What to Lose Sleep Over in Digital Color Imaging…

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Abstract

Much of today's color imaging is based on a trichromatic pixelwise representation of color. Yet a realistic color imaging experience involves consideration of additional dimensions such as spectral, spatial, and goniometric effects. This paper presents challenges encountered in incorporating these higher dimensions into mainstream color imaging. We discuss important factors to be considered as these challenges are addressed. These include trends in color technologies, research in human color perception, intelligent interfaces, the importance of a systems approach, and the synergies acquired from cross-disciplinary interactions.

Introduction

The world of digital color imaging has undergone much change and advancement over the past twenty years. We have seen a tremendous evolution of color imaging devices, applications, and systems brought together to achieve a wide range of functions in a variety of market domains ranging from production printing and proofing to medical imaging, digital photography, and digital cinema. Color imaging has also been democratized– it is no longer restricted to the domain of skilled experts. In fact as digital color becomes more commonplace, consumer expectations are constantly rising. This paper presents a series of observations on the current state of digital color imaging, some significant challenges that lie ahead, and important factors that must be considered as these challenges are addressed.

Thirty years of CIELAB and ΔE

The original CIELAB color space and associated color difference equations (ΔE) were standardized in 1976 [1]. Three decades later, they are still perhaps the most widely cited models in the color imaging literature. Many color imaging systems are optimized with respect to ΔE (or a recent version thereof). Today the mathematics, algorithms, and hardware required to execute this optimization are fairly mature. It is therefore difficult to use ΔE as a differentiating feature when selling a color imaging product. In fact, conforming to a certain ΔE tolerance is now a necessity in order to stay competitive. Also, while CIELAB and ΔE play a vital role in quantifying basic color accuracy and stability, one must exercise caution in relating them to overall image quality. As is well known, these are simple 3-D models intended to predict the perception of static uniform stimuli against a uniform background. However, in practice, evaluation of a color system involves judgments on complex images viewed under varied conditions and contexts. Furthermore, accurate reproduction does not always imply preferred reproduction. The optimization of a color imaging system should ideally take these additional factors into account. Some of which are discussed next.

Progressing to Higher Dimensions

Recently the author presented a paper on the incorporation of "higher dimensions" in color imaging [2]. These are summarized below.

Spectral imaging

A three-channel colorimetric representation does not fully capture the information necessary to accurately reproduce color across different viewing conditions. Therefore, it is natural to consider the spectral dimension when striving to improve color quality. We make the distinction between spectral measurement for modeling and characterization purposes vs. spectral representation of the image itself. In the measurement arena, research has shown that spectral models generally offer more accurate device characterization than their colorimetric counterparts. Fortunately, the cost of spectrophotometric instrumentation has been steadily declining, and ease of use has improved significantly. Thus spectral measurement is being increasingly adopted by color management systems.

Spectral image representation involves the sampling of entire image data with narrowband spectral channels, not necessarily confined to the visible spectrum. The remote sensing field has long used such representations for applications ranging from military reconnaissance to agriculture and natural resource preservation. Within the domain of color image reproduction, the main purported benefit of maintaining a spectral representation is the elimination of metamerism, and the ability to handle multiple viewing conditions. Much research has gone into investigating problems such as the optimum number of spectral channels, spectral sensor design, and efficient spectral representations. A practical issue is that the cost in designing, manufacturing and operating spectral image capture and output systems is still prohibitive for the mainstream color imaging markets. One can also argue that most mainstream applications tolerate some amount of metamerism, and in fact rely upon this phenomenon for successful color reproduction (e.g. photography and television). Furthermore, recent research has indicated a low incidence of metamerism in natural scenes [3].Thus today, the use of spectral technology in color imaging is confined to niche applications where metamerism cannot be tolerated, and cost is not critical. Examples include artwork reproduction, and imaging of paints and fabrics for e-commerce applications. The medical imaging community is also beginning to embrace spectral imaging technology in diagnostics and prosthetics applications [4, 5]. Adoption into the mainstream color imaging market may occur with a substantial reduction in cost and complexity of the technology.

