Spectral and Metameric Color Imaging

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Abstract

Spectral imaging has become a topic of growing interest in color-reproduction, remote-sensing, medical-imaging, and other systems. These increased research efforts are likely to propagate into other application areas such as computer vision and pattern recognition. This paper defines, compares, and contrasts spectral imaging and more typical metameric imaging which integrates spectral regions. The history of spectral and metameric imaging is reviewed. A public-domain research tool, Spectralizer, for spectral image manipulation, reproduction, and visualization is described. In addition, the advantages of spectral imaging over metameric imaging for object detection applications is demonstrated through simulations created using public domain spectral rendering software and real imaged objects. Finally, all of these pieces are put together in a discussion of system design issues for spectral and metameric systems. It is hoped that these freely-available research tools and systems concepts can be brought to bear on novel imaging problems by researchers in a variety of fields.

1. Introduction

Most imaging systems used in computer vision and pattern recognition utilize a small number of channels that typically integrate over relatively wide spectral bands. Single-channel, monochrome systems are still quite prevalent and three-channel color systems are often implemented with engineering and cost-control concerns being paramount such that differences from model to model in how light source, object, and sensor interact result in a wide variety of captured image data. This paper reviews some of the fundamental aspects of spectral imaging, in which a high number of image channels are captured and processed, and metameric imaging, in which limited numbers of channels are utilized but can be carefully designed to produce the desired image data. Spectral imaging is rapidly growing in a number of research applications. Some of this recent research and related simulations of spectral and metameric imaging systems are described with the goal of increasing the reach of and interest in such techniques.

1.1. Definition of Spectral Imaging

Spectral imaging is defined as the capture, processing, display, and interpretation of images with a high number of spectral channels. In general the number of channels in a spectral image exceeds the three found in typical color imaging and can range to several hundred in some applications.[1] In remote sensing applications, so-called hyperspectral images often have several hundred channels, each representing a very narrow band of wavelengths.[2] In color imaging applications, spectral images can be as large as 30-40 narrow spectral bands through the visible spectrum, but are often represented by 5-9 image channels each consisting of coefficients of statistically derived basis functions.[3] In medical imaging, the spectral bands considered often exceed the ranges of optical, or even electromagnetic energy.[4] The key defining feature of spectral images is that the number of sampled image dimensions exceeds the 3-D color resolution of the human visual system.

1.2. Definition of Metameric Imaging

Generally, metameric imaging[5] is considered with respect to the human visual system. For example, the human visual system integrates spectral data with three types of cone receptors to produce a three-channel color image. It is considered metameric since an infinite variety of potential spectral power distributions in the scene can produce the same color response in the three integrated channels. Metamerism is broadly defined as the production of identical spectrally integrated responses from disparate spectral power distributions.[6] However, there is no fundamental reason to limit the concept of metamerism to the human visual system or to imaging systems with three spectral channels. A color CCD camera produces metameric images since a variety of spectral power distributions can result in identical integrated RGB outputs from the camera. Note however, that most CCD cameras will produce metameric matches that differ from those of a human observer (an example of observer, or sensor, metamerism). Additionally, a monochrome imaging system can be considered metameric since it is functionally equivalent to a single channel of a color system.

1.3. Applications of Spectral and Metameric Imaging

The vast majority of images produced and utilized today are metameric. It would not be too much of a stretch to say that nearly every imaging application is an application of metameric imaging. That said, it is clear that the field of pictorial color reproduction is the one that most takes advantage of metameric properties in order to optimize and control the production of color images. This is prevalent throughout classic color reproduction texts[7] and is clear through the large number of industrial standards concerned with the spectral power distributions of illumination, image viewing conditions, and device characterization.[8,9]

Spectral imaging, on the other hand, is more novel and limited in the scope of current applications. Some recent examples are presented here for context. In pictorial image reproduction, spectral imaging has found applications in the reproduction and conservation of artwork,[10] production of minimally-metameric prints,[11] and portraiture.[12] Medical applications include the measurement of various constituents in human skin (*e.g.*, melanin and hemoglobin).[13] Spectral images are used in remote sensing to model various physical phenomena and classify objects in the scene.[2] Similar applications, such as analyzing the chemical makeup of objects, can also be found in astronomical imaging.[14]

2. Spectral Imaging

Spectral imaging has a fascinating history dating back to early attempts to create systems of color photography. With recent advances in digital technology and solid-state image-capture devices, the modern applications mentioned above have led to a renaissance in spectral imaging. The following sections outline some of the history of spectral imaging, it's advantages and limitations, and some recent research and simulation tools.

