Colour spaces - perceptual, historical and applicational background

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Abstract— **In this paper we present an overview of colour spaces used in electrical engineering and image processing. We stress the importance of the perceptual, historical and applicational background that led to a colour space. The colour spaces presented are : RGB, opponent-colours spaces, phenomenal colour spaces, CMY, CMYK, TV colour spaces (YUV and YIQ), PhotoYCC, CIE XYZ, Lab and Luv colour spaces.**

Keywords—**colour spaces, RGB, HSV, CIE**

I. INTRODUCTION

The choice of the colour space can be a very important decision which can dramatically influence the results of the processing. The knowledge of various colour spaces can ease the choice of the appropriate colour space. The aim of this paper is to present various colour spaces and their perceptual, historical and applicational background. We believe that the knowledge of the background that led to the definition of a certain colour space makes the difference between *knowing a colour space* and *understanding a colour space*.

II. DEFINITIONS

Colour is the way the HVS (the *human visual system*) measures a part of the electromagnetic spectrum, approximately between 300 and 830 nm. Because of certain properties of the HVS we are not able to see all of the possible combinations of the visible spectrum but we tend to group various spectra into colours.

A *colour space* is a notation by which we can specify colours, ie the human perception of the visible electromagnetic spectrum.

III. CLASSIFICATION OF COLOUR SPACES

Based on our experience and on some excellent texts on the subject [6], [7], [8], [5], [3], [1], [4] we propose the following categorization of colour spaces:

- **HVS based colour spaces** include the *RGB colour space* , the *opponent colours theory based colour spaces* and the *phenomenal colour spaces*. These colour spaces are motivated by the properties of the HVS.
- **Application specific colour spaces** include the colour spaces adopted from TV systems (*YUV, YIQ*), photo systems (*Kodak PhotoYCC*) and printing systems (*CMY(K)*)
- **CIE colour spaces** are spaces proposed by the CIE and have some properties of high importance like device-independency and perceptual linearity (*CIE XYZ*, *Lab* and *Luv*)

IV. COLOUR SPACES BASED ON THE HUMAN VISUAL SYSTEM

A. RGB colour space

A.1 Perceptual preamble

The main idea that led to the specification of the RGB colour space was :

if we manage to describe the visible spectrum in such a way that simulates the very first detection of light in the human eye, we have all the information needed for the storage, processing and generation (visualization) of a perceptually equivalent spectrum.

This idea implies a certain knowledge of the acquirement of visual information by the human visual system. The trichromatic theory (based on the work of Maxwell, Young and Helmholtz) states that there are three types of photoreceptors, approximately sensitive to the red, green and blue region of the spectrum. There are, in fact, three types of cones, which are usually referred as L, M and S cones (Long, Middle and Short-wavelength sensitivity) [5, page 582].

A.2 The RGB space

Thus, most of the devices for capturing images have an LMS-fashion light detector. We ususally refer to these devices as RGB. The colour is described with three components : R,G and B. The value of these components is the sum of the respective sensitivity functions and the incoming light:

$$R = \int_{300}^{830} S(\lambda) R(\lambda) d\lambda$$

$$G = \int_{300}^{830} S(\lambda) G(\lambda) d\lambda$$

$$B = \int_{300}^{830} S(\lambda) B(\lambda) d\lambda$$

where $S(\lambda)$ is the light spectrum, $R(\lambda)$, $G(\lambda)$ and $B(\lambda)$ are the sensitivity functions for the R, G and B sensors respectively. This transformation from the spectral power distribution to a three-dimensional vector is a powerful compression technique with a compression ratio of more than 10 : 1 (see [3, page 3] for a detailed explanation of this ratio). A side effect of this transformation is a loss of information which leads to the existance of so-called *metamers*. These are colours with different spectra but with same perceptual values [1, pages 4, 15].

As we can see from the above equations, the RGB values depend on the specific sensitivity function of the capturing device. This makes the RGB colour space a **device-dependant** colour space.

Printing and displaying devices also works on an RGB-fashion basis. And they also have their specific sensitivity functions which makes the term *controlled environment* even more difficult to achieve.

