Toward Higher Dimensionality in Cinema Color:
Multispectral Video Systems   By David Long and Christopher Mondiek

The current digital transition being experienced by the motion picture industry has afforded an effective increase in dimensionality in the domains of time and space; however, comparatively little effort has been put into expanding a rigorous treatment of color. All practical motion-imaging systems continue to rely on the metamerism illusion wherein a particular integrated stimulation of the three cone types found on the human retina is sufficient to reproduce the sensation of color of any real object regardless of higher order spectral composition. Such treatments fundamentally restrict cinema color reproduction, offering limitations in absolute color accuracy and gamut, observer metamerism, and consistent creative communication. Optimized multiprimary reproduction focused on spectral reproduction accuracy or metamerism reduction may ultimately prove a better answer to enhancing the color experience in future systems. It also promises to open new color management paradigms for visual effects compositing of live action and computer-generated imagery or for virtual cinematography. Research in progress at Rochester Institute of Technology has focused on exploring essential design attributes for abridged multispectral capture and display systems for motion-imaging applications.

INTRODUCTION

Electronic imaging technologies for cinema and television applications have evolved at an impressive pace during the course of the past 20 years. In particular, three trends have dominated the story: a move from analog to digital systems, an enhancement of spatial resolution, and an increase in frame rate. In each plotline, the fundamental ways in which we interact with motion content have been altered. While the digital transition has afforded an effective increase in dimensionality in the domains of time and space, comparatively little effort has been put into expanding a rigorous treatment of color. More than 150 years after Maxwell first proposed the theory of trichromatic color reproduction, all practical motion-imaging systems continue to rely on the metamerism illusion wherein a particular integrated stimulation of the three cone types found on the human retina is sufficient to reproduce the sensation of color of any real object, regardless of higher order spectral composition. This simplified treatment, though effective, is necessarily restrictive in light of emerging trends such as the convergence of live action and computer-generated imagery and the introduction of wide-gamut display technologies. Full spectral color treatments may render improved realism in digital visual effects and enhanced uniformity of viewing experience across large audiences.

Problems in the trichromatic reproduction model are found in two principal areas, gamut limitation and observer metamerism. In the former, fully characterized scene content may constitute a reproduction stimuli outside the colorimetric capabilities of the traditional limited primary display device. In the latter, controlled metameric matches of color within the display for a single observer may prove not to be matches for another observer with slightly different color-matching functions or may prove inconsistent even for single observers as they age.

The solution to both problems lies, in part, in generating a full spectral-based reproduction environment. In the ideal case, narrow-bandwidth, high-spectral-resolution systems would be conceived to accomplish the goals of controllable spectral capture and reproduction of target stimuli. By combining near-monochromatic characteristics at a high sample rate across the visible electromagnetic spectrum, many sufficiently complex stimuli could be rigorously rendered. In a practical sense, however, an abridged spectral reproduction model makes more sense for hardware design, image processing complexity, and storage considerations, utilizing capture and display devices in which individual spectral features are purposefully optimized to deliver a measurable advantage in a limited spectral resolution.

THE METAMERISM PROBLEM

Motivations for multispectral imaging systems, complete with strategies for capture, color management, and display, have been expressed by several researchers for more than a decade, all attempting to address the limitations of three-channel imaging paradigms that do not match the fundamental spectral signatures of human color matching functions (CMFs).[1] Trichromatic theory, whether applied to engineered devices or human observers, has its foundation in the integrated spectral signature represented in **Eq. 1**. An object with spectral reflectance, $R(\lambda)$, illuminated by a source with spectral power distribution, $Il(\lambda)$, is spectrally integrated with the sensitivity signature of a detector, $SS(\lambda)_k$, across $k = 1 \ldots K$ independent channels of response. After appropriate normalization, h_k, the resulting quantity is generically dubbed tristimulus, W_k.

A more specific replacement of $SS(\lambda)_k$ with the CIE 1931 2° standard observer CMFs (or any other appropriate observer CMF) yields XYZ tristimulus values. Likewise, individual observer *signal* responses in the long, mid and short primary cone types, *LMS*, are

specified when $SS(\lambda)_k$ are replaced by $l(\lambda)$, $m(\lambda)$, and $s(\lambda)$ spectral cone fundamentals. For film or digital image capture systems, insertion of the device's spectral sensitivities generates quantities indicative of the captured energy signal at a specific position on the image plane in each channel:

$$W_k = h_k \int_{\lambda_{min}}^{\lambda_{max}} Il(\lambda) \cdot R(\lambda) \cdot SS(\lambda)_k \, d\lambda. \qquad (1)$$

A dimensional analysis of **Eq. 1** suggests there are infinite combinations of spectral reflectance and illumination that may deliver integrated tristimulus values equivalent to some established target stimulus for a given detector. This principle is defined as metamerism and is especially useful in both soft-copy and hard-copy image display where the spectral characteristics of colorants used do not afford a precise spectral match to the target. However, metamerism in its apparent simplicity can also pose problems in engineered imaging systems.