2.1. History

In the late nineteenth century a number of photographic engineers in search of a commercially viable color imaging system invented amazingly elegant platforms for capturing and reproducing the spectra of original scenes. Lippmann's 1891 process[7,15,16] relied on the interference properties of light. Exposing a scene onto his specialized emulsion placed upon a mercury mirror captured a record of wavelengths present in an imaged scene. When illuminated properly, the processed photograph backed again by a mirror reconstituted the scene allowing only the exact original photon energies to emerge from the reproduction. Unfortunately, prints were only viewable from particular narrow angles and the approach remained obscure. Lancaster in 1895 described a micro-dispersion process[7,16] which utilized a grating and a prism. The grating divided the original scene into tiny strips and the prism spectrally dispersed the strips onto a silver-halide negative. For viewing, a dimensionally identical positive was made and placed in the apparatus where the negative had been. The grating was illuminated with white light, strips of which were dispersed by the prism onto the positive, which transmitted a spectral reconstruction of the original scene. It too ventured little beyond the laboratory due to the complicated gadgetry needed for both capture and viewing.

Modern spectral image capture systems tend to rely on combinations of CCD cameras with various types of narrow- or broad-band filters. The images are then processed using normal high-capacity computational machinery with software developed to properly treat the spectral data, finally spectral image display is a field of burgeoning interest as the technologies for both hard-copy and soft-copy display rapidly expand to include more than 3 or 4 channels.[17]

2.2. Advantages

The advantages of spectral imaging revolve around the simple availability of more information. Since specific advantages are application dependent, the remainder of the discussion will focus on pictorial color imaging applications and their extension to the location and identification of objects that might be of interest in computer vision. One of the most significant advantages of spectral imaging is the potential to accurately segment image signals into a part due to the illumination and a part due to the object itself. A spectral imaging system allows spectral power distributions (or spectral reflectance distributions) of imaged objects to be distinguished from others, and thus detected and recognized, in situations where a metameric imaging system might completely fail or be unable to separate the effects of illumination from changes in an object. It follows that spectral imaging systems are also capable of producing images that are robust to changes in illumination. For example, if a printed image of an object has the same spectral reflectance properties as the original object, then the original and reproduction will match under any illumination for any observer (or any metameric imaging system!). Such advantages allow the potential for nearly flawless color reproduction, transformation of image appearances across changes in viewing conditions, and compositing or image-editing of content from various captured and rendered sources with extreme realism.

2.3. Limitations

The obvious advantages of spectral imaging systems are often outweighed by their one inescapable limitation –

data volume. A typical, high-quality, uncompressed pictorial image might require approximately 18MB of data. A similarly high-quality, uncompressed spectral image would require approximately 10-times more data, nearly 200MB. These data volumes stress the infrastructure of imaging systems and the application systems in which they are imbedded. Processing that can be completed in real-time with monochrome or color images are often impossible to perform, or require prohibitively expensive hardware if spectral images are used. Fortunately, this limitation has been rapidly decreased with advances of digital technology. However, the fact will always remain that a scaling in resources (or compensatory compression techniques) will be required for spectral imaging.

Along with the additional image data in a spectral system comes additional noise. Some spectral imaging approaches capture channels over very narrow wavelength bands resulting in little energy being available for detection. Others require high-powered matrix multiplication of signals that tends to amplify inherent noise levels. Some spectral imaging approaches require extreme high-speed clock rates for the transfer of charges causing further increase in noise. In recent years, inherent noise levels in imaging devices has improved greatly, but dealing with the relatively larger amounts of noise will always be a disadvantage of spectral imaging in comparison with metameric systems.

