Reflective Color Sensing with Avago Technologies' RGB Color Sensor

White Paper

***Abstract* — Reflective color sensing is typically realized through photodiodes with multiple illuminant or photodiodes coated with color filters with single illuminant. This paper presents the concept of reflective color sensing using an RGB color sensor. First, reflective color sensing theory and the basic elements will be discussed. Then, we will continue on the hardware design consideration and how the sensor output can be interpreted.**

Reflective Sensing Theory

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

In a reflective color sensing system, the detector and illuminant is 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 back 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 Consideration

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? It 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 light intensity is lower than the direct lighting type.

The spectral response of the individual Red, Green and Blue channel 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.

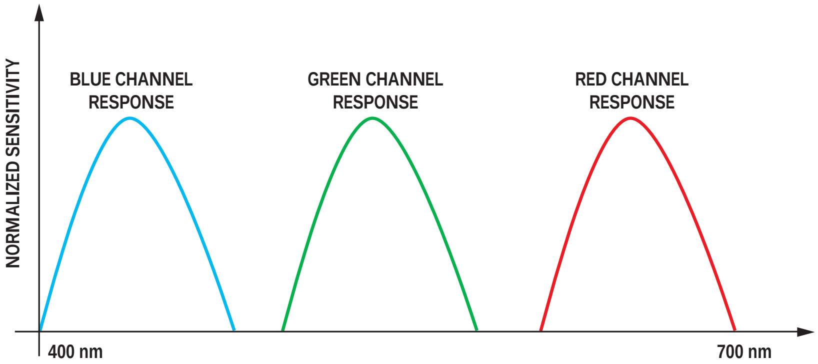


Figure 1. Non-overlapping spectral response

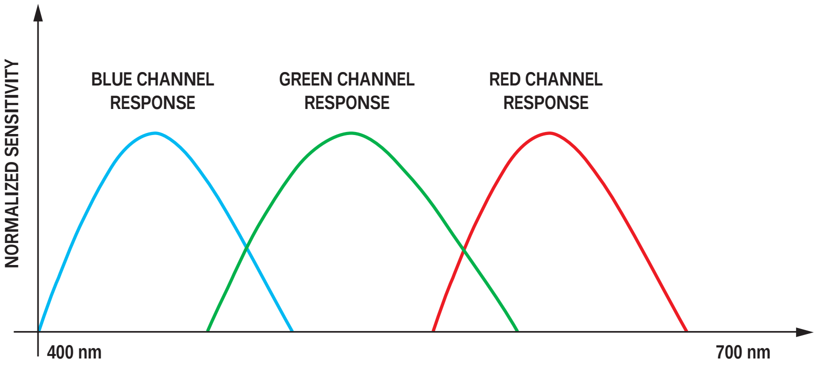


Figure 2. Overlapping spectral response

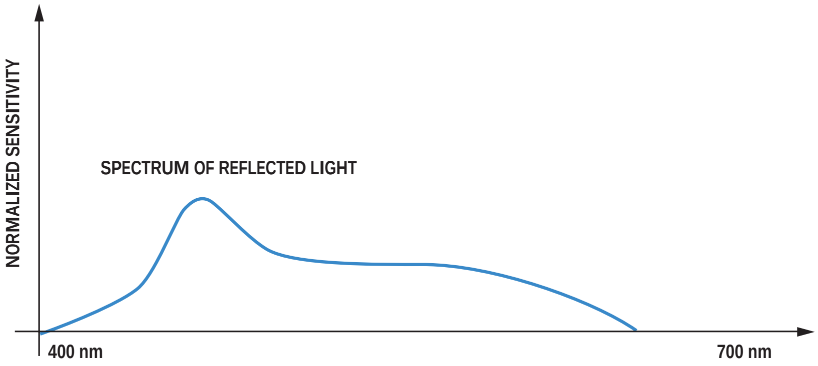


Figure 3. Spectrum of light reflected from bluish surface

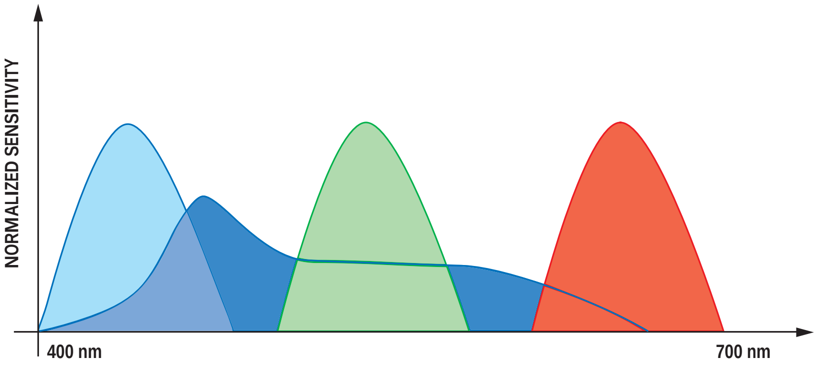


Figure 4. Sensor spectral profile overlaps with reflected light

