Colour physics and colour measurement: state-of-the-art and challenges

S Westland
University of Leeds, Woodhouse Lane, Leeds, LS2 9EN, United Kingdom

This article presents key concepts in colour measurement for solid-coloured surface coatings. These include the measurement of reflectance, the CIE XYZ system of colour specification and the CIELAB colour space. The state-of-the-art is then explored through a discussion of the important challenges that remain to be solved. These include the prediction of colour difference, the prediction of colour appearance, measuring colour with cameras, and total colour appearance.

Outlines

- The key concepts in colour measurement systems are described, including the measurement of reflectance, the CIE XYZ system of colour specification and the CIELAB colour space. The difficulties and challenges involved in correlating this objective information with colour as observed by the human eye are outlined.
- Reflectance spectrophotometers give the most accurate and detailed colour information, but simpler instruments may be useful in certain applications. Surfaces with identical reflectance spectra will be perceived as a visual match; the difficulties lie in deciding when surfaces with different spectra will be perceived as matching, and when near-matches will be judged as acceptable.
- The 1931 CIE colour measurement system has been refined and developed in various forms, in attempts to create a colour space which appears more uniform.
- Further difficulties in correlating instrumental measurement to human perception arise because colour perceptions are modified by the lighting level in various ways, and are also affected by the background against which a colour is presented.
- In recent years, digital cameras have been used as colour measurement devices. They have the advantage of being able to analyse differences across the sample area, but it is difficult to correlate their results to standard measurement systems.

Defining the colour of surface coatings

We experience the sensation of colour when we observe the light reflected from surfaces in a scene, or when we look directly at the light emitted by light sources. The term *light* is used to describe electromagnetic radiation, in the wavelength range of approximately 360 to 780nm, to which the human visual system is sensitive.

Surface coatings interact with light in complex and varied ways that include processes of absorption, refraction and diffraction; but it is the light that is reflected by materials in a scene that we use to identify those materials by their colour. The reflectance properties of prints or painted surfaces can be defined by spectral reflectance factors that are normally measured at regular intervals across the visible spectrum of radiation.

The reflectance factor at a certain wavelength is the proportion of incident light at that wavelength that is reflected, and is never less than zero and only occasionally greater than unity. The term *surface reflectance factor* is sometimes used but this is somewhat misleading since it could be understood to imply that the light is reflected at the air/material surface of the coating.

Although a small amount of light (typically about 4% for inks and paints) is indeed reflected at the surface, the majority of reflected light results from absorption and scattering processes that occur within the body of the coating after the light has passed through the air/material interface. Consequently, the measured reflectance is normally a mixture of light that is reflected at the surface and light that has been reflected from the body.

Colour measurement devices

Commercially available reflectance spectrophotometers are able to measure reflectance factors (typically at intervals of 10nm in the range 400 to 700nm) and generally provide the most accurate measurement of colour. Three other types of measurement devices for colour are also used in the surface coatings industry: densitometers, colorimeters, and digital cameras (see Table 1). Densitometers strictly speaking do not measure colour at all. They measure the optical density (known as the status density) in several wavelength ranges using broadband filters and are usually configured to record the densities of the print process colours CMYK. They are typically used to monitor colour consistency, particularly for CMYK printing, mainly because the devices are simple to use, robust and inexpensive.

Colorimeters measure the amount of light reflected using three broadband filters and yield CIE *XYZ* values (see below) directly. Colorimeters are not considered to be as accurate as spectrophotometers (and certainly provide less information) but can be useful devices for quality control when, for example, comparative measurements are required.

Recent years have seen the use of digital colour cameras as colour measurement devices. The advantage of these devices is that they can provide colour information at each spatial position in the printed or painted surface, whereas colorimeters and spectrophotometers are limited to measuring spatially uniform colour patches. However, it is difficult to obtain consistent and meaningful colour information from digital colour cameras (as explained below).

