brightness ~300Hz continuous LED (right)

(3) To test if the maximum brightness is the same in continuous and blinking modes, an oscilloscope was used to measure the voltage across the resistor directly preceding the LED for both light modes. The mean continuous voltage was found to be 5.424 ± 0.003V, while the mean blinking voltage was found to be 5.425 ± 0.004V. A two-tail one-sample t-test was conducted to compare the voltages for blinking and continuous modes. The null hypothesis was that there is no difference between the maximum brightness continuous and blinking mode voltages. The t-test gave a p-value of 0.374, which is greater than 0.05, so the null hypothesis is accepted. This indicates that the two sets of data are not statistically different, indicating the maximum brightness is equivalent in both light modes.

Table 3: Testing Summary Data for Battery Design

User Need	Test	Trials	Ideal Value	Marginal Value
Powered using voltage-regulated, 9V battery	Power circuit with 9V battery to determine	5	Yes	Yes
(4) Battery is replaceable in under 5 min	Time how long it takes to remove and replace the battery	5	< 5 minutes (±0.2 min)	1.515 ± 0.191 min
(5) Battery life ≥ 4 hours	Measure the amount of current drawn from the battery on the power supply while the box is in the brightest continuous and blinking modes and calculate the time for 9V to run out of 500 mAh	5	≥ 4 hours (±0.2 hours)	Blinking: 6.494 ± 8.7E-16 hours Continuous: 4.817 ± 0.0339 hours

(4) To test if the battery is replaceable in under 5 minutes, battery replacement was timed, giving a value of 1.515 ± 0.191 minutes. The 95% confidence interval of this value is within the marginal value, so the test was passed.

(5) To test battery life, 9V of power was connected to the circuit using a power supply, and the amount of current drawn was recorded from the power supply for both continuous and blinking light modes at maximum brightness. The battery's current output, 500 mAh, was divided by the recorded current to calculate the number of hours to battery depletion. Blinking mode gave a value of 6.494 ± 8.7E-16 hours, while continuous mode gave a value of 4.817 ± 0.0339 hours. Since both 95% confidence intervals of these values are within the marginal value, the test was passed.

Additional Battery Testing

In order to calculate which three items draw the most power in the circuit, the voltage drop was measured across several components, and the power was then calculated using Watt's law, P=IV, using literature and datasheet values for current. Power across six different components is listed in Table 3a below. The three components that draw the most power are the 270 Ohm resistor preceding the LED, the LED itself, and the voltage regulator, highlighted in orange.

Table 3a: Power Dissipation of Various Circuit Components

Component	Voltage (V)	Current (A)	Power (W)
Resistor Preceding LED	5.425	I = V/R = 5.425/270 = 0.0201	0.1090
LED	2.425	0.02 (from datasheet)	0.0485
Voltage Regulator	3.9375	0.01 (entire circuit current)	0.0394
555 Blinking	4.4375	0.006 (typical current draw)	0.0266
555 Modulation	1.625	0.006 (typical current draw)	0.0098
Resistor Preceding BJT	0.555	I = V/R = 0.555/100 = 0.00555	0.0031

Table 4: Testing Summary Data for Box Design

User Need	Test	Trials	Ideal Value	Marginal Value
Single-sided printed circuit board	Visual identification of single-sided printed circuit board	1	Yes	Yes
(6) Weight ≤ 0.5 lbs	Measure weight of circuit board on scale	1	≤ 0.5 lbs (±0.02 lbs)	0.380 lbs
(7) Dimensions < 3 in	Measure length, width, and height using calipers	1	≤ 3 in (±0.1 in)	3 x 3 x 2.616 in
Enclosure is "sealed" / air gaps minimized	Visual identification of enclosure sealed with no parts falling out	1	Yes	Yes
(8) ≤ $20 to duplicate unit	Add the prices of all components together to determine the total price	1	≤ $20 (±$0.50)	$12.83
Survive 3 ft drop	Visual identification of secure mounting of all internal components, fillet corners/edges, few protruding switches and knobs Official test by Dr. Palmeri: drop box from 3-foot height and visually identify if components remain secure	1	Yes	Yes
Safe	Visual identification of no protruding or sharp edges and no external components that are hot to the touch	1	Yes	Yes

(6) To test the weight of the unit, the entire box with all internal and external components was placed on a scale. The value was found to be 0.380 lbs, which meets the ≤ 0.5 lbs requirement.

(7) To test the dimensions of the enclosure, calipers were used to measure the largest length, width, and height. The box was found to be 3x3x2.616 in, which all satisfy the ≤ 3 in requirement.

(8) To calculate the price of the unit, all components were compiled into a spreadsheet, and individual component prices were found online. These values are listed in Table 4a below. The total price was calculated as $12.83, which meets the ≤ $20 requirement.