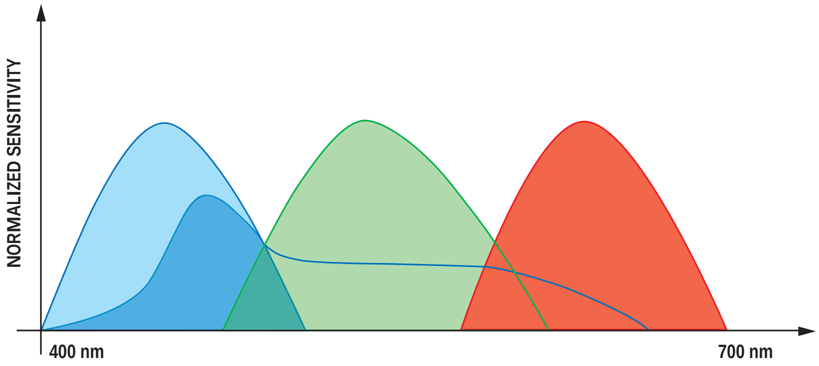


Figure 5. Sensor spectral profile overlaps with reflected light

In a mathematical context, sensor output is directly proportional to the overlapping area of the reflected signal and sensor spectral profile. Figure 4 shows there are two non-overlapping areas. This means that information in that region 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, which are suitable for reflective color sensing. These color sensors have good sensitivity and spectral response profile. Look for these Avago 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? Broad-spectrum illuminant will ensure that the object surface reflectance or characteristic is fully recovered. Figure 6 shows the D65 illuminant spectrum.

Other than broad spectrum, illuminant should be relatively bright and available in various sizes. One of the options we consider is white LED. White LED with high brightness and 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 will be the ideal choice. Vice versa for through hole lamps. Some part numbers recommended are: HLMP-CW11 and HSMW-C191. To find out more about Avago Technologies color sensing solutions, contact your distributor, or visit the Avago Technologies website, www.avagotech.com.

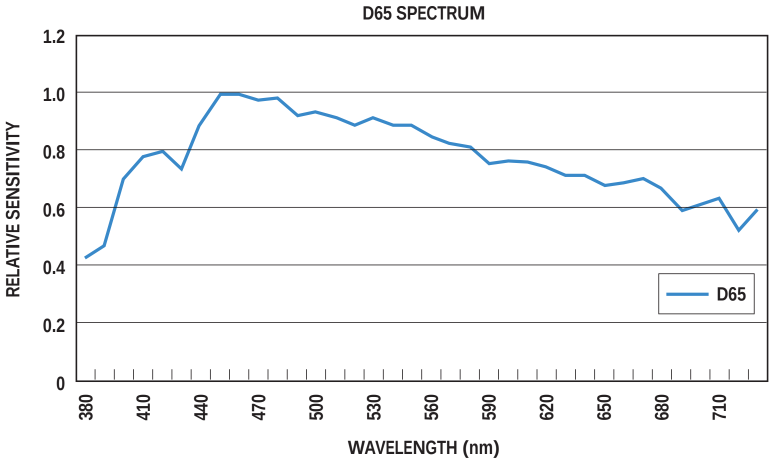


Figure 6. D65 illuminant spectrum

3) Mounting of Detector and Illuminant

How is 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 the 90º 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.