As a simple example, assume the goal of an image capture device is to mimic the responsivity of the 1931 2° standard observer, an approach in camera design referred to generically as the Luther condition and one thought to support supposedly perfect color reproduction. To accomplish this directly, the capture system should possess $SS(\lambda)_k$ that are equivalent to either the standard observer's CMFs or linearly related cone fundamentals. As both of these responsivity sets are physically realizable, appropriate optical filtration could theoretically be designed to accomplish the objective. Unfortunately the nature of human color vision is such that the integrated tristimulus signals from this model represent display primaries that are physically nonrealizable. Peculiarities of the linear transforms involved in human color matching dictate that both the *XYZ* and *LMS* primaries must have negative energies in various regions of their spectral signatures in order to properly represent a metameric match to the target stimuli captured via the respective sensitivity functions.

Conversely, when direct capture of human tristimulus signals becomes imprudent for practical display processing, imaging system designers typically look to compromises employing minimal color processing between capture and display. In particular, device responsivities may be chosen that are as near as possible to CMFs of a chosen set of display primaries, though in a three-channel system there are no such choices where both sensitivity functions and primary spectra are all positive and realizable. The result is that real function shapes are designed and related by statistically optimized color processing transforms instead, typically 3 x 3 matrices or more customized three-dimensional look-up tables. The specification of colorimetric video cameras employing ITU-R Rec. 709 encoding characteristics and intended for display on sRGB additive displays are, as is well known, described in this approach.[2]

The primary consequence of spectral responsivity compromises in real image capture equipment is that these systems no longer represent actual standard CMFs. Further, presumption that the standard observer represents all human response functions can cause significant issues. Just as a camera system may fail to metamerically coincide with the response of the standard observer, real human observers vary significantly in their spectral response characteristics. These variations have been studied extensively with some success found in systematically characterizing average differences as a function of observer age and field-of-view.[3] Of course, even studies such as this can claim only to summarize the mean trends in human observers, recognizing there are still unique results found in real populations.

DESIGNING A MULTISPECTRAL SYSTEM

Successful spectral image reproduction systems require both image capture and reproduction devices capable of characterizing and representing real world scene spectra across a wide range of the spectral gamut. The purpose of multispectral capture is to either directly or indirectly collect energetic profiles of scene objects under native illumination and to convey those profiles to an appropriate storage or display system. Motion-imaging systems are expected to accommodate dynamic image content often with non-uniform mixed-source lighting and with challenging high contrast ratios. Further in video applications, this must be accomplished for each pixel in each frame of a motion sequence.

Capture

For spectral capture, an ultimate design objective constitutes high-resolution spectral sampling accomplished with temporal or spatial overhead. This sampling has been demonstrated using raster-scan spectrometers, occlusion-mask prismatic dispersion cameras, coded aperture snapshot cameras, and computed tomographic spectrometer systems, though not at as high as HD video resolution in any of these cases.[4] Other solutions invoke beam splitters to generate high-spatial-resolution RGB images concurrently with high-spectral-resolution signals at a much reduced spatial sampling to be recombined in post-processing.[5] Beyond these, other reasonably adequate systems for generating multispectral image data have been demonstrated by a number of researchers for both still and motion applications.[6] Where sequential capture of multiple narrow bands of the spectrum in some large number of system channels, *K*, is feasible when imaging stationary objects, the approach is currently impractical for the high data and frame rates expected of video. In these applications, conventional trichromatic integrating cameras can be engineered to deliver intermediate predictions of statistical spectral behavior necessary for pixel-by-pixel spectral estimation.

Early efforts in generating a working multispectral capture system for video applications can be attributed to the Akasaka Natural Vi-
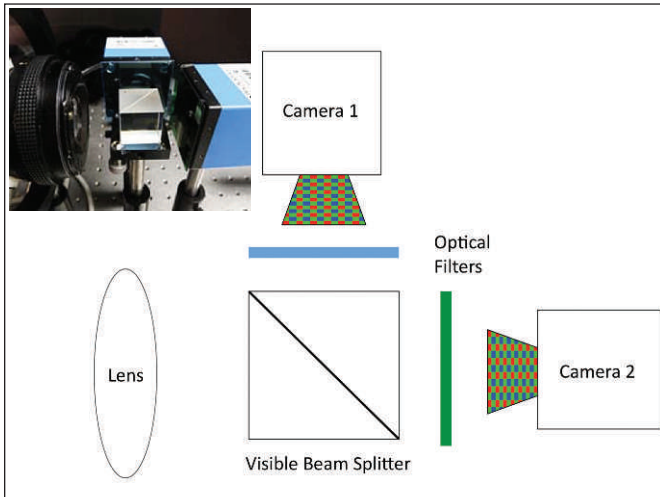
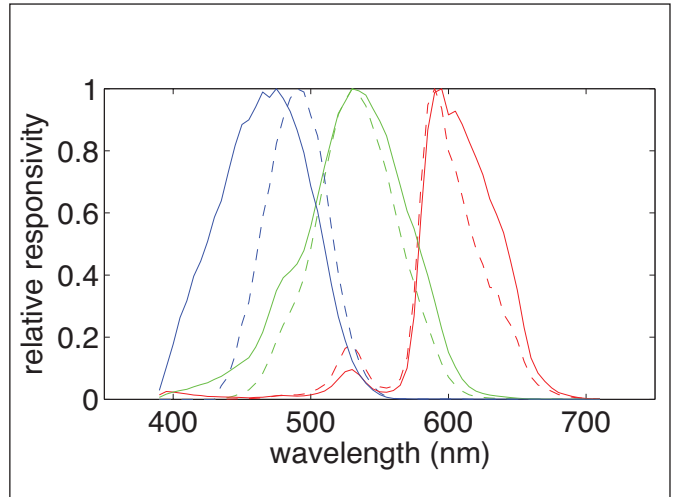**Figure 1.** RIT multispectral camera schematic.