Table 1: Colour properties of measurement devices

Device	Spectral data	Colorimetric data	Spatial data	Comments
Densitometer	No	No	No	The densitometer is used primarily for reading status densities for CMYK inks
Colorimeter	No	Yes	No	The colorimeter measures CIE XYZ and can compute CIELAB colour coordinates and colour differences
Spectrophotometer	Yes	Yes	No	The spectrophotometer measures spectral data and can compute CIE XYZ, CIELAB colour coordinates and colour differences
Digital camera	No	Yes	Yes	The camera records RGB values and thesecan be converted to approximate CIE XYZ values. Spectral data can be estimated with difficulty

Exact and conditional colour matches

One of the greatest achievements of colour measurement has been the ability to be able to predict whether two prints or coated surfaces will be a visual match. If they have identical reflectance factors at each wavelength then they will be a spectral match and would match visually when viewed by any observer under any light source.

However, challenges arise because two samples that have very different spectral reflectance factors can be a perfect visual match under certain conditions. Our colour vision is mediated by three types of light-sensitive cell in the retina known as cones. The cones have peak sensitivities peaking at 420nm, 530nm and 560nm[1] but each type has broadband sensitivity and gives a univariant response.[2]

A conditional match occurs when the light reflected from two samples of differing reflectance factors activates the three types of cones in the human retina in the same way. Since two samples can have very different reflectance factors and yet still evoke the same cone responses, a system that predicts when two samples are a visual match must take into account properties of the visual system.

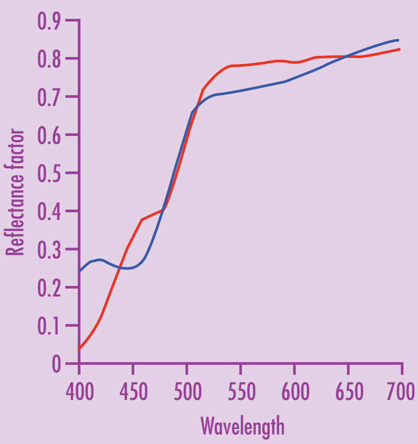
This understanding led to the development of the CIE (*Commission Internationale de l'Eclairage*) system of colour specification. Figure 1 illustrates the reflectance factors for two prints; they are dissimilar but the prints are a close visual match when viewed under some light sources (but not under others) – the CIE system's main purpose is to be able to predict when two such samples will match.

The CIE colour measurement system

The CIE developed a system for the specification of colour stimuli that was recommended for widespread use in 1931.[3] The system allows the calculation of so-called tristimulus values (CIE 1986a;[4] CIE 1986b[5]). The tristimulus values *XYZ* are the amounts of three primaries that an observer would use in an additive colour mixture to visually match a colour stimulus. This visual match occurs when the colour stimulus and the additive mixture of the three primaries evoke the same triplet of cone responses.

The calculation of *XYZ* is possible in the CIE system because the CIE measured the colour-matching functions of a number of observers; that is, the CIE recorded the tristimulus values required to match each wavelength in the visible spectrum separately. Details of how to carry out the calculations are widely available in the literature[6,7] but are normally implemented within software that is provided as part of a colour-measurement system or device.

Figure 1: Spectral reflectance factors for two prints. Although spectrally dissimilar, the two prints are a close visual match when viewed under some light sources



Primary transformations and standard illuminants

The original primaries used by Wright and Guild in their colour-matching experiments in the late 1920s were based on red, green and blue lights. It turned out that it was not possible to match every wavelength with all-positive amounts of the three primaries and so the colour-matching functions were mathematically transformed into a different set of primaries called *XYZ* that are sometimes referred to as imaginary primaries because they cannot be realised physically.

The CIE also defined standard illuminants – tables of spectral power distributions – that can be used to compute the *XYZ* values of a material imagined to be viewed under that illuminant, given the material's spectral reflectance factors.

A normalising factor incorporated into the way in which the CIE *XYZ* values are calculated means that Y = 100 for a perfect reflecting diffuser (one for which the reflectance factor is unity at every wavelength) irrespective of the intensity or colour of the illumination. This intentionally mirrors somewhat the visual phenomenon of colour constancy, whereby objects retain their approximate daylight appearance when viewed under a wide range of different light sources by human observers.