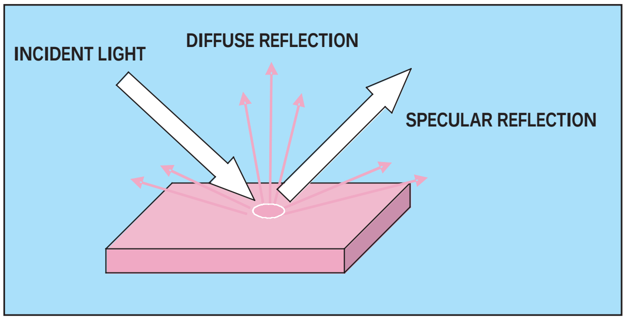


Figure 7. Specular and diffuse reflection

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.

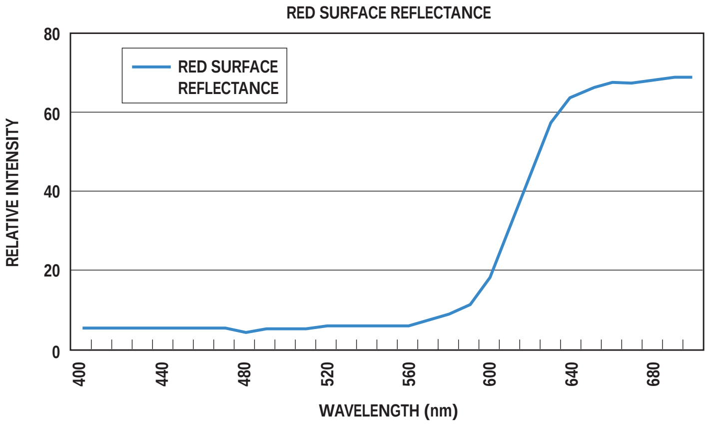


Figure 8. Example surface reflectance plot of a reddish surface

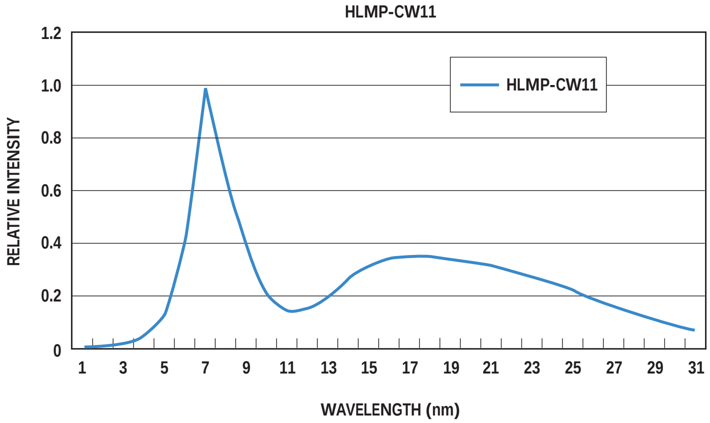


Figure 9. HLMP-CW11 spectrum

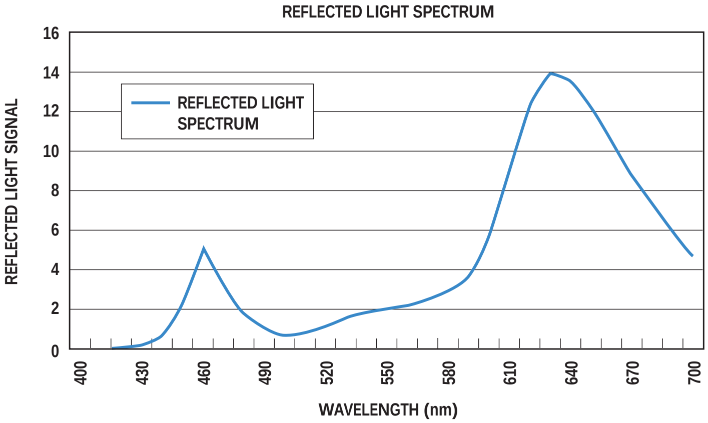


Figure 10. Reflected light signal

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 is not enough from one bulb. Figure 13 shows the top view of a detector with 4 LEDs.

