Reflective Color Sensing with Avago Technologies' RGB Color Sensor

White Paper

Abstract—Reflective color sensing is typically realized through photodiodes with multiple illuminants or photodiodes coated with color filters containing a single illuminant. This paper presents the concept of reflective color sensing using an RGB color sensor. First, reflective color sensing theory and its basic elements are discussed. Then hardware design considerations and sensor output interpretations are addressed.

Reflective Sensing Theory

There are three important elements in reflective sensing: detector, target and illuminant. The detector is a device that captures light reflected from an object. The target is an object whose color is measured, like colored paper or paint. Typically non-emissive, it reflects and absorbs different amounts of light at different wavelengths. The illuminant is a light source whose spectrum covers the visible wavelengths, like sunlight.

In a reflective color sensing system, the detector and illuminant are usually mounted together in a module. When the module is placed close to the target, light from the illuminant will fall onto the target surface and reflect to the detector. The color of the light reflected off the surface is a function of the color of the surface. For example, white light focused onto a red surface is reflected as red. The reflected red light impinges on the color sensor producing R, G, and B output voltages. By interpreting the three voltages, the color can be determined. Since the three output voltages increase linearly with the intensity of the reflected light, the color sensor also measures the reflectivity of the surface or object.

Reflective Sensing System Hardware Design Considerations

There are three basic elements in a reflective sensing system: the RGB color sensor, an external illuminant such as an LED, and a non-emissive object.

1) Selecting a detector

What kind of detector is suitable for reflective sensing? A suitable detector needs to have good sensitivity and spectral coverage. In reflective sensing, light captured by the detector is reflected from the object under measurement. Hence, the intensity of the reflected light is lower than the intensity of the direct lighting source.

The spectral response of the individual Red, Green and Blue channels should be overlapping to ensure all wavelength information is captured. Figures 1 and 2 below show the overlapping and non-overlapping spectral responses, respectively. Figure 3 shows an arbitrary spectrum of a signal reflected from a bluish surface.

