Use color sensors for precise measurement

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Although the human eye is very capable of differentiating colors, people will describe the same color differently. This makes verbal description inadequate in applications that require precise color detection and management. A better solution is to describe color in numeric terms using adequately calibrated color-sensing devices—from expensive laboratory-grade spectrophotometers to economical RGB color sensors. This article will provide some insight into color perception, measurement and specification, and how the data produced by color sensors is applied.

Before going into the theory of how electronic devices sense colors, it is useful to understand how humans perceive color. Color is the result of interaction between a light source, an object and an observer. In the case of reflected light, light falling on an object will be reflected or absorbed depending on surface characteristics such as reflectance and transmittance. For example, red paper will absorb most of the greenish and bluish part of the spectrum while reflecting the reddish part of the spectrum, making it appear reddish to the observer. In the case of self-illuminated objects, the principle is the same: the light will reach the human eye, be processed by the eye's receptors, and interpreted by the nervous system and brain.

The human visual system can detect the electromagnetic spectrum from about 400nm (violet) to about 700nm (red), and can adapt to widely varying illumination levels and amounts of color saturation (the proportion of pure color to white). The light sensor cells capable of working over a wide illumination level and of providing quick response to changes are called rods. However, the rod cells are incapable of detecting color. Light sensor cells called cones provide high-resolution color imaging. There are three sets of cones with peak sensitivities at wavelengths that we identify as red (580nm), green (540nm) and blue (450nm). Light at any wavelength in the visual spectrum will excite one or more of these three types of cone cells to varying degrees, with our perception of the color being that information as processed by our optic nerve and brain.

Apparently, humans with normal color vision basically perceive the same color when shown light with the same mixture of wavelengths. Scientific experiments have shown that humans can discriminate between very subtle differences in color, with estimates as high as 10 million; the problem is that we simply do not have enough words to name all the subtly different colors.

Colorimetric and photometric are two general types of measuring instruments. With the colorimetric method, the device measures light from an object using a sensor with three filters. Normally, the sensor profile is optimized so that it will closely resemble the human eye response. The output will be in terms of International Commission on Illumination in English (CIE) tristimulus values X, Y, Z.

The photometric method uses a multiplicity of sensors to measure color over a large number of narrow wavelength ranges. The instrument's microcomputer then calculates the tristimulus values by integrating the resulting data.