However there exist methods for the calibration of devices and we can transform the RGB space into a linear, perceptually uniform colour space anytime we want. With this in mind we can state that the RGB colour space is the basic colour space, which can be (providing calibration data) transformed into other colour spaces as needed.

A.3 Short comings of the RGB space

The main disadvantage of the RGB colour space in applications with natural images is a high correlation between its components : about 0.78 for r_{BR} (cross correlation between the B and R channel), 0.98 for r_{RG} and 0.94 for r_{GB} [7, page 68].

Its psychological non-intuitivity is another problem because a human has problems with the visualization of a colour defined with the R, G and B attributes.

Another problem is the perceptual non-uniformity, ie the low correlation between the perceived difference of two colours and the Euclidian distance in the RGB space.

B. Opponent colour spaces

B.1 Perceptual preamble

In the late 19th century, a German physiologist called Ewald Hering, proposed the *opponent colours theory* [6], [7], [5], [1]. Hering noted that certain hues were never perceived to occur together. For example, a colour perception is never described as reddish-green or yellowish-blue, while all other combinations are possible. Although he first stated that there were three types of photoreceptors : white-black, yellow-blue and red-green, which was in contrast with the theory of trichromacy (L, M and S photoreceptors), later researchers found out that there is a layer in the HVS that converts the RGB values from the cones into an opponent colour vector. This vector has an achromatic component (White-Black) and two chromatic components (Red-Green and Yellow-Blue). This transformation is done in the postreceptors retina cells called ganglion cells. These cells drive the cells in the lateral geniculate nucleus which also responds to opponent colour stimulus [1, page 13].

There exist many models of the opponent colours theory like the Muller and Judd model, the Adams model, the Hurvich and Jameson model and the Guth model, all described in [5, page 633].

B.2 The opponent colours spaces

A simple model of this transformation is [7, page 74]

$$RG = R - G$$

$$YeB = 2B - R - G$$

$$WhBl = R + G + B$$

There is also a *logarithmic* version of the above transformation (following the logarithmic response of the cones) proposed by Fleck, Forsyth and Bregler [7, page 75]:

$$RG = \log R - \log G$$

$$YeB = \log B - \frac{(\log R + \log G)}{2}$$

$$WhBl = \log G$$

An excellent colour space has been proposed by Ohta. This colour space is a very good approximation of the Karhunen-Loeve transformation of the RGB (decorrelation of RGB components) which makes it very suitable for many image processing applications [7, page 75]:

$$I_1 = \frac{R + G + B}{3}$$

$$I_2 = \frac{R - B}{2}$$

$$I_3 = \frac{2G - R - B}{4}$$

C. Phenomenal colour spaces

C.1 Perceptual preamble

One of the pioneers of colour science, Isaac Newton, arranged colours in a circle called the Newton's colour circle [1]. This circle, although it neglects the brightness property of colour, uses the attributes of *hue* and *saturation* for describing colours. It turns out that this is the most *natural* way for humans of describing colours. By *natural* we mean that the human brain tends to organize colours by hue, saturation and brightness. This is the *mind's representation of colours* - the highest level in human visual processing.

C.2 The phenomenal colour spaces

This representation of colours is the basis for a family of colour spaces called *phenomenal colour spaces*. All these colour spaces use the following three attributes for describing a colour (see figure IV-C.2) [1] :

- **Hue** is the attribute which tells us whether the colour is red, green, yellow, blue, purple ...
- **Saturation** is the level of non-whiteness. Saturated colours are very pure, vivid. An extremely saturated colour has only one spectral component while an unsaturated colour has lots of white added (see figure IV-C.2). Sometimes this attribute is called also *chroma*.
- **Brightness** is a measure of the intensity of light. Sometimes this attribute is called also *intensity*.

Phenomenal colour spaces are deformations of the RGB colour space. They are usually a linear transformations of the RGB space [8].

C.3 Munsell colour space

The Munsell colour space is an atlas of 1500 systematically ordered colour samples. These samples are chosen in such a way that the steps are *perceptually equal* [6], [1].