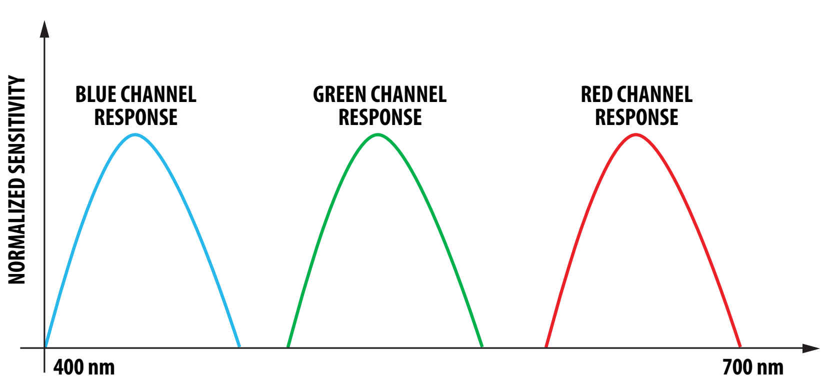


Figure 1. Non-overlapping spectral response

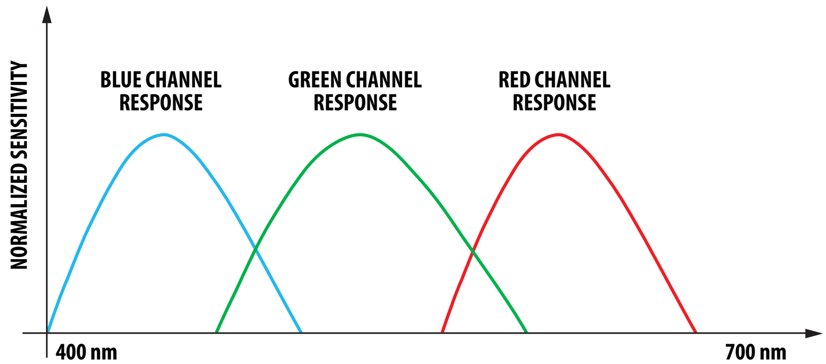


Figure 2. Overlapping spectral response

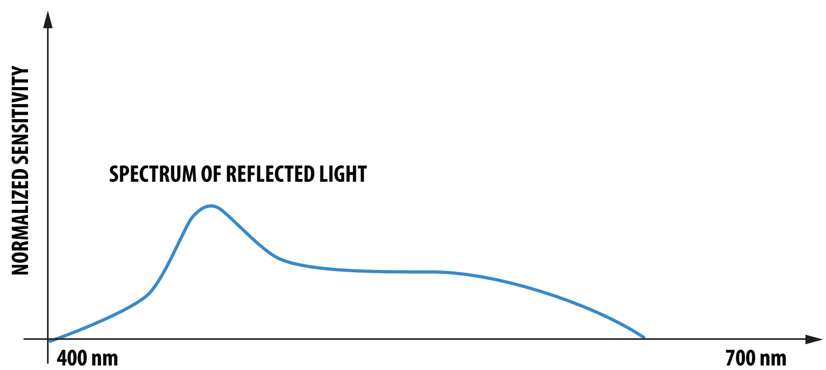


Figure 3. Spectrum of light reflected from bluish surface

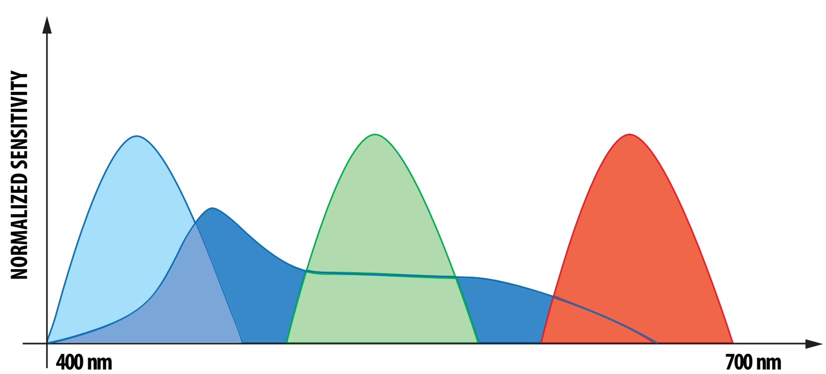


Figure 4. Sensor spectral profile overlaps with reflected light

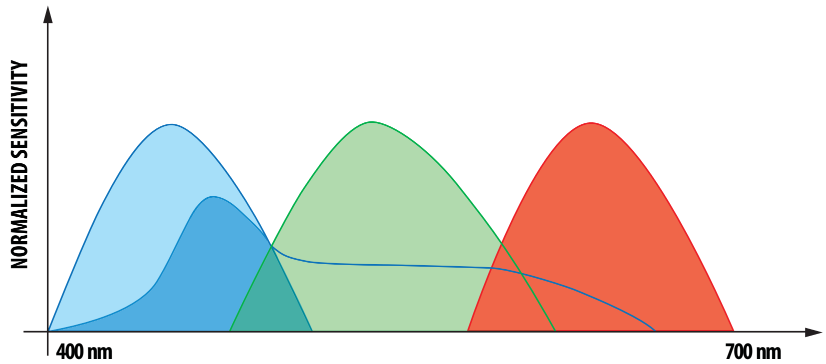


Figure 5. Sensor spectral profile overlaps with reflected light

In a mathematical context, sensor output is directly proportional to the overlapping area of the reflected signal and sensor spectral profile. Figure 4 shows two non-overlapping areas. Information in those regions will not be captured by the sensor. In Figure 5, we observe that the information of the reflected signal is properly captured by the sensor with an overlapping spectral response.

Avago Technologies has a range of color sensors suitable for reflective color sensing. These color sensors have good sensitivity and spectral response profiles. Look for these Avago Technologies' part numbers:

a) HDJD-S722-QR999

b) ADJD-E622-QR999

c) ADJD-S313-QR999

d) ADJD-S312-QR999

2) Selection of Illuminant

The illuminant should have a spectrum that is as broad as possible. Why? A broad-spectrum illuminant ensures that the object surface reflectance or characteristic is fully recovered. Figure 6 shows the D65 illuminant spectrum.

Other than having a broad spectrum, the illuminant should be relatively bright and available in various sizes. One option to consider is a white LED. One with high brightness and a narrow angle is preferable. In addition, the selection of packages greatly depends on the end application. If space is a constraint, surface mount white LEDs are the ideal choice; otherwise, use through hole lamps. Several recommendations are the HLMP-CW11 and the HSMW-C191. To find out more about Avago Technologies' color sensing solutions, contact your distributor, or visit the Avago Technologies' website, www.avagotech.com.

