ECE 445

Spring 2025
Senior Design Project Proposal
Makeup Color Matcher

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Introduction

1.1 Problem

The beauty and skincare industry faces significant sustainability challenges due to systemic inefficiencies in accurately analyzing and matching human skin tones to color products. Variations in lighting, skin conditions, and subjective assessment methods often result in consumer dissatisfaction, driving return rates for cosmetics. This cycle of mismatched products and returns creates a crisis of environmental degradation and economic losses [1]. Additionally, many consumers lack awareness of the impact of UV exposure on skin health, leading to increased risks of premature aging, hyperpigmentation, and skin cancer. Despite the availability of SPF-infused cosmetics and sunscreens, many consumers do not incorporate adequate sun protection into their routines. Addressing both shade-matching inefficiencies and UV exposure awareness is essential for improving product effectiveness, consumer satisfaction, and overall skin health.

1.2 Solution

We propose a colorimeter device that enhances both beauty and skin protection by accurately analyzing skin tone and assessing UV exposure. Our device integrates a high-precision color sensor to detect skin tone using RGB, HSV, and YCbCr models, reducing inaccuracies caused by lighting and melanin distribution. The UV sensor detects UVA radiation (300-350 nm) and calculates UV index values, allowing the device to recommend SPF protection alongside the best foundation match.

The ESP32 microcontroller serves as the system's core, processing data from both sensors and transmitting results to a mobile interface, where users can view their personalized foundation shade and SPF recommendations. By compiling an extensive database of foundations, skin tints, and serums across various brands and price points, we ensure accessibility for all users.

More than just enhancing appearance, our device prioritizes skin health and longevity, empowering users to make informed decisions that protect against UV damage while achieving their ideal look.

1.3 Visual Aid(s)

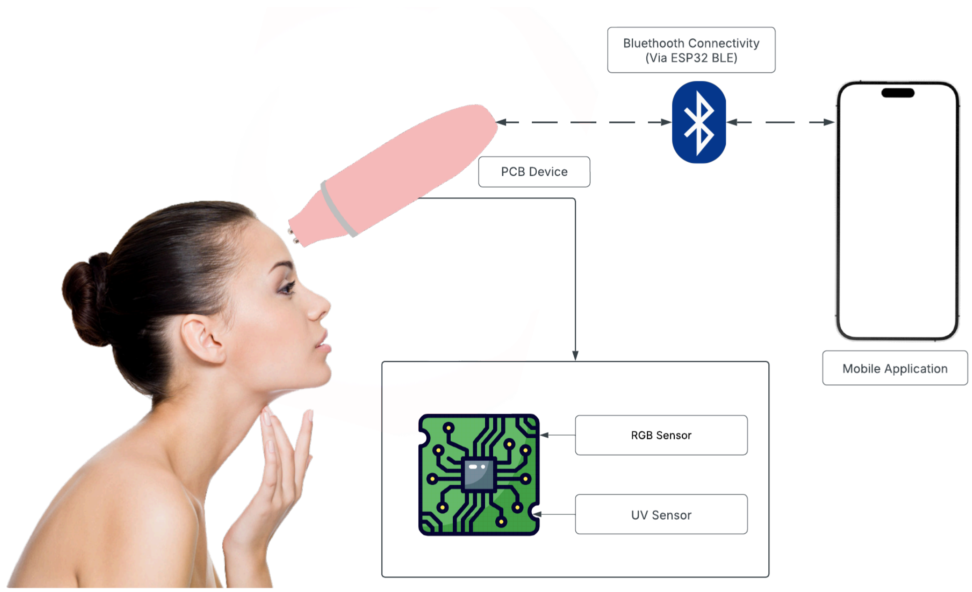

Figure 1 Visual Aid Representation of device (without USB)

1.4 High-Level Requirements

- The RGB Sensor will accurately determine the breakdown of skin tone with at least 85% accuracy using RGB-HSV-YCbCr models.
    - Based on the RGB values, we want to determine the undertone (warm, neutral, cool) values of the skin based on a higher percentage of red to blue in the raw data.
- Accurately determine the UV intensity of the surrounding environment with at least 85% accuracy
- Recommend and display a specific foundation and SPF range that has the correct shade match and the appropriate UV protection
    - Accurately provide product information to users based on their RGB value range and the UV index.