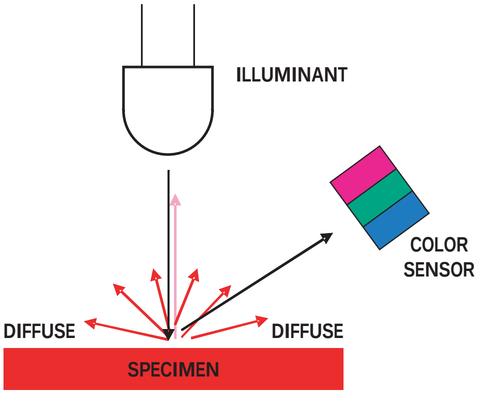


Figure 11. A typical setup is 45°/0° geometry

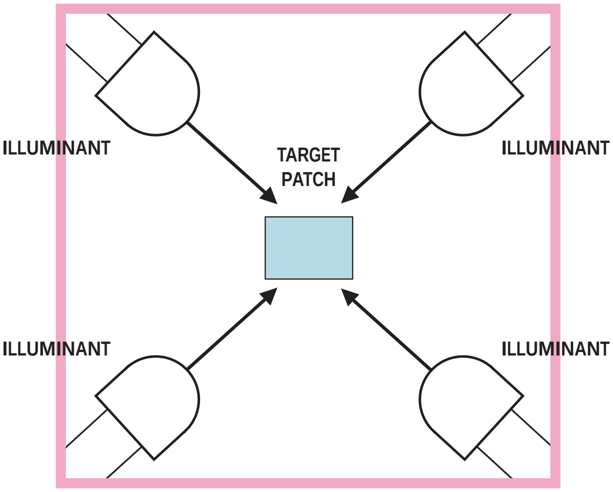


Figure 13. 45°/0° geometry

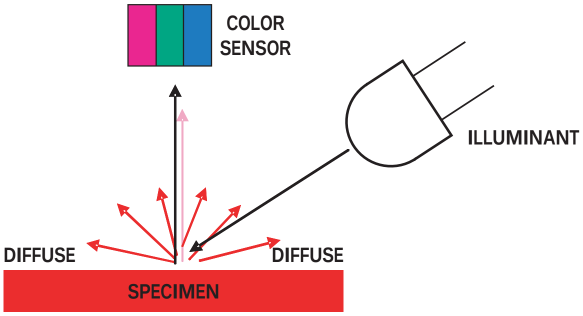


Figure 12. A 45°/0° geometry

Ambient light rejection/ elimination

- The detector and illuminant pair are enclosed in a housing to eliminate ambient light
- The design rule is simple: the enclosure will minimize light that travels directly from the illuminant to the detector and also ambient light.

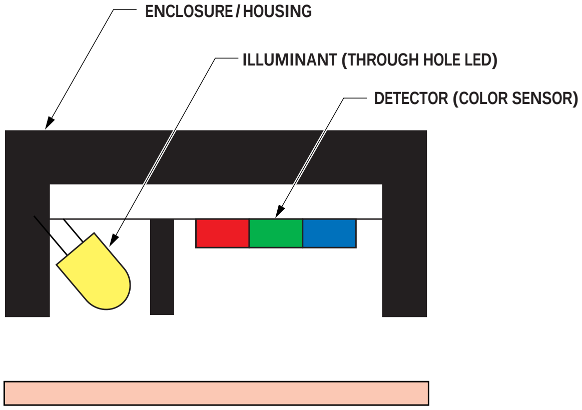


Figure 14. Example setup for a through-hole LED with color sensor

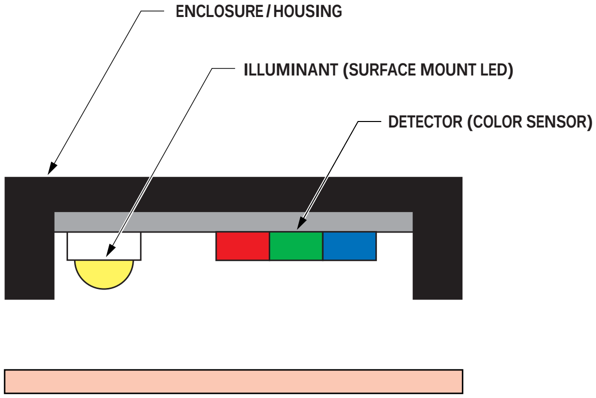
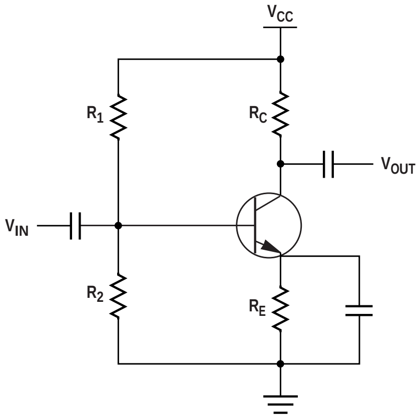