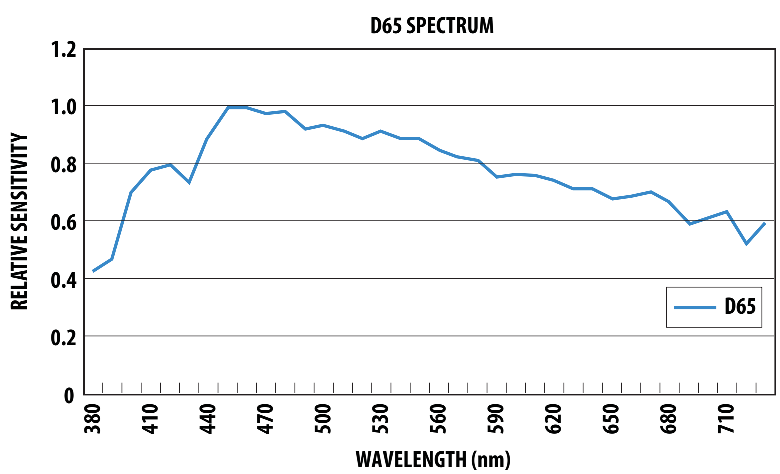


Figure 6. D65 illuminant spectrum

3) Mounting of the Detector and Illuminant

How are the detector and illuminant mounted? Is the mounting of the device important? There are two types of reflection: specular and diffuse reflection (see Figure 7). In specular reflection, equal light is bounced off the surface at a 90 degree angle with respect to the incident light. This type of reflection does not carry much color information. Glossy material will have a higher specular reflectance compared to a matte surface.