Section 2: Design

2.1 Block Diagram

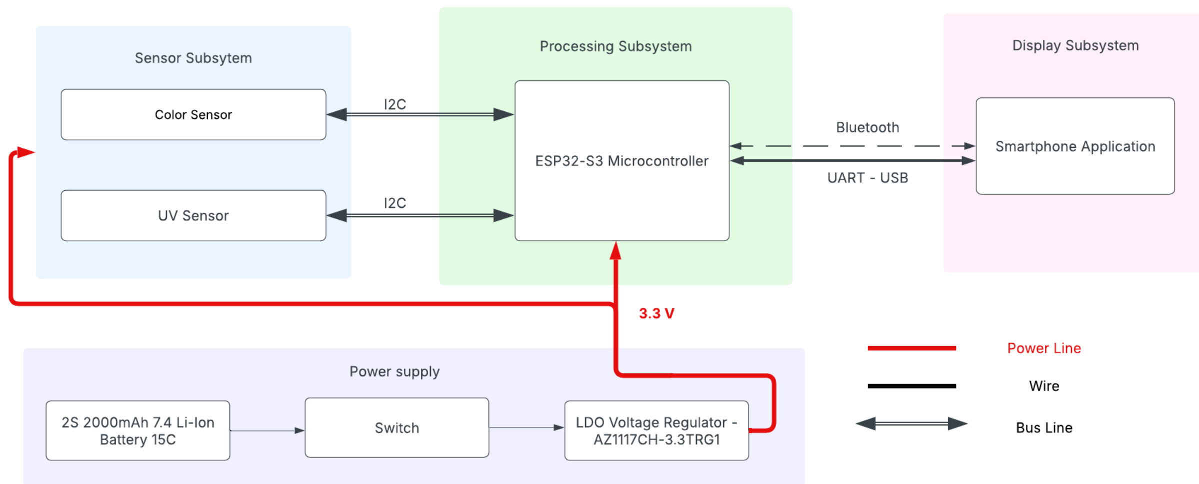

Figure 2 Block Diagram

2.2 Electronics Subsystem

2.2.1 Power Subsystems

The power subsystem is designed to provide reliable and regulated power to the various components to ensure efficient operations. The color-matching device utilizes 3.3V and will provide power to the color sensor, UV sensor, and microcontroller. We will utilize a low dropout converter to reduce battery voltage from 7.4 V to 3.3 V. We specifically chose an LDO over a buck converter as it offers better noise performance compared to a buck converter. Additionally, there is a small voltage difference between the input and output which will provide a faster load transient response to conserve energy when not in use.

We will utilize a 2S 2000 mAh 7.4 Li-ion battery 15C (amazon) which consists of 2 lithium-ion cells in series with nominal voltages of 3.7V (7.4V total). The battery will provide 2 Amps of current for 1 hour before being fully discharged, assuming our device will be on for no longer than 10 minutes. For this battery, the C rating indicates the maximum safe continuous discharge rate. The maximum current can safely deliver 30 A [$2000\ mAh\ *\ 15C\ =\ 30000\ mA$].

For the safety of our Li-ion battery and electrical components, we aim to use a toggle switch to disconnect both battery leads ensuring a 0A standby current. This would ensure our device can shut down manually when not in use.

<u>Interactions:</u>

The subsystem interacts with all other electrical subsystems by providing power to the sensors and microcontroller.