Figure 2. RIT camera spectral responsivities.

sion project in Japan, a joint effort of the Tokyo Institute of Technology, and the Japanese Ministry of Internal Affairs and Communication along with other industrial and academic partners.[7] For motion capture applications, the Natural Vision project constructed a video camera capable of six-channel sensing from two trichromatic HDTV CCD cameras connected through an optical splitter. In work performed at the Munsell Color Science Laboratory at Rochester Institute of Technology (RIT) by Berns et al., spectral capture has been designed for different camera systems comprising both full and abridged spectral resolution.[8]

In optimizing a camera design, fundamental color science questions associated with the spectral estimation generated from the capture system must be addressed. Object spectra may be represented with the goal of minimum radiometric root mean square error between aim and render or with a co-optimization between spectral and colorimetric accuracy for a standard observer. Alternatively, minimization of observer metamerism may be introduced by a fully colorimetric match goal but across several candidate CMFs simultaneously. These functions may be a collection of standard observers (1931 and 1964), physiologically relevant observers (CIE TC1-36), or a statistical sampling of real measured observers (such as those participating in Stiles-Burch 10° observer experiments).

Algorithms for producing scene spectral estimations from integrated camera signals fall into three classifications; direct, interpolated and learning-based. For the first two, the spectral characteristic of a particular stimuli are directly interpreted from peak sensitivity and bandpass characteristics of each of the K channels in the acquisition system. Spectral signatures may be presented in N=K dimensions of resolution or increased resolution may be interpolated via suitable spline or other curve-fitting techniques. In the third approach, estimation algorithms are derived and optimized from *a priori* information from select system training spectra. For systems with lesser spectral sampling, this approach proves reasonably effective.

The RIT Video Camera

With all of these hardware and image processing design options available, recent work at RIT has yielded a functional six-channel video camera designed for abridged multispectral recording. Twin Imaging Source DFK 31BF03 CCD cameras capable of 1024 x 768 sampling at 30 frames/sec are oriented as in **Fig. 1**. The design enables imaging through a white light beamsplitter to simultaneously record six channels of integrated information. Although the cameras employ native Bayer CFAs, external filters for the transmission and reflection paths have been optimized to shape preferred spectral responsivities across the visible spectrum in all six channels. An exhaustive search of commonly available filter materials optically coupled to the native CFA sensitivities was performed via simulation. The goal was minimization of observer metamerism in the estimated spectra of the MacBeth CCDC color target illuminated by a combination of a 2856 K Planckian blackbody (effectively, CIE illuminant A), CIE D65, and the CIE F2 standard fluorescent illuminant. The filters chosen were Schott BG40 and VG09 glass, each 1mm thick. The six-channel spectral responsivities are shown in **Fig. 2** and an example spectral estimation of a MacBeth green patch made via the camera is shown in **Fig. 3.** Native CFA responses optimized for traditional three-channel color reproduction applications can be a restrictive element in yielding ultimate spectral estimation performance in systems like this and so investigations into custom materials and alternate optical designs remains active.

Spectral estimation of stimuli captured with the six-channel system is accomplished utilizing an *a priori* training strategy and principal components analysis (PCA). In this approach, known spectral data to be imaged are expanded into a scaled summation of orthonormal basis functions (eigenvectors). Care is taken to identify basis functions from a decomposition of target stimuli with spectral characteristics fully representative of the intended imaging situation. Several techniques have been reported for effective selection of training patch sets for these abridged multispectral capture systems.[9,10] Once a collection of I significant eigenvectors, $\mathbf{e}_{N,I}$ with spectral resolu-
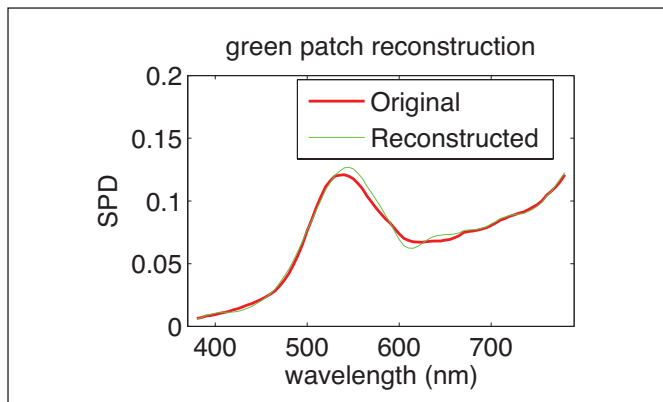
Figure 3. MacBeth green patch spectral estimation via RIT camera.