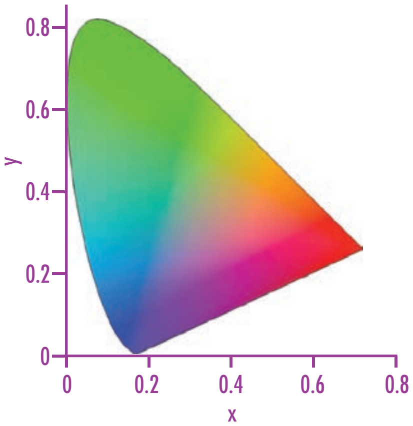
The key achievement of the 1931 CIE system of colorimetry is the ability to predict whether, and under which circumstances, two spectrally dissimilar materials would be a visual match.

In 1964 a new set of colour-matching functions was published by the CIE. The 1931 functions were obtained for a stimulus of 2° of visual angle. Practical colour matching decisions are frequently made with much larger stimuli and therefore a 10° set of functions was introduced in 1964. The 1931 and 1964 functions differ because the cones which create our colour vision are not uniformly distributed in the human retina.[8]

Chromaticity coordinates

The CIE *XYZ* tristimulus values specify a colour stimulus in terms of the visual system. It is often useful, however, to compute chromaticity coordinates *xy* as proportions of the sum of the tristimulus values. Since, by definition, $x+y+z = 1$ it is conventional to plot only two of the three chromaticity coordinates (see Figure 2).

Figure 2: The CIE chromaticity coordinate diagram: the gamut of all physically realisable colours is contained by the convex shape of the spectral locus



This chromaticity diagram is derived by plotting *y* against *x* and this provides a useful map of colour space. However, it should be noted that stimuli of identical chromaticity but different luminance are necessarily collapsed onto the same point in the 2-D plane of the chromaticity diagram; the representation of luminance requires a 3-D colour space.

One of the benefits of the chromaticity diagram is that, in accordance with what is known as Grassman's law, additive mixtures of two primaries fall on a straight line joining the two points that represent the two primaries in the chromaticity diagram.

If three primaries are used then the gamut of the additive system is given by a triangle, with the vertices defined by the chromaticities of the three primaries. The gamut of all physically realisable colours is contained by the convex shape of the spectral locus and a straight line that can be considered to be drawn between the two ends of the spectral locus.

The complexities of subjective colour appearance

The CIE system of colorimetry is a system of colour specification and in this respect it has been extraordinarily successful. However, it has two limitations that it is important to understand. Firstly, the system was designed for colour *specification* rather than for colour *appearance*.

The chromaticities of a perfect reflecting diffuser will change as the illumination changes. However, it has already been mentioned that the colour appearance of such a stimulus to human observers would be expected to remain approximately constant under quite large changes in illumination.

Secondly, the system is perceptually non-uniform. For a given Euclidean distance between two points in *XYZ* space the magnitude of the perceived colour difference between the two stimuli represented by those points can vary by an order of magnitude or more. This second limitation in particular has presented industrial practitioners of colorimetry with serious problems and even today those problems have not all been resolved.

Although it is useful to be able to state that two stimuli are a visual match (under the strict conditions under which the colour-matching functions were derived) if they have the same tristimulus values, it would perhaps be even more useful to be able to predict whether two stimuli that are *not* identical would be accepted as a visual match. Ideally, we would like a uniform colour space in which equal distances in that space correspond to equal perceptual differences.

Creating a uniform colour space

A major advance was made by the CIE in 1976 with the introduction of the CIE (1976) L*a*b*, or CIELAB, system of colour specification. This non-linear transform of the *XYZ* values provided partial solutions to both the problems of colour appearance and colour difference.

CIELAB provides a three-dimensional colour space where the a*–b* axes form one plane and the Lightness L* axis is orthogonal to this plane. The introduction of CIELAB represented three key advances.

Firstly, the inclusion of difference signals crudely models processes that are believed to take place in the human visual system. Thus, whereas the retina initially captures responses derived from the cone spectral sensitivities, these responses are combined at an early (retinal) stage of visual processing to provide a luminance signal and two opposing signals that can be described as being yellow-blue and red-green.

