

PAINT AND GLOSS CLASSIFICATION PROTOTYPE DEVICE

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Abstract

This report outlines the design and implementation of a non-destructive Paint Color and Gloss Classification Device. The prototype utilizes a spectral color sensor and a secondary optical subsystem with angled lighting to accurately identify wall color and sheen. An onboard ESP32 microcontroller processes the sensor data, converting it into the CIELAB color space to calculate Delta E and find the closest paint match within a local database. Three photodiodes measure specular diffraction to classify the finish. The system is designed to achieve color accuracy within a Delta E of less than 5 and a sheen classification accuracy of 80%. Additionally, the report details the system's power, sensing, control, and user interface subsystems, alongside tolerance analysis and verification procedures

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1. Introduction

1.1 Problem

Accurate paint matching for touch-ups is a highly inefficient process for homeowners, renters, and painters. Without knowing the exact color, the traditional method required peeling a physical paint chip off the wall to scan at a hardware store. This process is highly inconvenient, damages the property, and is often forbidden for renters.

While digital alternatives exist, they rely heavily on standard smartphone cameras. These cameras utilize automatic white-balancing algorithms and are highly susceptible to variations in ambient lighting, leading to inaccurate color readings and mismatched product recommendations.

Most critically, these existing solutions completely fail to account for the paint's sheen (e.g. matte, semi-gloss, high-gloss). Even a perfect color match will look like an error if the sheen is incorrect. This lack of accuracy results in high volumes of wasted paint, wasted time, an economic loss for the consumer, and a deeply frustrating user experience that yields a poor final result.

1.2 Solution

To address these challenges, we propose the development of a non-destructive Paint/Surface Analysis Device Prototype that accurately identifies precise wall color and gloss directly on the surface. Our device integrates a high-precision spectral color sensor housed within a custom, light-isolating enclosure to eliminate ambient light interference. Color is measured using the CIELAB space [8], which is the standard color space used for differentiating color. [1] We use the metric Delta E, which is the distance two colors are from the CIELAB space, to measure how much two colors differ when perceived. The device must maintain a $\Delta E < 5$, which is slightly perceivable to the human eye, for 90% of the measurements. Finally, the device must also correctly classify sheen into three categories: Matte, Gloss, and Semi-gloss with 80% accuracy.

To overcome the limitations of color-only matching, our device integrates a secondary optical subsystem utilizing an angled light. This specific illumination technique allows our system to accurately analyze light reflectance and classify the specific paint finish (e.g., matte, semi-gloss, or high-gloss). The enclosure must provide light isolation such that the spectral sensor reading varies less than 10% when external ambient light changes from dark (0 lux) to bright lighting (500 lux).

By combining the spectral color data and the gloss classification, our device processes the readings through an onboard microcontroller to output a highly accurate color match and finish type. This comprehensive approach ensures a more accurate "first-time" match, empowering users to confidently repair their walls without removing physical chips, while significantly reducing the environmental and economic impact of wasted, mismatched paint.

1.3 Block Diagram

Figure 1 shows the high-level block diagram. It includes five main subsystems: User Interface(UI), Sensing, Control, Power, and Enclosure. The Control subsystem includes the ESP32 microcontroller, and it is responsible for controlling the timing of LEDs and sensor data retrieval from the sensing subsystem, classifying color and gloss, and outputting it to the UI. The sensing subsystem includes the gloss and color sensors, and it is responsible for accurate measurements of the two qualities. It outputs to the ESP32 in the control subsystem. The UI receives outputs from the ESP32 by Bluetooth and shows the classification of gloss and color on a mobile app screen. The enclosure ensures that the lighting environment is consistent throughout different measurements, and enables the device to have higher accuracy. Finally, the power subsystem provides 5V, 3.3V, and 1.8V rails to power the other subsystems. The 5V rail is supplied by the USB-C, which is then converted into 3.3V and 1.8V by LDO regulators. It also includes the 1.8 to 3.3V level shifter, responsible for translating the color sensor data for the ESP32.

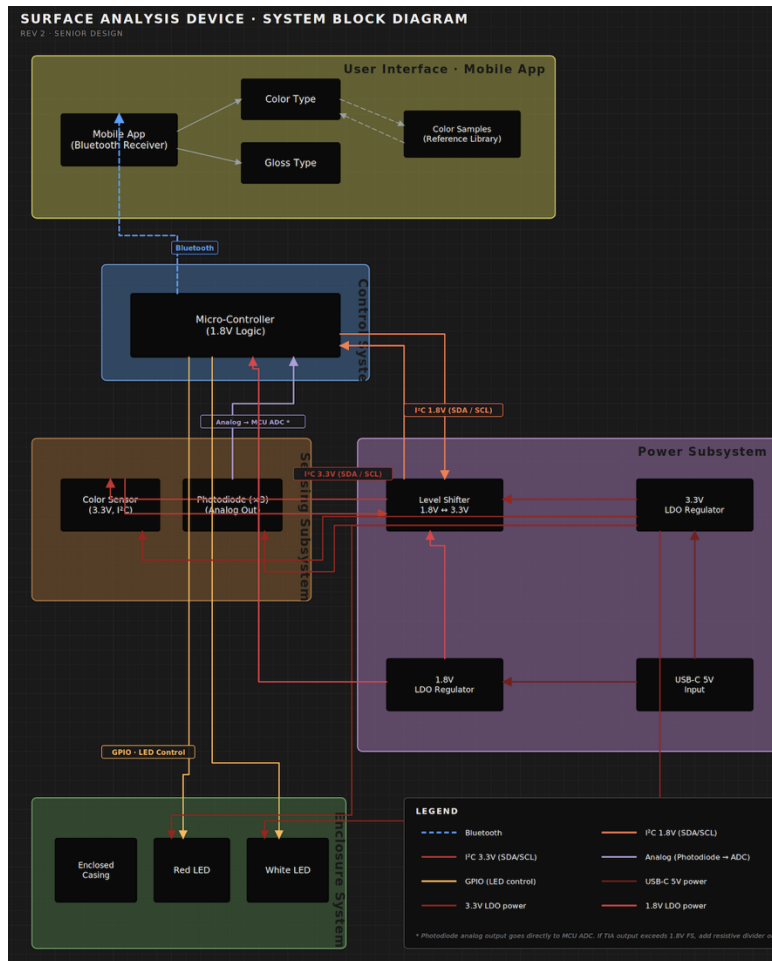


Figure 1: Block Diagram

2 Design

Color accuracy within $\Delta E < 5$

Delta E (or ΔE) is the distance between two colors in the color space. We will be using the CIELAB space, which is the standard color space used for Delta E [1]

