Understanding Avago Technologies RGB Color Sensors

White Paper

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Introduction

Although the human eye is quite capable of differentiating colors, different people will describe the same color differently. Consequently, a verbal description is inadequate in applications where precise color detection and management is required. A better solution describes the color in numeric terms using an adequately calibrated, color-sensing device. Such devices range from expensive laboratory-grade spectrophotometers to economical Red-Green-Blue (RGB) color sensors like those produced by Avago Technologies. Its' wide range of color sensors are viable solutions for many of today's practical color sensing and measuring applications.

The objective of this white paper is to provide insight into color perception, measurement and specification, and the application of data produced by color sensors. It will also provide a detailed look at Avago Technologies' line of RGB color sensors and offer information on how these products may be utilized in various color-sensing applications.

Color Perception

Before delving 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 green and blue parts of the spectrum while reflecting the red part of the spectrum. Consequently, it appears red to an observer. In the case of self illuminated objects, the principle is the same: light reaches the human eye, is processed by the eye's receptors and is then interpreted by the nervous system and brain.

The human visual system can detect the electromagnetic spectrum from about 400 nanometers (violet) to about 700 nanometers (red), and can adapt to widely varying illumination levels and amounts of color saturation (the proportion of pure color to white). Light sensor cells capable of working over a wide illumination level and of providing a quick response to changes are called rods and 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 the human eye can identify. They are: red (580 nm), green (540 nm) and blue (450 nm). Light at any wavelength in the visual spectrum will excite one or more of these three types of cone cells to varying degrees, with the human eye's perception of the color being that information as processed by the optic nerve and brain.

Humans with normal color vision essentially 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, but humans simply do not have enough words to name all of the subtly different colors.

Principles of Color Measurement

Figure 1.1 shows the basic principle of color detection by the human eye as compared to color measurements using an instrument or sensor. The sensing device can range from a high-end device such as a spectrophotometer or International Commission on Illumination in English (CIE) calibrated camera to a lower-end device like a RGB color sensor.

There are two general types of measurement instruments: colorimetric and photometric. Using the colorimetric method, the device measures light from an object using a sensor with three filters (Figure 1.1b). Normally, the sensor profile is optimized so that it will closely resemble the human eye response. The output will be in terms of CIE tristimulus values X, Y, Z.

The photometric method (Figure 1.1c) 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.

Avago's color sensors (Figure 1.1d) are three-filter devices, which provide colorimetric measurement. The sensor output consists of voltage outputs VR, VG, and VB or numerical values of R, G, and B after analog to digital conversion.