An interesting hybrid approach would be to incorporate spectral sensors into standard trichromatic imaging devices. The sensors would provide auxiliary spectral information that could aid the optimized capture or reproduction of standard 3-channel imagery. An example could be the use of a sensor in a digital camera to estimate the spectrum of the illuminant.

Spatial context in color imaging

It has long been known that human color perception is strongly affected by the spatial characteristics of the stimulus [6]. Most of today's color management systems essentially ignore such spatial effects. Recently we have developed a framework to incorporate local spatial surround in color management transforms such as gamut-mapping. The algorithms are described in detail in Ref [7, 8] and summarized in Ref [2]. These and similar techniques proposed by other researchers [9, 10] demonstrate that the incorporation of spatial context in color imaging can offer significant gain in image quality. Interestingly, this benefit is often achieved at the expense of pixel-wise ΔE accuracy – thus reiterating the fact that color perception goes beyond simple colorimetric matching at each pixel.

Another compelling example of the importance of the spatial dimension is high-dynamic-range (HDR) image compression. While significant advances have been made in the capture and synthetic generation of HDR images, the dynamic range capabilities on the output side have not quite caught up. This calls for dynamic range compression from the original scene to output device, the latter ranging from desktop displays to digital cinema projectors. Much research has gone into HDR compression, producing a suite of algorithms from pixel-wise tone mapping operators to spatial functions that take into account the preservation of image contrast [11]. As with the gamut-mapping case, there is overwhelming evidence to indicate that spatially adaptive HDR algorithms outperform their pixel-wise counterparts [12].

Other examples that incorporate the spatial dimension into color processing can be found in digital photography [13, 14] and color printing [15]. The main challenge in introducing spatial aspects into color management is an architectural one. Many of today's color management systems are based on the International Color Consortium (ICC) standard, and thus designed for pixel-wise processing. Redesigning these systems to handle spatial context can be non-trivial, but must be undertaken in order to progress to the next level of color quality.

Finally there are applications outside the realm of image reproduction that also benefit from a synergistic interaction of spatial and color dimensions. One such example is content-based image search and retrieval. It has been recognized that search techniques based purely on color histograms have limited success, unless they are combined with knowledge of spatial relationships between objects and image regions. The observation also holds for the general area of image understanding.

Goniometric considerations

Goniometric or angular effects can play an important role in color perception. For example, color appearance studies have shown that at non-specular viewing angles, the perceived chroma of a color stimulus increases with its gloss [16]. For many years, the computer graphics community has developed and used gloss models in rendering synthetic images. However, within the color management community, the goniometric dimension has been largely ignored until very recently.

In the past two years, several researchers [17, 18] have investigated the incorporation of gloss effects into softproofing - an important problem in the production color market. These methods compute a diffuse image component via standard color softproofing transforms, and a specular image component via a known gloss model. These components are then combined to provide a gonio-chromatic image using a real-time rendering program. The result is that the user can move the softproof around in 3D, and get a realistic perception of gloss on the virtual prints. This research marks an important cornerstone in digital proofing, and is expected to encourage more widespread acceptance of the softproof as a surrogate for the hardcopy. Other researchers have studied the incorporation of gloss models in realistic color rendering of 3-D objects [19].

The incorporation of goniometry in color management is an important step towards offering a realistic imaging experience to the user. One challenge is that spectro-goniometric instrumentation is expensive and cumbersome to operate. Another hurdle is the lack of familiarity of goniometric concepts within the color management community. This can be addressed by tapping into the computer graphics community as an excellent resource of knowledge and computational tools in this field. On the other hand, an enabling factor is the tremendous advancement in graphics hardware spurred by gaming applications.

Device Technologies – Noteworthy Trends

The last decade has experienced an explosive increase in the number and variety of color scanners, cameras, displays, printers, and other imaging devices. The following observations may be useful to keep in mind as we think about future directions in color imaging.