Sheen Classification

Sheen classification of (Matte vs Gloss vs Semi-Gloss) within 80% accuracy across 10 different test samples

Environmental Isolation

The enclosure must provide light isolation such that the spectral sensor reading varies less than 10% when external ambient light changes from dark (0 lux) to bright lighting (500 lux)

2.1 Power Subsystem

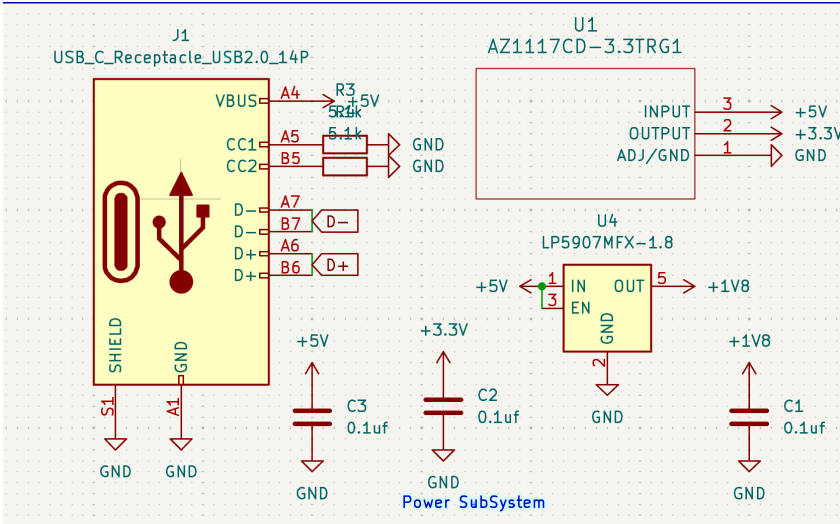


Figure 2 Power Subsystem Schematic

The power subsystem is responsible for receiving the primary 5V supply from the USB-C receptacle and delivering regulated power to all the onboard components. Since the microcontroller and color sensor operate on different voltage levels, the system utilizes dual low-dropout (LDO) regulators and an I2C level shifter.

Voltage Regulation

Power is first routed through an AZ1117CD-3.3 fixed LDO regulator. The regulator successfully steps the 5V USB-C input down to the main 3.3V that is required to power the ESP32 microcontroller and generate digital logic

The AS7343 color sensor required a 1.8 V power supply. To achieve this, we used an LP5907MPX-1.8 low-noise LDO. This reduces the voltage ripple, which could corrupt our color readings. Decoupling capacitors of .1uF were also used near the inputs and outputs of both regulators to further stabilize the voltage

Logic level translation

The ESP32 MCU operates at 3.3 V, and the AS7343 color sensor operates at 1.8 V. A direct connection would risk hardware damage or cause signal failure. To resolve this voltage mismatch, a PCA9306 level shifter was implemented to translate the data on the I2C bus.

PCB Integration Correction

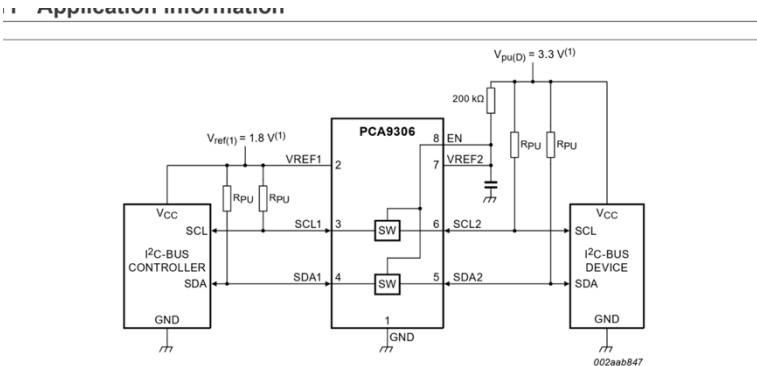


Figure 3: Correct PCA9306 Schematic

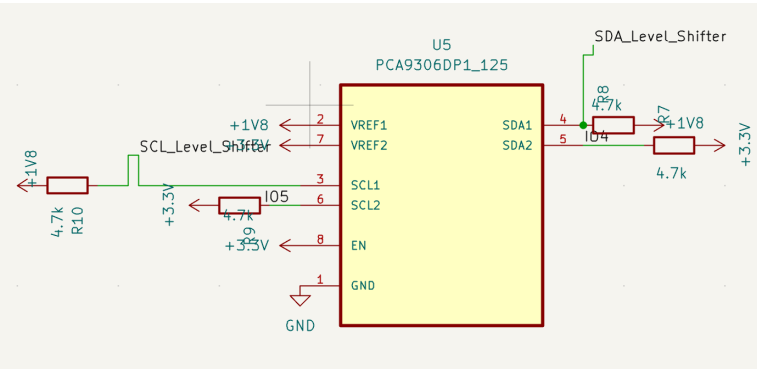


Figure 4: PCA9306 Schematic Missing 200k Ohm Resistor

During soldering and unit testing, we discovered that 2.2V was being sent to the color sensor instead of 1.8V. This was because of the necessary resistor shown in Figure 2. This oversight was corrected on the PCB by pulling pins 7 and 8 of the PCA to prevent it from touching the PCB, and a resistor was added that connects to R7 on our PCB. This solved the voltage problem, and 1.8 V was then being transmitted to our color sensor.

2.2 Gloss Subsystem

Overview and Optical Geometry

The gloss subsystem utilized an angled illumination strategy and a custom array of photodiodes to measure light diffraction and calculate the finish of the target surface. A red LED was specifically selected as the designated illumination source for the surface since the chosen photodiodes show higher spectral sensitivity to red wavelengths [10].

The physical arrangement relies on a three-photodiode geometry. Photodiode 3 (PD2) is positioned to capture the direct specular reflection. Meanwhile, the photodiodes 1 and 2 are positioned to sample scattered diffused reflections.

