Multispectral Color Imaging

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Abstract

In a previous issue of NORSIGnalet [1] we have presented the principle of Color Management, and given some solutions that can ensure consistent reproduction of colors throughout a complex digital imaging system. A related paper in Piksel'n [2] treated the problem of color conversion into the sRGB color space for desktop scanners. Both these papers, along with the rest of the color science and imaging community, both in the industry and academia, are based on the paradigm that three variables are sufficient to characterize a color. However, in particular due to the effect of metamerism, three color channels are often insufficient for high quality imaging e.g. for museum applications. This paper addresses several aspects of this interesting emerging field of research and development — imaging using more than three image channels.

1 Introduction

Already in 1853 Grassmann [3] stated that three variables are necessary and sufficient to characterize a color. This principle, the three-dimensionality of color, has since been confirmed by thorough biological studies of the human eye. This is the reason why digital color images are mostly composed of three color channels, such as red, green and blue.

However, for digital image acquisition and reproduction, three-channel images have several limitations. First, in a color image acquisition process, the scene of interest is imaged using a given illuminant. Due to metamerism, the color image of this scene under another illuminant cannot be accurately estimated. Furthermore, since the spectral sensitivities of the acquisition device generally differ from the standardized color matching functions, it is also impossible to obtain device-independent color. By augmenting the number of channels in the image acquisition and reproduction devices we can remedy these problems, and thus increase the color image quality significantly.

Multispectral color imaging systems are developing rapidly because of their strong potential in many domains of application, such as remote sensing, astronomy, physics, museum, cosmetics, medicine, high-accuracy color printing, computer graphics, etc. Several academic research groups worldwide are working on these matters, for example at the University of Chiba [4, 5], Rochester Institute of Technology [6, 7], RWTH Aachen [8, 9], University of Joensuu [10], and ENST Paris [11–18]. We also now see some emerging industrial applications [5, 9].

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In order to understand the limitations of conventional color imaging, we start in Section 2 by giving a short introduction to the science of light, surfaces, and color, as well as the phenomenon known as metamerism. Then, in Section 3 we present a multispectral color image acquisition system. In Section 4 we then present briefly some of the problems that needs to be solved in the design of such a system, as well as some interesting applications.

2 Some basic principles

2.1 Light and surfaces

Aristotle viewed all color to be the product of a mixture of white and black, and this was the prevailing belief until Sir Isaac Newton's prism experiments provided the scientific basis for the understanding of color and light [19]. Newton showed that a prism could break up white light into a range of colors, which he called the spectrum (see Figure 1), and that the recombination of these spectral colors re-created the white light. Although he recognized that the spectrum was continuous, Newton used the seven color names red, orange, yellow, green, blue, indigo, and violet for different parts of the spectrum by analogy with the seven notes of the musical scale.

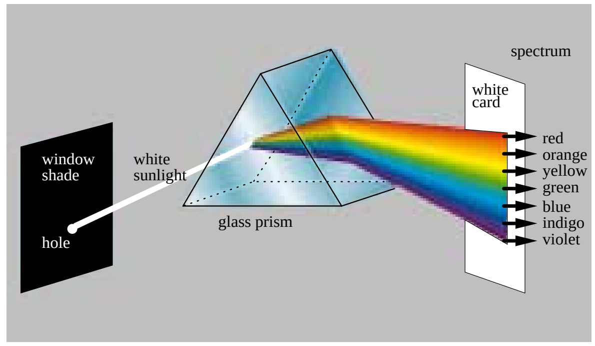

Figure 1: *Newton's experiment with sunlight and a prism whicqh led to the realization that the color of light depended on its spectral composition.*

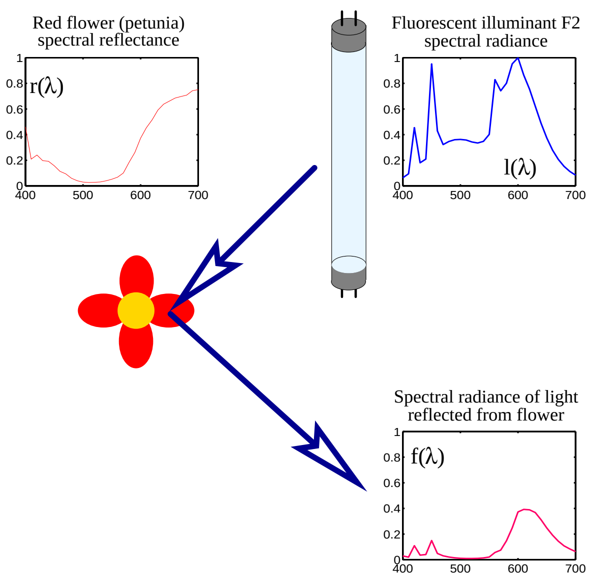

Figure 2: *A simple spectral model for the interaction between light and surfaces:* $f(\lambda) = l(\lambda)r(\lambda)$.