tion, N, is computed (see Tzeng and Berns for an expanded treatment of the full PCA computations used with spectral data[11]), an input aim or measured spectral stimuli set, $s_{N,J}$ comprised of J total patches is decomposed via projection operators as in **Eq. 2** to its I principal components, $b_{I,J}$ (i=1 to I). Reconstruction of the PCA-estimated stimuli, $š_{N,J}$ is then achieved according to **Eq. 3** and the difference between **s** and **š** represents the baseline or minimum system spectral error.

$$b_{I,J} = inv(e_{N,I})s_{N,J} \qquad (2)$$

$$š_{N,J} = e_{N,I} \cdot b_{I,J} \qquad (3)$$

In the implemented imaging system, the principal component vector, b_I, for any spectral target stimuli must be predicted from integrated camera signals derived for that target. This, however, requires an established relationship known between the camera signals and the target principal components and is the result of the camera training process. Training may be executed through either simulation of camera response or direct measurement of imaged patches. In simulation, the integrated response of the k-th channel of the capture system, c_k, for a given stimulus is a function of the spectral radiance of the illuminant associated with the stimulus, $Il(\lambda)$, the reflectance of the stimulus, $R(\lambda)$, the spectral transmittance of optical features ahead of the detector in the system, $o(\lambda)$, the spectral transmission of the kth optical color filter, $\phi(\lambda)_k$, the native responsivity of the detector, $a(\lambda)$, and the internal system noise associated with the system, ε_k, **Eq. 4**.

$$c_k = \int_{min}^{max} Il(\lambda) \cdot R(\lambda) \cdot o(\lambda) \cdot \phi(\lambda)_k \cdot a(\lambda) \partial\lambda + \varepsilon_k \quad (4)$$

In the RIT camera, 6 eigenvectors have been shown sufficient for high-accuray reconstruction of target stimuli with the added benefit of mathematical symmetry to the camera response vectors. By linearly relating multichannel camera outputs, **c**, to principal components, **b**, for a set of conditioning stimuli, a best fit linear transform, **L**, can be determined. **Equation 5** summarizes the established linear relationship with **L** possessing a dimensionality of I x K (6 x 6). Solution of **L** can be achieved using a psuedo-inverse re-arrangement of this expression across J patches. Subsequently, any real camera signal set, **c**, derived from capture of a full gamut

of subject colors can be multiplied by **L** to generate pixel-by-pixel principal component scalars, which in turn, are used in **Eq. 3** to deliver the pixel's spectral estimation.

$$b_{I,J} = L_{I,K}(c_{J,K})^T \qquad (5)$$

L as solved linearly for integrated responses from **Eq. 5** may, of course, not be optimized to deliver minimized error according to design objectives of spectral accuracy, colorimetric accuracy or observer metamerism in the initial computation. To refine the matrix quality, **L** is further nonlinearly optimized via a specified spectral estimation objective. For the RIT camera, observer metamerism is chosen as the objective metric for this system. In an example implementation, physiological CMFs for hypothetical observers at age 20, 32, and 80 and for visual fields-of-view of 2° and 10° are generated according to models developed by the CIE[3]. To minimize observer metamerism, ΔE00 color difference results between actual and estimated target stimuli for each of the six simulated observer color-matching-functions across all J patches are absolutely minimized.

Display

Though not an easy problem to solve, spectral sensing is generally more straightforward to implement than spectral display, particularly because display carries the dubious task of physically recreating the enormous spectral gamut present in the natural world. Most reproduction devices rely on colorimetric matches with finite primary sets rather than attempting to actually reconstruct full spectra. Further, motivation for newer display types lies heavily in expanding colorimetric gamut via increasingly monochromatic primaries (such as found in laser-based projectors), though Fairchild and Wyble have shown that those enhancements in near-monochromatic systems may also come with a risk of increased observer metamerism in a purely colorimetric display model.[12] Some groups such as Sharp,[13] Texas Instruments,[14] and the Natural Vision Project[15,16] have promoted larger gamuts through adding more primaries to the standard RGB set. In these multiprimary devices, great care is taken with advanced color management when the display primaries no longer conform to the spectral sensitivities of the image capture device or when there is a mismatch in number of color channels between capture and display (requiring effective management of degrees of freedom). Of paramount importance to these designs is determination of the number and nature of primaries needed to reasonably reconstruct target spectral stimuli and enhance spectral gamut as well as encompass a broader colorimetric gamut to include all real surface colors (utilizing databases summarized by Pointer,[17] for example).