By taking three separate readings, the system reduces its mathematical sensitivity to variations in LED brightness, color of the sample, and minor ambient light leakage. The final classification value is calculated using the following ratio:

$$\text{Gloss Index} = \text{PD2}/(\text{PD1}+\text{PD2}+\text{PD3})$$

Design Iteration and Optical Simplifications

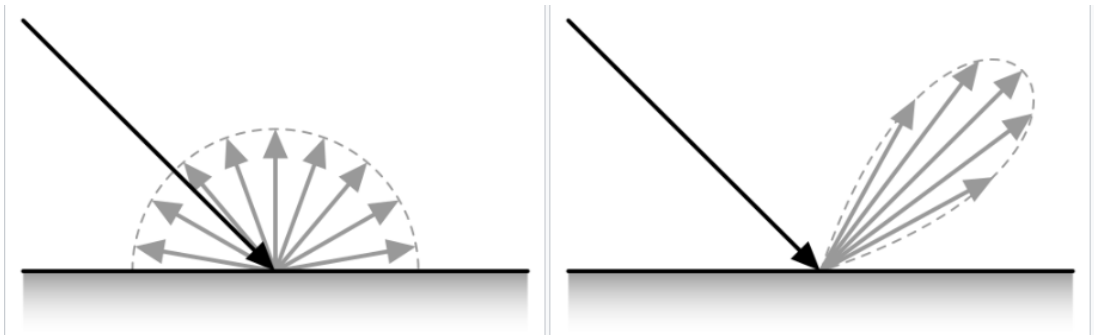


Figure 5: Difference in the Diffusion of Light between Matte and Glossy Surfaces

Our mathematical approach to measuring gloss was inspired by the concepts in the Bidirectional Reflectance Distribution Function (BRDF). [5] In the commercial paint industry, a 60-degree angle is the universal standard used by gloss meters to measure the general sheen. [6] Based on this standard, one photodiode was placed at the specular angle to capture the peak of the light distribution, and two photodiodes were placed at +/- 15 degrees from the peak to capture diffused light. As Figure 6 indicates, matte surfaces do not necessarily reflect less total light but rather they diffuse it more widely.

Additionally, we noticed that the red LED was not bright enough and changed the 300 ohm resistor to 69 ohms.

$$I = (V_{\text{supply}} - V_f)/R$$

V supply is 3.3V and the red light forward voltage (V_f) is 2V. The use of 69 ohms allows for a current of 18.8 mA. This allows for a safe and bright operation.

Because our software calculates a gloss index by comparing the light reflected at the specular angle against the sum of light measured across all photodiodes, the math inherently normalizes that data. Emitting the collimating lens and diffusion paper simplified our mechanical design, reduced our bill of materials, and eliminated any potential optical alignment errors without sacrificing out 80% classification accuracy.

Transimpedance Amplifier (TIA) Circuit

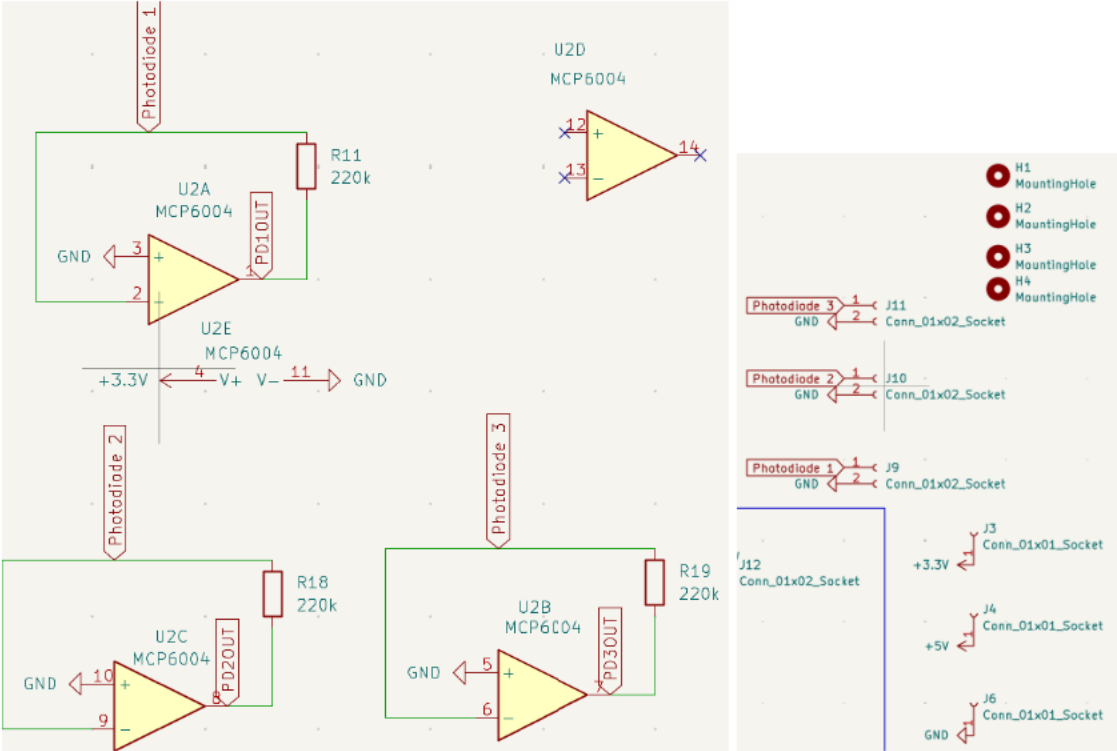


Figure 6: Transimpedance Amplifier (TIA) Circuit and Photodiodes

The raw output from each photodiode is a microscopic current in the microampere range; a TIA is required for current-to-voltage conversion. The ADC pins of the ESP32 then read the voltage and classify gloss. The output voltage is determined by the feedback resistor (R_f) according to the formula:

$$V_{out} = -I_{PD} \times R_f$$

To ensure maximum sensitivity, this resistor must be sized to push the maximum expected photocurrent near the full ADC scale. During hardware testing, the initial baseline gain was too insufficient. When shining a light directly into the photodiodes, we read 2.5 μA. The feedback resistor was initially 200 kΩ and was changed to 1 MΩ. With 200 kΩ resistors, we were only

using .5V of our 3.3V range. When using 1MΩ resistors, we are using much more of a voltage range and have more distinct data. This configuration proved more stable and readable, with voltage proportional to the reflected light.

$$V_{out} = 2.5 \mu A \times 200 \text{ k}\Omega = 0.5 \text{ V}$$

$$V_{out} = 2.5 \mu A \times 1 \text{ M}\Omega = 2.5 \text{ V}$$

Our Calibration and Anomies and further comments are discussed in the gloss subsystem design verification section.