1) There is a growing appetite for combining multiple functions onto one physical device. Multifunction printers can now also copy, scan, and fax documents. Digital still cameras often offer some video capture capability, and vice versa. Many digital cameras also offer easy connectivity to printers to enable photofinishing. And there is the popular phone-camera that adds digital photography to the growing array of functions found on a mobile phone. This "Swiss-army-knife" approach to color imaging brings about challenges in user interface design, form factor, and resource management. However, it also connects devices in novel ways and creates workflows never before conceived.

2) In certain realms, we see an increasing chasm between the professional and consumer markets. In digital photography, for example, professional SLR cameras are on the rise, with steep demands on quality, noise containment, and functionality that enables creative capture. Simultaneously, at the consumer end, there is a surge in phone camera technology. The key requirements here are low power consumption, compactness, and ease-of-use [14]. A similar observation can be made for displays. At the high end, new technologies are emerging with increased color gamut, dynamic range, sharpness, and resolution. At the same time, there is a growing market for inexpensive displays on mobile devices, the important considerations being cost, compactness, power consumption, and accounting for diverse surround conditions [20].

In both cases the intermediate "middle class" of technologies seems to have reached a plateau, possibly suggesting a bimodal profile in color imaging research.

3) The ever-advancing field of semiconductor technology, and its logical progression to nanotechnology, allows extremely powerful imaging capabilities to be placed into very compact devices. At the same time major strides have been made in networking infrastructure. Together these two trends suggest a shift from a device-oriented (or centralized) paradigm to a network-oriented (or distributed) model. In the latter scenario, the desired color imaging function is not executed at a single specific device, but rather via a networked service that invokes the appropriate imaging resources. The latter would include the appropriate combination of devices, algorithms, hardware required to accomplish the requested function. Today's online photofinishing services exemplify the onset of such a model. This paradigm shift changes can have profound implications on color imaging architectures, as it changes the way in which color imaging functions are delegated among devices, clients, and servers. One might coin the term "ubiquitous color imaging" as a logical extension of this model.*

Human Visual System Considerations

An overriding factor in the design and optimization of color imaging systems is human color perception - the ultimate yardstick by which color is judged. In recent years, much effort has been expended into deriving models for predicting color appearance and color difference. Until very recently, these models were applicable primarily for uniform stimuli, and underwent a long series of incremental refinements, each version attempting an improved fit to empirical data than its predecessors. The color perception community has since prudently opted to put to rest the empirical tweaks, and turn to more fundamental studies of color vision and appearance. Latest research efforts include the development of a color appearance model for complex images [21], and studies on the effect of spatial noise [22], sharpness [23], size and viewing distance [24] on perception of color images. These efforts signify an important step in evolving beyond classic colorimetry, towards more robust models that embrace the higher dimensions of color imaging. This advancement is also timely, as many of the newer imaging applications involve capture and reproduction of images under very diverse viewing conditions. These will surely pose unique challenges to appearance modeling.

Tenets for Success

Intelligent automation: When designing color imaging systems, it is important to frequently remind ourselves of the end user's skill level and expectations. In many applications, ease-of-use, rather than color quality, is the differentiating factor. At the consumer end, users seek simplicity rather than complexity; calling for a significant amount of automation of color imaging functions "under the hood". The sRGB model was intended to fall in this category. The more advanced "pro-sumer" may desire a hybrid approach where certain mundane tasks are automated, while functions involving creativity and human judgment are executed via a manual interface. The recent Windows Vista color management system offered by Microsoft and Canon purports to offer a range of interfaces in this intermediate space. Finally, professional users want complete control of the imaging operations. Adobe Photoshop is a good example of an application in this class. The balance between automatic and manual interaction must be carefully chosen to suit the intuition and expertise of the user. These issues will become even more challenging as color imaging systems encompass higher dimensions and take on diverse form factors.

System interactions: There is a common tendency to design and optimize a given color imaging element in isolation of other elements in the system. Such a mindset may have been acceptable in traditional closed systems, but can lead to sub-optimal performance in today's open systems. Ref. [25] presents a series of case studies of desirable system interactions that can be harnessed, and undesirable interactions that can be avoided with a holistic approach. Also the term "system" is a relative concept; i.e. what one considers a system might only be a single element in another larger system. Thought should be given to the contexts within which a given element could be used. This is especially true with the multifunction and distributed imaging models discussed above, as these greatly expand the ways in which users can connect different elements to accomplish their tasks.