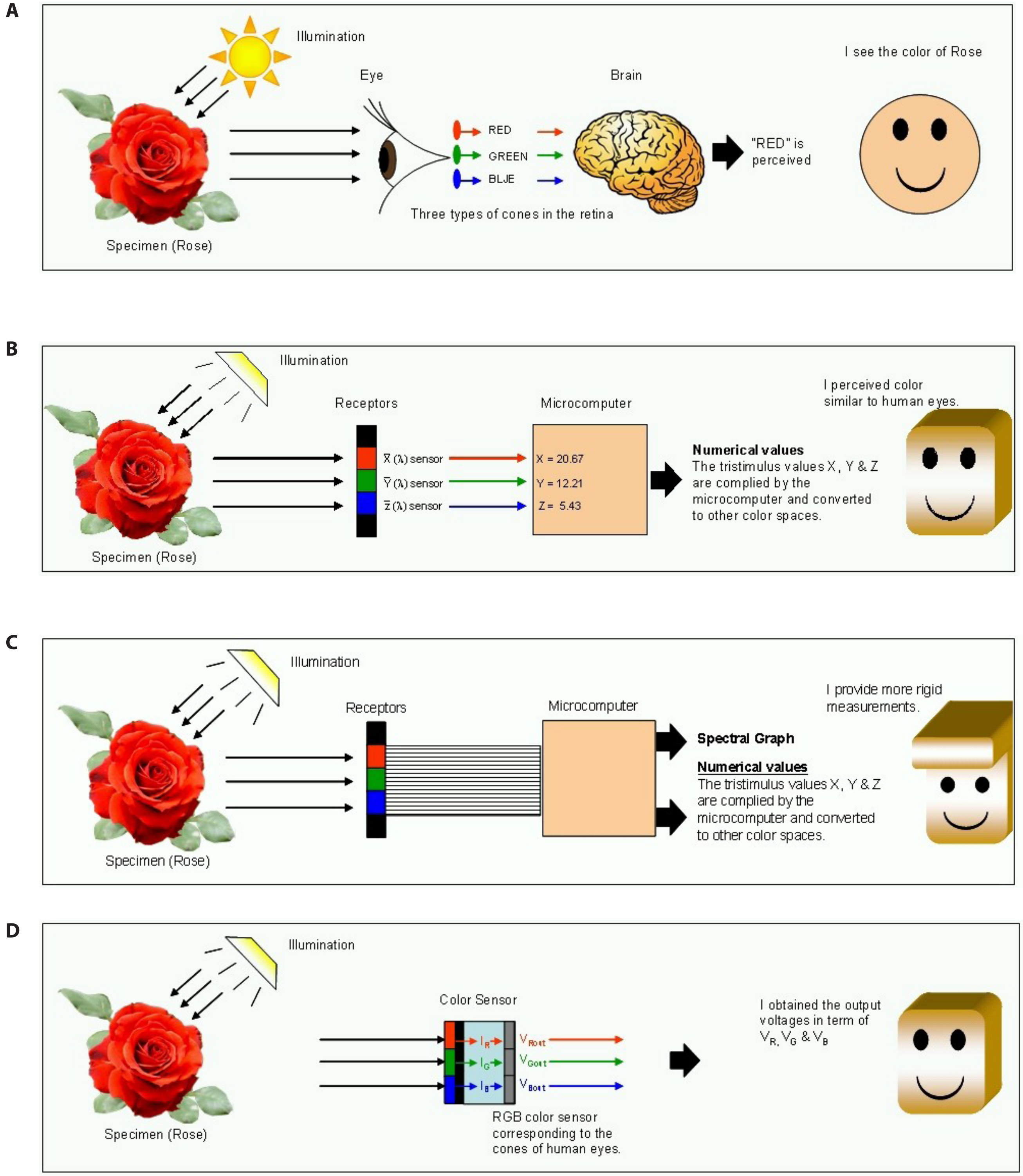


Figure 1.1. Color measurements with the human eye (a), colorimeter (b), spectrophotometer (c), and RGB sensor (d).

Theory of Color Sensor Operation

There are three different 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.

A light-to-analog voltage color sensor is comprised of an array of photodiodes behind color filters and an integrated current-to-voltage conversion circuit (usually a transimpedance amplifier) as shown in Figure 1.2. Light falling on each of the photodiodes is converted to a photocurrent, the magnitude of which is dependent on both the brightness and, due to the color filter, the 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 of between 800 and 950 nm in the near-infrared part of the spectrum. The red, green and blue transmissive color filters reshape and optimize the photodiode's spectral response. Properly designed filters 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 VRout, VGout and VBout using a current-to-voltage converter.

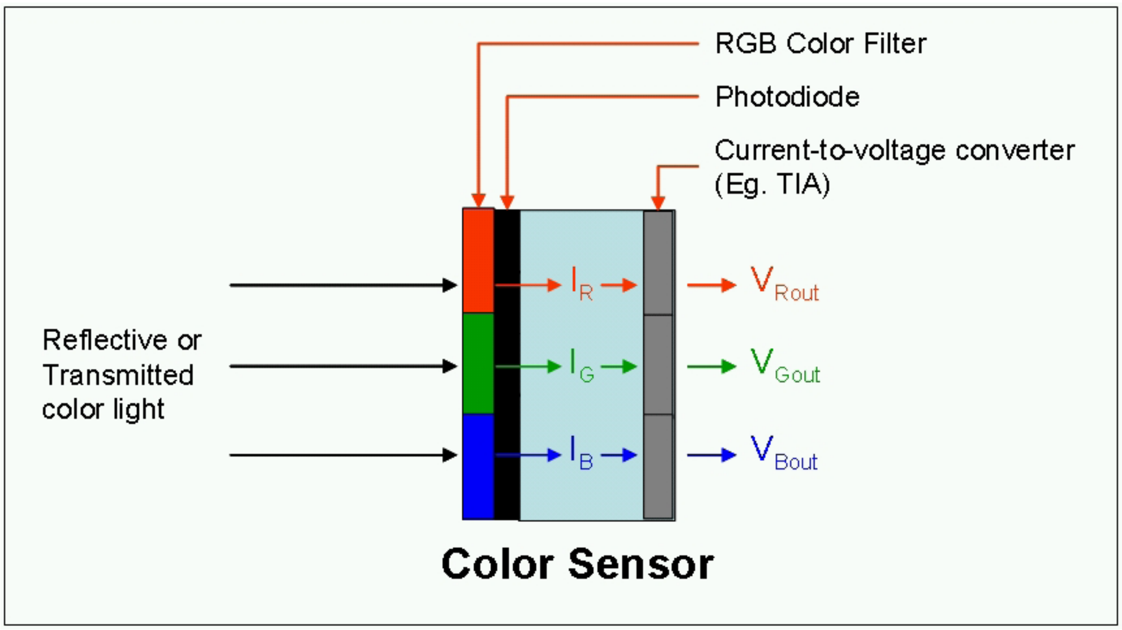


Figure 1.2. Color sensor with light-to-analog voltage conversion.

