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Spectral Colour Order Systems and Appearance Metrics for Fluorescent Solid Colours

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Abstract

One aspect of Computational Aesthetics is the finding of harmonic colours for the objects in a scene. Although the obtained degree of colour harmony is a subjective criterion, experience shows that on average human observers tend to have quite similar responses to individual colour stimuli and their combinations. This observation is the basis for what is commonly referred to as Colour Order Systems *(COS), which aim to arrange colours in a fashion such that users can intuitively select individual colours – or even whole sets of them – according to some criterion. However, when dealing with a spectral rendering system, the use of traditional colour space COS to obtain pleasant associations of colours becomes impossible, principally due to metamerism. An interesting problem would be the derivation of a COS for spectral data which includes the ability to deal with fluorescent colours, the indirect goal of such a metric system being the selection of aesthetically pleasing colour values for a spectral renderer.*

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism: Color

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1. Introduction: Colour Metrics as a Core Tool for Computational Aesthetics

Aesthetics is all about perception, and is therefore a highly subjective aspect of taste. However, due to the basic similarity of their physiology and psychology humans are sensitive to visual stimuli in more or less the same way, which means that – except for individuals with a visual deficiency such as colour blindness – a given scene will be perceived as being of roughly similar aesthetic value by a majority of people inside a group.

Based on this observation, and the fact that a metric for the fundamental operations of human perception, such as the perception of colour, can be defined, one can introduce derived metrics to evaluate those aspects of synthetic scenes one is particularly interested in. These can then be used to directly derive aesthetic attributes for the objects in a given scene by selecting them according to one or several of these metrics.

Such metrics can be based on a wide variety of properties which range from quantifications of geometric properties describing how objects are distributed in a scene, the overall scene entropy or how the individual objects are shaped over appearance attributes such as their shininess, their texture properties to their basic colour. We can classify those metrics into different categories:

- Shape-based: shape and size of objects, their distribution;
- Surface-based: texture, colour, gloss;
- Image-based: resolution, histogram;
- Rendering attributes: vectorisation, stylisation properties.

Colour metrics have always been rightly considered a core property of the objects in a scene; the selection of aesthetically pleasing, matching colours is a research area that has drawn considerable interest for ages, and which is still just as pertinent to Computer Graphics today as it was to the Graphical Arts a century ago. One example of a modern, perceptually and mathematically oriented system for colour selection is the Coloroid system [Nem80, Nem87], but a large number of such systems with varying complexity have been proposed in the past.

2. Motivations: Spectral Rendering Systems

When using a spectral rendering system for 3*D* image synthesis, assigning colours to the objects in the scene is problematic in the sense that it is not possible to choose HLS or RGB values like in normal 3D design applications.

So far the only way to solve this problem is to use a library of spectral measurements, which can be based on measurements of canonical colour sets (such as a Munsell Book of Color) or on sets of samples which fall into the general area of interest (e.g. interior paint samples for architectural purposes).

Two problems then arise. First, how do we define a set of aesthetically compatible colours, considering the fact that a COS like Coloroid does not exist for spectral data? Secondly, how do we introduce fluorescent colours in the system, the appearance of which is particularly sensitive to changes in illumination, and of which very few measurements exist? Fluorescent colours, such as the day-glo range of highlight colours, are normally not explicitly included in normal COS, since their wavelength-shifting properties make them difficult to integrate in such a colour-based system.

Before attempting to outline how one might go about solving those two problems, we will first describe existing colour metrics and discuss their limitations.

3. Background

There are two fundamentally different types of numerical specifications of colour values: the colour metric spaces, used to measure absolute values and differences between colours, and the colour order systems, which *order* the colours according to some criterion, and which are designed to find colours that go together well.

3.1. Colourimetry

Colourimetry is the branch of colour science concerned with numerically specifying the colour sensation for a given visual stimulus, such as the RGB values which can be derived for a given input spectrum. The classical process to derive such a numerical correlate of human perception is to perform visual difference experiments, where observers have to match a test light by combining three fixed primary colours (usually red, green and blue); the only constraint on the colour of these three lights is that they have to be linearly independent in the sense that none of them should be representable as a combination of the other two (see figure 1).

A fundamental aspect of this process is that it is a strong *simplification*, and, as such, a lot of information is lost (the continuous spectral distribution is replaced by a colour value specified by three numbers). Because our eyes are sensors which contain photo-pigments with just three different absorption spectra, one in the red wavelengths, one in the green and one in the blue, there is an infinite number of spectral stimuli which can cause the same colour sensation, and will therefore be described by the same RGB triplet.