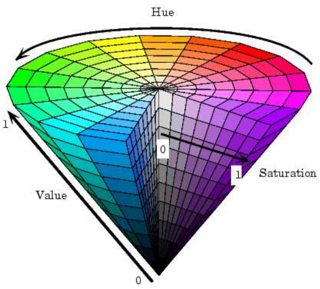

Fig. 1. A phenomenal colour space (source : http://www.mathworks.com)

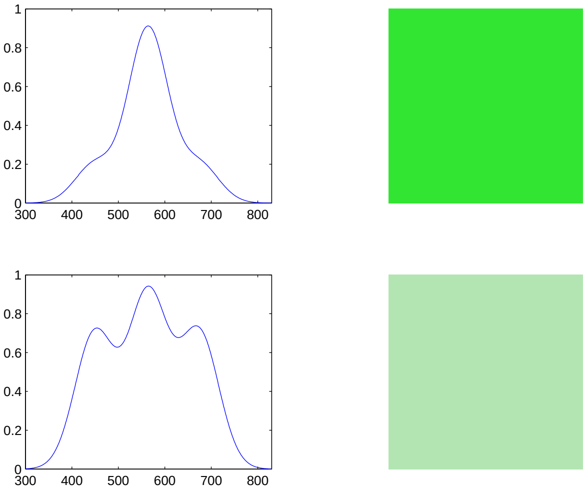

Fig. 2. Note how the highly saturated green colour in the first row (right) has a more isolated peak in the green part of the spectrum (left) than the the low saturated (almost grey) green colour in the second row

C.4 HSL colour spaces

HSL (*hue, saturation, value*) colour spaces are linear transformations from the RGB space and therefore inherit all the shortcomings of tha latter (device dependancy, nonlinearity). Unfortunately there are lots of *HSL* spaces defined in literature (see [8, page 15]), therefore one needs to know exactly the relationship between RGB and HSL values in order to be consistent.

Here we present some of the transformations from a device dependant RGB space to an HSL space we found in various papers.

Travis [8] suggests the following method for calculating HSV values from RGB. Saturation is

$$S = \frac{\max(R,G,B) - \min(R,G,B)}{\max(R,G,B)}$$

and value is

$$V = \max(R,G,B)$$

To calculate the hue attribute we must first calculat R', G' and B' :

$$R' = \frac{\max(R,G,B) - R}{\max(R,G,B) - \min(R,G,B)}$$

$$G' = \frac{\max(R,G,B) - G}{\max(R,G,B) - \min(R,G,B)}$$

$$B' = \frac{\max(R,G,B) - B}{\max(R,G,B) - \min(R,G,B)}$$

If $S = 0$ then hue is undefined, otherwise

$$H = 5 + B' \quad R = \max(R,G,B), G = \min(R,G,B)$$

$$H = 1 - G' \quad R = \max(R,G,B), G \neq \min(R,G,B)$$

$$H = R' + 1 \quad G = \max(R,G,B), B = \min(R,G,B)$$

$$H = 3 - B' \quad G = \max(R,G,B), B \neq \min(R,G,B)$$

$$H = 3 + G' \quad B = \max(R,G,B)$$

$$H = 5 - R' \quad otherwise$$

H is then converted to degrees by multiplying with 60.

Gonzales and Woods [8, page 17] use the following equations:

$$I = \frac{R+G+B}{3}$$

$$S = 1 - \left(\frac{3}{R+G+B}\right) \min(R,G,B)$$

$$H = \cos^{-1}\left(\frac{0.5\,(R-G) + (R-B)}{\sqrt{(R-G)^2 + (R-B)(G-B)}}\right)$$

where I (intensity) is used instead of V (value).

C.5 Short comings of phenomenal colour spaces

Although they are very intuitive to use (many commercial image processing packages like Paint Shop Pro or Photoshop use the phenomenal colour space in their GUIs), the phenomenal colour spaces have a number of shortcomings which limit their use in practical applications [4, page 18].

First is the device dependency. Since they are mostly linear transformations from RGB they do not include any information about chromaticity and white point.

There is usually a hue discontinuity around 360^o. This makes difficult to make arithmetic operations in such a colour space.

Except for the Munsell colour space there is no relation between the phenomenal colour spaces and the human perception in view of the perceptual uniformity of such spaces. There is also a bad correlation between the computed and the perceived lightness.