Reflective Sensing

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 coming from the light source (such as an incandescent/fluorescent lamp, white LED or calibrated RGB LED module) is bounced off the surface and measured by the color sensor. The color of the light reflected off the surface is a function of the color of the surface (Figure 1.3). 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.

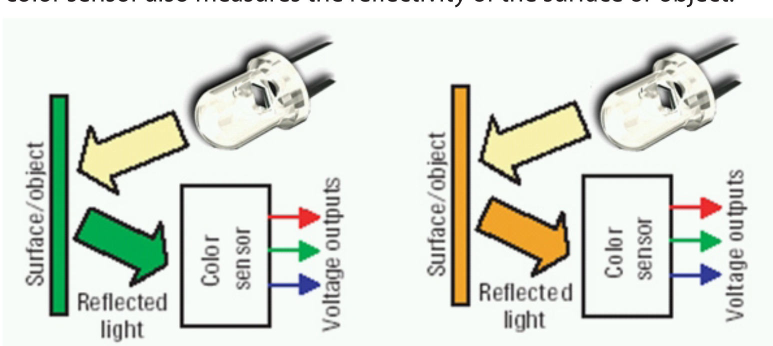


Figure 1.3. The color of reflected light depends on the colors that a surface reflects and absorbs.

Transmissive Sensing

In the transmissive mode of operation, 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 then amplified and converted to analog voltages. Since all three outputs increase linearly with increasing light intensity, the sensor can measure both the color and total intensity of the light (Figure 1.4).

Transmissive sensing is used to determine the color of a transparent medium such as glass, transparent plastic, a liquid, or gas (Figure 1.5). Here, 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's voltages.

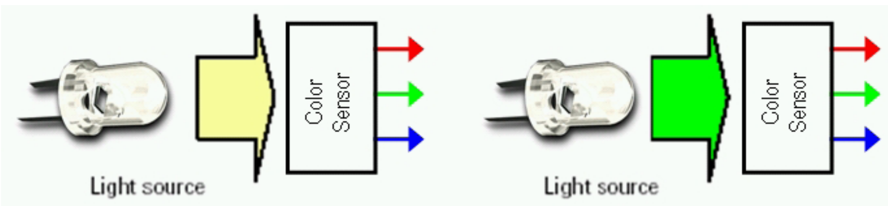


Figure 1.4. The R, G, and B outputs of the sensor are determined by the color of light falling on sensor.

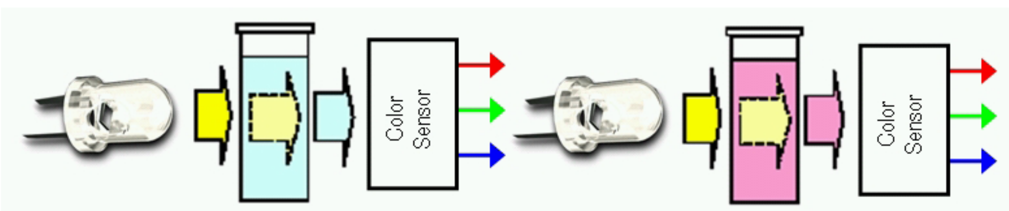


Figure 1.5. Color sensing of a transparent medium such as a color filter, liquid or gas.

Interpretation of Color Sensor Values

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

a) Matrix Method

This method is suitable if there are many colors to be distinguished. It is based on the matrix equation given below, where X, Y, Z represents the CIE tristimulus values and RGB represents the color sensor digital values.

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

A known set of reference colors are measured and the R, G, B sensor values obtained for each standard X, Y, Z value. The matrix coefficients C00, C01, C02, C10, C11, C12, C20, C21 and C22 are determined from these known standard values. Once these matrix coefficients are determined, the X, Y, Z value of the unknown color is calculated from the R, G, and B digital sensor values.

b) 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 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 may be 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. In other words, if the set (Rn, Gn, Bn), n = 1, 2, 3… N, represents the color sensor measurements of all the N reference colors, then 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. Note that selection of which color channel to use is a matter of preference.

The unknown color is determined to be the reference color if the unknown color is nearest to that particular reference color, for example, 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 as follows:

a) For the case where brightness is important:

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

b) For the case where brightness is not important:

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

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

Note:
1. (Ru, Gu, Bu) are the unknown color sensor values.
2. (Rr, Gr, Br) are the reference color sensor values.
3. For the case where brightness is not important, the value of one sensor channel (e.g. the green channel) is used as a divisor.