A related limitation is the application infrastructure. For example, in pictorial color imaging, industry-wide standards exist for the capture, processing, display, and reproduction of 3-, or sometimes 4-, channel images. While significant advances are possible with spectral images, they currently must be realized through customized systems that stress the current infrastructure and often are incompatible. This is further discussed in section 4.

2.4. Research

In several laboratories around the world, research is ongoing to develop and implement spectral imaging systems for a variety of applications. The various researchers in these areas have joined together to facilitate growth of the field and share their advances through the creation of image databases, publications, and software tools.[18] One example of work in this growing collaborative area has been the development of a spectral image visualization and manipulation tool.[17] This tool, known as *Spectralizer*, is a public-domain, cross-platform, software package developed in the *Interactive Data Language* (IDL) from Research Systems, Inc.[19]

Figure 1 illustrates a screen capture of a *Spectralizer* session. The tool allows spectral images in a variety of formats to be opened and examined. The initial display is a colored series of thumbnail images, one for each wavelength in the spectral image. Users can then use the interface to specify how the spectral image should be rendered to the display for further visualization. For example, a user could render a single channel of the display as a monochrome image and then select individual pixels in order to examine the spectral distribution at that spatial location. Alternatively, the user could select three channels of the spectral image to be mapped to the RGB channels of the display. More advanced visualizations can be completed by selecting a light source (for reflectance images; radiance images would be rendered directly or require the light source to first be removed and then a new source factored in), sensor response functions (human or otherwise), and display characteristics in order to render a color image. This allows users to visualize the effects of various light sources on the imaged objects or to simulate the effects of various image sensors on the detection of the scene elements. *Spectralizer* can be obtained and used free of charge and was developed with the goal of expanding the number of researchers working with spectral images.[20]

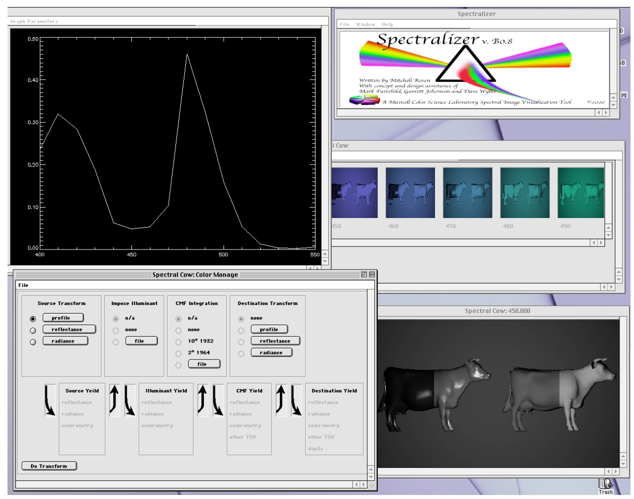

Figure 1. Screen capture of *Spectralizer,* a spectral imaging research tool. Various windows illustrate (clockwise from upper left) spectral power distribution of a selected pixel, title screen, part of the spectral-thumbnails display, rendering of a single channel, and visualization control panel.

3. Metameric Imaging

Metameric imaging has a rich history and is applied in every area of imaging by default. This section will briefly outline some of the history of metameric imaging in the context of spectral imaging. It will then go on to illustrate important concepts of metameric imaging that can be explored and simulated using spectral imaging techniques