2.3 Color Subsystem

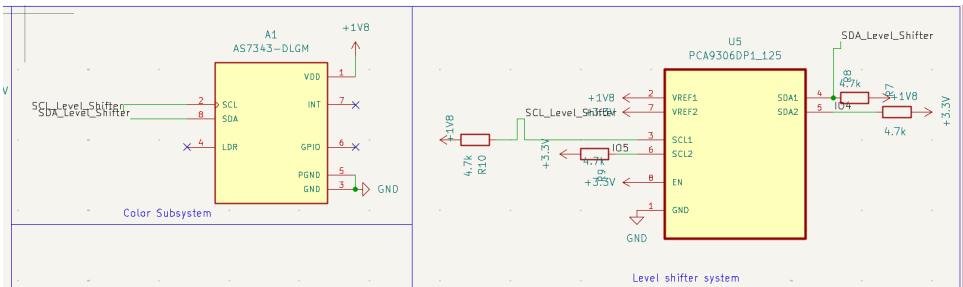


Figure 7: Color Subsystem and Level Shifter Subsystem Schematic

Components

We used the AS7343-DLGM as our color sensor, notably for its 14-channel output for a range of wavelengths. This color sensor’s max voltage was 1.8V, which required the use of LP5907MFX-1.8, a 1.8V LDO. Consequently, a level shifter was added to translate the data from 1.8V to 3.3V on the I2C bus for the ESP32 to read.

We used a JE2835AHR LED, notably for its high color rendering index(CRI), which is the metric used to measure how well a light can reproduce the color of the surface it shines[2].

Color Matching Algorithm

Initially, we attempted to convert the channel data into the CIELAB space using linear regression, and then match it with a database of colors using the Delta E metric.

$$[L * a * b *]^T = [Calibration Matrix] * [Ch1, Ch2, Ch3...]^T + [bias matrix]$$

Figure 8: Formula for Linear Regression into CIELAB space

However, with 14 channels, the linear regression model was inaccurate due to two main reasons: Our channel readings were not perfect due to noise and slight fluctuations in our enclosed environment. Although our enclosure successfully blocked out light, our color sensor proved to be extremely sensitive, with channel readings differing by one or two units between measurements. The sensor became confused with colors with Delta E < 5. Another reason is due

to the large amount of channels increasing the effect of noise on the system. Most channels differed by one or two units in the 0- 4096 that the color sensor output, and these fluctuations across multiple channels led to inaccuracies.

Our second method was to calculate the distance between channel readings of different colors.

```
float rawDistance(float measured[NUM_CHANNELS], float saved[NUM_CHANNELS])
{
    float sum = 0.0;

    for (int i = 0; i < NUM_CHANNELS; i++) {
        float diff = measured[i] - saved[i];
        sum += diff * diff;
    }

    return sqrt(sum);
}
```

Figure 9: Algorithm to Calculate Distance in the 14-Channel Space of Color Sensor

Our new matching algorithm proved successful with 100% accuracy over 30 selected colors. However, a downside to this method was that as sample sizes grew, the less accurate it got. We hypothesize that this is due to larger data sets introducing more room for error in human measurement. Some factors that affected readings include how hard you pressed down the device to a surface, which varied lighting slightly. Another factor was by introducing more colors, the algorithm had smaller margins to classify by.

Table 1: Effects of Increasing Color Datapoints on Accuracy

Number of Color Datapoints	Accuracy over 10 runs
10	10/10
20	10/10
30	10/10
40	9/10
50	8/10
60	8/10

bolero	9	61	100	5	116	999	5	10	16	155	116	999	2	85	8	9	116
heartfelt	16		155	8	175	999	9	16	22	223	175	999	4	161	13	12	175
cheerful	29	247	300	22	289	999	22	34	97	282	291	999	18	132	24	63	293
caviar	7	29	33	1	34	801	2	7	12	34	34	800	1	18	2	7	34
loyal blue	14	32	33	1	37	833	4	14	20	29	37	833	1	14	2	8	38
dahila	47	127	40	6	172	999	15	45	67	133	172	999	3	70	9	28	172
Greenblack	23	97	110	4	155	999	8	28	50	113	155	999	3	82	9	20	155
tricorn black	35	47	169	5	206	999	11	39	67	164	206	999	5	99	11	32	206
izmir purple	45	171	199	8	237	999	15	48	78	195	237	999	6	113	13	37	236
sands of time	60	259	299	20	328	999	29	66	116	281	329	999	18	150	25	65	328
smoky beige	59	253	291	19	322	999	27	64	114	273	322	999	17	147	24	63	322
iced mocha	52	229	267	15	296	999	23	57	100	254	296	999	13	136	20	55	296
beige intenso	58	259	301	22	324	999	28	64	113	283	324	999	18	128	25	65	324
sensational sand	62	259	298	20	321	999	29	66	115	277	321	999	17	145	24	64	321
quinoa	82	316	357	32	372	999	44	84	147	322	372	999	29	157	34	88	373
positive red	21	118	170	10	232	999	11	29	49	249	232	999	6	145	17	19	232
dragon fruit	64	258	321	27	356	999	34	71	112	339	356	999	23	180	32	63	356
exuberant pink	47	179	212	10	227	999	19	44	78	211	228	999	7	98	14	42	230

Figure 10: Channel Readings of Colors Dataset

2.4 Control Subsystem

The control system includes the ESP32 microcontroller. It is responsible for controlling the timing of the hardware sequence, acquiring raw data from the optical sensor, performing mathematical transformations and transmitting final paint and sheen classifications to the user interface. We flash firmware to the ESP32 using a USB-UART adapter.

Boot and Start Systems

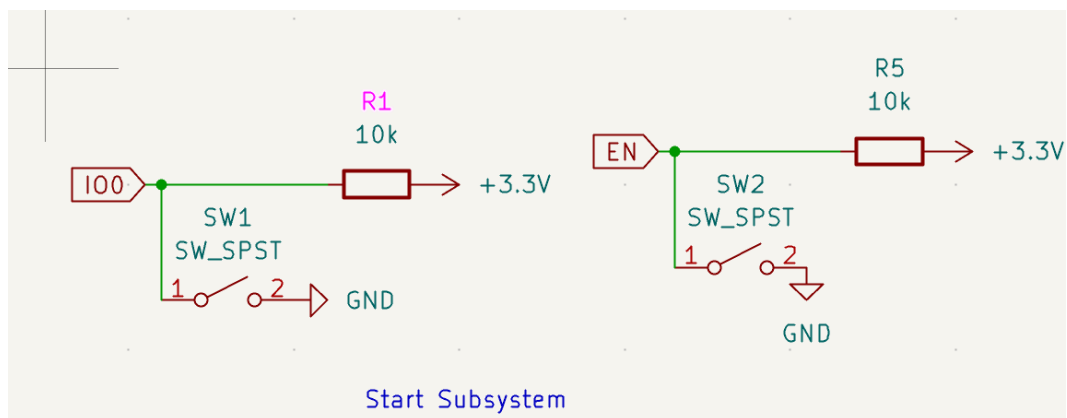


Figure 11: State Subsystem

To ensure the ESP32 boots reliably and can be reprogrammed during testing, two tactile push-buttons were integrated into the microcontroller's hardware configuration.