A maximum distance limit is established for each reference color in order 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.

Comparing Types Of Color Sensors

Light-to-Photocurrent Converter

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. The voltage can then be converted to a digital format via a discrete A/D converter and fed to a microcontroller. 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.

Benefit:

- Provides design flexibility. The gain and bandwidth of the amplifier as well as the speed and resolution of the A/D converter can be tailored to individual applications.

Tradeoff:

- Additional assembly cost
- Increased design complexity

Light-to-Analog Voltage Converter

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 to a digital output before being fed to a digital signal processor. 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.

Benefit:

- Simplifies peripheral circuit design
- Improves space efficiency
- Reduces assembly cost

Tradeoff:

- Response time is predetermined by the built-in current-to-voltage converter, such as a transimpedance amplifier.
- An additional A/D converter is required to convert the voltage output to a digital format.

Light-to-Digital Voltage Converter

A light-to-digital voltage converter consists of an array of photodiodes coated with RGB filters, an analog-to-digital converter and a digital core for communication and sensitivity control. The output allows direct interface to a microcontroller or other logic control via, for example, a 2-wire serial interface for further signal processing, without the need of any additional components. The light-to-digital converter is suitable for applications that require noise immunity, shorter design cycle, faster time to market, well-defined light conditions and space efficiency.

Benefit:

- Provides noise immunity
- Simplifies peripheral circuit design
- Improve space efficiency
- Reduces assembly cost

Tradeoff:

- Direct interface to microcontroller or PC is only available via 2-wire serial interface mode.
- Response time is predetermined by the built-in analog and digital circuits.
- A/D resolution is predefined.

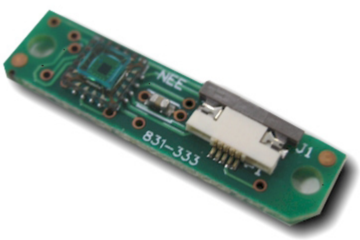
Avago Technologies' Range of Color Sensors

A wide range of Avago color sensor products is available to suit the diverse range of applications in the display, lighting, industrial, consumer and medical market segments. Solutions are available in both analog and digital formats (Table 1.0). They include:

Analog RGB Color Sensors

- An array of photodiodes coated with RGB filters
- Integrated with transimpedance amplifier delivering linear analog voltage output
- Independent gain selection for the R, G and B channels
- Available in module and component level

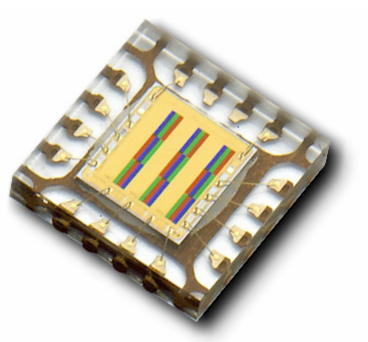
HDJD-S831-QT333



Analog color sensor module (Module 27.6 x 7 x 3)

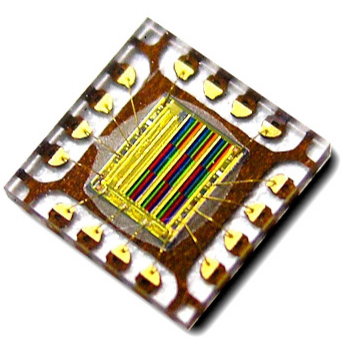
- consisting of a color sensor packaged in a 5 x 5 x 2 mm surface mount QFN-16 package, a flat flexible cable connector and a decoupling capacitor mounted on a printed circuit board.
- Four selectable gain levels for the R, G and B channels
- Spectral response of the sensor is optimized for RGB-LED backlighting applications.
- Has good ability to detect chromaticity drift. When used with a closed loop feedback controller, adjusts the backlight system to realize good du'v' performance.
- Potential applications include white point control in emissive displays, environmental lighting, color control in industrial processes.
- Sensing range: 30 klux to 60 klux

HDJD-S722-QR999



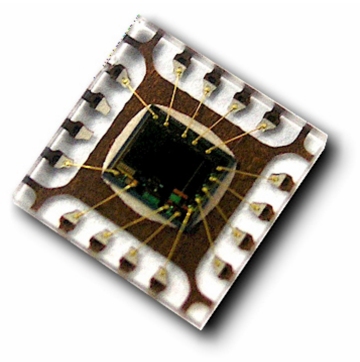
- Analog color sensor packaged in a 5 x 5 x 1 mm surface mount QFN-16 package.
- Three selectable gain levels for the R, G and B channels.
- Higher sensitivity for low luminance applications.
- Potential applications include color detection, environmental lighting, and industrial process control.
- Sensing range: 0.1 klux to 5.5 klux