3.1. History

Well before early attempts at spectral photography, modern metameric reproduction was born with Maxwell's 1861 demonstration.[21] He projected three filtered photographic color separations in registration, showing what was claimed to be a full color reproduction of the scene. There are some historical questions[22] concerning the accuracy of the original demonstration, but it was soon established that Maxwell's reliance on trichromatic theory was sound. The simplicity of reducing all color information down to three signals was extremely seductive and once the pieces were in place to fully exploit it, the approach would dominate the market to the exclusion of all other practice. By the turn of the century, three-color photoengraving emerged following the introduction by Ives and others of three-channel cameras.[23] Throughout the 20th Century the three-channel approach to color reproduction remained supreme. Technicolor movies and Kodachrome of the 1930's were three-channel systems as are modern televisions, video cameras, computer displays, film-based photography and digital photography. Printing has remained a three-channel, metameric art although often a fourth and sometimes additional separations are added as a final processing step. These additional separations have done little to challenge Maxwell's metameric principle in that they are there to increase realizable gamut, or to increase stability of specific colors or are sometimes used to reduce visible "grain" in highlight areas. But, they have not been introduced to improve reproduction of original spectra, and will rarely have any impact on reducing metamerism.[11]

3.2. Advantages

The clear advantage of metameric imaging systems is practicality. For most pictorial color reproductions, three channels are sufficient as was illustrated originally by Maxwell. Utilizing only the three required channels results in systems that are as inexpensive as possible in every way. Data requirements are reduced, noise concerns are minimized, and generally very high quality results are possible.[7] There are however, some very important limitations.

3.3. Limitations

The main limitation of a metameric imaging system is metamerism itself. A metameric system with spectral responsivities identical to the ultimate viewer of the image (whether human or machine) will produce images completely congruent with the experience of that viewer when examining the original. However, metameric imaging systems are rarely created with such congruence. For example, the RGB responses of a digital camera are rarely related to the human cone responses in any simple way. Thus, two image regions that match for the camera might mismatch for the viewer and vice versa. Of course, with proper system design, this can become an advantage if one wants to design an imaging system capable of detecting objects that would go unseen by other observers (*e.g*, detecting counterfeit documents). However, it should be noted that a spectral imaging system will always have this advantage.

The limitations of metamerism are only expanded when the effects of variations in illumination are added. For example, it is entirely possible for a metameric imaging system to be unable to distinguish a white object under red light from a red object under white light. While this is an extreme example that is unlikely to arise in practical situations, it helps illustrate how differences in the spectral power distributions of the illumination can confuse a metameric imaging system. For example, objects might appear similar to one imaging system whether imaged under real daylight or a fluorescent daylight simulator. However, another metameric imaging system might produce completely different images under the two different light sources. Some of these properties of metameric imaging systems are illustrated via simulations in the following section.

3.4. Simulations

All of the features and benefits of spectral imaging apply in the world of computer image rendering as well as in image capture. Recently, the OpenGL computer graphics library was extended and the extensions made publicly available to allow researchers to easily synthesize and render spectral images.[24,25,26] Spectral image synthesis allows all of the advantages of spectral imaging described above to be incorporated into computer generated imagery that can be used for visual stimuli, compositing into captured imagery, or as test targets for simulation of other imaging systems. Specimens can be noise-free or with carefully added noise. The following examples use simple rendered noiseless spectral images to illustrate important concepts of metameric imaging in computer vision applications.

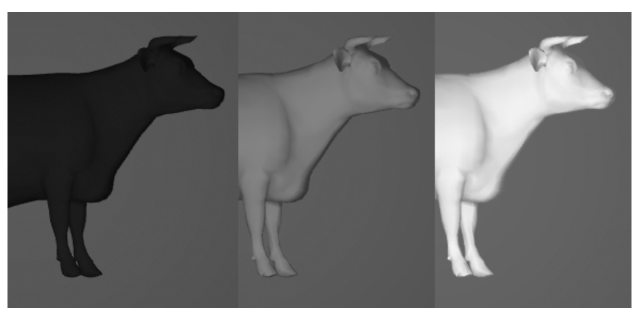

Figure 2. Monochomatic detection of an object (identical in all three images) with three different image sensors. Depending on the sensor used, the object is darker, matches, or is lighter than the background.

Figure 2 illustrates an example of three monochrome imaging systems, each with differing spectral responsivities. As can be seen in the three images, one system renders the object in negative contrast with the background, one renders it indistinguishable from the background (except for 3D shading) and the third renders it in positive contrast. Clearly the interactions between the spectral properties of the object and background and the spectral responsivity of the imaging system complicate detection of the object. Figure 3 shows the spectral power distributions of the object and background and the spectral responsivities of the three sensors used.