- The enable/reset switch acts as a hardware reset for the microcontroller. To ensure that the 3.3V power rail is stable before the ESP32 begins executing code upon being plugged

into the RC, a delay circuit was added. There is a 10k ohm pull-up resistor to the 3.3V and a 1uF capacitor connected to ground. Pressing this switch forces a hard reset of the system

- The IO0 switch determines the boot of the ESP32. Holding the boot button low while pressing and releasing the EN switch manually forces the ESP32 into download mode and allows for new firmware to be flashed directly to the board

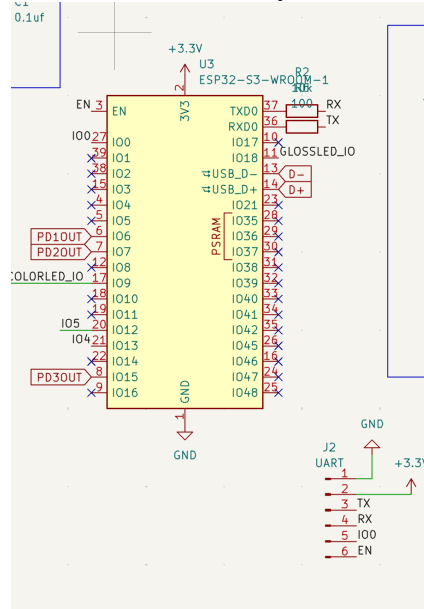


Figure 12:ESP32-S2-WROOM-1 Schematic

Lighting Control and MOSFET Switching

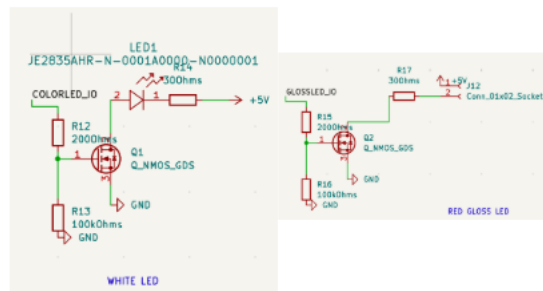


Figure 13: White LED and red LED Schematics

To execute a scan, the ESP32 sequentially triggers the high-CRI white LED for color acquisition, followed by the red LED for gloss acquisition. Since both LEDs cannot be active simultaneously, precise timing control is required.

The ESP32's GPIO pins are typically rated for a maximum continuous current of only 20 mA. Driving the high-power LEDs directly from the microcontroller would exceed this absolute

maximum rating, risking brownouts or permanent damage to the logic gates. To resolve this, we utilized N-channel MOSFETs configured as low-side switches. By connecting the GPIO pins to the MOSFET gates, the microcontroller only needs to supply a minimal signal voltage to actuate the switch, allowing the heavy LED current to be drawn directly from the 3.3V power rail instead of the ESP32.

During the testing of our PCB, we noticed that the originally specified surface-mount MOSFETs (T2N7002AQk, LM) did not physically align with the pads fabricated on the board. To resolve this without reordering a PCB, we substituted the original parts with (VN10KN3-D) N-Channel MOSFETs. Although these replacements used a different package style, we bent the leads to align with the existing footprint and carefully soldered them to the surface-mount pads.

Data Acquisition and Processing

Once the lighting sequences are triggered, the ESP32 acquires the optical data

- Color data: The microcontroller communicated with the AS7343 spectral sensor via the I2C bus to retrieve raw spectral readings
- Gloss data: The ESP uses its internal Analog-to-Digital Converter (ADC) to read the amplified voltage outputs from the Transimpedance amplifier (TIA) circuit connected to the three photodiodes

With the raw data acquired, the ESP32 executes the core classification algorithm. It converts special data into the CIELAB color space and calculates the Euclidean distance to find the closest match within the stored paint database. Simultaneously, it calculates the Gloss index ratio from the ADC readings to classify the surface as matte, semi-gloss, or high-gloss based on our tuned thresholds.

Communication

After processing the algorithms, the ESP32 sends a paint name and glass classification via Bluetooth to a web application. During final verification, the control subsystem proved to be highly efficient and sent data in less than 1 second, successfully meeting our performance efficiency requirements.

2.5 User Interface (UI) Subsystem

The user interface receives the color name, CIELAB value, and gloss classification from the ESP32 using its built-in Bluetooth Low Energy (BLE) function. After losing one of our teammates, we simplified our UI to use an already-available app LightBlue to receive data and output it to a screen for the user to read.

21:17:53.492
Color:Greenbelt | L:41.9 a:-39.4 b:17.9 |
Surface:Semigloss

21:17:50.402
Color:Greenbelt | L:41.9 a:-39.4 b:17.9 |
Surface:Semigloss

21:17:47.312
Color:Greenbelt | L:41.9 a:-39.4 b:17.9 |
Surface:Semigloss

Figure 14: User Interface LightBlue

2.6 Enclosure Subsystem

The enclosure subsystem serves the purpose of creating a standardized light-isolated environment to ensure reproducibility of the color and the gloss subsystem.

As shown in figure X several holes are positioned to allow for the PCB to screw into the 3D-printed enclosure. The walls of the enclosure are covered in Gaffer's tape [7], which reduces light reflectivity and provides a uniform surface that remains consistent regardless of the color of our 3D printed surface.

Height of Enclosure

The enclosure was 3D printed and the height was calculated using a specular reflection angle of 60 degrees. The enclosure's internal geometry was calculated to guarantee the angle between the red LED and the target photodiode. Given the total horizontal distance (X) of 48 mm between the photodiode and the LED and the ideal height (Y) of the sensor from the wall was calculated using the following trigonometric relationship.

$$\begin{aligned} \tan(60) &= (X/2) / Y \\ Y &= 48 / (2\tan(60)) = 13.86 \text{ mm} \end{aligned}$$

Figure 15: Calculation of Height of Enclosure

Thermal management

During breadboard testing, the ESP32 experienced overheating, which caused sensor drift. To mitigate this, the enclosure required a thermal management solution.