ADJD-E622-QR999



- Analog color sensor packaged in a 5 x 5 x 0.75 mm surface mount QFN-16 package with AEC grade 3 qualification.
- Eight selectable gain levels for the R, G and B channels.
- Higher sensitivity for low luminance applications.
- Potential applications include color detection, lighting and automotive lighting.
- Sensing range: 0.1 klux to 10 klux

ADJD-S822-QR999 [1]

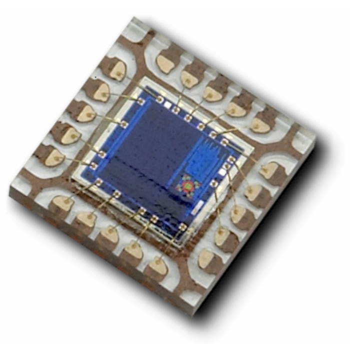


- Analog color sensor packaged in a 5 x 5 x 0.75 mm surface mount QFN-16 package.
- Four selectable gain levels for the R, G and B channels
- Potential applications include lighting and display.

Digital RGB Color Sensors

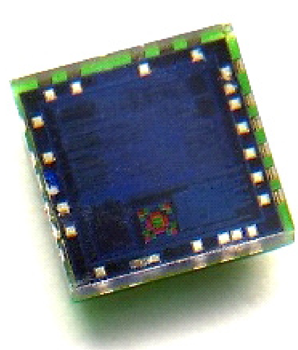
- An array of photodiodes coated with RGB filters
- Integrated with an A/D converter and a digital core for communication via 2-wire serial interface
- Direct interface to microcontroller or other logic control
- Software-programmable gain and sensitivity control
- Miniature package suitable for portable devices

ADJD-S313-QR999



- 7-bit resolution digital output RGB color sensor packaged in 5 x 5 x 0.75 mm surface mount QFN package
- Integrated A/D converter and digital core for communication and sensitivity control
- Output allows direct interface to microcontroller or other logic control for further signal processing
- Potential applications include portable or mobile devices, which demand higher integration, smaller size and low power consumption.
- Can be used together with a white LED for reflective color sensing
- Sensing range: 0.6 klux to 10 klux

ADJD-S312-QR999 [1]



- 7-bit digital output RGB color sensor packaged in 3 x 3 x 0.77 mm chip scale package
- Integrated analog-to-digital converter and digital core for communication and sensitivity control
- Output allows direct interface to microcontroller or other logic control for further signal processing
- Potential applications include portable or mobile devices, which demand higher integration, smaller size and low power consumption.

Note 1: As of this publication, this product is under development. Please contact your Avago sales representative for more information about availability.

ADJD-S31X-QR999 [1]

- 10-bit color sensor with digital RGB + brightness channel output packaged in 2.3 x 2.3 x 0.77 mm chip scale package
- Integrated analog-to-digital converter and digital core for communication and sensitivity control
- Output allows direct interface to microcontroller or other logic control for further signal processing
- Potential applications include portable or mobile devices, which demand higher integration, smaller size and low power consumption.

Note 1:
As of this publication, this product is under development. Please contact your Avago sales representative for more information about availability.

Table 1.0. Brief specifications of Avago color sensor products

Device	Output Channel	Output Type	Package Type & Size (mm)	Supply Voltage (Typ)	Max Output voltage swing / resolution	Operating Temperature	Sensor Range (klux)	Responsivity		Spectral Response (nm)
HDJD-S831-QT333	RGB	Analog	Module 27.6 x 7 x 3	5.0 V	3.0 V	-20°C to +85°C	30 to 60	R: 1.1 G: 3.9 B: 3.1	V/ (mW/cm2)	400 nm to 700 nm
HDJD-S722-QR999	RGB	Analog	QFN 5 x 5 x 1	5.0 V	4.7 V	-40°C to +85°C	0.1 to 5.5	R: 27.0 G: 19.0 B: 15.0	V/ (mW/cm2)	400 nm to 700 nm
ADJD-E622-QR999	RGB	Analog	QFN 5 x 5 x 0.75	5.0 V	4.7 V	-40°C to +85°C	0.1 to 10	R: 27.0 G: 19.0 B: 13.0	V/ (mW/cm2)	400 nm to 700 nm
ADJD-S313-QR999	RGB	Digital	QFN 5 x 5 x 0.75	2.6 V	7 bit resolution	0°C to +70°C	0.6 to 10	R: 1250 G: 1750 B: 2490	LSB/ (mW/cm2)	400 nm to 700 nm

Benefits of Avago Technologies' RGB Color Sensors

Wide range of color sensing devices: Avago Technologies provides a wide variety of color sensing devices that range from bare silicon photodiodes to sophisticated RGB color sensors. For customers who prefer off-the-shelf and plug-and-play solutions, the integrated RGB color sensor is the ideal choice. Customers who want the flexibility of designing their own photocurrent-to-voltage converter and A/D circuitry can purchase photodiodes.