The photometric method uses

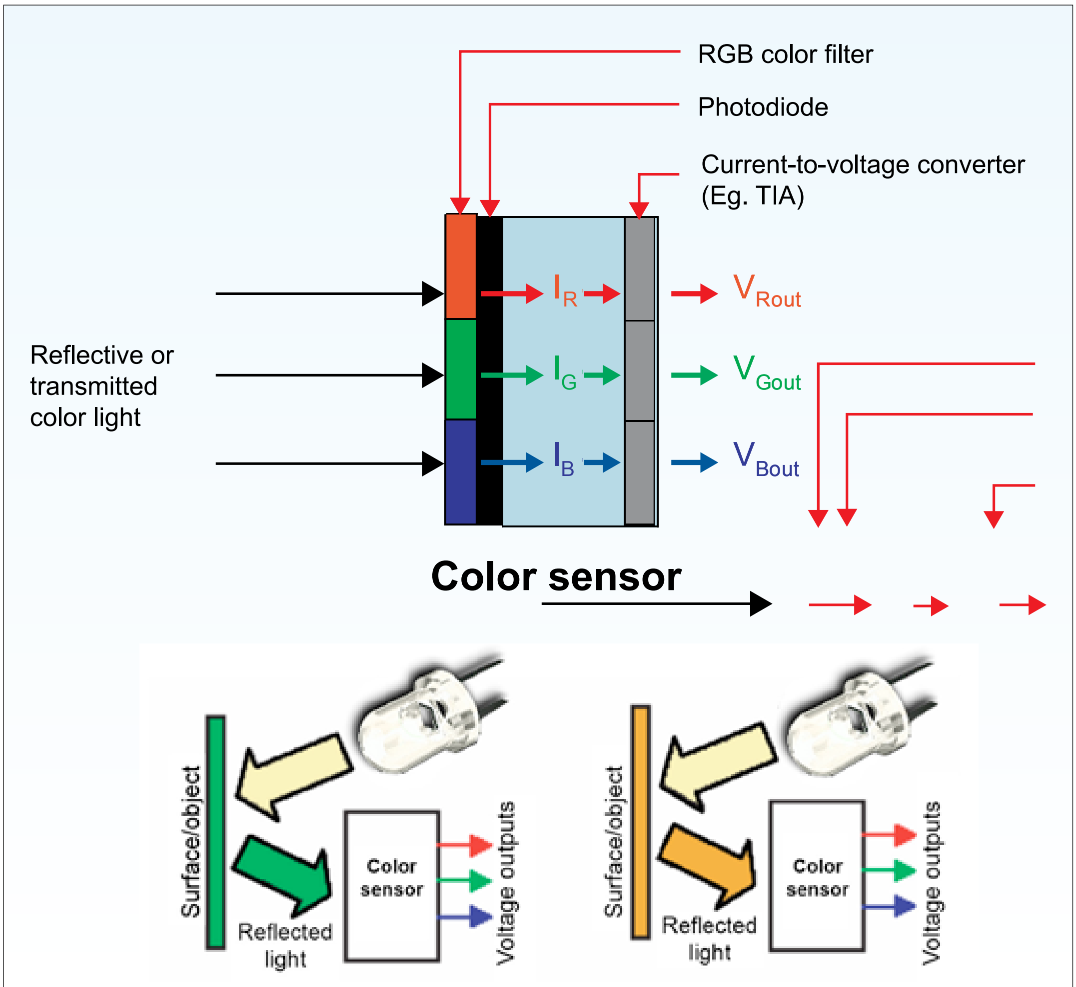

Figure 1: A light-to-analog voltage color sensor comprises an array of photodiodes behind color filters and an integrated current-to-voltage conversion circuit.

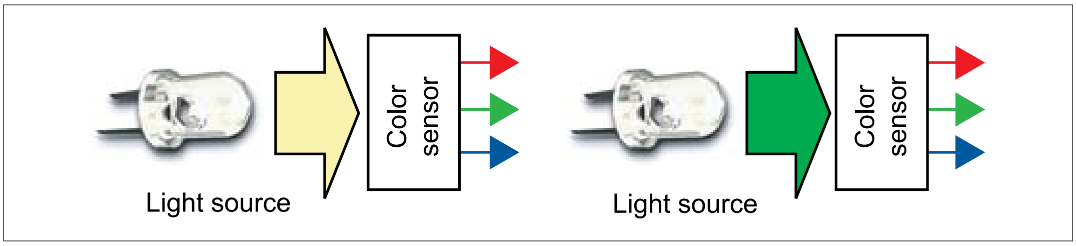

Figure 2: The color of reflected light depends on the colors that a surface reflects and absorbs.

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Sensor operation

There are three types of color sensors: light-to-photocurrent, light-to-analog voltage and light-to-digital. The former usually represents only the input part of a practical color sensor, since the raw photocurrents are of extremely low amplitude and invariably require amplification to convert the photocurrents to useable levels. Thus, most practical analog-output color sensors incorporate at a minimum a transimpedance amplifier and provide voltage outputs.

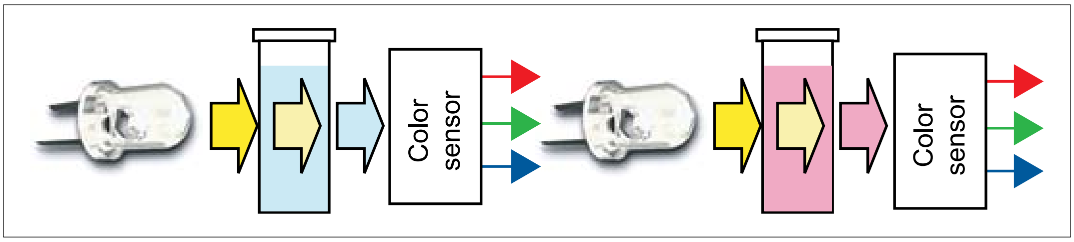

Figure 3: The R, G and B outputs of the sensor are determined by the color of light falling on the sensor.