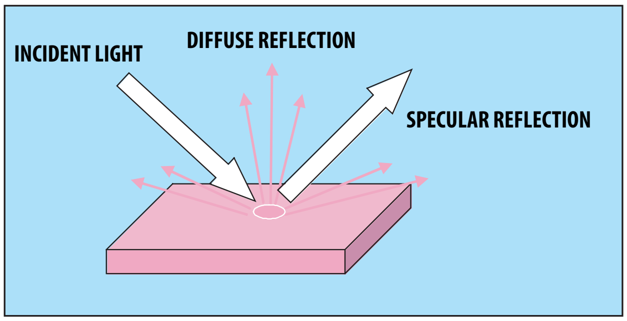


Figure 7. Specular and diffuse reflection

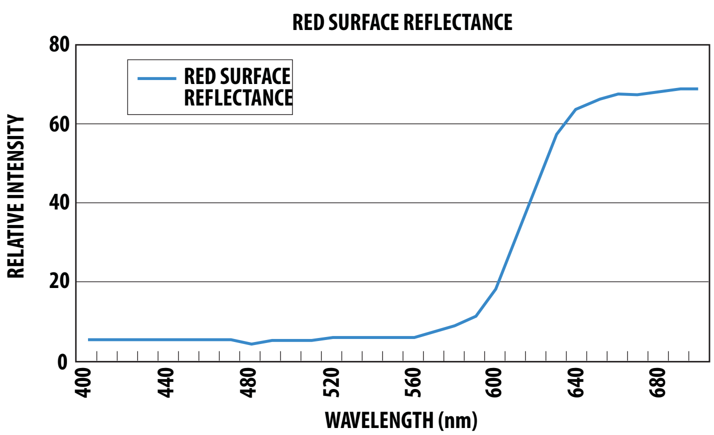


Figure 8. Example surface reflectance plot of a reddish surface

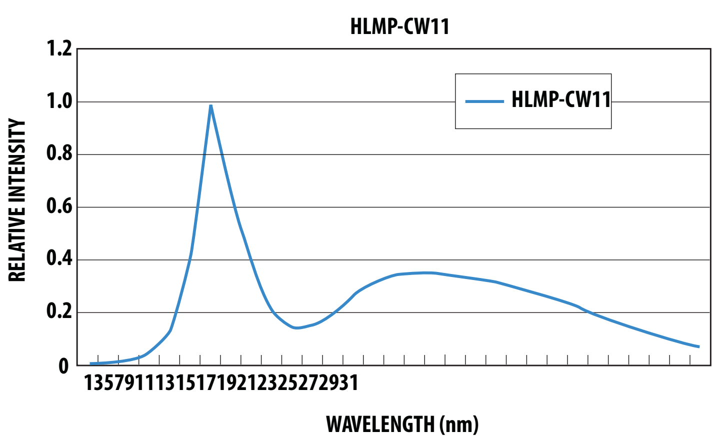


Figure 9. HLMP-CW11 spectrum

In reflective color sensing, we are more interested in diffuse reflectance. In this type of reflection, incident light is modified by the surface properties. The degree of reflection at each wavelength is dependent on the surface reflectance.

The spectrum of the incident light source will be modified by the object/target surface reflectance. Figures 8 and 9 show the surface reflectance of a red target and the white LED spectrum, respectively. Figure 10 shows the spectrum of the reflected light signal.

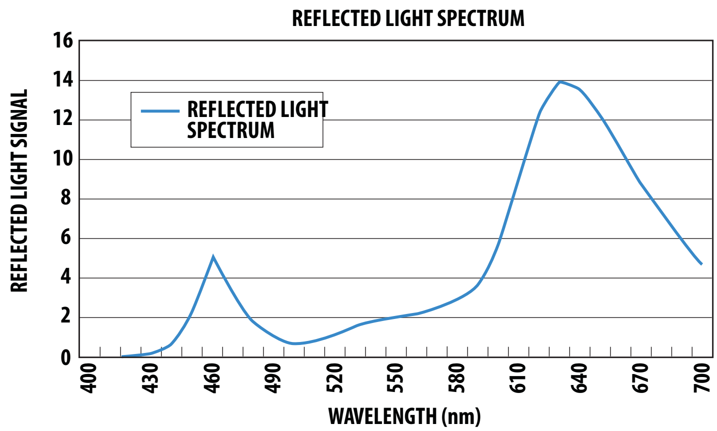


Figure 10. Reflected light signal

Figures 11 and 12 show the geometrical setup of the illuminant and detector. The setup can also include more than one LED if the brightness from one bulb is not sufficient. Figure 13 shows the top view of a detector with four LEDs.

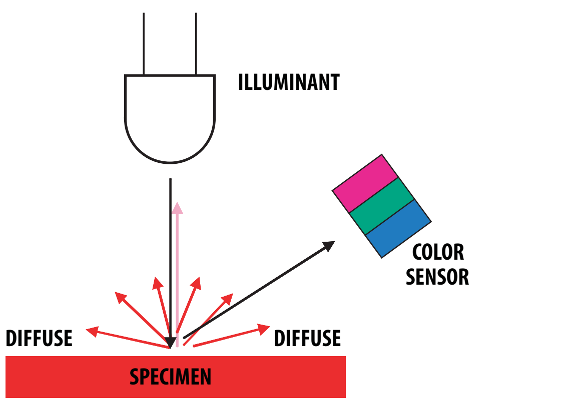


Figure 11. A typical setup is 45°/0° geometry

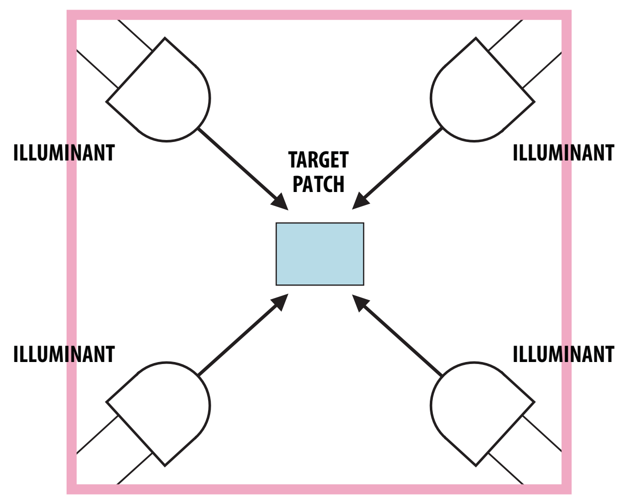


Figure 13. 45°/0° geometry

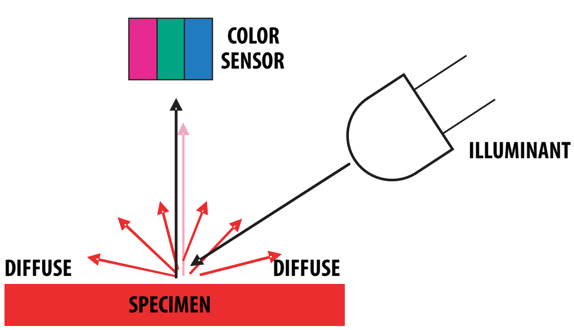


Figure 12. A 45°/0° geometry

Ambient light rejection/elimination

– The detector and illuminant pair are enclosed in a housing to eliminate ambient light.