Simplifies peripheral circuitry design: Avago Technologies' integrated RGB color sensor solutions feature built-in current-to-voltage converters. Output is available in analog or digital format depending on which type of color sensor is selected. This simplifies the peripheral circuitry design and hence, reduces the overall product design cycle.

Provides design flexibility: Avago Technologies' RGB color sensors have built-in independent gain selection for the R, G and B color channels. For low light level operation, a higher gain can be selected. For high illumination applications, a lower gain can be selected. The product datasheets provide details on the overall dynamic range of each device.

Improves space efficiency: Avago Technologies supplies its sensors in miniature packages, which are suitable for application in portable devices.

Reduces effects of misalignment and contamination: Each Avago Technologies RGB color sensor is coated with a uniform color filter array. This greatly reduces the problems caused by misalignment and contamination.

Enables extreme temperature operation: Avago Technologies provides products that can cover extreme operating temperatures: e.g. –40 °C to +85 °C

Lead-free products: All Avago Technologies color sensors are lead-free and RoHS compliant

Target Market Segments

Automotive Market

Avago Technologies offers solutions with AEC grade 3 qualification for the following automotive applications:

- Navigation Panels
- Mood Lighting
- Dashboard Lighting

Lighting Market

Avago Technologies provides sensors with stable sensitivity over time and temperature for the following lighting and display applications:

- Architectural Lighting
- Decorative Lighting Displays
- Interior Lighting
- Cabin Lighting

Example: Decorative Lighting (Figure 1.6)

- Using a color sensor to measure LED intensity over time and provide optical feedback to control the color point of the light source.
- Can also be coupled with Avago Technologies' patented color controller, HDJD-J822-SCR00, to form a closed loop color management system.

Example: Cabin Lighting

Function: Control of environmental lighting effects.

- Color sensor is installed in optical feedback control system.
- Light source color point management for LED color intensity control.
- Durable for reliable operation over time and temperature.
- Can also be coupled with Avago Technologies' patented, HDJD-J822-SCR00 color controller, to form a closed-loop color management system.