Synergies across disciplines: Many color imaging problems can be solved more effectively by cooperation among the various communities that constitute this diverse discipline. An example given earlier was the collaboration between the computer graphics and color management communities towards incorporating goniometry into color imaging. In the medical imaging arena, it is gratifying to see cooperation between medical specialists (e.g. radiologists, doctors) and spectral imaging researchers. The area of image search and retrieval tends to suffer from a dearth of proper color science and device calibration methodology, and could benefit from participation by color management experts. Ref [25] provides several examples where image processing specialists and color scientists could collaborate to co-optimize the color and spatial dimensions. The video community and color scientists stand to gain from jointly exploring the temporal dimension of color imaging. In general, the higher dimensions discussed earlier should be treated jointly where possible, rather than in isolation. Finally, one could stand to see more collaboration between the art and the science of color imaging. What could scientists learn from artists, who have a remarkable ability to create realistic color images from a small number of paints and dyes that are quite different from CMYK colorants?

Conclusions

This paper reviews some of the major technological efforts in color imaging today, some of the significant challenges that lie ahead, and considerations to keep in mind as these challenges are tackled. As a parting note, we remark that most technologies undergo a "hype cycle" as they progress from initial concept to end product [26]. The hype cycle is shown in Fig. 1, and the various phases are explained below.

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* This is the topic of a keynote presentation at ICIS 2006.

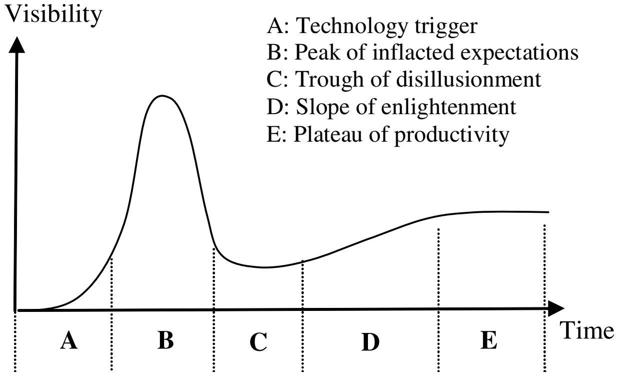

***Figure 1**. Technology Hype Cycle*

Technology trigger – a breakthrough, public demonstration, press release.

Peak of inflated expectations – a period of unrealistic projections, inflated expectations

Trough of disillusionment – a realization that technology does not meet up to its over-inflated expectations

Slope of enlightenment – focused experimentation leads to true understanding of technology's capabilities

Plateau of productivity – real-world benefits of the technology are demonstrated and accepted.

One can think about where the various technologies discussed in this paper fall on this hype cycle [2]. For example, device independent color management is presumably entering the plateau of productivity, while spectral imaging may have just passed the peak of inflated expectations and entering the trough of disillusionment. One might posit that spatial and goniometric technologies are in the initial trigger phase. We leave it to the reader to muse about where other color imaging technologies lie on this plot. The point is that the journey from concept to a real application is typically an arduous one; met with high and low points of excitement; and eventually settling to a steady state of widespread acceptance. The final phases D and E are often lengthy, partly because the necessary standards and infrastructure must be in place for widespread adoption. Fortunately, there are many efforts in this vein, including ICC, CIE, ISO, JDF, and others.

References

[1] R. W. G. Hunt, The reproduction of colour in photography, printing, and television, 4th Ed. Fountain Press, Tolworth, U.K., 1987.

[2] R. Bala, Challenges in color reproduction: towards higher dimensions, SPIE Vol. 5667, pp. 162-169.

[3] D. H. Foster et al., Incidence of metamerism in natural scenes, *Proc. IS&T/SID's13th Color Imaging Conference,* pp. 36-39, 2005.