At RIT, Long and Fairchild have attempted six-channel spectral reproduction using external filtration in conjunction with a pair of P3 HDTV video projectors, optically superimposed as in **Fig. 4**. Steeply cutting bandpass filters (Schott GG455 and UG5) selected via training simulations of real color patch spectra illuminated by practical light sources are used to narrow the native primary spectra and effectively enlarge colorimetric gamut. Candidate filter pairs were chosen via exhaustive search with co-optimization criteria focused on both absolute spectral reconstruction accuracy and colorimetric accuracy for a standard observer. **Fig. 5** shows
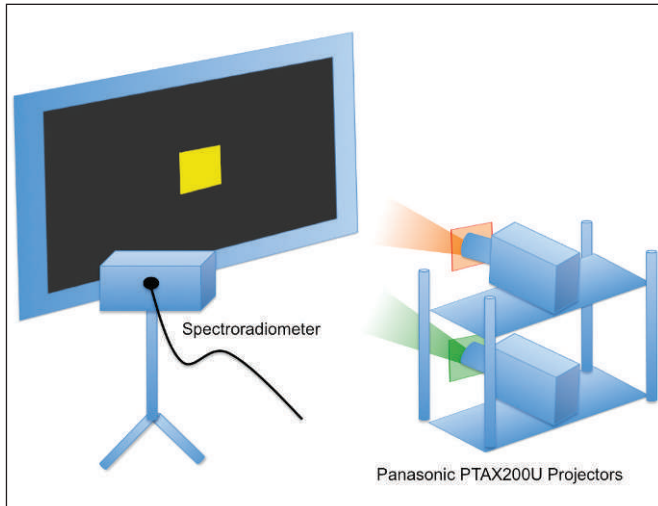
Figure 4. Dual overlaid projection paradigm of Long and Fairchild.

Figure 5. MacBeth white patch reproduced by RIT prototype projector.

an example optimized spectral reproduction for a MacBeth color checker white patch illuminated by CIE D65. Failures to achieve a precise spectral match in the abridged system are evident and are largely attributable to the already narrow native spectra necessary in the projectors to achieve P3 colorimetric goals. In certain regions of the visible spectrum, such as near 580nm, the constructed projection system emits no energy and so cannot possibly mimic the characteristic profile of real stimuli at those wavelengths.

To generate better results, a candidate set of Gaussian primaries was investigated to see if mathematically simplified spectra could yield improved matches in six channels versus the narrow native primary reconstruction of the Panasonic projectors. Though not physically realized, these Gaussian spectra represent plausible radiometric profiles achievable with standard projection illuminants and modern interference filter coatings. A spectral root mean square error optimization model was invoked to generate ideal spectral matches to a subset of the D65-illuminated MacBeth patches: light skin, red, green, blue, cyan, magenta, yellow, and white. Resulting spectral reproductions (in green) for all 24 MacBeth patches are shown in **Fig. 6**. These spectral matches show clear promise for improved observer metamerism and spectral reproduction in future systems where high saturation monochromatic primaries are exchanged for multiple strategically tuned color primaries.

ADVANCED OBSERVER METAMERISM APPROACHES

Acknowledging the difficulty of generating precise spectral matches to target stimuli using multiprimary displays, several additional researchers have focused on the goal of reducing observer metamerism.[18] Hill has suggested a stochastic optimization based on the responses of 24 observers that was shown to work well for both ideal display primaries of dimension K' and an actual six-primary display built as part of the Natural Vision project.

Another interesting option can be found in the work of Sarkar et al.,[19] who successfully grouped 47 original Stiles-Burch observ-
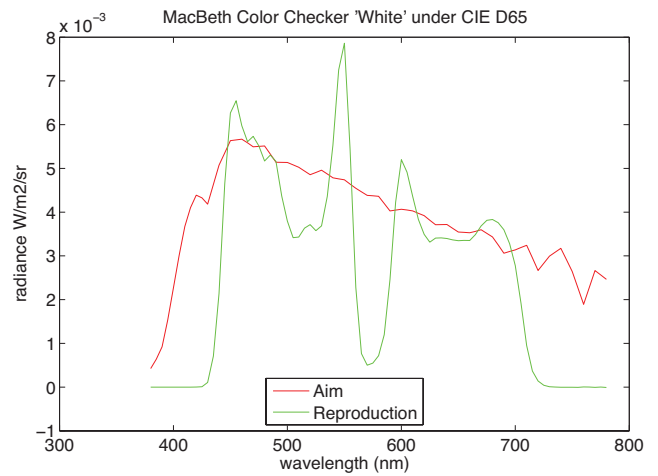
ers into just eight generalized CMF classifications by minimizing colorimetric prediction errors. The full candidate CMF sets were originated as 125 permutations derived from five distinct $l(\lambda)$, $m(\lambda)$, and $s(\lambda)$ cone fundamentals each (from cluster analysis on the Stiles-Burch set) and 61 variations calculated from the CIE age-dependency models for ages between 20 and 80 years. In related work, Alfvin and Fairchild have used Monte Carlo simulation based on physiological and psychophysical measurements of ocular media and cone responsivity functions to derive thousands of theoretical observer CMFs.[20] These have generally proven more predictive of interobserver color matching experiment variability than any generalized visual system model.