– The design rule is simple: use an enclosure to minimize ambient light and light traveling directly from the illuminant to the detector.

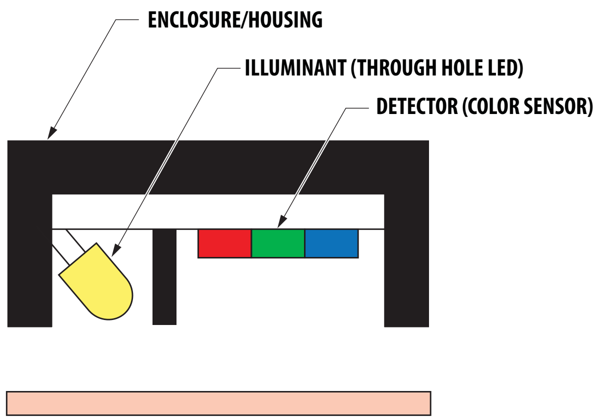


Figure 14. Example setup for a through-hole LED with color sensor

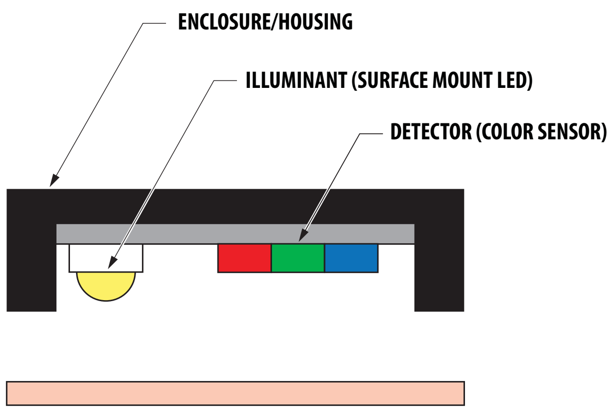
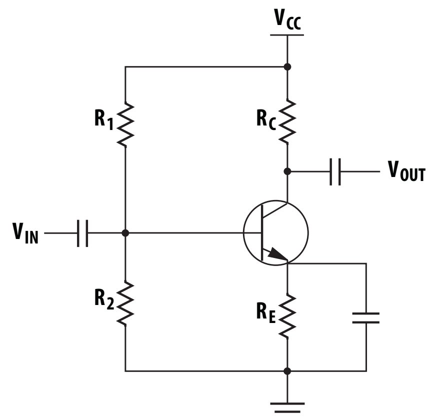


Figure 15. Example setup for a surface mount LED with color sensor

4) Post Sensor Output Signal Processing

a) Second level amplification.

Sometimes the output voltage level from the sensor may be too low. Adding a post amplifier will amplify the voltage. A simple amplifier can be constructed using a bipolar junction transistor as shown below.



The circuit above is a Current-Gain-Stabilized Circuit that provides both stabilization for leakage and current gain change. It is necessary to determine the four resistor values. Usually the manufacturer's datasheet will provide information for the recommended supply voltage (Vcc) and operating point (VCEQ, ICQ, IBQ). Otherwise, the operating point can be chosen as half the supply voltage (VCEQ = 1/2 VCC) to maximize the efficiency of the amplifier. The ICQ and IBQ can then be found by drawing a load line on the transistor characteristics graphs.