Requirements:

- Provide 30 A average/continuous current
- Provide stable 3.3V for the microcontroller and sensor ICs with $\leq$ 5% voltage ripple
- Shutdown safely when not actively using the device
- Support 30A surge current capacity for sensor subsystems

Current Parts:

- 2S 2000 mAh 7.4 Li-ion battery 15C
- LDO Voltage Regulator AZ1117CH - 3.3TRG1
- Toggle switch (handle 15/30A surge)

2.2.2 Sensor Subsystems

I. Color Sensor

The proposed color sensor subsystem leverages insight from color space analysis to address the challenges of precise skin tone analysis in cosmetic products. The sensor will combine thresholds and detection ranges from RGB, HSV, and YCbCr color models to minimize environmental interference while improving measurement accuracy for diverse skin tones.

To capture the raw RGB values under controlled illumination, we will initially utilize the Adafruit APDS9960 Proximity, Light, RGB, and Gesture Sensor for testing. Additionally, we are considering using the OPT4048 High-Speed High Precision Tristimulus XYZ Color Sensor IC [3][4][5] for our final design and creating a custom PCB with this sensor instead of relying on the Adafruit breakout component. Both sensors will be connected to the ESP32 via I2C lines (SDA and SCL), allowing us to print the precise 6-digit hex value of the RGB color associated with a skin tone. We plan to start with the Adafruit APDS9960 for initial testing and later transition to the OPT4048 sensor when finalizing our PCB design.

Interactions:

This subsystem is powered by the power subsystem at 3.3V via LDO. It will interact with the processing subsystem, specifically the ESP32 Microcontroller via I2C to process the data that will then be displayed on the display subsystem (indirect interaction).

Requirements:

- Achieve $\geq$ 85% accuracy in skin tone detection
- Capture raw RGB data of the user's skin color
- Implement Cornell University chrominance constraints

Current Parts:

- Adafruit APDS9960 Proximity, Light, RGB, and Gesture Sensor (Development)
- OPT4048 High-Speed High Precision Tristimulus XYZ Color Sensor [3][4][5]

II. UV Sensor

Exposure to UV radiation can cause skin damage and increase the risk of skin diseases for individuals of all skin tones. While people with darker skin have more melanin, which offers some natural protection against UV rays, they are still susceptible to UV-induced skin damage over time according to the American Cancer Society [7]. In contrast, individuals with lighter skin tones have less melanin and are more prone to sunburns, which significantly increases the risk of skin cancer [7]. Regardless of skin tone, prolonged UV exposure can lead to premature aging, hyperpigmentation, and increased risk of skin diseases [7].

The purpose of our UV Sensor is to monitor surrounding UV exposure levels to provide skincare recommendations, such as SPF-based foundation products or standalone SPF protection personalized to our user. By integrating UV detection into our device, users prevent future skin damage with personalized SPF recommendations based on their environmental exposure.

We will utilize the Adafruit LTR390 UV sensor as a low cost, high precision UVA and ambient light sensor. Unlike some sensors that estimate UV exposure using visible and infrared light, the LTR390 has a dedicated UV photodiode for more accurate UV level measurements. Its spectral sensitivity allows for the detection of UV light in the 300-350 nm range, making it very suitable for measuring environmental UV exposure.

Overall, the UV sensor component of our sensor subsystem will enhance our device's functionality by adding an environmental skin protection feature. By considering both skin tone and UV exposure, our device not only provides an accurate foundation shade match range but also prompts sun safety through personalized SPF recommendations. This ensures that users are equipped to protect their skin against future damage, as we provide our users with a personalized foundation recommendation and proactive skin care advice

Interactions:

In terms of communicating with the microcontroller on our PCB, the sensor uses an I2C interface which is compatible with ESP32. Regarding connectivity to our power subsystem, the sensor chip uses 3VDC but also includes a voltage regulator that will take 3-5VDC and safely convert it down[8]. Lastly, our software/display subsystem will process the sensor readings and output the foundation shade match range along with SPF recommendations based on UV exposure.

Requirements:

- Detect UVA radiation in the 300-350 nm range with $\pm$ 10% error tolerance
- Provide raw UV light measurements
  - From which UV index values can be calculated using the sensor's built-in library[8]
- Supply Voltage
  - Min: 1.7V
  - Max: 3.6V
- Input Current:
  - Min: -100 mA
  - Max: 100 mA

Current Parts:

- Adafruit LTR390 UV Sensor

2.3.3 Processing Subsystem

The processing subsystem will be powered by the ESP32 microcontroller, which will serve as the brains of the system. The ESP32 will manage communication with the color sensors and the UV sensor, both of which utilize the I2C protocol, ensuring seamless data exchange through the shared SDA and SCL lines.