Similarly, CIELAB represents colour stimuli as an achromatic signal (L*) and two chromatic channels representing yellow-blue (b*) and red-green (a*).

Secondly, the non-linear transform of tristimulus values in the CIELAB equations allows the Euclidean distance between two points in the new space to better predict the visual colour difference between the colour stimuli represented by those two points. Consequently, the colour difference metric known as ΔE* has been used effectively to quantify colour difference in a wide range of industries.

Thirdly, the transform includes a normalisation by the illuminant that results in a colour space that makes better predictions of colour appearance than the tristimulus space from which it is derived.[9] Thus, whereas the *xy* chromaticities of a perfect white surface vary with the illuminant, the CIELAB coordinates remain constant at L*=100, a*=b*=0.

CIELAB also allows the representation of a colour stimulus by dimensions of lightness, chroma and hue and it is therefore reasonable to describe CIELAB as a colour *appearance* space, whereas this label is not appropriate for tristimulus space which is strictly only for colour *specification*. CIELAB is the internationally accepted method for colour specification and remains the recommended method for calculating large colour differences.

Challenges and partial solutions

Colour dfferences

Unfortunately, although CIELAB is more perceptually uniform than *XYZ* space, it is still a long way from being truly perceptually uniform. Printers and print users would like to be able to apply a single tolerance on the value of ΔE* that defines the perceptibility or acceptability boundaries throughout colour space, but this is not possible.

The concept of ΔE* is simple; ΔE* is the distance in CIELAB space between two points that represent two colours. If ΔE*=0 then the two colours are a perfect match but as ΔE* increases the colour difference between the two colours increases. At some threshold value of ΔE* it would be useful to be able to say that below this threshold the colour difference will be too small to be seen and sometimes it is assumed that this threshold is ΔE*=1.

However, in practice the size of the threshold depends upon many factors such as the size of the samples, the distance they are viewed from, whether they are butted up against each other or whether there is a space between them, and the colour of the background against which they are viewed, to name but a few.

More seriously, the size of the threshold depends upon the colour of the samples being considered. This is why printers, paintmakers and others involved in matching colours commercially cannot apply a single threshold value of ΔE^* for pass/fail colour decisions.

Improving perceptual predictions

The last two decades of the twentieth century saw a great deal of research into the development of effective colour difference formulae. It has not been possible to improve the transform from XYZ to CIELAB; that is, the new colour-difference formulae are still based upon the CIELAB colour space, but they use equations that weight the component colour differences (ΔL, ΔC, and ΔH) differently depending upon where the colours are in colour space.

Early improvements on CIELAB included the JPC79 equation and the M&S83a equation. However, a notable breakthrough was achieved in 1983 with the introduction of the CMC formula (named after the Colour Measurement Committee of the Society of Dyers and Colourists) and this has been widely used in industry.[10]

The CMC equation included two user-configurable variables *l* and *c*. Two configurations were normally used; l=2, *c*=1 and *l*=1, *c*=1. When *l*=2, lightness differences are weighted half as much as differences in chroma or hue and this has been found useful to predict colour-difference *acceptability* (which is not necessarily the same as colour-difference *perceptibility*).

By the 1990s, some limitations of the CMC equation were apparent and further work was underway to rectify these. A new CIE equation, CIE94, was recommended for study but this was shortly replaced by CIEDE2000.[11] The CIEDE2000 equation should be used for small colour differences (where CIELAB $\Delta E^* < 5$)[12] but for large colour differences CIELAB is still preferred.

Colour appearance models

The human visual system in most cases has a remarkable ability to maintain the apparent colour of an object constant despite quite large changes in the quality and intensity of the illumination. A white piece of paper tends to look white whether it is viewed by daylight, tungsten light or candlelight.

The CIE XYZ system was never intended to predict colour appearance and the *XYZ* values for a white vary with the illuminant. However, colour appearance models (CAMs) attempt to deal with this, and other, colour-appearance phenomena. Fairchild[13] defines a CAM as any model that includes predictors of at least the relative colour-appearance attributes of lightness, chroma and hue. The attribute *brightness* is a visual perception according to which an area appears to exhibit more or less light. *Lightness* is the brightness of an area judged relative to the brightness of a similarly illuminated reference white.