It is more appropriate to use the *CIE Lab* or *CIE Luv* colour spaces and transform the uv or ab components into a polar coordinate system.

V. APPLICATION SPECIFIC COLOUR SPACES

A. Printing

A.1 Subtractive mixturing of colours

In contrast to additive mixturing of colours, which occurs on self-luminous displays, subtractive mixturing of colours is a way to produce colours by selectively removing a portion of the visual spectrum [3, page 12]. Suppose we have a light source (illuminant) with the spectrum $S_{illuminant}(\lambda)$. Suppose then, that we have a surface whose reflection is described by $R_{surface}(\lambda)$. The spectrum of the reflected light can then be computed with

$$S_{reflected}(\lambda) = S_{illuminant}(\lambda) R_{surface}(\lambda)$$

If we want a surface to appear blue, this surface needs to absorb the green and the red part of the spectrum and to reflect the blue part. If we add some green ink (which absorbs the blue and red part of the spectrum and reflects the green part) we get black (subtractive mixturing) instead of blueish-green (as we would get if we additively mixed blue and green - for example if we fire the blue and green guns in a CRT).

A.2 CMY(K) colour space

The CMY (*Cyan-Magenta-Yellow*) colour space is a subtractive colour space and is mainly used in printing applications [8], [3], [4]. It is quite unintuitive and perceptually non-linear. The three components represent three reflection filters. There is also the CMYK colour space where the fourth component K represents the amount of black ink.

There are two types of transformations to the CMY(K) colour space : simple ones are referred as *one minus RGB* and give bad results. The other ones, used in practical applications, use complicated polynomial arithmetic or three-dimensional interpolations of lookup tables [3, page 14].

Here is a simple transformation from the *RGB* to the *CMY* colour space [8, page 14]

$$C = 1 - R$$

$$M = 1 - G$$

$$Y = 1 - B$$

The transformation from *CMY* to the *CMYK* colour space is performed with the following equations

$$K = \min(C, M, Y)$$

$$C = \frac{C - K}{1 - K}$$

$$M = \frac{M - K}{1 - K}$$

$$Y = \frac{Y - K}{1 - K}$$

As emphasized previously, these transforms are merely good for printing a pie chart or for pedagogical reasons, but fail anywhere else.

B. TV related colour spaces

Contemporary CRT devices used in TV boxes and computer monitors comply with the ITU-R Reccomendation BT.709. This means that if you drive different CRT devices with the same RGB values you should get perceptually equal colours [3, page 10]. Ther exists a linear transformation from the *CIE XYZ* colour space (see section VI-B) to the RGB_{709} colour space [4].

Because of some historical reasons the first TV systems transmitted only a luminance component. Later as the need for colour TV was growing, researchers started to study how to encode the RGB_{709} values in the TV signal and to stay compatible with the old system. They decided to add two chrominance components : $R - Y$ and $B - Y$. This system was designed to minimize the bandwidth of the composite signals. Because the HVS is far less sensitive to chrominance data than to luminance, these two components can be transmitted with a smaller bandwidth.

In the European PAL standard the RGB_{709} signals are encoded in the YUV space with the following equations [7, page 72]

$$Y = 0.299R + 0.587G + 0.114B$$

$$U = -0.147R - 0.289G + 0.437B = 0.493\,(B - Y)$$

$$V = 0.615R - 0.515G - 0.1B = 0.877\,(R - Y)$$

The YUV space can be transformed in a phenomenal colour space with Y representing the V component and

$$H_{UV} = \tan^{-1}\left(\frac{V}{U}\right)$$

$$S_{UV} = \sqrt{U^2 + V^2}$$

Similarly, the American NTSC system is defined with the YIQ colour space, where the Y component is the same as in the YUV space and the I and Q components are defined with

$$I = 0.596R - 0.274G - 0.322B = 0.74(R - Y) - 0.27(B - Y)$$

$$Q = 0.211R - 0.523G + 0.312B = 0.48(R - Y) + 0.41(B - Y)$$

The YIQ space can also be transformed into a phenomenal colour space with saturation and hue equal to

$$H_{IQ} = \tan^{-1}\left(\frac{Q}{I}\right)$$

$$S_{IQ} = \sqrt{I^2 + Q^2}$$

For more detailed information on TV colour spaces see [8, page 18], [7, page 71] and [3, page 9].