Additionally, the ESP32 will connect to and coordinate with the power subsystem and the display/software subsystem. It will process raw RGB data from the color sensors, convert it into precise 6-digit hex values for associated skin colors, and monitor/output surrounding UV exposure levels to provide skincare recommendations. The ESP32 will also provide data to the display or software interface for real-time visualization and analysis. Its ability to integrate multiple subsystems through I2C communication, combined with its low power consumption and wireless connectivity, makes it a highly efficient and reliable central controller for this system.

Interactions:

The microcontroller will be powered by the power subsystem and used to send data from the sensor subsystems to the display subsystem. It will interact with the sensor subsystems via I2C and interact with the display subsystem via Bluetooth and UART-USB.

Requirements:

- Provide a stable and responsive Bluetooth connection

Current Parts:

- Bluetooth ESP32-S3 (MCU)

2.3.4 Software / Display Subsystem

Our display subsystem will primarily be on an iOS application programmed with Swift. We will initialize the BLE service on the ESP32-S3 microcontroller to connect to an iOS device. Using either ESP-IDF (Espressif IoT Development Framework(or Arduino Framework we can make the ESP32-S3 discoverable by iOS Device and create a custom BLE Service to read, write, and connect to our device.

On the iOS development side, we will utilize CoreBluetooth Framework for BLE and scan for BLE peripherals to identify our device.

Using the kaggle cosmetic foundation shade cvs file we can create a viewable iOS application showcasing the Brand, product, Image, Shade name, and hex value. We will use Apple's Core Data framework to host the information and parse through the database using SQLite to fetch data.

Based on the Data provided by the color sensor, we will display to the user the following:

- RGB breakdown of user's skin as percentages and integers
- Hex value of their skin tone
- List of products matching their hex value (if they exist)

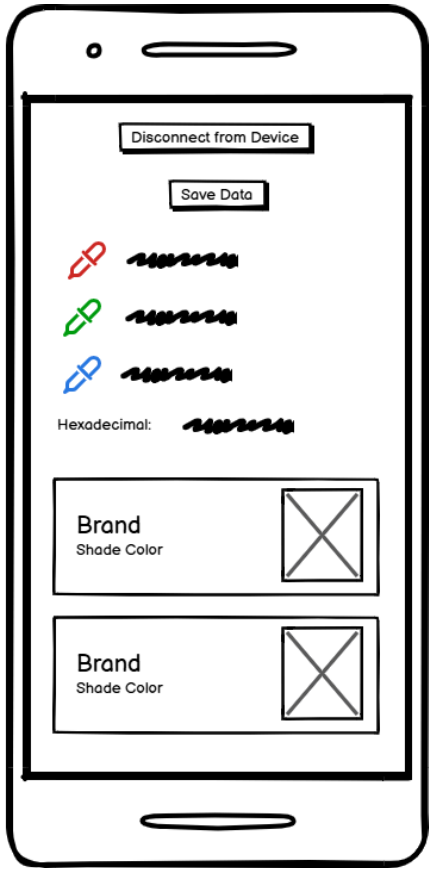

Figure 3 Mobile Application Prototype

The above image is a prototype of how the UI would appear to the user for easy readability and further application use.

In the case that the BLE fails, the raw data provided from the color sensor and our PCB will be displayed via a USB cable. Users can manually enter the RGB and/or hex value and view their corresponding makeup brands and shades.

The subsystem will require some level of algorithm and processing to determine matching makeup products. We expect that the hex values of makeup products are not 100% RGB to match the user's hex value so we have to determine a valid tolerance of R, G, B between the sensor and makeup. In order to accurately determine if a product shade is valid, we need to know the undertone match (eg, cool, warm), shade depth (eg. red/brown for dark tones, peach, pink, ivory for lighter tones), and saturation.