Light is an important aspect of color. But equally important is the notion of the color of *surfaces* such as green grass, red roses, yellow submarines, etc. The color of a surface is strongly dependent on its spectral reflectance, that is, the amount of the incident light that is reflected from the surface, for different wavelengths. If we represent the spectral radiance of the illuminant by the function $l(\lambda)$, λ being the wavelength, and the spectral reflectance in a given surface point of an object by $r(\lambda)$, the radiance of the light reflected from this surface point $f(\lambda)$ is, by definition of reflectance, given by the equation $f(\lambda) = l(\lambda)r(\lambda)$, see Figure 2. Note that obviously a surface has many attributes that are not adequately described by this simple equation - for example gloss.

2.2 Color

What *is* color? This apparently simple question turns out to be rather difficult to answer concisely, and as a result, confusions and misunderstanding are common when color is discussed. As a scientific starting point, let us turn to the most widely accepted technical definition of color, given by the Optical Society of America back in 1940: *Color consists of the characteristics of light other than spatial and temporal inhomogeneities; light being that aspect of radiant energy of which a human observer is aware through the visual sensations which arise from the stimulation of the retina of the eye.*

Now, I would not expect that this necessarily makes the matters very much clearer for the reader. I will, however, draw your attention to one particular word - *sensation*. Color is a sensation! Obviously, the colors of the world around us depend on physical entities such as the spectral distribution of light and the spectral reflectance of the surfaces, but it does also depend on how we perceive them. Figure 3 illustrates this.

Figure 3: *The two crosses are printed with exactly the same amount of ink.*

To explain and predict what happens in Figure 3 is a problem scientists in the fields of color, vision, and imaging are still struggling with. And already this brief introduction to the wonders of visual perception is way out of scope of this paper. For further reading refer for example to an excellent book in Norwegian by Valberg [20], or another book on vision by Wandell [21].

But before we leave the subject of color vision completely, we need to establish a model of the very first stage of the human visual system. In the human eye, an image is formed by light focused onto the retina by the eye's lens. The retina contains two main types of light-sensitive cells, the *rods* and the *cones*. The rods are responsible for night (scotopic) vision and the cones for daylight (photopic) vision under normal levels of illumination. There are three types of cones, named L, M, and S, which are sensitive mainly to light containing long, middle and short wavelengths, respectively. Denoting by $s_i(\lambda)$ the spectral sensitivity of the ith type of cone, the responses of the three cones can be represented as the 3-component vector $\mathbf{c} = [c_1 c_2 c_3]^t$ where

$$c_i = \int_{\lambda_{\min}}^{\lambda_{\max}} l(\lambda) r(\lambda) s_i(\lambda) d\lambda, \quad i = 1, 2, 3. \tag{1}$$

This equation forms the basis of *colorimetry* — the quantification of color. By uniformly sampling the spectra above with a proper wavelength interval, we can rewrite Equation 1 in a matrix form as follows:

$$\mathbf{c} = \mathbf{S}^t \mathbf{L} \mathbf{r}, \tag{2}$$

where $\mathbf{S} = [\mathbf{s}_1 \mathbf{s}_2 \mathbf{s}_3]$ is the matrix of eye sensor sensitivities $\mathbf{s}_i = [s_i(\lambda_1) s_i(\lambda_2) \ldots s_i(\lambda_N)]^t$, $\lambda_1 = \lambda_{\min}$, $\lambda_N = \lambda_{\max}$, and the sampling interval $\delta\lambda = \lambda_i - \lambda_{i-1} = \frac{1}{N-1}(\lambda_{\max} - \lambda_{\min})$, $i = 2, \ldots, N$. $\mathbf{L}$ is the diagonal illuminant matrix with entries from the samples of $l(\lambda)$ along the diagonal, and $\mathbf{r}$ is the sampled spectral reflectance of the object. This matrix notation has several advantages, in particular it enables us to use techniques based on matrix algebra, such as vector space projections, to solve problems related to color.

Note that the illustration in Figure 3 is best appreciated in color on a reasonably well-behaved output medium such as a monitor. If you're reading this on a second generation black and white photocopy, don't expect miracles to happen... You can always look for an electronic version of this paper at `http://color.hardeberg.com`.