Option A (Open Cutout): While this provided maximum airflow, the resulting wall was too thin, creating a risk of the material snapping when removing 3D printing supports.

Option B (Raised Ventilation Bars): This was the chosen design. It features a 2 mm depth that accommodates a 1.8 mm maximum component stick-out. This allows for proper airflow to cool the microcontroller without sacrificing the enclosure's structural integrity.

2.7 PCB Design Choices

To ensure signal integrity, ease of testing, and proper mechanical placement within the enclosure, the PCB layout incorporates several different design choices

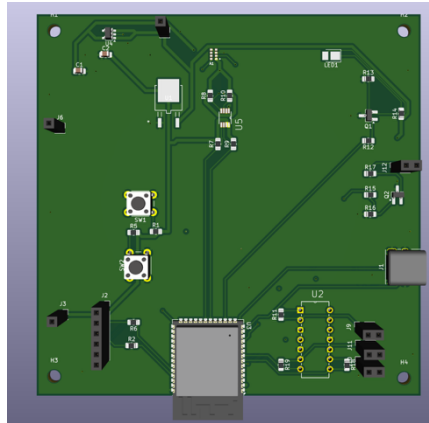


Figure 16: PCB Layout

- **Power Redundancy Headers:** The board includes 1x1 headers for GND, 5 V, and 3.3 V connections. This redundancy allows the system to bypass the USB-C front end and draw power directly from a benchtop supply in the event the USB connection injects unwanted noise.
- **Edge-Biased Subsystem Placement:** The optical components are intentionally separated, with the photodiodes and red LED grouped on one edge, and the color sensor and white LED positioned on another. This specific placement leaves adequate physical room to install light-blocking dividers inside the enclosure.
- **Length-Matched Data Lines:** To minimize propagation skew on the I²C bus between the ESP32 microcontroller and the sensor, the parallel data traces are kept as close in length as possible.
- **Accessible Test Points:** Connectors and test points are intentionally moved to the outer edges of the board. This ensures that diagnostic tools like a multimeter or logic probe can be used easily without physical interference from other mounted components.

3. Design Verification

3.1 Power Subsystem

Power DMM and Oscilloscope 1.8V



Figure 17: DMM and Oscilloscope Readings 1.8V Max Voltage

Power DMM and Oscilloscope 3.3V



Figure 18: DMM and Oscilloscope Readings 3.3V Max Voltage

Both figures 17 and 18 were taken under the maximum expected continuous load of the ESP32 and White LED. The ripples for 1.8V and 3.3V do not exceed 50 mV peak-to-peak.

Oscilloscope Showing ESP 32 Signals

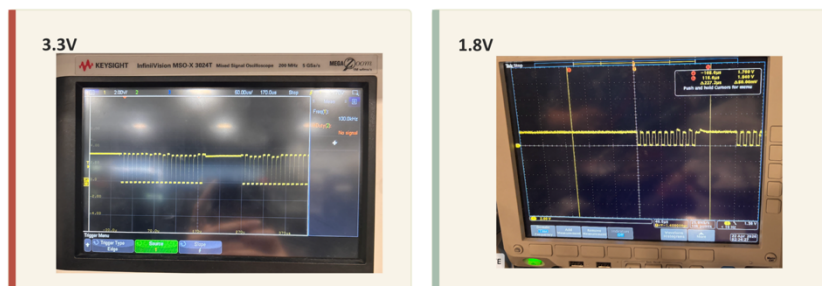


Figure 19: I2C Level Shifter Steps down 3.3V 1.8V

The I2C level shifter successfully steps down the 3.3 V ESP32 signals to 1.8 V +/- 10% and for the AS7343 step up the 1.8 V sensor to >2.5V.

**3.2 Gloss Subsystem
Calibration and Anomalies**

Table 1: Gloss Classification Threshold Testing

	PD1	PD2	PD3	Gloss Index
Matte Paint Sample	26	32	3	0.049
Glossy Paint Sample	38	42	17	0.175
Wall (Semigloss)	50	64	17	0.13
Cardboard (Matte)	32	39	10	0.093
Paper (Matte)	69	58	10	0.073
Mirror(Glossy)	50	64	29	0.21

As shown in table 1, PD1 has higher values than PD3, due to it being physically closer to the LED. This did not affect our gloss index, as matte surfaces had less gloss index than glossy surfaces, regardless of how dark or light the surface was.

The baseline threshold was confirmed as shown in table 3:

Table 2: Gloss Classification Threshold Testing

Matte	< 0.125
Semi gloss	0.125 - 0.18
High – Gloss	> 0.18

During verification testing, the gloss classification subsystem demonstrated an 83.3% accuracy rate across six initial surface trials, successfully satisfying the >80% high-level requirement. The system proved highly accurate when classifying real-world, macro-level surfaces, correctly identifying a painted wall (semi-gloss), standard cardboard (matte), standard paper (matte), and a mirror (high-gloss). The single misclassification occurred with an isolated glossy paint sample, which registered a gloss index of 0.175, falling just inside the semi-gloss threshold. This anomaly is attributed to the physical constraints of testing small, isolated paint swatches; minor surface curvatures and edge effects on small samples scatter the sensor's LED light differently than a large, continuous flat surface.

Because the device is ultimately designed for non-destructive analysis on macro-surfaces like walls, the thresholds tuned to these large physical surfaces are considered verified and functionally accurate for the system's intended use case. The system successfully maintained its accuracy, correctly classifying surfaces such as desks, folders, and floor types to their respective gloss levels.

3.3 Color Subsystem

Overall, the color subsystem met its core design objective of reliable, repeatable color identification within a defined sample set. With a database of up to 30 reference points, the matching algorithm achieved consistent identification across repeated trials, and remained functional as the database scaled further, with accuracy gradually decreasing as colors samples became more similar.