Interactions:

The display subsystem will interact with the processing subsystem (microcontroller) and display the data provided from the sensors to the screen. It will not directly interact with the sensor subsystem but will be responsible for showing the output of the sensors based on data given by the microcontroller. It will interact with the microcontroller via BLE and UART-USB

Requirements:

- Display real-time RGB and UV index on the screen

- Implement tolerance calculations for perceptually accurate product matches
- Display product information that matches RGB values from the color sensor
- Utilize Kaggle's foundation dataset

Current Parts:

- iOS Smart Device (v. 15 or higher)
- UART to USB Cable

2.3 Tolerance Analysis

The most critical aspects of our project are the sensors and capturing and analyzing the data appropriately and accurately. While we cannot simulate this design, the design is heavily built on algorithms and calculations which are determined below. By accurately calculating the RGB and UV values from the sensors we will be able to complete the project.

2.3.1 Electronics System

Color Sensor

(The following information is detailed from Cornell University Research [2])

RGB is the default color space and each pixel's color is represented as (R, G, B) values ranging from 0 to 255, the below thresholds identify the dominant nature of the skin and filter out low-intensity pixels and non-skin colors.

We will normalize raw RGB values using the following equations:

$$r = \frac{R}{R+G+B}, g = \frac{G}{R+G+B}, b = \frac{B}{R+G+B}$$

HSV (Hue, Saturation, Value) is the intuitive representation of color; separating color, intensity, and colorfulness. Hue is measured from a range of $0° \; to \; 360°$ sources, while saturation and value range from $0 \; to \; 1.0$. The ranges help exclude non-skin hues and account for variations in lighting and undertones in the skin.

YCbCr (Luminance, Blue Difference, Red Difference) separates luminance from chrominance, which makes it less sensitive to lighting variations. (Y, Cb, Cr) ranges from 0 to 255 and the ranges define a 'skin locus' in chrominance space which aims to isolate skin tones from non-skin regions. YCbCR values can be obtained from the RGB color space using the following formulas:

$$Y = 0.299R + 0.287G + 0.11B, Cr = R - Y, Cb = B - Y$$

The constraints below also reduce false positives from backgrounds:

$Cr \leq 1.5862 \bullet Cb + 20, Cr \geq 0.3448 \bullet Cb + 76.20069$

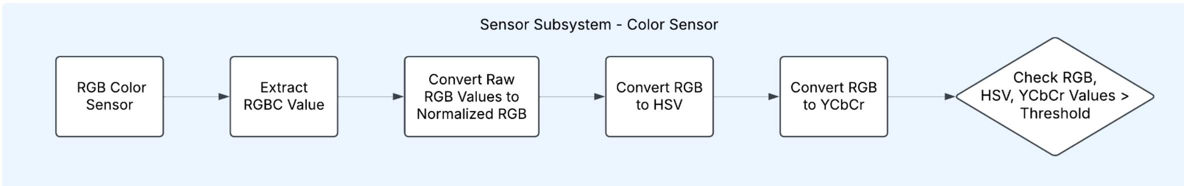

Figure 4 Color Sensor Subsystem

Based on research from Cornell University, we can mathematically break down skin tone by pixels as follows:

RGB Constraints	HSV Ranges	YCbCr Chrominance Boundaries
$R > 95, G > 40, B > 20$ $R > G, R > B, \|R - G\| > 15$	Hue: $0° \leq H \leq 50°$ SV: $0.23 \leq S \leq 0.68$	$85 \leq Cb \leq 135, 135 \leq Cr \leq 180$ $Y > 80$ (Luminance Threshold)
Filters isolate skin pixels by leveraging the dominant red component in human skin tones	The HSV parameters exclude no skin hues (blues/green) and low saturation shadows	YCbCr separation of luminance (Y) and chrominance (Cb/Cr) reduces lighting dependency

The Cornell study achieved 94-96% precision in skin detection using the above metrics using the Pratheepan dataset for human skin detection. We aim for an accuracy of 80-85% using the same metrics as their research was primarily based on image processing.