2.3 Metamerism

From Equation 1, and the fact that the reflectance spectra are continuous functions, while the sensor response only has three values, it is clear that there are several different spectra that can appear as the same color to the observer. A set of two such spectra having different spectral compositions but giving rise to the same psychophysical characterization are called *metamers* [22]. An example of metamerism is given in Figure 4. The spectral power distribution of daylight reflected from a violet flower is very different from the one emitted by a computer monitor tuned to match the color of the flower.

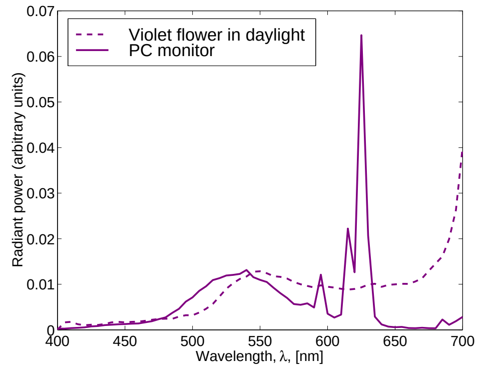

Figure 4: *Example of metamers.*

For imaging, metamerism is both a curse and a blessing. Without metamerism there would be no color image reproduction as we know it. Technologies such as photography, printing, and television, are all based on metamerism. The reproduced images have spectral distributions that show little or no similarity to those of the original scene (cf. Figure 4), rather they are created in order be *perceived* as equal by us humans. (Maybe other creatures would not be able to recognize anything on television?)

On the downside, perhaps the most striking effect of metamerism is objects that have matching colors seen under one illuminant, but not under another. A most realistic example is when you buy a new red scarf to go with your coat — it matches perfectly in the store, but when you get out in the sunlight, it's pink! (I know this firsthand, I got one from my mother several years ago, not a favorite :-)

Even more relevant to imaging is the case of creating an exact reproduction of for example a painting. The imaging professional spends a lot of time and energy tweaking the color reproduction process to match the original colors perfectly under his reference illuminant - but in the end, when a customer displays the print in her typical office fluorescent light, it looks bad...

3 A multispectral color image acquisition system

A multispectral color image acquisition system contains the same elements as a color image acquisition device [1], the only principal difference is that it has more than three channels. Figure 5 illustrates schematically the different elements of a multispectral camera using a set of K different color filters. The K channels are acquired sequentially by changing the filter, typically either by using a filter wheel, or an electronically tunable filter.

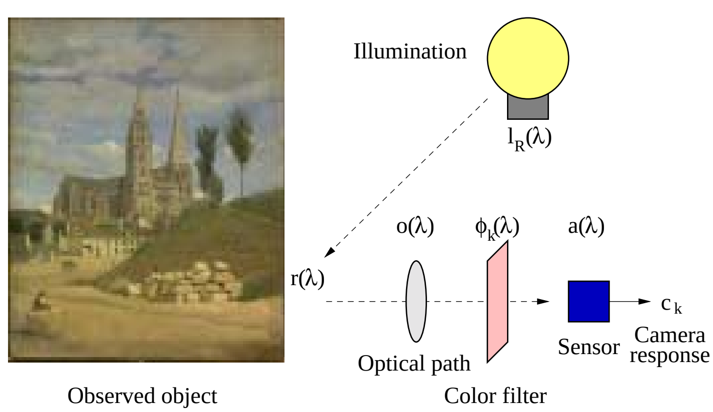

Figure 5: *Schematic view of the image acquisition process.*

By sampling the spectra and applying matrix notation, similarly to what we did with Equation 1, we can express the K-channel camera response as the vector $\mathbf{c}_K = [c_1 c_2 \ldots c_K]^t$

given by

$$\mathbf{c}_K = \mathbf{\Theta}^t\mathbf{r}, \tag{3}$$

where $\mathbf{\Theta}$ is the known N-line, K-column matrix of the spectral transmittances of the filters multiplied by the camera sensitivities, the optical path transmittance, and the spectral distribution of the illuminant, that is, the matrix elements of $\mathbf{\Theta}$ can be expressed as $\theta_{kn} = [\phi_k(\lambda_n)a(\lambda_n)o(\lambda_n)l_R(\lambda_n)]$.

Equation 3 represents a basic linear model of the image acquisition system, and this model will typically be used for further interpretation of the multispectral image data.