A light-to-analog voltage color sensor comprises an array of photodiodes behind color filters and an integrated current-to-voltage conversion circuit (usually a transimpedance amplifier). Light falling on each of the photodiodes is converted into a photocurrent, the magnitude of which is dependent on both the brightness and, due to the color filter, wavelength of the incident light. Without a color filter, a typical silicon photodiode responds to wavelengths ranging from the ultraviolet region through the visible, with a peak response region between 800nm and 950nm in the near-IR part of the spectrum. The red, green and blue transmissive color filters will reshape and optimize the photodiode's spectral response. Properly designed filters will result in a spectral response for the filtered photodiode array that mimics that of the human eye. The photocurrents from each of the three photodiodes are converted to V_{Rout}, V_{Gout} and V_{Bout} using a current-to-voltage converter.

There are two color-sensing modes: reflective and transmissive. In reflective sensing, the color sensor detects light reflected from a surface or object, with both the light source and the color sensor placed close to the target surface. Light from the light source bounces off the surface, and is measured by the color sensor. The color of the light reflected off the surface is a function of the color of the surface. For example, white light incident 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.

In transmissive sensings, the sensor is placed facing the light source. The filter-coated photodiode array of the color sensor converts the incident light into R, G and B photocurrents, which are amplified and converted to analog voltages. Since all three outputs increase linearly with increasing light intensity, the sensor can measure both color and total intensity of the light.

Transmissive sensing can be used to determine the color of a transparent medium, such as glass or transparent plastic, a liquid, or a gas. Light passes through the transparent medium before impinging on the color sensor. The color of the transparent medium is determined by interpreting the color-sensor voltages.

Interpreting values

The three analog output voltages of the color sensor may be used to directly control hardware or be converted to digital values so that a digital processor can analyze the data. The color and brightness information is obtained from these digital values. There are two methods of describing the color and brightness.

Matrix method—This method is suitable if there are many colors to be distinguished. The method is based on the matrix equation given below:

$$\begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = \begin{bmatrix} C_{00} & C_{01} & C_{02} \\ C_{10} & C_{11} & C_{12} \\ C_{20} & C_{21} & C_{22} \end{bmatrix} \times \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

Where X, Y, Z represent the CIE tristimulus values and RGB the color-sensor digital values.

A known set of reference colors are measured and the R, G and B sensor values are obtained for each standard X, Y and Z values. The matrix coefficients C_{00}, C_{01}, C_{02}, C_{10}, C_{11}, C_{12}, C_{20}, C_{21} and C_{22} are determined from these known standard values. Once these matrix coefficients are determined, the X, Y and Z values of the unknown color is calculated from the R, G and B digital sensor values.

Lookup table method—This method is suitable if a few reference colors are to be distinguished. First, the reference color sensor values, which include brightness information, for each color are obtained during calibration. A decision has to be made on whether brightness information is important or not. If brightness information is important, the actual color sensor values are used in interpretation.

If brightness is not significant to an application, the ratio or proportion between red, green and blue sensor values are obtained for the reference colors during calibration and for the unknown color during testing. The ratio is obtained by using one selected color channel as the basis for all measurement sets. For example, if the green channel is selected, the ratio is obtained by dividing the sensor measurements by the corresponding green channel value so that the resulting green channel value is always 1. To demonstrate, if the set (R_{nS}, G_n, B_n), n = 1, 2, 3… N, represents the color sensor measurements of all the N reference colors, the ratio is given by the set:

$$\left(\frac{R_n}{G_n}, 1, \frac{B_n}{G_n}\right), \quad n = 1,2,3, \ldots N.$$

Red or blue channel values can also be used as the divisor.

The selection of which color

Device	Output channel	Output type	Package type & size (mm)	Supply voltage (Typ)	Max output voltage swing / resolution	Operating temperature	Dynamic sensing range (klux)	Responsivity		Spectral response (nm)
HDJD-S831-QT333	RGB	Analog	Module 27.6 x 7 x 3	5.0V	3.0V	-20°C to +85°C	30 to 60	R: 1.1 G: 3.9 B: 3.1	V/(mW/cm^2)	400-700
HDJD-S722-QR999	RGB	Analog	QFN 5 x 5 x 1	5.0V	4.7V	-40°C to +85°C	0.1 to 5.5	R: 27.0 G: 19.0 B: 15.0	V/(mW/cm^2)	400-700
ADJD-E622-QR999	RGB	Analog	QFN 5 x 5 x 0.75	5.0V	4.7V	-40°C to +85°C	0.1 to 10	R: 27.0 G: 19.0 B: 13.0	V/(mW/cm^2)	400-700
ADJD-S313-QR999	RGB	Digital	QFN 5 x 5 x 0.75	2.6V	7bit resolution	0°C to +70°C	0.6 to 10	R: 1104 G: 1552 B: 2210	LSB/(mW/cm^2)	400-700

Table 1: Avago offers a wide range of color sensor products.