The selection of the emitter resistor needs some engineering judgment. It must not be too large where it limits the range of the voltage swing of collector to emitter voltage. The typical value of RE will be:

$$R_E = \frac{k \cdot V_{CC}}{I_{CQ}} \quad \text{where } 0.1 < k < 0.25$$

$$R_E = \frac{V_{CC} - V_{CEQ}}{I_{CQ}} - R_E$$

Next are some considerations when selecting the base resistors, R1 and R2. For the circuit to operate efficiently, it is assumed that the current through R1 and R2 be approximately equal to or greater than the base current by 10:1.

$$R_E \leq 0.1 \times h_{FE} \times R_E$$

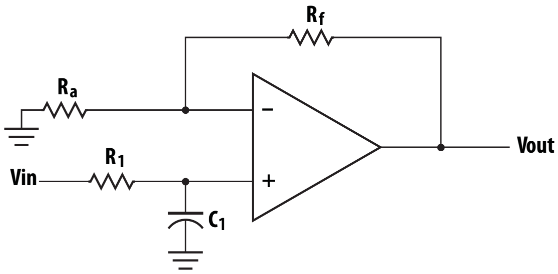
$$V_B = \frac{R_2}{R_1 + R_2} \cdot V_{CC} = V_{BE} + V_E$$

$$\therefore R_1 = \frac{R_2}{V_{BE} + V_E} \cdot V_{CC} - R_2$$

Another common method of constructing an amplifier is to use an op-amp. The figure below shows the circuit of a non-inverting amplifier with a low-pass filter. The gain and the cutoff frequency are defined with the following equations:

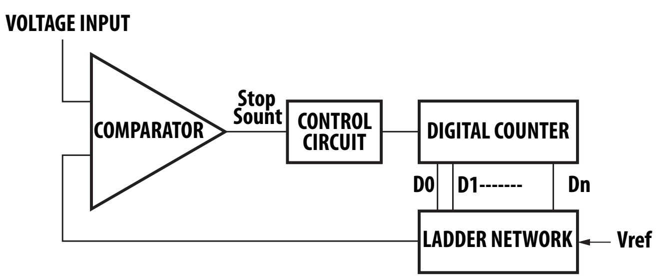
$$Vout = 1 + \frac{R_f}{R_a} \cdot Vin$$

$$f_{OH} = \frac{1}{2\pi R_1 C_1}$$



b) A/D conversion.

An analog to digital converter may be needed to convert the analog voltage outputs from the RGB color sensor if further processing by the microprocessor is needed. Most microcontrollers have built-in ADC, however, a simple microcontroller can be built using a ladder network with a counter and comparator circuits.



In the circuit diagram above, the digital counter counts from zero, driving a ladder network that produces a staircase voltage increasing one voltage level for each step count. A comparator circuit, receiving both the staircase voltage and analog input voltage, provides a stop signal once the staircase voltage is greater than the input voltage. The counter value at that time is the digital output.

The resolution of this circuit will depend on the number of bits of the counter, "n", and the reference voltage of the ladder network.

$$\text{Resolution} = \frac{Vref}{2^{n}}$$

There are many ADC chips in the market with a wide selection of resolutions. Avago Technologies' color controller chip, HDJD-J822-SCR00, can take in a 3-channel sensor voltage input and convert it to a digital value, which can then be interfaced with other devices using the 2-wire serial interface. The HDJD-J822 has a 10-bit resolution ADC and Vref up to 2.5 V. The best option is Avago Technologies' digital color sensor, the ADJD-S313/S312, with an integrated ADC and RGB color sensor in one-chip.

5) Sensor Output Interpretation

How do we interpret the sensor output? Color sensor output data can be interpreted via either a look-up table or transformation to a standard color space such as CIE XYZ, CIE LAB, etc.

