Colorimetric Fundamentals

Light + Object + Observer

Colorimetry---the measurement of color---allows colored objects to be logically and repeatably described, ordered, and compared for successful color communication. In turn, successful color communications are essential for satisfactory industrial color control.

Color is an aspect of visual perception that is not easy to define or to measure. It is a sensation whereby a human observer can see differences between two fields of view that are distinguished by spectral composition differences in the observed radiant energies. Hence color is:

- A sensation, dependent upon the observer.
- Of interest only if the observer can distinguish differences.
- Caused by spectral (wavelength-dependent) energy compositions (distributions).
- The spectral energy compositions that are sensed by the eye/brain system of the human observer, result from both:
    - Sources of light, and objects that modify light.

Although various systems have been developed to measure and order color, by far the most important is the CIE system. First published in 1931, this colorimetric system is based on the principle that the color of an object is a combination of light, object, and observer properties. The CIE (Commission Internationale de l'Eclairage) is an international organization concerned with light and color, which continues to further methods and standards concerning these subjects.

1. Causes of the color stimulus

The CIE system is based on the premise that the stimulus for color is provided by the proper combination of a source of light, an object, and an observer. The sensation of an object's color is produced by the combination of:

- A light source - illuminating an object.
- An object - reflecting or transmitting light to an observer.
- An observer - sensing the reflected light.
- The combination of these three is considered on a spectral (wavelength-by-wavelength) basis.

2. Light source

Electromagnetic energy exists as waves, which can be described by their wavelengths or frequencies. The wavelengths of these waves are distances in nanometer (nm), with 1 nm equal to 10^{-9} meters. Humans can "see" electromagnetic energy over a range of wavelengths from about 400nm to 700nm. This part of the electromagnetic spectrum is called the visible (or color) spectrum. Light sources can be described by their relative energy outputs, wavelength-by-wavelength. These outputs are called relative spectral energy (or power) distributions. The color-producing effects of light sources result from the relative amount of energy available, not the absolute amount of the energy. A light source is also sometimes described by the temperature (called correlated color temperature) of a blackbody radiator that is most similar in color to the light source. A blackbody radiator is an ideal surface that absorbs all energy incident upon it, and re-emits all this energy. The spectral output distribution of an incandescent (tungsten) lamp approximates a blackbody at the same temperature. Correlated color temperature is typically expressed using the absolute centigrade scale, degrees Kelvin (°K).The CIE has published spectral output data for various illuminants, in order to facilitate and standardize colorimetric computations. These illuminants include:

- D65 - daylight, color temperature 6500K.
- A - tungsten, color temperature 2856K.
- F2 - fluorescent, cool white.
- F11 - fluorescent, narrow band cool white. CIE Illuminant spectral output data is used in the process of calculating the color of illuminated objects.

3. Optical characteristics of colored objects

The spectral distribution of light reflected from an object depends upon:

- The light illuminating the object; and
- how the object modifies the incident light.
- For opaque objects, reflectance is determined by the following optical characteristics:
- Surface reflection - diffuse (rough surface), or directional (smooth surface) reflection
- Absorption - light enters the object and does not emerge (on a wavelength-by wavelength basis), as it is converted to heat.
- Scattering - light enters the object and is deflected (on a wavelength-by wavelength basis); and is then eventually absorbed, or exits the object.

The reflectance of an object is determined by a spectrophoto-metric measurement, with calibration relative to an ideal white, and perfect black. Spectral reflectance curves, graphical plots of the reflectance data, are often a useful way of presenting this information. Reflectance data (of the object) is used in the process of calculating the color of the object.

4. Observer

The human eye/brain system senses color through three types of sensors (cones), located in the eye's retina. These cones are sensitive to light in three different wavelength bands, referred to as the L, M, and S bands. Processing of the cone signals, by the brain, eventually yields output sensations interpreted as red, green, and blue (and/or combinations and differences of these primary colors). There are two CIE standard observers that can be used when computing CIE tristimulus values. They are as follows:

- 2° Observer (CIE 1931) - for small objects.
- 10° Observer (CIE 1964) - for large objects.

The color matching functions of these observers, with wavelength-by-wavelength tabulated data, are used in the tristimulus calculations. The term “CIE standard observer” is often used to denote the color-matching functions of the standard observer.

Tristimulus Values

CIE tristimulus values X, Y, and Z, are coordinates of the precursors of color sensation, and form the foundation of the CIE color space. These tristimulus values are calculated by the spectral integration (multiplication of spectra and addition of the product across wavelengths) of the following wavelength-dependent data functions:

- A selected CIE Illuminant (D65, A, F2, etc.).
- An object’s spectrophotometric measurement.
- A selected CIE observer (2° or 10°).

The X, Y, and Z tristimulus values define particular colors. These values are used in the computation of CIE L*a*b* coordinates (where colors are described and ordered), and CIE L*a*b* color differences (where colors are compared).