Figure 15. Example setup for a surface mount LED with color sensor

4) Post Sensor Output Signal Processing

a) Second level amplification.

Sometimes, the output voltage level from the sensor may be too low. A post amplifier will be added to amplify the voltage. A simple amplifier can be constructed using a bi-polar junction transistor as shown below.



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

The selection of the emitter resistor will need some engineering judgment where it cannot be too large because it will limit the range of voltage swing of collector to emitter voltage. The typical value of R_E will be:

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

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

Some considerations are needed to select the base resistors, R_1 and R_2. For the circuit to operate efficiently, it is assumed that the current through R_1 and R_2 must be approximately equal and/or greater than the base current, by 10:1.

$$R_E \leq 0.1 \text{ x } h_{FE} \text{ x } R_E$$

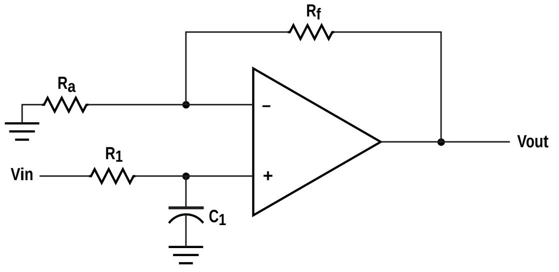
$$V_B = \frac{R_2}{R_1 + R_2} \bullet V_{CC} = V_{BE} + V_E$$

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

Another common method to construct an amplifier is using the 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:

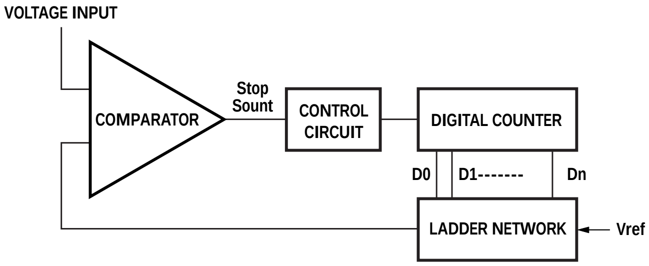
$$\mathrm{Vout} = 1 + \frac{R_f}{R_a} \bullet \mathrm{Vin}$$

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



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 along with a counter and comparator circuits.



In the circuit diagram above, the digital counter will count from zero, driving a ladder network that will produce staircase voltage which increases 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.

$$\mathrm{Resolution} = \frac{\mathrm{Vref}}{2''}$$

There are many ADC chips in the market with a wide selection of resolutions. Avago's 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 V_{ref} up to 2.5 V. The best option is to use Avago's 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.