4 Some interesting challenges and applications

4.1 Spectral characterization

In order to extract device-independent data from the acquired multichannel image, it is important to know the different spectral functions shown in Figure 5. Direct spectrophotometric measurements of these require expensive equipment. An alternative is an indirect approach where the vector $\boldsymbol{\omega}$ describing the system unknowns is estimated from the camera responses c_p to a set of P patches with known reflectances $\mathbf{r}_p$. (We typically do not include the filter set in this characterization; the vector elements of $\boldsymbol{\omega}$ are thus $\omega_n = [a(\lambda_n)o(\lambda_n)l_R(\lambda_n)]^t$.) Denoting the sampled spectral reflectances of all the patches as the matrix $\mathbf{R} = [\mathbf{r}_1\mathbf{r}_2\ldots\mathbf{r}_P]$, the camera response $\mathbf{c}_P = [c_1c_2\ldots c_P]^t$ to these P samples is then given by

$$\mathbf{c}_P = \mathbf{R}^t\boldsymbol{\omega}. \tag{4}$$

Several methods have been proposed for the estimation $\tilde{\boldsymbol{\omega}}$ of the camera characteristics $\boldsymbol{\omega}$. The simple system inversion by:

$$\tilde{\boldsymbol{\omega}} = (\mathbf{R}\mathbf{R}^t)^{-1}\mathbf{R}\mathbf{c}_P = (\mathbf{R}^t)^-\mathbf{c}_P, \tag{5}$$

where $(\mathbf{R}^t)^-$ denotes the Moore-Penrose pseudo-inverse of $\mathbf{R}^t$ works well in theory but yields very large errors in the presence of noise. Instead, the Principal Eigenvector method should be used, the noise sensitivity of the system inversion being reduced by only taking into account the singular vectors corresponding to the most significant singular values. See [12–14] for more details about this approach.

4.2 Reconstruction of spectral data

The problem of the estimation of a spectral reflectance $\tilde{\mathbf{r}}$ from the camera responses $\mathbf{c}_K$ is central in the design of a multispectral color imaging system.

One approach is to take advantage of *a priori* knowledge on the spectral reflectances that are to be imaged, by assuming that the reflectance $\mathbf{r}$ in each pixel is a linear combination of a known set of P smooth reflectance functions: $\mathbf{r} = \mathbf{R}\mathbf{a}$, with $\mathbf{R} = [\mathbf{r}_1\mathbf{r}_2\ldots\mathbf{r}_P]$ the matrix of the P known reflectances and $\mathbf{a} = [a_1a_2\ldots a_P]^t$ a vector of coefficients. We have defined [13, 14] a reconstruction operator that minimizes the Euclidian distance $d_E(\mathbf{r}, \tilde{\mathbf{r}})$ between the original spectrum $\mathbf{r}$ and the reconstructed spectrum $\tilde{\mathbf{r}}$:

$$\tilde{\mathbf{r}} = \mathbf{R}\mathbf{R}^t\mathbf{\Theta}(\mathbf{\Theta}^t\mathbf{R}\mathbf{R}^t\mathbf{\Theta})^{-1}\mathbf{c}_K. \tag{6}$$

Another approach proposed by Ribés et al. [18] is to use Neural Network-based methods for spectral reconstruction. This approach has been found to yield superior performance in the presence of acquisition noise.

4.3 Choice of filters

The quality of the acquisition system depends heavily on the number and on the choice of the color filters that will be used. We have proposed a solution where they are chosen from a set of readily available filters [11, 13, 14]. This choice is optimized by maximizing the orthogonality of the camera channels when applied to reflectances that are highly representative of the statistical spectral properties of the objects that are to be imaged in a particular application. The filters are selected sequentially to maximize their degree of orthogonality after projection into the vector space spanned by the most significant reflectance eigenvectors. Although this approach remains suboptimal, it avoids the heavy computation cost required with an exhaustive search. The results for the case of a selection of seven filters from a set of 37 Kodak Wratten, Hoffman, and Schott filters are shown in Figure 6.

Another approach that we have proposed is to use a Liquid Crystal Tunable Filter in which the spectral transmittance can be controlled electronically [14, 15, 17]. Such a system presents several strong interests, in particular its flexibility, enabling for example to optimize the filter set for a given application.