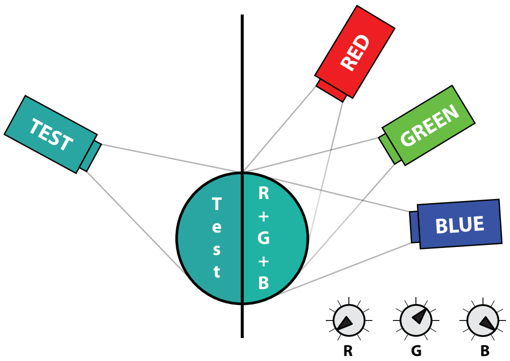

Figure 1: *The classical colour matching experiment: a process of determining a unique RGB triplet for each stimulus.*

This phenomenon is referred as *metamerism*, and two such colours that have different spectra but match one another are called *metameric* (see figure 2). The direct consequence of this is that chemically distinct reflective colours that match for a given illuminant may not match for a different one.

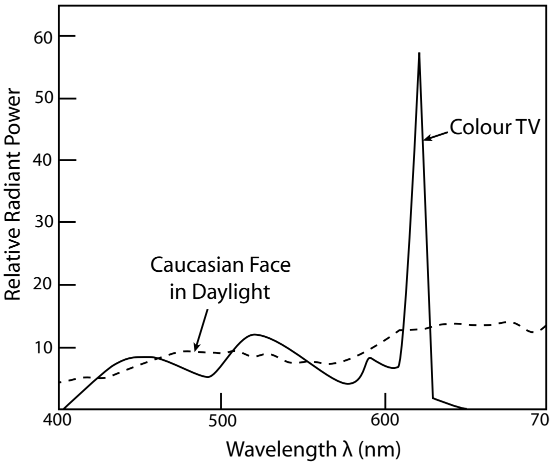

Figure 2: *An example for metamerism: while skin tones displayed on a television are perceived as being realistic, the actual spectral composition of the light emitted from the screen (plain line) is very different from the reflection of real skin (dashed line). Redrawn from [WS82].*

3.2. Colour Order Systems

The primary aim of *Colour Order Systems* or *COS* is to enable the user to intuitively choose colour values according to some criterion. To this end, various COS have been defined over the years, and each of them uses a different ordering function to satisfy different goals.

However, every COS arranges colours according to their major perceptual attributes, such as their *hue*, *lightness* and *saturation*. For instance, on one page of a given colour atlas (a common form of COS), the same hue will be used; the brightest colours are at the top, the darkest ones at the bottom, and the colours get more saturated from left to right. The page is constructed with discrete samples of colours in such a way that it is possible to interpolate between these samples, and that the distance between the samples colour has some meaning. See figure 3 for an example of such a COS, namely some pages from the matte Munsell Book of Color.

Figure 3: *An example of a traditional COS: some pages from the matte Munsell Book of Color.*

For example, in the *Munsell System* [Mun05, Mun15, Mun76], the colours are arranged so that for each perceptual attribute which is used, the perceptual difference between two neighboring samples is as constant as possible. The *Natural Colours System* or *NCS* [Hes55,Hår65,Hår78] describes the colours in terms of the relative amounts (percentages) of the basic colours that are perceived by humans. In the *Coloroid* system [Nem80, Nem87], the colours are spaced evenly in terms of their aesthetic effects. Other systems do exist, like *The Tintometer* [tin53] which was first designed to measure the colour of beer, or the *RAL Design*.

4. Spectral Colour Order Systems

However, a key feature common to all of these colour order systems is that the ordering and selection of physical colour samples is made under a fixed illuminant. This restriction is a consequence of the fact that all of these COS are numerically organised through and by their colour space coordinate systems, which are usually very low-dimensional. It is thus unclear how one would go about directly performing such an implicit ordering for the usually continuous realm of reflection spectra.

The main problem caused by this restriction to colour space is that any set of colours that match in a particularly harmonic fashion for a given illuminant may be highly unappealing under other common light sources. This is more likely to happen if the neighboring samples have a very different spectral composition.

Finding a compromise here is therefore a task which can only be carried out manually, and for which no help in the form of heuristics or algorithms is available so far. A spectral COS which attempts to find not just colour values, but reflection spectra which match harmoniously under several given illuminants might therefore be a highly productive research goal.