UV Sensor

The Adafruit LTR390 UV sensor is responsible for detecting UVA radiation (300-350 nm) and converting it into a UV Index (UVI) value. To ensure accurate SPF recommendations, we must validate that the sensor's UVI output closely matches actual environmental UV exposure within an acceptable ±10% tolerance range.

To assess the accuracy of the LTR390, we will compare its output to a standard UV index reference in the same real-world conditions as our device. This includes:

1. Reference Measurement: Using trusted UV Index measurement sources such as:
    a. National Weather Service (NWS) or EPA UV Index data
    b. A secondary commercial UV meter for direct comparison
2. Measurement setup:
    a. Place the LTR390 sensor and the reference UV meter side by side under the same conditions for measurement
    b. Take their readings during different times and different locations to capture UV variations

3. Error Calculation:
    a. Compute the percentage error between the LTR390's output and the reference UV index using this approximation error formula (percent error):
        i. $\%Error = \left|\frac{UVI_{sensor} - UVI_{actual}}{UVI_{actual}}\right| * 100$
        ii. A valid reading should fall within ±10% of the actual UV index

Through direct comparison with a reference UV index, we ensure that the LTR390 sensor maintains an accuracy of ±10%. This guarantees that our device provides reliable UV exposure readings, strengthening its ability to recommend proper SPF protection alongside foundation matching.

Software/Display System

To match each product's hex value to skin tones and calculate a valid RGB comparison range we have to calculate a tolerance of each hex pair (RR, GG, BB). We can follow the above metric to compare the product's RGB values and transform and validate the YCbCR and HSV values.

While it is feasible to produce a hex value 100% matching skin tone RGB, we wish to still determine close-match products that the user may obtain.

We want to calculate an absolute difference between the skin and makeup values for each channel (R,G,B) [2]:

- Skintone: (R_s, G_s, B_s)
- Makeup: (R_M, G_M, B_M)

Absolute Difference

- Red: $|R_M - R_s|$
- Green: $|G_M - G_S|$
- Blue: $|B_M - B_S|$

The absolute difference can help us understand how similar or different the two colors are. We will add an extra column to the dataset of makeup products "R, G, B" to speed up queries to make sure that the undertones match and the absolute difference is at a minimum.

Additionally, CIELAB is a 3D color space device-independent used for measuring and comparing perceptible colors to determine the numerical differences [9]. Delta E is measured on a scale of 0 to 100 to measure the amount of color difference or variation that is acceptable. We want a Delta E that is > 2 as ≤ 1.0 is not perceptible by the human eye while $1 - 2$ is perceptible through close observation [10].

However, while CIELAB would produce the most accurate value it requires heavier computation. For the purpose of this project, we aim for a more flexible per-channel tolerance and relational constraints.

$Tolerance: \pm \Delta = 10, 15,$

10 would provide the most suitable match while 15 offers more flexibility. Our relational constraints will be:

- $R > G$
- $R > B$
- $|R - G| > 15$

The relational constraints make sure that makeup's undertone is similar to the undertones of the skin.

Section 3: Ethics & Safety

3.1 Ethics

3.1.1 Algorithmic Fairness & Bias Mitigation

- Our device relies on Cornell University's RGB/YCbCr skin tone detection model, which presents a risk of excluding underrepresented Fitzpatrick skin types. In alignment with the ACM Code of Ethics 2.7 (fairness) [11], we will implement the following measures:
    - Validate detection thresholds using the Pratheepan dataset to achieve ≥95% accuracy across all skin types.
    - Utilize MIT-licensed Kaggle foundation datasets to eliminate proprietary brand bias and ensure inclusivity.
    - In alignment with the ACM Code of Ethics (1.5) [11] which outlines giving credit and respecting intellectual property rights, we will ensure that the references to Cornell University's algorithm is properly cited and comply with their licensing.