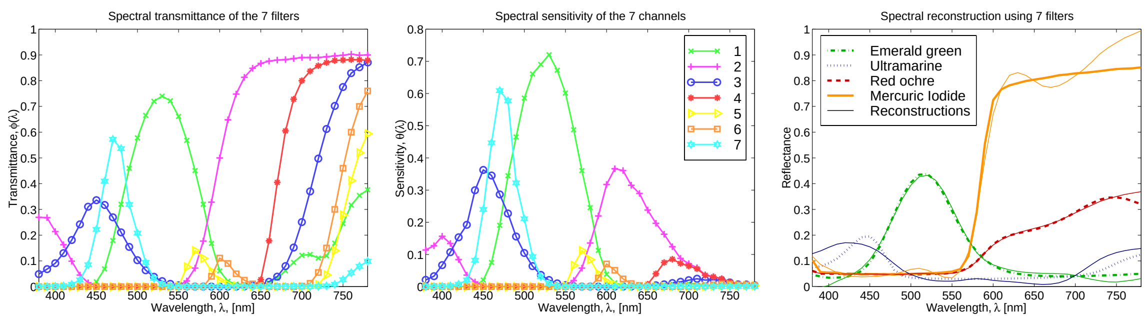

Figure 6: *Optimized selection of seven filters : (left) Spectral transmittance; (center) Spectral channel sensitivity, the numbers denote the sequence in which the filters have been chosen; (right) Reconstruction of four spectral reflectances from the camera responses using Equation 6 [13, 14].*

4.4 Illumination simulation

An interesting application of multispectral color images is to simulate on a computer monitor, how the imaged scene would have appeared under different illuminants. We have demonstrated this concept and found the simulation to be very accurate, and working on a wide range of illuminants having very different spectral properties [13, 14].

4.5 Spectral image reproduction

Quite recently, desktop printers with six and seven inks have become available. The use of more than four printing inks is often denoted Hi-Fi color, and was up till now only used in very expensive high-end printing systems. Multi-ink printing brings new possibilities for image reproduction. One now has the option of attempting to reproduce not only the original color, but to create a spectral match to the original. By doing this it is possible to avoid the problems caused by a metameric match, when changing observer or illumination. This is a very new and exciting research area [6, 7].

5 Conclusions and perspectives

After a brief introduction to some basic principles of light and color, we have described a multispectral color imaging system and some of the challenges of realizing such a system. Multispectral color imaging is the imaging technology of the future, since it overcomes the problems related to metamerism. We are seeing now an increased interest in this technology, not only within the academic world, but also by the industry.

For further reading on the subject of multispectral color imaging, a good starting point could be the book by MacDonald and Luo [23], and of course also my Ph.D. dissertation [14], which has the advantage of being downloadable for free from `http://color.hardeberg.com`. For the latest of the latest, refer to the series of International Conferences on Multispectral Color Science - the one for this year takes place in Joensuu, Finland, in June, see `http://cs.joensuu.fi/mcs/`.

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Figure 1. Monochrome, color, and multispectral sensor configurations. The vast majority of multispectral imaging applications utilize unique combinations of optical filter bands. Generally, no two applications use the same combination of bands and applications differ in their spectral bandwidth requirements. Therefore, the use of a generic MFA that has many bands that are distributed evenly across the optical spectrum are poorly suited to most multispectral imaging applications. Masahiro Yamaguchi, et. al., â€œMultispectral color imaging for dermatoligy:application in inflammatory and immunologic deseases,â€ 10 Proc. IS&T/SID 13th Color Imaging Conference, pp. 52-58, (2005). Dermatology (Video). â€¢ Experiments using 6-band and conventional-RGB HD videos.Â especially in reddish colors, not suitable for the diagnosis of subtle. flare such as measles, virus infection, and drug allergy. â€¢ The image color in 6B system looks natural, and the reddish and. yellowish colors can be easily discriminated. Multispectral imaging can add tremendous value in medical applications, especially in surgical tasks. Combining color imaging with NIR bands can help to locate and distinguish between tumors and surrounding tissues. The multispectral setup can be achieved in many ways but a very efficient and cost-effective way which also reduces the system complexities is by using prism-based multi-sensor cameras. In a real surgical situation, ICG might be injected into blood vessels, tissue or lymphatic vessels. False colour composite multispectral SPOT image: Red: XS3; Green: XS2; Blue: XS1. Another common false colour composite scheme for displaying an optical image with a short-wave infrared (SWIR) band is shown below: R = SWIR band (SPOT4 band 4, Landsat TM band 5) G = NIR band (SPOT4 band 3, Landsat TM band 4) B = Red band (SPOT4 band 2, Landsat TM band 3). An example of this false colour composite display is shown below for a SPOT 4 image. Color-image-processing procedures involve three steps: background removal, HSI (hue, saturation, intensity) conversion, and histogram calculation. Features of three histograms (hue, saturation, intensity) were used as inputs of the neural network for detecting large-scale defects (e.g. septicemic carcasses, or cadavers).Â Multispectral imaging provides image information in the spectral domain as well as in the spatial domain.