Table 1: Effects of Increasing Color Datapoints on Accuracy Test Color Points on Accuracy

Number of Color Datapoints	Accuracy over 10 runs
10	10/10
20	10/10
30	10/10
40	9/10
50	8/10
60	8/10

3.4 Enclosure Subsystem

A requirement of our project was for the enclosure to maintain a baseline reading drift of less than 10% when external ambient light transitions for 0 lux to 500 lux (dark to bright room). During verification testing, the enclosure for first place was facing up in the light, then facing down in the light, and finally facing down in the dark. The maximum light leakage was recorded on a 12-bit ADC, which had a full-scale value of 4095, and was read at 45.

$$\text{Fullscale Value} = 2^{12} - 1 = 4095$$

$$\text{Variance}(\%) = (45/4095) \times 100 = 1.1\%$$

Using a maximum leakage value of 45 from the facedown test.

$$(45/4095) \times 100 = 1.1\%$$

$$\text{Variance}(\%) = (45/(2^{12} - 1)) \times 100 = 1.1\%$$

With a maximum variance of only 1.1% in a brightly lit environment, the 3D printed enclosure passed the light isolation requirement.

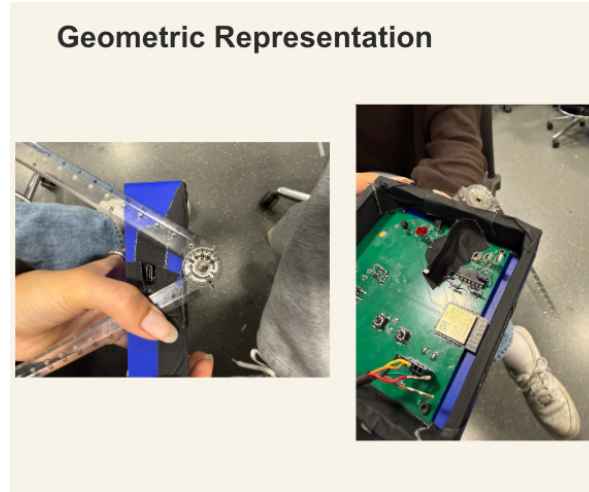


Figure 20: Standardized and Stable Angle of the red LED and photodiodes

3.5 Control Subsystem

The UI updated within 1-2 seconds as shown in our video. This number was initially calculated with a tolerance analysis. The spectral sensor required three sequential 100ms readings to cover all channels. We initially placed to calculate delta E across the entire Sherwin-Williams catalog of (Ncolors=1800) at an estimated microcontroller processing speed of 0.1ms per color. Assuming a standard display refresh time of 100ms the worst case timing is defined as:

$$T_{total} = T_{sensor} + (N_{colors} \times T_{calc}) + T_{Display}$$

$$T_{total} = 300\text{ ms} + 180\text{ ms} + 100\text{ ms} = 580\text{ ms}$$

This theoretical maximum processing time of .48 seconds successfully demonstrates system feasibility and falls under the 2 second requirement limit.

4. Costs

4.1 Parts

Table 3: Parts Cost

Part	Manufacturer	Retail Cost (\$)	Quantity Required	Actual Cost (\$)
AS7343-DLGM OLGA8 LF T&RDP	ams-OSRAM USA INC.	\$7.92	3	\$39.6

LP5907MFX-1.8	LP38852MRX-ADJ/NOPB	\$2.58	5	\$12.9
OpAmp	MCP6004-I/P	\$0.59	6	\$3.54
Photodiode	BPW46	\$0.79	10	\$7.91
LED White	LedLightsWorld	\$3.5	5	\$17.5
LED RED	Dialight	\$1.3	6	\$7.91
USB-UART Adapter	zhayouqingdzsw	\$31.60	1	\$31.60
N MOSFETS	Microchip Technology	\$0.72	10	\$7.20
VN10KN3-G-P002				
ESP-32	Espressif	\$5.49	3	\$0
Level Shifter	NXP USA Inc.	\$0.7	5	\$3.50
Gaffers Tape	D-NYX	\$5.99	1	\$5.99
PCB: Resistors			20	\$0
PCB: Capacitors			5	\$0
Total				\$137.54

4.2 Labor

Table 4: Labor Per Person

Name	Hourly Rate	Hours Invested	Total
James Lee	\$45	64	\$7200
Victoria Lee	\$45	64	\$7200
Total			\$14,400

$$\text{Labor Cost} = \text{Hourly Rate} \times \text{Actual Hours Spent} \times 2.5$$

Table 4: Total Cost

Type	Total
Labor	\$14,400
Parts (Actual Cost)	\$137.54
Total	\$14,537.54

6. Conclusion

6.1 Accomplishments

We successfully built a non-destructive paint color and gloss classification device that met all of our high-level requirements and functioned as intended. The color-matching subsystem achieved our primary accuracy target, consistently identifying colors with a Delta E of less than 5 across our sample set. Our gloss subsystem reached an 80% classification accuracy, reliably distinguishing between matte, semi-gloss, and high-gloss finishes. Our custom 3D-printed enclosure effectively isolated the sensors from external light, demonstrating a maximum variance of only 1.1% in a bright room when placed face-down against a surface. Finally, the integrated ESP32 microcontroller and Bluetooth web application enabled rapid data processing, delivering complete color and sheen results to the user in under one second.

6.2 Uncertainties

While the device performed reliably, we encountered some uncertainties and anomalies during testing. We observed that smaller paint samples introduced higher variance in the sheen classification readings. Additionally, we discovered a calibration anomaly when scanning non-paint surfaces such as cardboard and paper; despite being visually matte, their gloss indices were unusually high. We hypothesize that this was caused either by distance asymmetry, since the specular photodiode was positioned farther away, or by brightness scaling, where lighter surfaces reflect more total light and inflate the ratio. An attempt to correct this by adding a +40 offset to the specular photodiode did not resolve the issue, and the ratio remained inflated for bright, non-paint surfaces. Consequently, we had to tune our classification thresholds using entire surfaces rather than relying strictly on the initial paint samples.

6.3 Ethical Considerations

Our design process closely adhered to IEEE Code of Ethics Section 1.5 (Honesty & Realism)[3]. Because color matching is subjective to the human eye, we recognized the ethical risk of overpromising accuracy. To prevent users from purchasing incorrect paint and potentially incurring economic loss or property damage, our system evaluates the Delta E against strict thresholds and displays a "low confidence" warning rather than making a blind guess. Furthermore, the device serves as a tool for environmental responsibility; by increasing the "first-time success rate" of paint purchases, it reduces the volume of mismatched chemical paint waste entering landfills [9]. For user safety, power loads were safely distributed to prevent thermal failures, and all laboratory and e-waste disposal protocols were strictly followed throughout the project lifecycle.