C. Photo colour spaces

C.1 Kodak PhotoYCC colour space

This colour space was defined by Kodak in 1992 for the storage of digital colour images on PhotoCDs. The transformation from the RGB_{709} components to PhotoYCC values is done in three steps [7, page 87]:

1. Gamma correction from RGB values to $R'G'B'$
2. Linear transformation from $R'G'B'$ to $Y'C'C'$
3. Quantization of $Y'C'C'$ to 8-bit YCC data

VI. CIE COLOUR SPACES

A. CIE

CIE, the International Commission on Illumination - abbreviated as CIE from its French title Commission Internationale de l'Eclairage - is an organization devoted to international cooperation and exchange of information among its member countries on all matters relating to the science and art of lighting [2].

In 1931 CIE laid down the *CIE 1931 standard colorimetric observer*. This is the data on the ideal observer on which all colorimetry is based [5, page 131].

B. CIE XYZ

CIE standardized the XYZ values as *tristimulus values* that can describe any colour that can be percepted by an average human observer (the CIE 1931 standard colorimetric observer). These primaries are nonreal, i.e. they cannot be realized by actual colour stimuli [5, page 138]. This colour space is chosen in such a way that every perceptible visual stimulus is described with positive XYZ values.

A very important attribute of the *CIE XYZ* colour space is that it is **device independent**. Every colour space that has a transformation from the *CIE XYZ* colour space (RGB_{709}, *CIELab*, *CIELuv*) can also be regarded as being device independent. The *CIE XYZ* colour space is usually used as a reference colour space and is as such an intermediate device-independent colour space.

C. CIE Luv and CIE Lab colour spaces

In 1976 the CIE proposed two colour spaces (*CIELuv* and *CIELab*) whose main goal was to provide a perceptually equal space. This means that the Euclidian distance between two colours in the *CIELuv/CIELab* colour space is strongly correlated with the human visual perception. To achieve this property there were two main constraints to take into account:

- chromatic adaptation
- non-linear visual response

The main difference between the two colour spaces is in the chromatic adaptation model implemented. The *CIE Lab* colour space normalizes its values by the division with the white point while the CIELuv colour space normalizes its values by the subtraction of the white point.

The transformation from *CIE XYZ* to *CIE Luv* is performed with the following equations

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16$$

$$u^* = 13L^*(u' - u'_n)$$

$$v^* = 13L^*(v' - v'_n)$$

for $\frac{Y}{Y_n} > 0.01$, otherwise the following L^* formulae is used

$$L^* = 903.3\frac{Y}{Y_n}$$

The quantities u', v' and u'_n, v'_n are calculated from

$$u' = \frac{4X}{X + 15Y + 3Z}$$

$$u'_n = \frac{4X_n}{X_n + 15Y_n + 3Z_n}$$

$$v' = \frac{9Y}{X + 15Y + 3Z}$$

$$v'_n = \frac{9Y_n}{X_n + 15Y_n + 3Z_n}$$

The tristimulus values X_n, Y_n, Z_n are those of the nominally white object-colour stimulus.

The transformation from *CIE XYZ* to *CIE Lab* is performed with the following equations

$$L^* = 116\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - 16$$

$$a^* = 500\left[\left(\frac{X}{X_n}\right)^{\frac{1}{3}} - \left(\frac{Y}{Y_n}\right)^{\frac{1}{3}}\right]$$

$$b^* = 200\left[\left(\frac{Y}{Y_n}\right)^{\frac{1}{3}} - \left(\frac{Z}{Z_n}\right)^{\frac{1}{3}}\right]$$

The perceptually linear colour difference formulaes between two colours are

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

$$\Delta E^*_{uv} = \sqrt{(\Delta L^*)^2 + (\Delta u^*)^2 + (\Delta v^*)^2}$$

VII. CONCLUSION

In this paper we have presented an overview of colour spaces used in image processing. We have tried to stress the importance of the historical and perceptual background that has led to the introduction of these colour spaces.

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