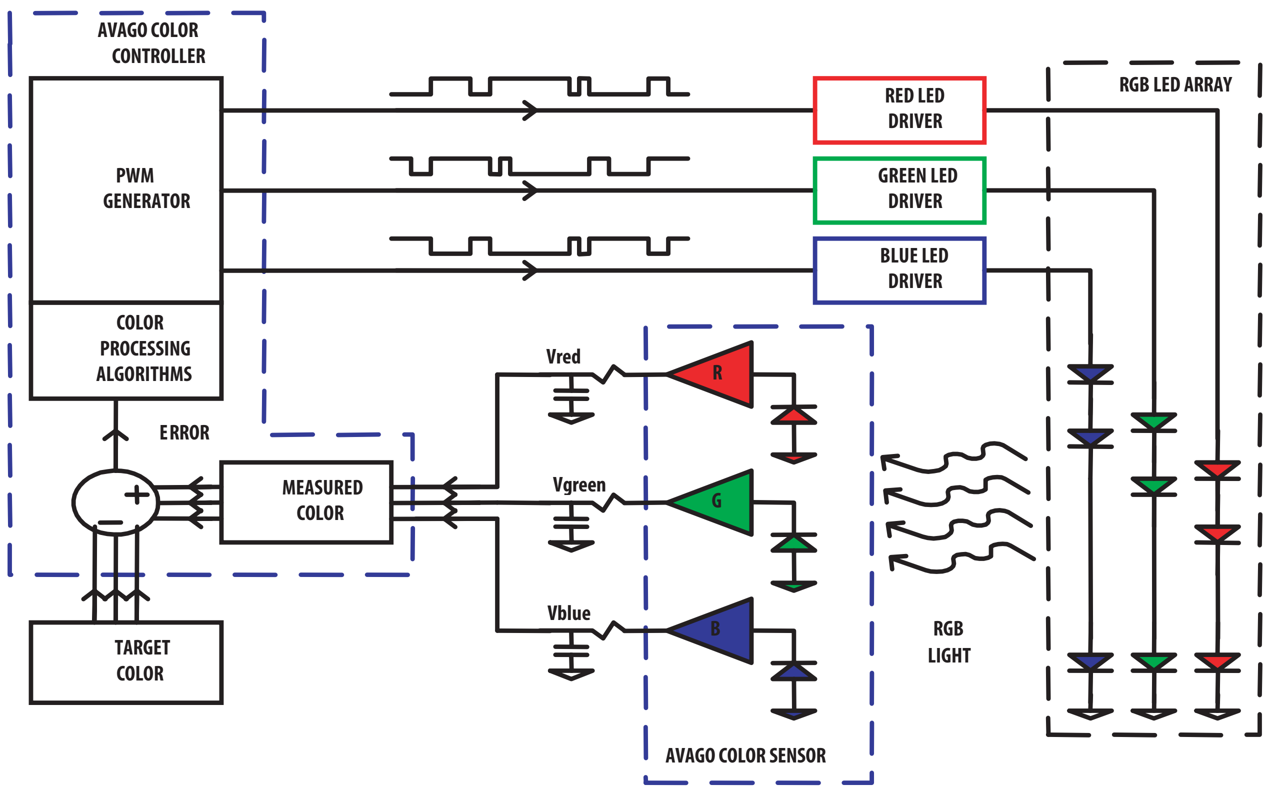


Figure 1.6. Schematic diagram illustrating the use of Avago color sensors in the lighting market.

Industrial Market

Avago Technologies has a wide portfolio of RGB color sensors to meet the extensive requirements of the following industrial applications:

- Packaging - label inspection and identification
- Cosmetics - product assembly segregation and color quality
- Textile - yarn contamination detection
- Paint And Pigment/Graphics Printing

Example: Yarn Contamination Detection (Figure 1.7)

- Color sensor is installed in yarn production line to detect the presence of contamination.
- System automatically halts when contamination is detected.
- Reduces human error, improves accuracy and efficiency.

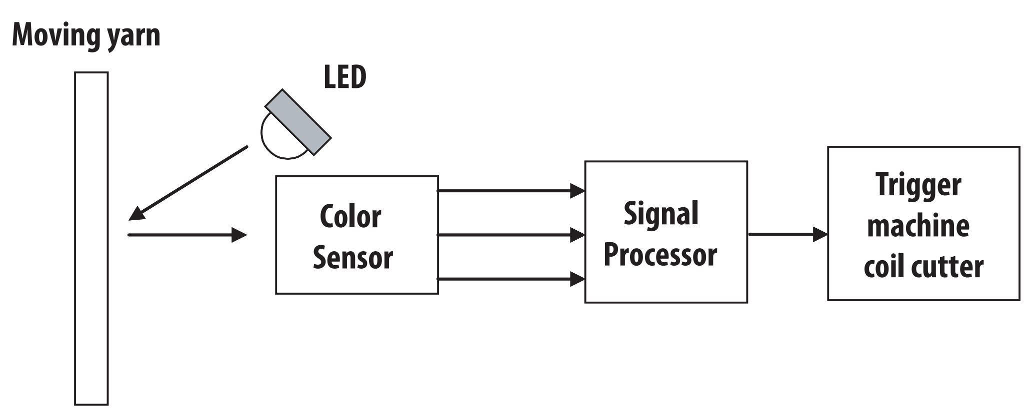


Figure 1.7. Block diagram of yarn contamination detection.

Medical Market

Avago Technologies offers color sensors with high sensitivity and accuracy to serve the following medical applications:

- Blood Glucose Meters
- Blood Cholesterol Meters
- Blood Ketone Meters

Example: Chemical Analysis 96-Well Plate System (Figure 1.8)

Function: Micro parallel liquid chromatography (µPLC) chemical test analyzer.

- Four color sensors are placed along the cartridges to provide color detection of chemical reaction.
- Enables automatic, instantaneous detection of color change.
- Eliminates human error.
- Reliable with high accuracy in color discrimination.

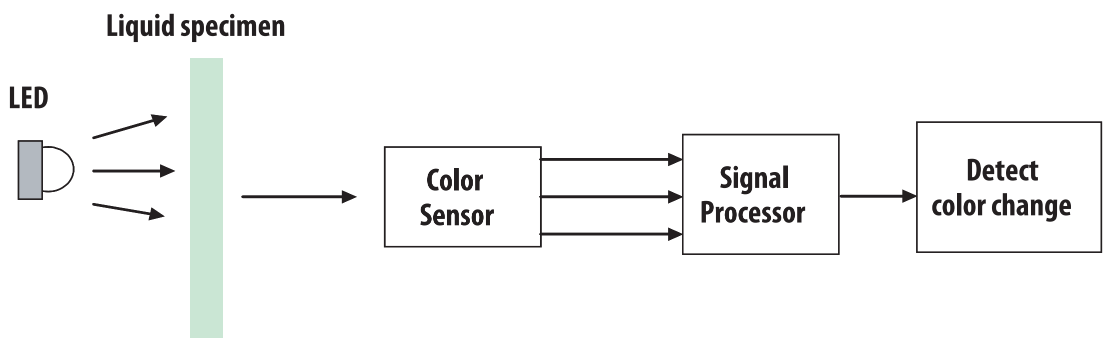


Figure 1.8. Block diagram of chemical analysis example.