[4] K. J. Parker and M. Zhang, Color in medical imaging, *Proc. IS&T/SID's12th Color Imaging Conference,* pp. 4-8, 2004.

[5] M. Yamaguchi et al., Multispectral color imaging for dermatology: application in inflammatory and immunological diseases, *Proc. IS&T/SID's13th Color Imaging Conference,* pp. 52-58, 2005.

[6] M. D. Fairchild, Color appearance models, Addison Wesley, Reading, MA, 1999.

[7] R. Bala et al., "Gamut mapping to preserve spatial luminance variations," *Journ. Imaging Science & Technology*, **45**(5), pp. 436-443, 2001.

[8] R. Bala, R. Eschbach, Spatial color-to-grayscale conversion preserving chrominance edge information, *Proc* IS*&T/SID's 12th Color Imaging Conference*, pp. 76-81, 2004.

[9] N. Moroney, Local color correction using non-linear masking, *Proc. IS&T/SID's 8th Color Imaging Conference*, pp. 108-111, 2000.

[10] J. Morovic and Y. Wang, A multi-resolution full-colour spatial gamut mapping algorithm, *Proc. IS&T/SID's 11th Color Imaging Conference*, pp. 282-287, 2003.

[11] G. Ward, High dynamic range imaging, *Proc. IS&T/SID's 9th Color Imaging Conference*, pp. 9-16, 2001.

[12] S. Park and E. Montag, Rendering non-pictorial (scientific) high dynamic range images, *Proc. IS&T/SID's 12th Color Imaging Conference*, pp. 321-326, 2004.

[13] B. McCleary, Methods to reduce the amplication of random noise in the color processing of imager data, *Proc. IS&T's PICS Conf.*, pp. 50-57, 2003.

[14] P. M. Hubel, Foveon technology and the changing landscape of digital cameras, *Proc. IS&T/SID's13th Color Imaging Conference,* pp. 314-317, 2005.

[15] R. V. Klassen et al., Color correcting JPEG compressed images, *Proc. IS&T and SID's 5th Color Imaging Conference*, pp. 83-87, 1997.

[16] E. Dalal and K. Natale-Hoffman, "The effect of gloss on color," *Color Research & Appl.*, Vol. 24, No. 5, pp. 369-375, 1999.

[17] R. Patil et al, 3D simulation of prints for improved softproofing, *Proc. IS&T/SID's 12th Color Imaging Conference*, pp. 193-199, 2004.

[18] F. Herbert and O. U. Ecker, Soft proofing of multi-color documents in a panoramic environment using real time spectral processing, *Proc. IS&T/SID's13th Color Imaging Conference,* p 320, 2005.

[19] M. Goesele et al., Validation of color managed 3D appearance acquisition, *Proc. IS&T/SID's 12th Color Imaging Conference*, pp. 265-270, 2004.

[20] L. D. Silverstein, Color display technology: from pixels to perception, *Proc. IS&T/SID's13th Color Imaging Conference,* pp. 136-140, 2005.

[21] M. Fairchild and G. Johnson, Meet iCAM: A next-generation color appearance model, *Proc. IS&T/SID's 10th Color Imaging Conference*, pp. 33-38, 2002.

[22] N. Moroney and S. Susstrunk, Spatial frequency and lightness, *Proc. IS&T/SID's 12th Color Imaging Conference,* pp. 18-21, 2004.

[23] M. D. Fairchild and G. M. Johnson, On the salience of novel stimuli, adaptation and image noise, *Proc. IS&T/SID's13th Color Imaging Conference,* pp. 333-338, 2005.

[24] G. M. Johnson and E. D. Montag, Size matters: the influence of viewing distance on perceived spatial frequency and contrast, *Proc. IS&T/SID's13th Color Imaging Conference,* pp. 339-343, 2005.

[25] R. Bala, G. Sharma, "System optimization in digital color imaging", *IEEE Signal Processing Magazine*, pp. 55-63, Jan. 2005.

[26] J. Fenn et al., "Hype cycle for emerging technologies, 2004," *Gartner Strategic Analysis* report, Gartner Research, July 2004.

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