Table 4a: Component Price List

Component	Quantity	Cost	Total Cost
SPST Switch	1	$1.64	$1.64
8 Pin DIP Socket	1	$0.33	$0.33
555 Timers	2	$0.75	$1.50
M2-0.4 Screws	6	$0.03	$0.19
M2-0.4 Inserts	6	$0.21	$1.26
SPDT Switch	1	$1.50	$1.50
1K Potentiometer	1	$0.86	$0.86
Red LED	1	$0.03	$0.03
2N2222 BJT	2	$0.12	$0.24
2.2 uF Capacitor	2	$0.20	$0.40
0.01 uF Capacitor	2	$0.90	$1.80
4.7 uF Capacitor	1	$0.23	$0.23
3.3 uF Capacitor	1	$0.23	$0.23
200 Ohm Resistor	1	$0.07	$0.07
100 kOhm Resistor	1	$0.10	$0.10
330 Ohm Resistor	1	$0.09	$0.09
100 Ohm Resistor	2	$0.10	$0.20
270 Ohm Resistor	1	$0.11	$0.11
N1451 Diodes	1	$0.12	$0.12
9V Battery	1	$1.50	$1.50
78L Voltage Regulator	1	$0.44	$0.44
Final Cost			**$12.83**

Bill of Materials

Table 5: Bill of Materials, generated in KiCad

Id	Designator	Package	Quantity	Designation
1	RV1	Potentiometer_ACP_CA6-H2,5_Horizontal	1	500
2	R3	R_Axial_DIN0207_L6.3mm_D2.5mm_P10.16mm_Horizontal	1	100k
3	R2	R_Axial_DIN0207_L6.3mm_D2.5mm_P10.16mm_Horizontal	1	330
4	BT1	PinSocket_1x02_P2.54mm_Vertical	1	Battery
5	Q1, Q2	TO-39-3	2	2N2219
6	R1	R_Axial_DIN0207_L6.3mm_D2.5mm_P10.16mm_Horizontal	1	200
7	U1	TO-92_Inline	1	KA78M05_TO252
8	TP1-TP9	TestPoint_2Pads_Pitch2.54mm_Drill0.8mm	9	TestPoint
9	C3	C_Axial_L3.8mm_D2.6mm_P10.00mm_Horizontal	1	4.7u
10	C5, C6	C_Axial_L3.8mm_D2.6mm_P10.00mm_Horizontal	2	10n
11	C1, C2	C_Axial_L3.8mm_D2.6mm_P10.00mm_Horizontal	2	2.2u
12	C4	C_Axial_L3.8mm_D2.6mm_P10.00mm_Horizontal	1	3.3u
13	R4	R_Axial_DIN0207_L6.3mm_D2.5mm_P10.16mm_Horizontal	1	270
14	R5, R6	R_Axial_DIN0207_L6.3mm_D2.5mm_P10.16mm_Horizontal	2	100
15	H1-H4	MountingHole_2.2mm_M2_DIN965_Pad	4	MountingHole
16	SW1	PinSocket_1x02_P2.54mm_Vertical	1	SW_SPST
17	D2	PinSocket_1x02_P2.54mm_Vertical	1	LED
18	SW2	PinSocket_1x03_P2.54mm_Vertical	1	SW_DPDT_x2
19	U2, U3	DIP-8_W7.62mm	2	LM555xM
20	D1	D_5KPW_P7.62mm_Vertical_AnodeUp	1	DIODE

Discussion of Successes and Failures

This project was writhe with success and failures in the CAD design, printed circuit board design, and full assembly construction. On a high note, the circuit initially worked perfectly in the box enclosure until one wire disconnected and the circuit shorted. Therefore, all testing was performed on the breadboard, which worked as intended and passed all tests with confidence intervals well within the marginal values. Therefore, the circuit can be considered generally successful. Moreover, the printed circuit board is very neat, efficiently packing many different components into a small space. The soldering on the PCB, despite its small size, was also very neat and required little revision. Due to the small PCB size, the enclosure is able to have very thick and sturdy walls that can survive a drop test and protect the inner contents. This is also amplified by the smooth filleted edges around the entire box. The entire box is very compact, portable, and durable. The user interface is also neat, with the two switches, the knob, and the LED secured on the lid and protruding as little as possible.