6.4 Future Work

For future iterations, we plan to design a more compact PCB to enhance the device's portability. During this redesign, we will focus on optimizing component placement to further reduce electrical noise, particularly around the highly sensitive photodiodes. To improve the robustness of our optical readings, we intend to test with larger paint swatches. This will provide a more uniform surface and make gloss differences more apparent within the optical path. On the

software side, future work will include scaling the reference color database, further optimizing the matching algorithm, and adding a user input feature to compensate for varying wall textures.

5. References

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Appendix A: Requirement and Verification Table

Table 5: System Requirements and Verifications

Requirement	Verification	Verification status (Y or N)
Power Subsystem The 3.3V LDO must output a stable 3.3V +/- 5% under the maximum expected continuous load of the ESP 32 and White LED	Use a DC electrical load and digital multimeter (DMM) to measure the output voltage under load.	Y
Power Subsystem The 1.8V LDO must output 1.8 +/- 5% to safely powers the AS7343 sensor without exceeding its max voltage rating	Use a DC electrical load and digital multimeter (DMM) to measure the output voltage under load.	Y
Power Subsystem The voltage ripple on both the 3.3V and 1.8V rails must not exceed 50 mV peak-to-peak to prevent analog noise from corrupting the special sensor readings	Use an oscilloscope to measure the output voltage ripple. Connect the oscilloscope prob to the 3.3 V and 1.8V test points, set the oscilloscope to AC coupling, simulate LEDs, and verify the oscilloscope screenshot, verifying the peak-to-peak ripple is less than 50mV	Y
Sensing Subsystem The I2C level shifter must step down the 3.3 V ESP32 signals to 1.8 V +/- 10% and for the AS7343 step up the 1.8 V sensor to >2.5V.	Use an oscilloscope to verify logical level voltages on data lines. Connect to each side of the level shifter. Transmit an I2C message from the ESP32. Measure the HIGH voltage level on the 1.8V side and 3.3V side. Record the oscilloscope waveforms to prove the logic levels meet the thresholds.	Y
User Interface Subsystem The UI Subsystem must correctly match the CIELAB values given via Bluetooth from the ESP32 with the corresponding paint color in the database within Delta E <5 It must also display the correct gloss level. It must correctly update the matched	-Separately calculate Delta E value between reference sample and predicted color, verify it matches within Delta E < 5 -Correctly classifies gloss level according to set ranges -Timestamp packet arrival from ESP32 and when the UI updates. Must update	Y

paint color and gloss level within	within 1.0s<2.0s	
Enclosure Subsystem The enclosure must block the external ambient light ensuring that the AS7343 sensor's raw baseline reading varies by less than 10% when external lighting changes from 0 lux to 500 lux.	Use an external 500 lux light source and a serial monitor to test light isolation. Place the enclosure flush against a wall in a completely dark room. Record the baseline reading via the serial monitor. Turn on the extra 500 lux light source directly outside the enclosure. Record the new reading and calculate the percentage variance to verify that it is <10%.	Y
Enclosure Subsystem The internal geometry of the enclosure must hold the Red LED at a precise angle of 60 degrees +/- 2 degrees relative to the surface normal of the wall. The internal geometry of the enclosure must hold the Middle Photo Diode at a precise angle of 60 degrees +/- 2 degrees relative to the surface normal of the wall.	Place a protractor against the Red LED and the flat base plane of the enclosure. Read the measured angle and record its measurement to verify it falls between 58 and 62 degrees. Place a protractor against the middle photodiode and the flat base plane of the enclosure. Read the measured angle and record its measurement to verify it falls between 58 and 62 degrees.	Y

Appendix B: Schedule

Weekly: Update Project Notebook (Individual)

Table 6: Schedule by Week

Week	Task
Week 1 (1/19-1/25)	Brainstorm initial project concepts - All
Week 2 (1/26-2/1)	Complete KiCad and lab safety trainings - All Determine scale and difficulty of the project - All
Week 3 (2/2-	Research commercial gloss sensors - All

2/8)	Focus on designing color subsystem and figuring out ideal lighting - All Determine high-level requirements - All
Week 4 (2/9-2/15)	Create system block diagram - All Develop tolerance analysis - All Submit proposal - All Complete soldering assignment - All
Week 5 (2/16-2/21)	Finalize decisions on parts - All Decide if we need to speak to the machine shop - All Create budget spreadsheet to ensure all parts are within budget and in stock - All
Week 6 (2/23-3/1)	Develop schematic - All Decide how to mechanically place different subsystems - All Design and Place first PCB order - All Work on design document and prepare for design review - All
Week 7 (3/2-3/8)	Take feedback from design review - All Simplify design from 4-1 PCBs - All Simplify scope and redefine high-level requirements - All Prepare a single PCB for round2 - Victoria Attend PCB office hours - Victoria Connect ESP32 to Bluetooth and show gloss on breadboard - James
Week 8 (3/9-3/15)	Take feedback from breadboard demo - All Descope texture for project, simplify UI due to smaller team size - All Order PCBway3 + Solder stencil - Victoria
Week 9 (3/16-3/23)	NA
Week 10 (3/24-3/29)	Complete parts audit - All Order remaining components - All 3D print enclosure - Victoria
Week 11 (3/30-4/5)	Write individual progress reports - All PCB arrived, begin soldering color subsystem - All Place order for larger 0805 sized resistors - Victoria Goal: Show color subsystem at progress demo
Week 12 (4/6-4/12)	Order replacement parts (USB UART, AS7343, LP590MFX-1.8) due to limited components and soldering errors - All Correct 2.2V to 1.8V - All
Week 13 (4/13-4/19)	Resolder and debug color subsystem - All Correct 2.2V to 1.8V - All

<p>Week 14 (4/20-4/26)</p>	<p>Connect and test color with Arduino after replacing spectral sensor due to hot air/over-voltage - All Corrected footprint alignment issue with white LED - All Begin soldering gloss subsystem - All Tested that the MOSFETs work by switching between white and red LED - James</p>
<p>Week 15 (4/27-5/3)</p>	<p>Swap photodiode feedback resistors to boost transimpedance amplifier gain - Victoria Recalculate enclosure height using trigonometry -James Reprint a new 3D enclosure - Victoria Create software algorithms and test color subsystem - James Calibrate color samples - All Create slides and practiced for final presentation - All Turn in video assignment - All</p>
<p>Week 16 (5/4-5/7)</p>	<p>Work on final lab report - All Turn in final lab notebook - All</p>

Appendix C: Example Images of Sheen



Figure 21: Example Images of Sheen [4]