3.1.2 Environmental Responsibility

- Consistent with ACM Code 1.1 (public good) [11], our design and manufacturing processes aim to minimize environmental impact. This includes selecting sustainable materials where possible, designing for energy efficiency, and adhering to e-waste recycling guidelines for all components, including batteries and electronic parts.

3.2 Safety

3.2.1 Battery Safety

- The 7.4V Li-ion battery pack used in our device complies with UL 2054 standards, incorporating overcurrent protection and FCC Part 15 EMI shielding to prevent potential hazards. However the LDO may risk dispatching more power than it is rated for, so we will use a heat sink for protection. This aligns with IEEE 1725 standards [12] for rechargeable battery safety.

3.2.2 Disposal

- To minimize environmental impact, we will adhere to campus e-waste disposal guidelines for recycling PCBs and UV LEDs through the UIUC Sustainable Electronics Center.

3.2.3 Laboratory Safety Compliance

- Development and testing will be conducted in University of Illinois laboratories, where full compliance with campus safety policies is essential. This involves following electrical safety procedures, handling PCB components with care, and observing all lab-specific regulations to maintain a safe and hazard-free workspace.

Section 4 References

[1] T. Davison. (2024, Nov, 5). *The Environmental Impact of the Beauty Industry*. [online]. Available: https://blog.cleanhub.com/beauty-industry-environmental-impact

[2] S. Kollur, D. Kalbande, P. Shimpi, C. Bapat, J. Jatakia. (2017, Aug, 9). *Human Skin Detection Using RGB, HSV and YCbCr Color Models.* [online]. Available: https://arxiv.org/pdf/1708.02694

[3] Texas Instruments, "OPT4048 High-Speed High-Precision Tristimulus XYZ Color Sensor IC Datasheet," [Online]. Available: https://www.ti.com/lit/ds/symlink/opt4048.pdf?ts=1739416997428&ref_url=https%253A%252F%252Fwww.mouser.com%252F.

[4] Mouser Electronics, "OPT4048DTSR - Texas Instruments Color Sensor IC," [Online]. Available: https://www.mouser.com/ProductDetail/Texas-Instruments/OPT4048DTSR?qs=rQFj71Wb1eUko9TNzYxksQ%3D%3D.

[5] SparkFun Electronics, "SparkFun Color Sensor OPT4048 Schematic," [Online]. Available: https://cdn.sparkfun.com/assets/a/b/0/5/c/22638-SparkFun_Color_Sensor_OPT4048-Schematic.pdf.

[6] B. Siepert, "Adafruit LTR390 UV Sensor," Adafruit Industries, June 3, 2024. [Online].Available:

https://cdn-learn.adafruit.com/downloads/pdf/adafruit-ltr390-uv-sensor.pdf

[7] American Cancer Society, "What Factors Affect UV Risk?," June 26, 2024. [Online]. Available:

https://www.cancer.org/content/dam/CRC/PDF/Public/9418.00.pdf

[8] Expressif. *"ESP32-S3 Series Datasheet v1.9"*. ESP32-S3 Series Datasheet https://www.espressif.com/sites/default/files/documentation/esp32-s3_datasheet_en.pdf

[9] k. Phillips. (2024, Aug. 22)*"What Is CIELAB Color Space?".* [Online]. Available:https://www.hunterlab.com/blog/what-is-cielab-color-space/

[10] ViewSonic. (2021, Jan, 05). "*What is Delta E? And Why Is It Important for Color Accuracy*?
[Online]. Availability:
https://www.viewsonic.com/library/creative-work/what-is-delta-e-and-why-is-it-important-for-color-accuracy/#:~:text=Delta%20E%20is%20measured%20on,2%3A%20Perceptible%20through%20close%20observation

[11] Association for Computing Machinery, "*ACM code of ethics and professional conduct*". [Online]. Available: https://www.acm.org/code-of-ethics. [Accessed: Feb. 13, 2025].

[12] Institute of Electrical and Electronics Engineers. *"IEE Code of Ethics"*.[Online]. Available: https://www.ieee.org/about/corporate/governance/p7-8.html [Accessed: Feb. 13. 2025]