With a smaller set of CMFs based in valid statistical reduction of larger populations, a more computationally robust display optimization can be formulated. Sarkar used the categorization approach to successfully identify the CMF descriptor of 30 real observers in a highly metameric matching experiment. Few observers fell outside the constraints of the seven identified categories, suggesting the technique holds promise for actually defining relevant deviate observers for multispectral system optimization.

In further relevant work, Fedutina showed how subtle suprathreshold coloration differences perceived by certain color critical viewers may not be seen as similarly different for observers from other CMF categories. This carries serious implications for collaborative color grading work such as that employed in motion picture and video applications.

COMPRESSION AND TRANSMISSION

One of the major design considerations of any multispectral imaging system is the physical image encoding scheme and the fundamental profile connection space used to link input and output devices of differing capability (dynamic range, gamut, number of image channels, etc.). Previous multispectral research efforts introduced thus far describe various capture technologies employing
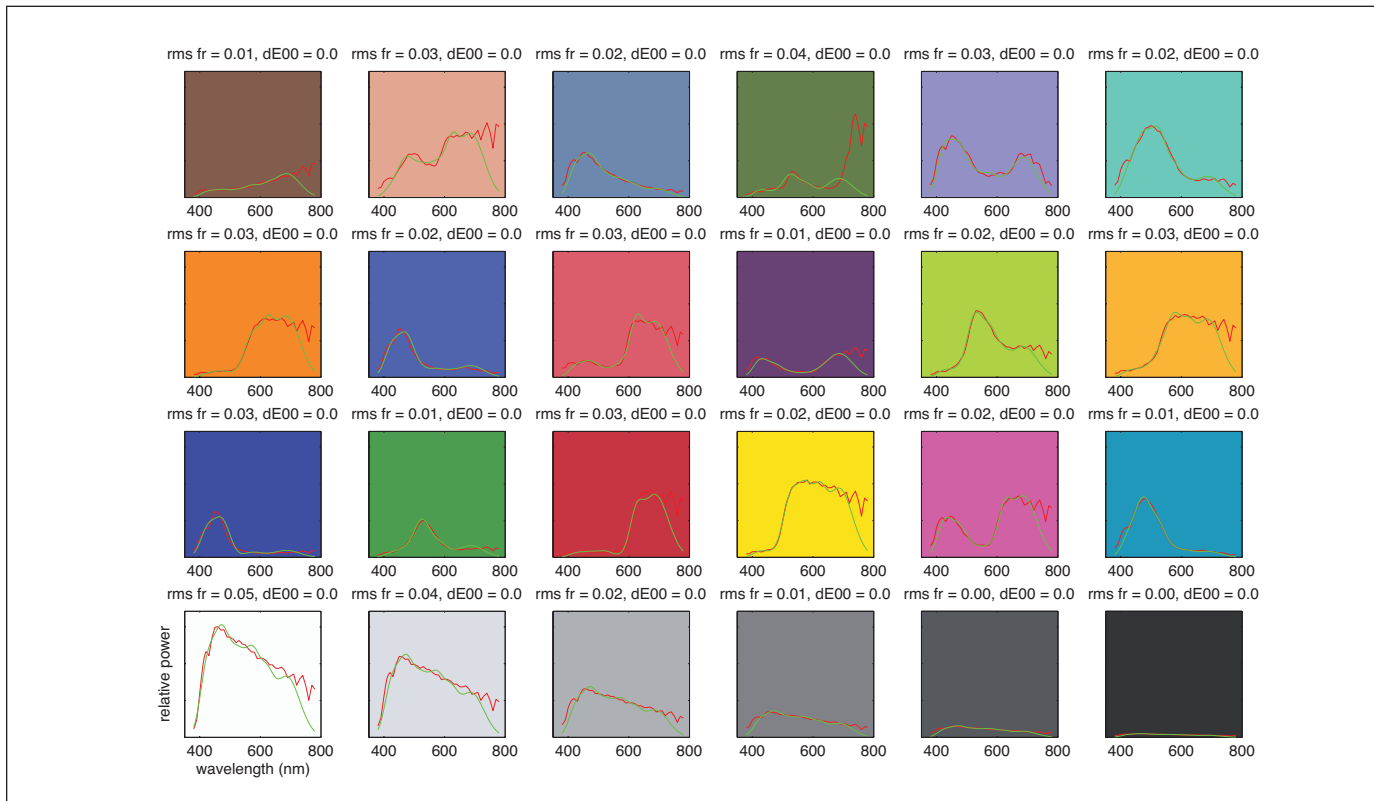
Figure 6. Ideal Gaussian primary six-channel spectral reconstructions after spectral and colorimetric co-optimization (green) versus actual D65-illuminated MacBeth color patches.

from $K = 6$ to 31 recording channels encompassing various unique spectral responsivities and abridged multispectral display systems of $K' = 4$ to 7 channels. With such discrepancy in K, K', and channel spectral profiles for candidate systems, it is clear that direct connection between input and output is only possible utilizing capture post-processing connected with the camera or reproduction pre-processing connected with the display (or possibly both).