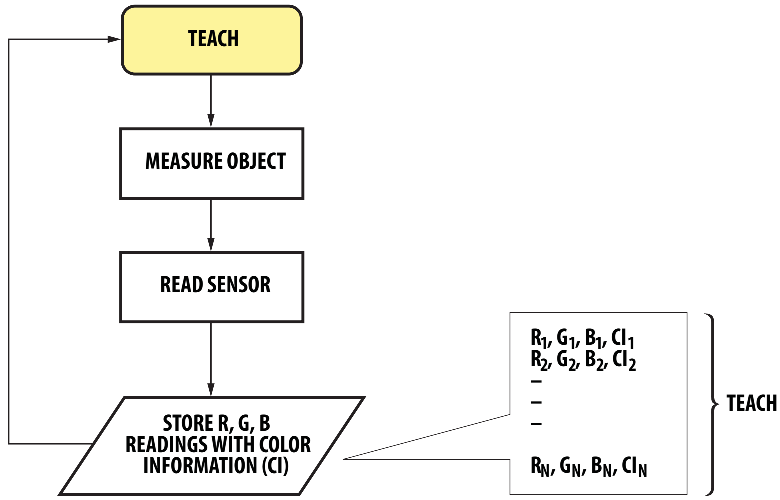
a) Look-up Table

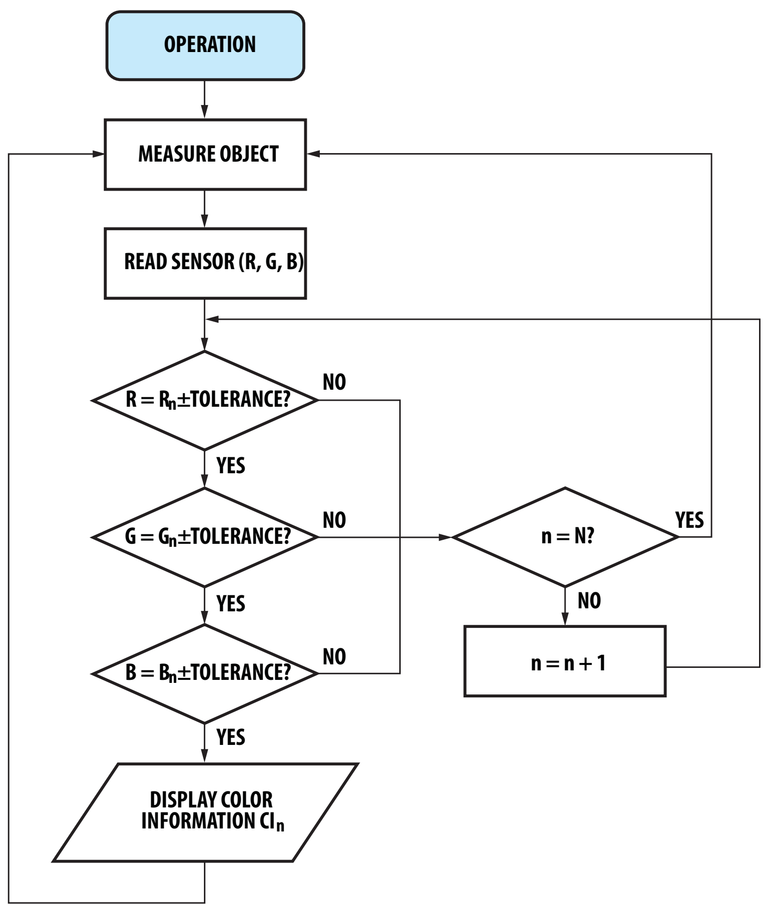
The look-up table method is suitable when a set of colors needs to be identified without requiring the actual color point. First, the color of the set of media is measured by the color sensor. The RGB readings are stored in memory together with the color information (teach mode). During the operation mode, the measured RGB readings are compared with the RGB data stored earlier. If the RGB measured matches the RGB stored, usually within a certain tolerance, then the color information for that color can be retrieved.

If brightness information is not significant in the application, the ratio of the Red, Green, and Blue readings can be stored instead of the RGB raw readings. The ratio is obtained by dividing the Red, Green, and Blue channels with the value of one of the channels. For example, if the Green channel is selected to be divided, the data stored will be:

$$\left[\frac{R_n}{G_n}, \frac{G_n}{G_n} = 1, \frac{B_n}{G_n}; \ Color\_inf_n\right] \quad \text{where } n = 1, 2, 3, \ldots N$$

Below are the flow charts for the programming of teach mode and operation mode:





b) Transformation Matrix

The color sensor output can be transformed to standard tri-stimulus values, CIE XYZ using linear models, by multiplying the RGB values with a 3x3 transformation matrix:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = [\, 3x3\ Matrix \,] \cdot \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

The question now is: how does one find the 3x3 transformation matrix? One method is the statistical method described below.