The lightness of a sample is usually in the range 0 to 100 and is influenced by the surrounding background. Colourfulness is that attribute of a visual sensation according to which an area appears to exhibit more or less chromatic content.

How light levels affect perceived colour

Hunt[14] has shown that the colourfulness of an object increases as the luminance increases so that a typical outdoor scene appears much more colourful in bright sunlight than it does on an overcast day (a phenomenon referred to as the Hunt Effect).

Chroma is the colourfulness of an area judged as a proportion of the brightness of a similarly illuminated reference white. The colourfulness of an area judged in proportion to its brightness is called the saturation. Finally, hue is the attribute of a sensation according to which an area appears to be similar to one, or to a proportion of two, of the perceived colours red, yellow, green and blue.

Other respects in which human visual perception differs from that of instruments include:

- The Stevens Effect: the perceived contrast between dark and light colours increases with increasing adapting luminance – ie dark colours look darker and light colours lighter.
- The Bezold–Brücke Effect: as the intensity of light increases, spectral colours are perceived as shifting towards blue at wavelengths shorter than 500nm and yellow at longer wavelengths. Correspondingly, at lower light intensities the greenness or redness of the colours appears greater.

CIELAB can be considered to be a CAM but it makes relatively poor predictions of colour appearance in most cases. Fairchild[15] notes that CIELAB has no luminance-level dependency and therefore cannot predict the Hunt, Bezold-Brücke or Stevens effects. CIELAB also fails to predict simple contrast effects such as those illustrated in Figure 3. The CIELAB colour coordinates for the grey patches shown in Figure 3 are identical but their colour appearances vary greatly depending upon the background.

Figure 3: The perceived appearance of a colour sample (here, neutral grey with constant CIELAB values) is affected by its surroundings; current colour measurement systems fail to take account of this phenomenon

A CAM should, for example, be able to predict an increase in lightness when a grey paper is viewed against a dark background compared to when it is viewed against a light background. For many technologies, of course, colour appearance is not important and basic colorimetry is sufficient. However, increasingly there is interest in measuring what colours look like and this is the realm of colour appearance models.

Over the last couple of decades a number of CAMS have been developed and published including CIECAM97, CIECAM97s, CMCCAM2000 and CIECAM02.[16,17] Details of how to compute and use the latest CAM are available in the literature.[7]

Capturing colour using cameras

Digital colour cameras capture red, green and blue, or *RGB*, values at each spatial position in a scene or on a sample. They therefore have the potential to be used as colour measurement devices that can measure very small sample sizes and measure spatial variability for coloured samples. However, several challenges need to be overcome.

Perhaps the most important challenge is that of consistency or precision. Cameras are non-contact devices and require an external light source; the *RGB* values that are obtained for a sample are likely to vary greatly depending upon the intensity and spectral quality of the light source and on a number of other parameters (including the distance of the camera from the sample, the exposure time, and various other settings on the camera).

Moreover, consumer cameras are designed to make pictures that please people, not to provide scientific data. Typically, the camera automatically performs various operations upon the captured image that change the *RGB* values. An example is white-point balance where the camera tries to adjust the images to compensate for assumed changes in the colour of the illumination. It is necessary to disable or account for these operations.

Nevertheless, even if efforts are made to a achieve consistent camera responses it is a non-trivial task to convert the camera *RGB* values (which are specific to each camera and each camera's settings; this can hardly be avoided, as different camera models use different sensors) to CIE *XYZ* values; indeed, unless the camera's spectral responses are linearly related to the colour responses of the human eye, satisfying what is referred to as the Luther condition (the chance of this being the case is extremely small) then it will only be possible to estimate the *XYZ* values approximately.[18]

However, computational methods that allow *XYZ* values to be recovered from camera *RGB* values are widely available in the literature[7] including some that allow the recovery of spectral data.[19] Despite the errors that result, cameras are sometimes preferred to spectrophotometers or colorimeters because of the trade-off of spatial information at the expense of less colour accuracy.

The added complexities of total colour appearance

Although there are a number of colour-appearance models that attempt to predict colour-appearance phenomena there is no such model that can successfully predict all such phenomena. However, colour is in fact only one aspect of appearance.