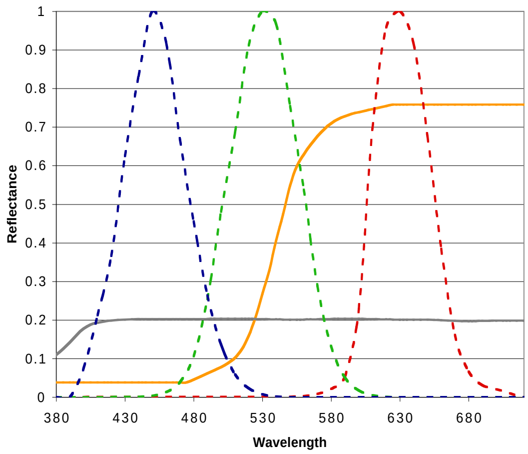

Figure 3. Spectral power distributions of object (orange line) and background (gray line) in Fig. 2 and the spectral responsivities of the three image sensors (dashed line).

The difficulties of object detection using metameric imaging systems are not always solved by color. Figure 4 illustrates a similar example in which two color imaging systems produce images of various chromatic contrasts with respect to the background. The image on the left (using the RGB responsivities from Fig. 3) easily discriminates the object from background, while the image on the right (colorimetric responsivities) results in the object and background matching in color. Figure 5 illustrates the spectral power distributions of the object and background from Fig. 4. Note that the simulated spectral reflectance characteristics illustrated in Figs. 5 and 7 were generated using metameric blacks (spectral power distributions with no contribution to color appearance) from Wyszecki and Stiles.[6]

If a spectral imaging system were used to tackle the object detection problem of Fig. 4, then all of the data presented in Fig. 5 would be available for each pixel. Clearly, the knowledge gained from the information in Fig. 5 could be used to develop an algorithm for object detection, a metameric imaging system capable of reliably solving the problem at hand, or a very flexible spectral system that could solve a variety of potential problems.

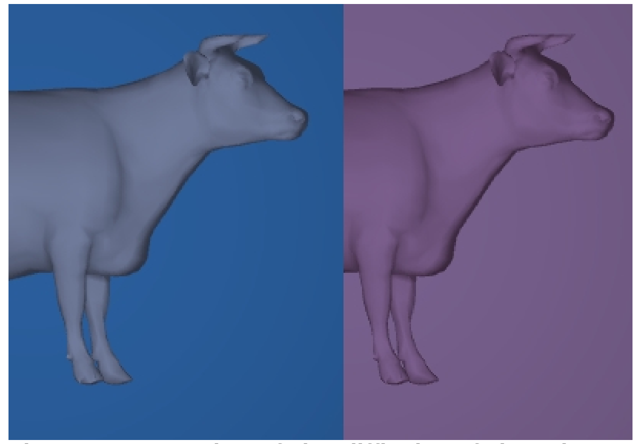

Figure 4. Examples of the difficulty of detecting an object with metameric color imaging systems. The color system producing the image on the left can easily detect the cow, while the system on the right produces no color contrast between the cow and background.

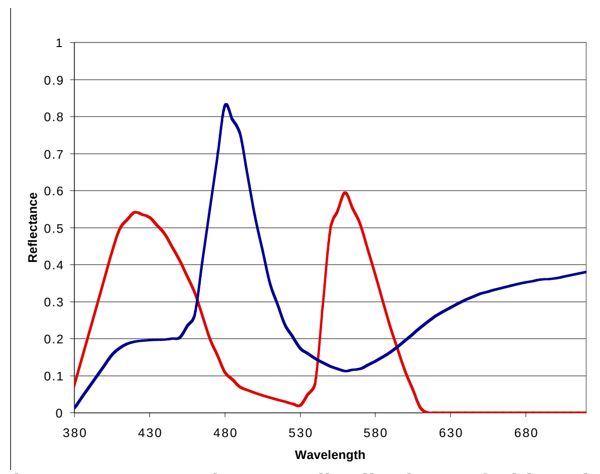

Figure 5. Spectral power distributions of object (red line) and background (blue line) in Fig. 4.