Given that it is comparatively hard to derive physical pigments which match a desired spectral distribution it is also not clear what the immediate practical benefits of such a spectral COS would be, apart from providing the reflectancy data of hypothetical spectra which would fit together in a particularly harmonic fashion under multiple, varying illuminants. However, such a *spectral COS* might conceivably still be useful if one restricted the spectral shapes it generates to those metamers which can probably be generated by mixtures of a given set of pigments. Since restrictions (or boundary conditions) of some kind have to be imposed on the problem of choosing spectral distributions, this should not restrict the functionality of such a system overmuch.

5. Creation of a Spectral COS

In this section we outline one potential approach to the derivation of such a COS system.

The choosing of the colours in the COS has to be done in colour space – a direct spectral selection is not a practical solution. The idea is then to derive the associated spectra for this set of chosen colours with boundary conditions which attempt to maintain the relationships between the perceived colour values under different typical illuminants.

This is an iterative process which should stop when the overall stability of the set of colours is sufficient for a certain number of typical illuminants.

The key problem – the step from colour to spectral space – is an under-determined operation that usually requires constraints (see the paper about spectrum derivation of Smits [Smi99]). If this step were to be performed without any constraints for a large number of reflective colours it would probably result in a sub-optimal solution for any given illuminant which is later to be used. The type of constraint involved could be, for example, to restrict the spectra used to the one contained in a library of real spectral colorant reflectance data. With a physically plausible mixing model this should yield realisable colours which achieve a harmonic balance.

An outline of the process is as follows:

- User picks colour(s) in an existing COS.
- Spectra for these colour values have to be found - initial derivation:
  - Constrained spectral reconstruction for the COS illuminant.
- Evaluation and optimisation of these spectra under all other illuminants - iterative process:

- Metameric changes are made under original illuminant;
- New spectra are re-evaluated - the process stops if the overall “score” for all illuminants is good enough.

6. Intuitive Selection of Fluorescent Hues

In Computer Graphics, the colour of non luminous objects is commonly understood to be a property that can be adequately described using RGB triplets. While this is a workable solution for most common tasks in graphics, it has been known for a very long time that this is actually subtly wrong, and that truly accurate image synthesis should take place using spectral distributions of light and reflectancy; this is especially true if any sort of prediction of reality is required.

It has to be noted that image synthesis in colour space can actually yield very good results if the colour values of the involved surfaces are already given for the illuminants which are used in the scene; in such cases the results of a colour space renderer can match those of a spectral renderer quite closely (see the work of Ward et al. [WEV02] for details).

Given that colour space renderers are much easier to write and operate (which is partly due to the existence of intuitive colour selection systems such as HLS, which greatly facilitate the task of assigning suitable colours to objects) this makes them the obvious choice in all cases where radiometric accuracy of the final image, or prediction of effects caused by metamerism is not the prime concern.

However, there is one – if not particularly large, but very visually prominent – class of surfaces for which the traditional colour selection process intrinsic to *classic* Computer Graphics (i.e. HLS, Coloroid et al. as front-end for RGB) is completely inapplicable: fluorescent materials.

To describe such materials from a designer’s viewpoint one needs additional categories besides the traditional ones of *hue*, *lightness* and *saturation* – for example in which range of the spectrum the material absorbs energy, and where it re-emits it. Figures 4 and 5 outline the effects of fluorescent material. On the first photograph (figure 4), a green laser light points towards an orange cardboard sample of normal paint: the green light is partly reflected and partly absorbed. In the second photograph (figure 5), the cardboard sample has been painted with a fluorescent orange paint. You can see that the reflected light stays green because it doesn’t interact with the paint molecules, while the absorbed light is re-emitted as an orange light.

That this area has not received a lot of attention yet is at least partly due to the fact that only a limited number of fluorescent pigments are known. This has probably restricted the amount of experimentation with descriptive models for such types of pigments in the colour community.

However, one of the potential key contributions of Computer Graphics allows one to experiment with new materials without them being physically available. Virtual scenes could be constructed to evaluate the appearance of materials that are specified using an extended, fluorescence-capable COS in conjunction with other such surfaces, and ordinary pigments. Given that fluorescent materials change their appearance far more significantly under varying illuminants than ordinary pigments, such an enlarged and much more variable colour space might offer entirely new opportunities for harmonic colour sequences that look convincing under varying illuminants.