However, there were many failures due to poor assumptions and fabrication errors that could be overcome in the future with a revised design. The most painful failure was when the PCB stopped functioning after working perfectly for several days. This was a result of one of the wires attached to an outside component coming out of the board while the 9V battery was plugged in, causing the 555 timer on the board to short, which resulted in several downstream errors and ultimately the failure of the board. This could have been avoided through several measures, one of which is using a power supply with a low maximum current setting to power the board instead of a 9V battery. Another preventative measure could have been to create an enclosure that had more room for connections to outside components. Since there is not much room above the PCB and the lid therefore sits relatively close to the PCB, the wires that connect the outside components to the PCB are pressed against the lid and are more likely to break or rip out of the board/components. A third option to prevent wires from breaking would be to house the outside components on an immobile part of the box, rather than the lid, which lifts up and down in order to access the PCB. Redesigning the base of the box with holes to fit the outside components would prevent the possibility of breaking wires when lifting the lid to access the PCB. Additionally, using heat shrink for all outside components would prevent shorting and would prevents connections from breaking as much. Another option to prevent shorting could be to use a TO-220 voltage regulator with a heatsink instead of an TO-92 because the circuit may draw too much current and cause the TO-92 to become very hot.

There were several issues with mounting and screw holes in the CAD design. First, all of the screw holes were too small and had to be hand drilled to fit the M2 screws, so these hole sizes should be increased in the CAD software. In addition, there were several holes in the design that were ultimately not used for screws in the box construction, namely all four holes on the lid, since the lid was already secure without screws, and two of the battery lid holes, since it took too much time to unscrew all four screws when replacing the battery. Therefore, these extra holes should be removed from a future CAD design to minimize unnecessary air gaps. While the lid of the box snugly fits on the base without the need for screws, it would likely be more secure during the drop test if screws were used, so the holes can be left in the lid if screws are added. Additionally, the lid covers the base and therefore protrudes past the edges of the base. This makes it less durable when falling, which could be prevented if the lid were made to just be a flat piece that is screwed in place. Several components of the user interface also protrude, especially the switches and rotary knob, which may be harmed during the drop. To prevent this, a valley can be added in the base to house all of the components, so they do not protrude past the surface of the box. It would also be a good idea to secure the battery to prevent it from moving around during the drop test and hitting the PCB. An extra plastic piece could be added above the two stabilizers in the base of the box for this. Finally, the costs of the PCB, plastic box, and glue were not accounted for in the ≤ \$20 limit, which would have driven the price over \$20. Therefore, it would be better to use less expensive components to account for the expensive PCB.

Appendix

Table 6a: Maximum and Minimum Brightness Voltages

Trial	**Min Brightness Voltage (V)**	**Max Brightness Voltage (V)**
1	0	5.425
2	0.001	5.42
3	0	5.425
4	0	5.43
5	0	5.425
Mean	0.0002	5.425
STDEV	0.00045	0.00353
CI	0.00039	0.00310

Table 6b: Voltages for Degrees of Rotation

Degree	0	30	45	60	90	120	135	150	180
Voltage (V)	0	3.076	4.0081	4.4306	4.8836	5.2765	5.396	5.435	5.593

Table 7a: Blink Rate

Trial	**Blinks in 10 sec**	**sec/blink**
1	20	2
2	20	2
3	19	1.9
4	20	2
5	20	2
Mean		1.98
STDEV		0.0447
CI		0.0392

Table 7b: Duty Cycle

Trial	**Time for High Voltage (ms)**	**Time for Entire Cycle (ms)**	**Fraction**	**Duty Cycle**
1	264	546	0.484	48.352
2	268	544	0.493	49.265
3	264	544	0.485	48.530
4	266	544	0.489	48.900
5	266	544	0.489	48.897
Mean				48.788
STDEV				0.356
CI				0.312

Table 8a: Maximum Continuous and Blinking Brightness

Trial	**Continuous Voltage (V)**	**Blinking Voltage (V)**
1	5.425	5.425
2	5.42	5.42
3	5.425	5.43

4	5.43	5.43
5	5.425	5.425
Mean	5.425	5.426
STDEV	0.00353553	0.0042
CI	0.00309898	0.0037

Table 9: Battery Replacement Time

Trial	**Time (s)**	**Time (h)**
1	106.28	1.771
2	83.85	1.398
3	80.65	1.344
4	79.84	1.331
5	103.85	1.731
Mean	90.894	1.515
STDEV	13.051	0.218
CI	11.440	0.191

Table 10a: Battery Life in Blinking Mode

Trial	**Current Across Battery (A)**	**Current Across Battery (mA)**	**Battery Life (hrs)**
1	0.077	77	6.494
2	0.077	77	6.494
3	0.077	77	6.494
4	0.077	77	6.494
5	0.077	77	6.494
Mean			6.494
STDEV			9.9301E-16
CI			8.704E-16

Table 10b: Battery Life in Continuous Mode

Trial	**Current Across Battery (A)**	**Current Across Battery (mA)**	**Battery Life (hrs)**
1	0.105	105	4.762
2	0.104	104	4.808
3	0.103	103	4.854
4	0.104	104	4.808
5	0.103	103	4.854
Mean			4.817
STDEV			0.039
CI			0.034