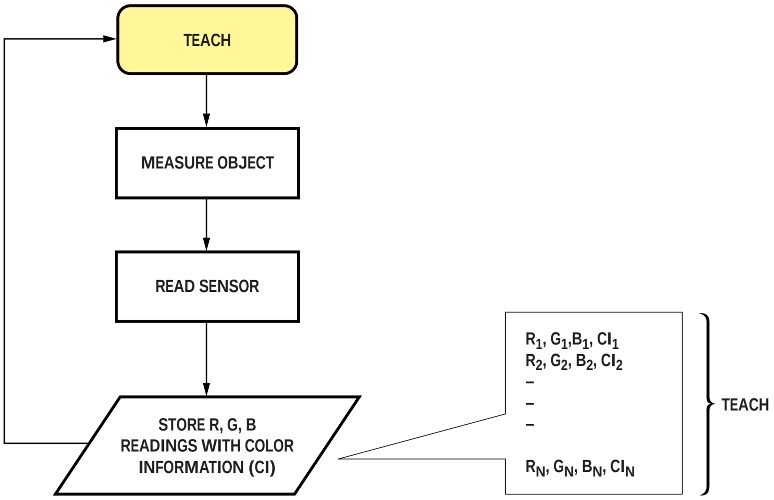
a) Look-up Table

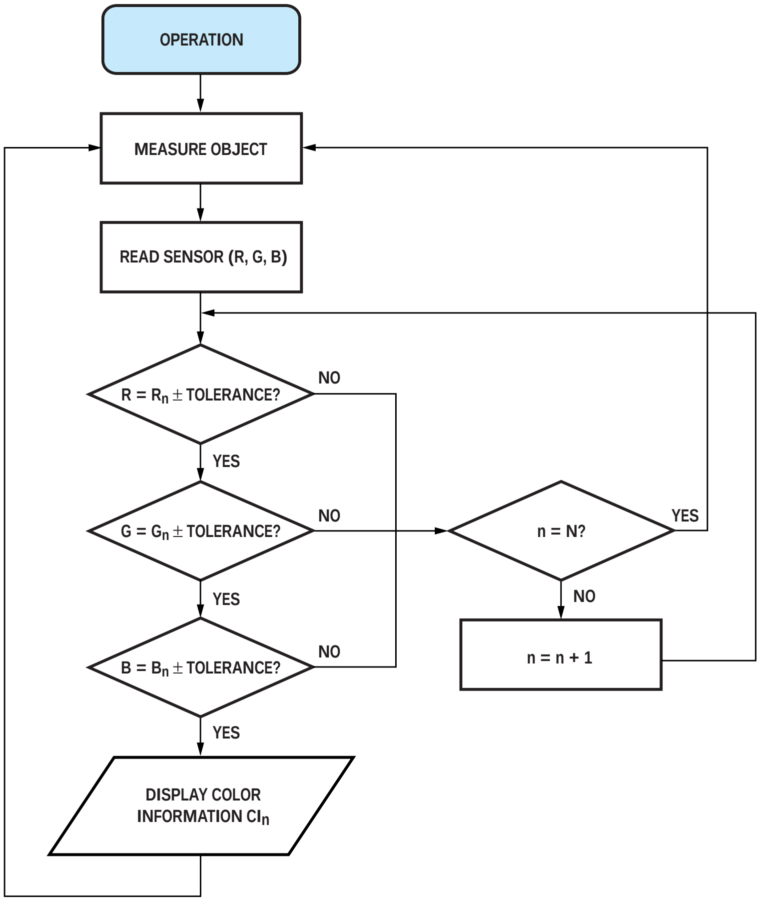
The look-up table method is suitable when a set of colors need to be identified without the requirement of the actual color point. First, the color of the set of media will be measured by the color sensor and the RGB readings will be stored in memory together with the color information (teach mode). During the operation mode, the RGB readings measured will be compared with the RGB data stored earlier for a match. If the RGB measured match with the RGB stored, usually with 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 channel with the value of one of the channel. For example, if the Green channel is selected to be divided, the data stored will be:

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

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:

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

The question now is how to find the 3x3 transformation matrix. One of the methods 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

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

or $\quad C = S \times T$

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 mapping equations to be formed.

$$X = a11 \times R + a21 \times G + a31 \times B$$
$$Y = a12 \times R + a22 \times G + a32 \times B$$
$$Z = a13 \times R + a23 \times G + a33 \times B$$

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 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, the 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 formula:

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

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

Y is identical to the tri-stimulus value Y.

d) Conversion from XYZ to other RGB Color Space

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

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

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.

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

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

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

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

If $0.00313 > R, G, B \geq 0$ 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 $1 \geq R, G, B \geq 0.00313$

$R'_{sRGB} = \text{round}(1.055 \bullet R^{(0.42)} - 0.055)$
$G'_{sRGB} = \text{round}(1.055 \bullet R^{(0.42)} - 0.055)$
$B'_{sRGB} = \text{round}(1.055 \bullet R^{(0.42)} - 0.055)$

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 the 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 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's RGB color sensors.

References

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For product information and a complete list of distributors, please go to our website: **www.avagotech.com**

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