Total appearance includes colour but also other factors such as gloss, texture, translucency and bronzing. Each of these additional features presents a challenge in terms of measurement systems. However, how to integrate these features into an integrated total colour appearance model is a task that is likely to be out of reach for several decades.

Nor does this take account of the additional complexities introduced by an ever-growing range of different types of effect pigment, some specifically designed to produce the maximum shift in colour appearance with viewing angle.

Conclusions

Accurate colour measurement devices are now widely available and affordable and colour coordinates can be easily calculated according to the CIE system. However, the prediction of colour difference (and the associated use of a single number for pass/fail tolerance) is still not quite possible although the latest colour-difference equation, CIEDE2000, performs much better than its predecessors such as CIELAB and CMC.

CIELAB remains the standard for large colour differences but for small colour differences CIEDE2000 should be used. Colour appearance is still not a mature science but a number of models exist for the prediction of colour appearance and CIECAM02 is the latest CIE model.

Reflectance spectrophotometers remain the 'gold standard' for colour measurement; however, digital cameras are being used to measure colour (and even spectral reflectance); these have the advantage of being able to provide fine spatial colour detail.

References

1. Bowmaker J K, 'The retina', *Signals and Perception. The Fundamentals of Human Sensation*, D Roberts (ed), 115–31; Basingstoke, The Open University: Palgrave Macmillan, 2002
2. Rushton W A, 'Pigments and signals in colour vision', *J Physiology*, **220**, (3), 1P–1P, 1972
3. Wyszecki G and W S Stiles, *Color Science*, John Wiley and Sons, 1982
4. CIE (1986a), Publication No S2, *CIE Standard Colorimetric Observers*, Vienna, Austria, Central Bureau of the CIE
5. CIE (1986b), Publication No 15.2, *Colorimetry*, (2nd edition), Vienna, Austria, Central Bureau of the CIE
6. ASTM (2001), E308–01, Standard Practice for Computing the Colors of Objects by Using the CIE System
7. Westland S, C Ripamonti and V Cheung, *Computational Colour Science using MATLAB*, John Wiley & Sons, 2012
8. Williams D, D I A MacLeod and M Hayhoe, 'Punctate sensitivity of the blue sensitive mechanism', *Vision Research*, **21**, 1357–75, 1981
9. Hunt R W G and M R Pointer, *Measuring Colour*, (4th edition), Wiley-IS&T series, 2011
10. Clarke F J J, R McDonald and B Rigg, 'Modification to the JPC79 Colour-difference Formula', *J Soc Dyers & Colourists*, *100*, (4), 128–32, 1984
11. Luo M R, G Cui and B Rigg, 'The development of the CIE 2000 colour-difference formula: CIEDE2000', *Color Res and App*, **26**, (5), 340–50, 2001
12. Shen S and R S Berns, 'Color-difference formula performance for several datasets of small color differences based on visual uncertainty', *Color Res and App*, **36**, (1), 15–26, 2011
13. Fairchild M D, *Color Appearance Models*, (1st edition), Addison Wesley Longman, 1998
14. Hunt R W G, 'Light and dark adaptation and the reception of color', *J Optical Soc Amer*, **42**, 190–9, 1952
15. Fairchild M D, *Color Appearance Models*, (2nd edition), John Wiley & Sons, 2005
16. Moroney N, M D Fairchild, R W G Hunt, C Li, M R Luo and T Newman, 'The CIECAM02 color appearance model', Proc IS&T/SID's 10th Color Imaging Conf, 23–7, Scottsdale, Arizona, 2002
17. Li C J and M R Luo, 'Testing the robustness of CIECAM02', *Color Res & App*, **30**, (2), 99–106, 2005
18. Hong W, M R Luo and P A Rhodes, 'A study of digital camera colour characterization based on polynomial modelling', *Color Res & App*, **26**, (1), 76–84, 2000.
19. Maloney L T and B A Wandell, 'Color constancy: a method for recovering surface spectral reflectance', *J Optical Soc Amer*, **A3**, 29–33, 1986