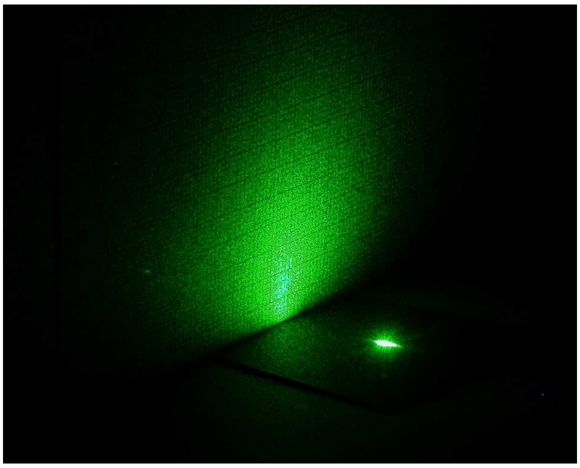

Figure 4: *Reflection pattern on a real plain orange cardboard sample for an incident angle of about 20 degrees. Note that as no fluorescent surface is involved, both the immediate bright dot on the material and the reflection pattern are monochromatic green with no hints of orange. This photograph is to be compared with the one of figure 5 which involves a fluorescent day-glo orange cardboard sample.*

One possibility for such a colour selection scheme could be based on the physical properties of fluorescent colours. Indeed they bundle certain parts of the incident light to a particular output frequency band; steering this behaviour is the key to altering the appearance of the surface. Direct control over this adds three dimensions to the selection process: the relative *intensity* of the phenomenon, and the *areas* in the spectrum where the fluorescence effect absorbs and reradiates the energy.

For all-synthetic scenes this can be done in an unconstrained fashion, and for other cases the selection process can be limited to parameter values which are realisable with existing pigments.

7. Conclusion

Together with the spectral COS idea this technique might provide entirely new opportunities for designers, and the proof of their validity which we can nowadays provide through the methods of photo-realistic image synthesis

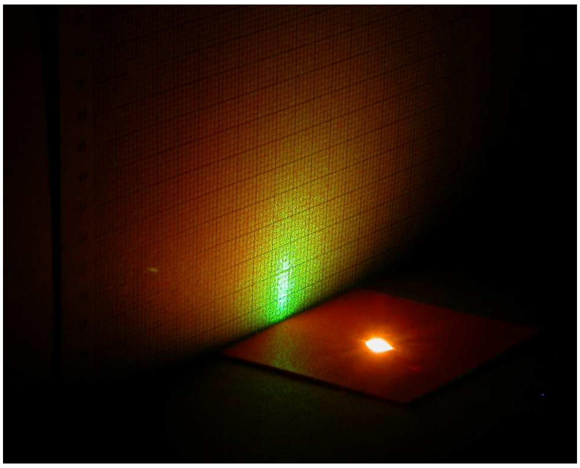

Figure 5: *Reflection Patterns on a real diffuse day-glo fluorescent orange cardboard sample for an incident angle of about 20 degrees. Note that while the bright dot where the laser hits the surface – and also parts of the reflection pattern – are a bright orange caused by the frequency shift typical for this kind of fluorescent colorant, other parts of the reflection – essentially the specular component – are still the* native *green of the incident laser beam.*

might provide the virtual showcase to convince communities outside the immediate field of Computer Graphics that considerable possibilities still lie undiscovered in this area.

References

[Hes55] HESSELGREN S.: *Colour-Atlas*. 1955.

[Hår65] HÅRD A.: Philosophy of the hering-johansson natural color system. In *Proceedings of the International Colour Meeting* (1965), pp. 357–365.

[Hår78] HÅRD A.: *NCS Colour Atlas*. 1978.

[Mun05] MUNSELL A. H.: *A Color Notation*. 1905.

[Mun15] MUNSELL A. H.: *Atlas of the Munsell Color System*. 1915.

[Mun76] MUNSELL C. C.: *Book of Color*. 1976.

[Nem80] NEMCSICS A.: The coloroid color order system. *Color Research and Application 5* (1980), 113–120.

[Nem87] NEMCSICS A.: The color space of the coloroid color order system. *Color Research and Application 12* (1987), 135–146.

[Smi99] SMITS B.: An RGB-to-spectrum conversion for reflectances. *Journal of Graphics Tools 4*, 4 (1999), 11–22.

[tin53] *Colorimetric Chemical Analytical Methods (CCAM)*. 1953.

[WEV02] WARD G., EYDELBERG-VILESHIN E.: Picture perfect rgb rendering using spectral prefiltering and sharp color primaries. In *Proceedings of the Thirteenth Eurographics Workshop on Rendering* (June 2002), Debevec P., Gibson S., (Eds.).

[WS82] WYSZECKI G., STILES W. S.: *Color Science: Concepts and Methods, Quantitative Data and Formulae*. John Wiley and Sons, New York, ISBN 0-471-02106-7, 1982.