This represents a serious departure from the image chains used in traditional Rec. 709/sRGB video. Even the colorimetric digital cinema encoding schemes standardized by SMPTE are marred by underrepresentation of observer variability studied by Sarkar and may benefit from a multispectral update; but in all cases, computing power and hardware designs must be sufficient to cope with high spatial resolution images at realistic frame rates. Further, multispectral compression schemes such as those supported by JPEG 2000-MCT, MPEG4 Studio Profile, and H.264/AVC are necessary for efficiently encoding multiple channels of data. Ironically, six-channel systems like the RIT camera can benefit from the current work in image encoding for stereoscopic distribution. Research into efficient image interchange, though, must continue with focus on preservation of spectral quality throughout post-production image chains.

THE APPEARANCE PROBLEM

Finally, issues of color appearance, color preference, and color editing must be addressed in multispectral cinema. While much of the previous research in spectral imaging has focused on industries concerned with absolute color accuracy such as telemedicine, cultural heritage archiving and preservation, and electronic commerce, the motion picture marketplace demands more creative control. In the reproduction of images for theatrical projection or television display, the artist's aesthetic intent is the dominant concern. Professionally produced images invariably are subjected to secondary color and tone manipulation by skilled colorists until the intended vision of all of the principal creatives has been realized in the post-production mastering environment.

One complication most visual artists are complacently ignorant of though is the exact impact of physical and perceptual phenomena on visual appearance differences between scene and screen. On-set illumination typically possesses a white point distinctly different from that used in standardized display. Further, image-mastering environments usually comprise a darkened room with a luminous white point far dimmer than the typical reflection values for the captured scene, both of which influence apparent reproduction contrast. Giorgianni extensively describes the compensating tone and color manipulations that must be made in order to build a television or cinema imaging system faithful to the color appearance of the captured scene, including accommodation of psychophysical phenomena and optical phenomena like flare.[21] The question remains of how spectral reconstruction goals can be similarly augmented by proper accommodation of appearance phenomena for real system applications. Ultimately, providing colorists with multichannel color correction systems and simulation environments

that are predictive of the appearance tolerances of various observer classes becomes a viable goal of multispectral video. Further, these systems can be tuned to the specific CMF qualities of critical observers in post-production so less time is wasted attempting to tune color correction for a room full of disparate viewers. Having more than three color knobs should also enable exploration of new color correction approaches and widen the creative palette beyond what is currently available.

MOTION IMAGING APPLICATION SPACES

Spectral content can be compatible with current best practices in image manipulation but also provide added flexibility and benefit. Multispectral capture is one key to more photorealistic compositing of live action and computer-generated content. Advanced digitization strategies for recreating virtual models of actor's facial features are already enabling advanced visual effects work and reducing complexity otherwise required from live action visual effects shots.[22] Adding multispectral data to the simulation environment can permit seamless alteration of virtual lighting and surface reflectivity once the virtual actors are placed in the computer graphics (CG) environment. For example, an actor who sits to be digitized using a traditional three-channel imaging system has his skin tones forever simplified to the metameric response defined by the camera's spectral sensitivities. Trichromatic manipulation in the virtual system may not be faithful to the actual color rendition changes accompanying a lighting change on set. If the virtual actor is to be spatially intercut with other objects captured in live action across multiple lighting setups, the spectral representation permits more realistic and seamless color reproduction.

Multispectral camera systems could also be used as universal capture platforms, capable of emulating the color and tone characteristics of any electronic or film-based imaging system. Virtual cinematography has been pioneered in films such as *Avatar* in which actors, lights, and camera are all computer-tracked props on a motion capture stage. Not only is action in front of the camera choreographed somewhat virtually but so too are camera moves and lighting angles. If the stored CG environment used with the motion capture is characterized spectrally, the behavior of the camera itself can be faithfully represented. The astute director of photography who chooses an Arri or Red camera for their engineered color reproduction could retain that benefit even on the virtual set.

Finally, electronic multispectral displays could better emulate the color gamut and spectral profiles of motion picture print films than do current DCI three-primary systems, at the same time reducing observer metamerism. A common issue for any digital intermediate suite is the quality of color match achieved between the digital grading projector and the answer print film projector. Part of this difficulty derives from the lack of similarity in color gamut and colorant spectral behavior between the two devices. A match meticulously forced for one observer may prove completely different for another. Necessity for color control like this will become even

more important as film projection systems manufacturerd by just a few consistent vendors are replaced by a myriad of technologies on the digital side, all with different spectral signatures.

CONCLUSION

The evolution of digital motion picture technology has afforded tremendous advancements in image quality, content distribution, and artistic options for contemporary filmmakers. But what has gathered thus far only minimal attention in the motion picture industry is expansion of spectral dimensionality in captured, manipulated, and displayed content. Though metameric image construction has successfully dominated analog and digital image technologies since the industry's inception, it presents material weaknesses to advancing cinematographic techniques. In particular, multispectral motion imaging promises to solve fundamental issues of color inconsistency and inaccuracy associated with observer metamerism while opening new opportunities for streamlined compositing of live action footage with CG material and new techniques in virtual cinematography. Multispectral motion-imaging workflows also provide a new paradigm for creative color correction with possibilities well beyond limited three-color systems currently employed.