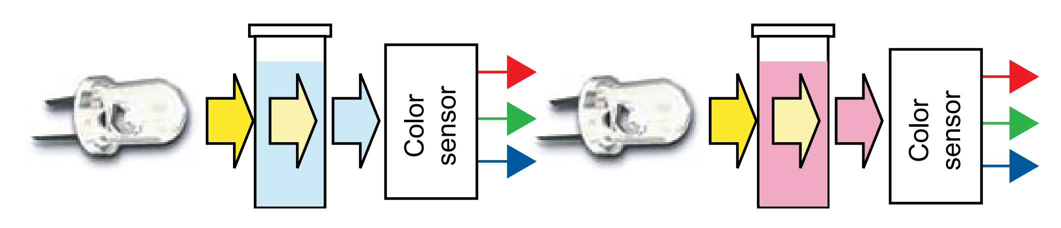

Figure 4: Figure shows color sensing of a transparent medium such as a color filter, liquid or gas.

channel to use is a matter of preference.

The unknown color is determined to be the reference color if the unknown color is the nearest to that particular reference color—i.e. if the distance between the unknown color and that particular reference color is the shortest among all other distances between the unknown color and all other reference colors.

The distance between the unknown color and reference color is given by the equations below:

a) For the case where brightness is important,

Distance =

$$\text{Distance} = \sqrt{(R_u - R_r)^2 + (G_u - G_r)^2 + (B_u - B_r)^2}$$

b) For the case where brightness is not important,

Distance =

$$\text{Distance} = \sqrt{\left(\frac{R_u}{G_u} - \frac{R_r}{G_r}\right)^2 + (1-1)^2 + \left(\frac{B_u}{G_u} - \frac{B_r}{G_r}\right)^2} = \sqrt{\left(\frac{R_u}{G_u} - \frac{R_r}{G_r}\right)^2 + \left(\frac{B_u}{G_u} - \frac{B_r}{G_r}\right)^2}$$

Note:

1. (R_u, G_u, B_u) are the unknown color sensor values.
2. (R_r, G_r, B_r) are the reference color sensor values.
3. For the case where brightness is not important, the value of one sensor channel (for example, the green channel) is used as a divisor.

A maximum distance limit is established for each reference color to avoid accepting colors that do not belong to the list of reference colors. This maximum limit can be different for each reference color, depending on the accuracy required.

Benefits, trade-offs

A light-to-photocurrent converter consists of nothing more than a photodiode, or a photodiode with a color filter, which converts light to a photocurrent. External circuitry can be used to convert the photocurrent to a proportional voltage output, and the voltage can then be converted to a digital format via a discrete ADC and fed to an MCU. A light-to-photocurrent converter is suitable for applications that require a short response time, customized gain and speed adjustment, and operate under varying light conditions.

Its key benefit is design flexibility. The gain and bandwidth of the amplifier, and the speed and resolution of the ADC can be tailored to individual applications. On the other hand, the trade-offs include additional assembly cost and increased design complexity.

A light-to-analog voltage converter consists of an array of photodiodes coated with color filters and integrated with transimpedance amplifiers. External circuitry is required to convert the analog voltage into a digital output before being fed to a DSP. The light-to-analog voltage converter is suitable for applications that require a shorter design cycle, faster time-to-market, well-defined light conditions and space efficiency. It simplifies peripheral circuit design, improves space efficiency and reduces assembly cost. On the other hand, response time is predetermined by the built-in current-to-voltage converter, such as a transimpedance amplifier. Furthermore, an additional ADC is required to convert the voltage output into a digital format

A light-to-digital voltage converter consists of an array of photodiodes coated with RGB filters, an ADC and a digital core for communication and sensitivity control. The output allows direct interface to an MCU or other logic control via, for example, a two-wire serial interface for further signal processing without the need for any additional components. The light-to-analog voltage converter is suitable for applications that require a shorter design cycle, faster time-to-market, well-defined light conditions and space efficiency. It provides noise immunity, simplifies peripheral circuit design, improves space efficiency and reduces assembly cost. On the other hand, direct interface to an MCU or PC is only available via two-wire serial interface mode. Also, response time is predetermined by the built-in A/D circuits, while A/D resolution is predefined.