The metameric imaging difficulties illustrated above are not limited to changes in sensors (referred to as observer metamerism). Similar problems crop up when the illumination is changed. Figure 6 illustrates monochromatic images of an object under daylight (left) and incandescent illumination (right) created with a single image sensor. Clearly, the object is easily detectable under incandescent illumination and visible only from 3D structure under daylight. A geometrically flat object would have completely disappeared under daylight illumination. With a different sensor, or a spectral imaging system, the differences between the objects would be readily apparent as illustrated by the spectral reflectance distributions of the objects and spectral power distributions of the two light sources in Fig. 7. Once again, this problem is not limited to monochrome systems as illustrated with color images in Fig. 8. The object is invisible by color contrast under daylight illumination, but readily apparent under incandescent illumination.

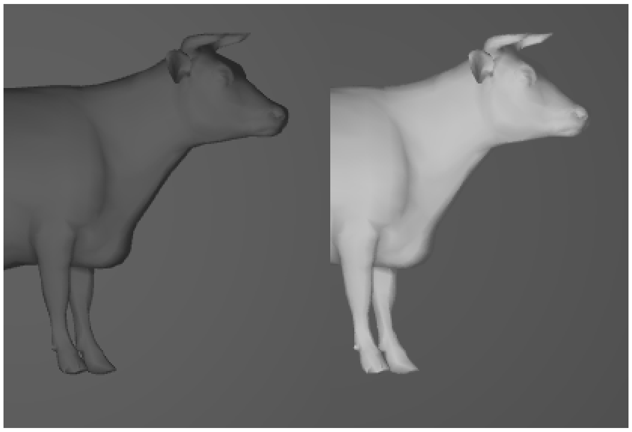

Figure 6. Monochromatic images with created using a single sensor, but changes in illumination (daylight on left, incandescent on right).

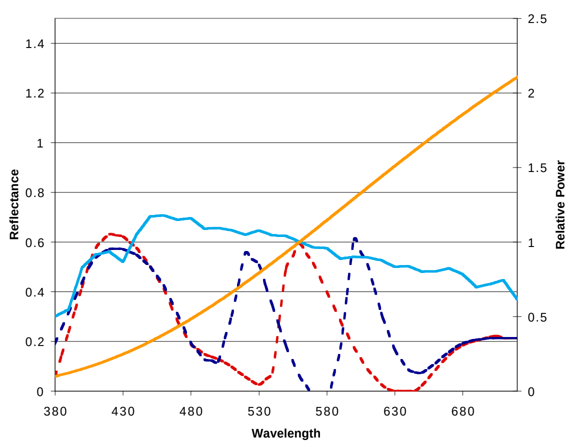

Figure 7. Spectral reflectances of the object (blue dashed line) and background (red dashed line) and spectral power distributions of the light sources (daylight = cyan line, incandescent = yellow line) used to generate Fig. 6. Sensor was photometric.

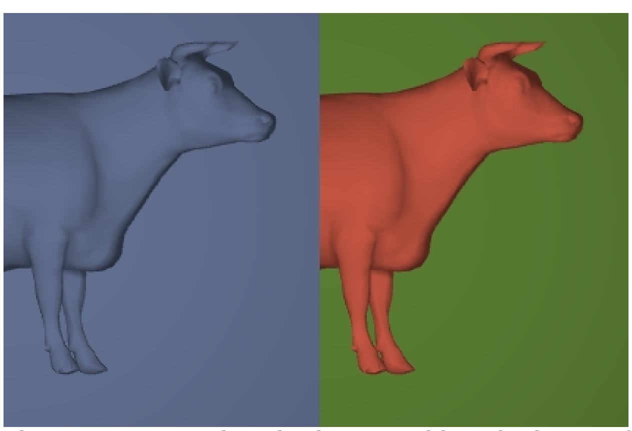

Figure 8. Metameric color images with a single set of three sensors (human responsivities), but a change in illumination. The object matches the background under daylight (left), but mismatches and changes appearance under incandescent light (right)