Multispectral imaging promises to expand useful color gamut in video applications in a controlled manner that enforces critical observer consistency. Ultimately, industry demands for higher resolution, higher frame rate, and higher dynamic range are made in the spirit of enabling more accurate and more stunning visual experiences. Enhancing the color dimension must be an obvious objective in the same spirit of technology evolution. But a better understanding of observer variability and the demands of absolute spectral reproduction accuracy must be gained for establishing meaningful design tolerances. Otherwise, we risk setting a spectral quality goal, based in blind specsmanship versus one rooted in sound science.

REFERENCES

1. B. Hill, "Color Capture, Color Management and the Problem of Metamerism: Does Multispectral Imaging Offer the Solution?" *SPIE*, 3963, 2000.

2. C. Poynton, *Digital Video and HDTV: Algorithms and Interfaces*, Elsevier/Morgan Kauffmann: Burlington, MA, 2012.

3. "Fundamental Chromaticity Diagram with Physiological Axes," CIE Pub. 170-1, 2006.

4. X. Cao et al., "A Prism-Mask System for Multispectral Video Acquisition," *IEEE Trans. Pattern Anal. Mach. Intell.*, 2011.

5. X. Cao et al., "High Resolution Multispectral Video Capture with a Hybrid Camera System," *Proc. IEEE Conference on Computer Vision and Pattern Recognition*, 2011.

6. R. S. Berns, "The Science of Digitizing Paintings for Color-Accurate Image Archives: A Review," *J. Imaging Sci. Tech.*, July/Aug. 2001.

7. M. Yamaguchi et al., "High-Fidelity Video and Still Image Communication Based on Spectral Information: Natural Vision System and Its Applications," *SPIE*, 6062, 2006.

8. R. S. Berns et al., "Modification of a Sinarback 54 Digital Camera for Spectral and High-Accuracy Colorimetric Imaging: Simulations and Experiments," Rochester Institute of Technology, Munsell Color Science Laboratory Technical Report 2004.

9. M. Mohammadi, et al., "A Prototype Calibration Target for Spectral Imaging," *Proc. AIC '05* 2005.

10. P. Pellegri, G. Novati, R. Schettini, "Training Set Selection for Multispectral Imaging Systems Characterization," Journal of Imaging Science & Technology, 48, 3 2004.

11. D. Tzeng and R. S. Berns, "A Review of Principal Component Analysis and Its Applications to Color Technology," *Color Res. App.*, Apr. 2005.

12. M. Fairchild and D. Wyble, "Mean Observer Metamerism and the Selection of Display Primaries," *Proc. CIC15*, 2007.

13. K. Tomizawa et al., "QuintPixel: Multi-primary Color Display Systems," *Proc. SIGGRAPH 2010 Emerging Technologies*, 2010.

14. D. Hutchinson, "Introducing Brilliant Color Technology," Texas Instruments white paper.

15. T. Ajito et al., "Expanded Color Gamut Reproduced by Six-Primary Projection Display," *Proc. SPIE 3954*, 2000.

16. T. Ajito et al., "Multiprimary Color Display for Liquid Crystal Display Projectors Using Diffraction Grating," *Opt. Eng.*, 38:11, 1999.

17. M. Pointer, "The gamut of real surface colours," Color Res. And Appl. 5, 3 1980.

18. D. Long and M. Fairchild, "Optimizing Spectral Color Reproduction in Digital Projection," *Proc. CIC19*, 2011.

19. A. Sarkar et al., "Toward Reducing Observer Metamerism in Industrial Applications: Colorimetric Observer Categories and Observer Classification," *Proc. CIC18*, 2010.

20. M. Fairchild, "Computational Model of CMFs," unpublished paper.

21. E. Giorgianni, *Digital Color Management, Encoding Solutions*, 2nd ed., Wiley: New York, 2009.

22. O. Alexander et al. "Creating a Photoreal Digital Actor : The Digital Emily Project," *IEEE European Conference on Visual Media Production (CVMP)*, Nov. 2009.

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Before joining RIT, Long worked as a development engineer and Imaging Scientist with Kodak's Entertainment Imaging Division. At Kodak, his primary responsibilities included new product development and image science and systems integration for the motion picture group, focusing on film and hybrid imaging products. Long contributed to the design and commercialization of the Vision2 family of color negative films, as well as several digital and hybrid imaging products for television and feature film post-production. His work has earned him numerous patents and a 2008 Scientific & Technical Academy Award for contributions made to the design of Vision2 films.

Long has a B.S. in Chemical Engineering from the University of Texas at Austin and an M.S. in Materials Science from the University of Rochester.

Christopher Mondiek graduated from Rochester Institute of Technology in 2012 with dual degrees in electrical engineering and motion picture science. His research at RIT included multispectral camera design and software development. Upon graduation, he was awarded a research co-op position with Arri in Burbank, CA, where he worked with ACES color management development for their digital camera group.