Consumer Market

Avago Technologies provides cost-effective RGB color sensors that serve the growing demand for the following applications in the consumer market:

- Portable Color Reader
- Automated Mahjong Table
- Dye Detector In Washing Machine
- Gaming

Example: Automatic Shuffling Of Mahjong Tiles (Figure 1.9)

- Color sensors are used to manage "tile orientation check".
- Tile pattern on both sides (front and rear) is sensed, compared and re-arranged.
- Full interface in closed loop system for logical decision on tile rearrangement.
- Eliminates manual shuffling and potential cheating.

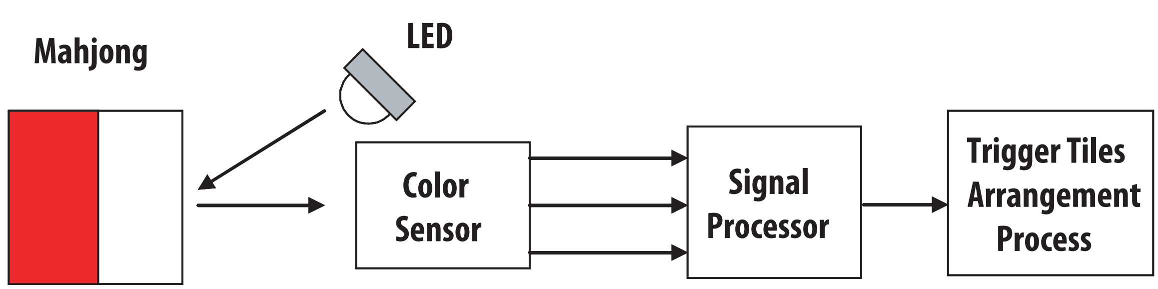


Figure 1.9. Block diagram of a color sensor used to shift mahjong tiles automatically.

Avago Technologies Illumination And Color Management System With RGB Color Sensor

Avago Technologies RGB color sensor (HDJD-S831-QT333) can be used together with the Avago Technologies color controller HDJD-J822-SCR00 to form a RGB LED light source management system. Color management applications involve displaying colors by accurately mixing the outputs of red, green and blue LEDs. The mix ratio is adjusted regularly to maintain consistent and accurate color despite variations in LED intensity and color shift of the LED components.

The HDJD-J822 is a color controller, which processes color sensor information and maintains the color and brightness. For detail information, refer to application note AN 5070.

Conclusion

For applications that require cost-effective solutions and short design cycle times, Avago Technologies' integrated RGB color sensor solution overcomes the inherent challenges of designing a color sensor from scratch. Avago Technologies also provides a photodiode level solution to serve customers who prefer to design their own color sensing system. By offering a broad range of cost effective, color sensor products in robust and lead-free packages, Avago Technologies serves as a one-stop supplier to the color sensing industry.

To find out more about Avago Technologies color sensing solutions, contact your distributor, or visit the Avago Technologies website, http://www.avagotech.com

References

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   Publication number: 5989-1984EN
2. Avago Technologies HDJD S831 QT333 data sheet
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3. Using the HDJD-S722 color sensor Application Note 5096
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5. Precise Color Communication, Minolta Co., Ltd.
6. The Basics of Color Perception And Measurement, HunterLab

Appendix 1. Classification of Typical Light Sources

Direct sunlight	100 klux-130 klux
Full daylight, indirect	10 klux-20 klux
Overcast day	1 klux
Indoor office	200 lux-400 lux
Very dark day	100 lux
Twilight	10 lux
Deep twilight	1 lux
Full Moon	0.1 lux
Quarter Moon	0.01 lux
Moonless clear night sky	0.001 lux
Moonless overcast night sky	0.0001 lux

Direct sunlight is the total spectrum of electromagnetic radiation given off by the sun.

Full daylight is when the sun is above the horizon.

Overcast day is when sunlight is reflected from a cloudy sky.

Indoor Office represents the general illumination level in a typical office.

Very dark day represents the period when sunlight is reflected from a dim and extremely cloudy sky.

Twilight is the sunset period of a day.

Deep Twilight is the period after sunset before lighting deepened into a night sky.

Full Moon is the total light appearing during a period of a full moon.

Quarter Moon is the total light appearing in the period between the full and new moons.

Moonless clear night sky is the total light during the period of a new moon

Moonless overcast night sky is the total light during the period of a cloudy night sky.

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

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