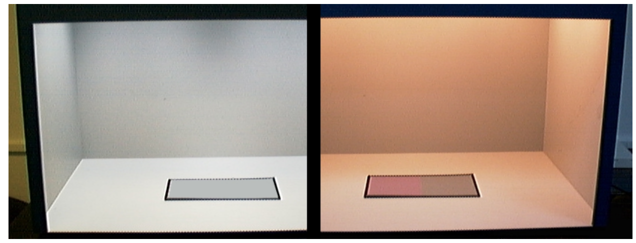

Figure 9. A real painted metal sample pair. Note that the two panels match under daylight (left) but mismatch significantly under incandescent light (right). Images captured with a color CCD camera.

Figure 9 illustrates that the concepts illustrated in the computer-synthesized simulations are not only theoretical in nature. Figure 9 includes two images made with a commercial color CCD camera. The subject is a pair of painted metal panels imaged under daylight illumination (left side of figure) and incandescent illumination (right) in a light booth. The two panels match under daylight (for this particular camera) and appear a single panel. However, under incandescent illumination, the left panel takes on a magenta appearance, while the right panel appears grayish-tan. Objects with such reflectance properties are surprisingly common in the man-made world.

4. Systems Considerations

The theoretical advantages and limitations of spectral imaging in various applications are fairly straightforward. However, there remain a number of practical issues with respect to the design of systems, imaging infrastructure, and ultimate utilization of the images.

4.1. Design of Metameric Imaging Systems

As illustrated in the previous section, spectral imaging through synthesis, processing, system simulation, rendering, and visualization can be a valuable tool in the design of metameric imaging systems for any application. Such systems could be used to derive the optimal camera responsivities for more traditional monochrome or color systems. Such work is currently ongoing in the design of digital cameras for pictorial applications.[27] These tools could also be used to design optimal illumination for applications in which the camera responsivities are predetermined. In this sense, spectral imaging can be thought of as a research tool for the development of improved metameric imaging systems.

4.2. Infrastructure for Spectral Imaging Systems

To go further and start using spectral images in final applications, one must overcome a number of issues within the infrastructure of current imaging systems. For example, most image processing software packages are extremely limited in their capabilities to deal with spectral images. For example, the ICC architecture[28] for color management of images across devices and platforms cannot readily handle spectral image information.[17] Even the process of storing spectral images and viewing the data is something that is limited mainly to research applications. The development of more robust imaging architectures in commodity hardware and software will be required before spectral imaging can become more widespread. Of course, the further development of successful and compelling applications for spectral image data and high-quality spectral images will push improvements in the infrastructure.

4.3. Implications for Computer Vision and Pattern Recognition

Computer vision and pattern recognition as a field have thrived to date on largely monochromatic images. Color images, where used, are seldom derived from characterized systems with known colorimetric properties and thus the interpretation of the color information is somewhat limited, and therefore empirical. There are, of course, exceptions for example the work of Funt and his colleagues on illuminant estimation which also provides additional insight into the applications of color in computer vision.[29,30] A concerted effort to adopt techniques of spectral imaging and their use in the development of well-designed, high-quality metameric imaging systems has the potential to move the field ahead substantially and also make significant contributions to other application areas by helping make the infrastructure of spectral image sensors, processing systems, and displays more readily accessible.

5. Conclusions

Spectral and metameric imaging have a history intertwined throughout the technological development of imaging systems. This is necessarily the case since one cannot exist without at least the concept of the other. Commercially, metameric imaging systems have dominated the market nearly to a point of exclusivity. Unfortunately this exclusivity has resulted in sub-optimal metameric imaging systems being utilized in a wide variety of applications. It is hoped that this paper can serve as one seed to help spread the practical application of spectral imaging and move it from high-cost research applications gradually to more and more practical applications.

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