Statistical Method:

The color sensor output can be transformed to a standard color space via a mapping process. The mapping process involves solving the following matrix equation:

CIE Camera Matrix | **Sensor Matrix** | **Coefficient Matrix**

$$\begin{bmatrix} X1 & Y1 & Z1 \\ X2 & Y2 & Z2 \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ Xn & Yn & Zn \end{bmatrix} = \begin{bmatrix} R1 & G1 & B1 \\ R2 & G2 & B2 \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ Rn & Gn & Bn \end{bmatrix} - \begin{bmatrix} a11 & a12 & a13 \\ a21 & a22 & a23 \\ a31 & a32 & a33 \end{bmatrix}$$

or $C = S \times T$

where Xn,Yn,Zn denotes the standard color checker values in CIE XYZ. Rn, Gn, Bn denotes the RGB values measured by a color sensor.

The goal here is to solve for the coefficient matrix to enable the formation of mapping equations.

$X = a11 \times R + a21 \times G + a31 \times B$

$Y = a12 \times R + a22 \times G + a32 \times B$

$Z = a13 \times R + a23 \times G + a33 \times B$

The coefficient matrix, and therefore the individual mapping coefficients, are easily obtained by multiplying the pseudo-inverse of the Sensor Matrix by the camera matrix.

$T = S^{-1} \times C$

(Methods for finding a Moore Penrose pseudo-inverse matrix are out of the scope of this paper, but are widely available in other literature). Once the coefficient matrix is established, any measured RGB values can be converted to the standard CIE XYZ space.

c) Conversion from XYZ to CIE Yxy

The tri-stimulus values X, Y, and Z define a color in the CIE XYZ space. The CIE XYZ is a 3-D linear color space, and the results are not easily visualized. Because of this, CIE also defined a color space in 1931 for graphing color in 2-D independent of lightness, known as Yxy color space. The Y is the lightness component of color, while the xy are the chromaticity coordinates calculated from the XYZ tri-stimulus values. The concept of color can be divided into two parts: brightness and chromaticity. For example, the color white is a bright color, while the color grey is considered to be a less bright version of that same white. In other words, the chromaticity of white and grey are the same, while their brightness differs.

The x and y are calculated based on the following formulas:

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

Y is identical to the tri-stimulus value Y.

d) Conversion from XYZ to another RGB Color Space

To convert XYZ to another RGB color space, we can again map it using a 3x3 matrix.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = [\, 3x3\ Matrix \,] \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

Note: Some XYZ systems use a (100, 100, 100) scale. In this case, divide the RGB by 100 to get a (1, 1, 1) scale.

Next, the RGB values obtained are inserted into the following equations to achieve the actual R'G'B' values.

$R' = round\,(255 \cdot (1 + offset) \cdot R^{(\gamma)} - offset) \quad$ for $1 \geq R \geq transition$

$R' = round\,(255 \times slope \times R) \quad$ for $transition > R \geq 0$

The same formula applies to obtain G' and B'.

The 3x3 Matrix, offset, gamma, and transition values for most of the RGB color space can be obtained from other literature.

Example: Conversion from XYZ to sRGB

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 3.2406 & -1.5372 & -0.4986 \\ -0.9689 & 1.8758 & 0.0415 \\ 0.0557 & -0.2040 & 1.0570 \end{bmatrix} \cdot \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

If 0.00313 > R, G, B ≥ 0 then

$$R'_{sRGB} = \text{round}\,(255 \times 12.92 \times R)$$

$$G'_{sRGB} = \text{round}\,(255 \times 12.92 \times G)$$

$$B'_{sRGB} = \text{round}\,(255 \times 12.92 \times B)$$

else if 1 ≥ R, G, B ≥ 0.00313

$$R'_{sRGB} = \text{round}\,(1.055 \cdot R(0.42) - 0.055)$$

$$G'_{sRGB} = \text{round}\,(1.055 \cdot R(0.42) - 0.055)$$

$$B'_{sRGB} = \text{round}\,(1.055 \cdot R(0.42) - 0.055)$$

The final sRGB values can be reproduced in any monitor.

Conclusion

The two basic elements in reflective sensing system hardware design are the detector and illuminant. A detector with good sensitivity and spectral coverage is desirable, while an illuminant with a broad spectrum is suitable for reflective sensing. Sensor output can be processed or interpreted via two methods: the look-up table and the transformation matrix. Avago Technologies offers a wide range of RGB color sensors and LEDs that meet the above mentioned requirements. The hardware design consideration, post sensor signal conditioning, and methods of sensor output interpretation serve as a general guideline for customers who wish to design a reflective sensing system with Avago Technologies' RGB color sensors.

References

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