

Film Capture for Digitization

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Abstract

Digital minilab photofinishing is beginning to spread rapidly in the market place, in part, as a means to provide access to network imaging services, and also to fulfill the printing needs of the growing base of consumer digital still cameras. When film scanning and digital writing have supplemented traditional optical photofinishing sufficiently, image-taking films designed for optimal scan-printing will be feasible.

Representative film digitization schemes are surveyed in order to determine some of the optimal features of input silver halide capture media. Key historical features of films designed for optical printing are considered with respect to this new image-printing paradigm. One example of an enabled new film feature is recording the scene with increased color accuracy through theoretically possible improvements in film spectral sensitivity, which is unachievable with conventional films intended for optical printing. Digital still camera spectral responsivities reported in the literature are compared with contemporary film sensitivities, suggesting significantly higher colorimetric accuracy is available with solid state capture.

Introduction

A major shift in technologies is currently taking place in the service image printing industry. Electronic image capture by consumer digital still cameras has reached significant levels and is continuing to grow. Consumer electronic photography is hampered by the lack of automated digital file printing, however. Consumers may capture images, view images displayed on a monitor, write digital files, save data, and share images using network services, but generally speaking they're unable to easily obtain hardcopy prints—except by self-printing with home inkjet printers. Recently, network service printing has begun to appear in the photofinishing trade, offering consumers the opportunity to send digital files to a wholesale photofinisher via World Wide Web services for printing. It is a prevalent belief that the availability of such service printing will tend to rapidly accelerate growth of digital cameras and possibly increase technology substitution for film-based capture. Thus, photofinishing equipment manufacturers are rapidly switching technologies from optical printing devices oriented around traditional color negative films to digital printing devices, including silver halide paper writers, inkjet printers, and thermal dye transfer printers, that will accept image data inputs from a variety of sources including digital still cameras, and film and paper scanners. When film scanning and digital writing have supplemented traditional optical photofinishing sufficiently, image-taking films designed for optimal scan printing will be feasible.

Design opportunities to improve silver halide image capture may be afforded as a result of these photofinishing technology changes. Some features of silver halide capture may merit improvement or alteration in order for it to remain a very attractive consumer and professional imaging technology. In addition, electronic image processing may allow new chemical or emulsion technologies in film system design that were difficult to manage with the strict requirements of trade optical printing compatibility.

This paper discusses the key features for image-capture films optimized for digitization and the possibility of improved system performance over simply scanning traditional films. It is vital to examine representative digitization schemes in order to determine the properties required of the silver halide capture element. It is also valuable to review the historical role of color negative films in the system responsible for their original design. From such considerations, optimal design features of films for scan printing will be determined.

Film Digitization

Basic Hybrid System Features and Operation

Optimizing silver halide film capture for digitization requires an end-to-end system perspective. Figure 1 shows the key steps that occur in a hybrid, digital photographic system, representative of contemporary commercial systems.[1-3] First and foremost, the primary role of the image capture device or medium is to record the scene light levels as accurately as possible. The broader role of contemporary color negative films in the current optical print system will be discussed later. Accurate capture is valuable to a digital photofinishing system even if the intended output quality level is modest or if "inaccurate" reproductions are intended in order to satisfy scene reproduction preferences.

There are a variety of aspects to accurate capture. The recording element must have sufficient sensitivity to give good photographic space coverage in order to allow scene capture with adequately high shutter speeds to stop motion

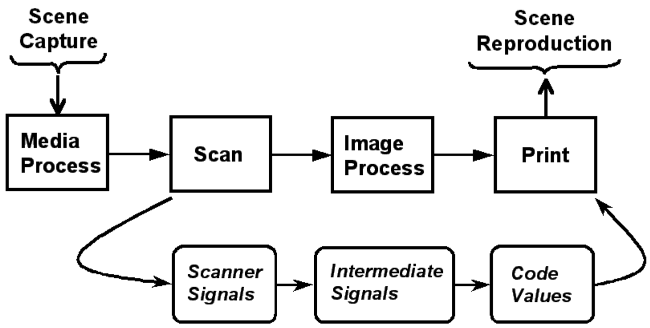

Figure 1. A basic film digitization scheme.

and sufficiently high lens apertures to afford good camera depth of field. The element must have sufficient recording range to capture many decades of light luminance levels in order to provide shadow detail and highlight detail. In addition, the recording element should capture the scene in a spectrally accurate fashion in order to prevent the propagation of color errors in the final output.

The contemporary standard of basic sensitivity and latitude is a modern ISO 400 speed color negative film, which provides very satisfactory photographic space coverage in 135-system (35-mm film format) photography. Systems designers can utilize even higher speeds, if quality levels derived from the recording material are adequate (e.g., one-time-use-cameras, which combine a recyclable single-use camera with high-speed film).[4] Of course, other important attributes relate to the device or medium signal-to-noise, which accounts for both device or medium image noise (i.e., granularity, relating to perceived graininess) and lower and higher spatial frequency information recording (i.e., resolution as indicated by modulation transfer function performance, relating to perceived sharpness).

Following image capture, the exposed photographic recording medium is subjected to chemical processing in order to apply the high amplification factor responsible for the consumer utility of silver halide films and reveal a scanable image. There has been no demonstration of practicable detection of latent image by electronic means that would allow a photofinisher to forgo this step. Conventional color processing is comprised of development to produce a dye image and tail end processing steps, in which the reduced metallic silver is oxidized (bleaching) and residual silver ion is removed from the film (fixing). In order to provide the data path with the highest quality input at a competitive cost point, there appears to be little latitude for compromise in fully carrying out these steps, despite incentives around more rapid image access for improved photofinisher productivity.

Hybrid systems require a method of introduction of data acquired in analog fashion from the photographic film into the electronic image processing system. In this regard, direct electronic capture by digital still cameras is a very effective system solution. The fully processed color negative film is digitized by scanning, which functionally resembles full-frame microdensitometry: the film image is subdivided into a high number of microscopic picture elements (pixels) and the local red, green, and blue record image dye amount is quantified as a transmittance or density value, affording an image-representative electronic signal of each of three color records, RGB. Film scanning can be accomplished by linear array or full-frame array CCD solid-state sensors using traditional lamp house and filter wheel technologies, or using newer approaches involving solid-state illumination with LED technology to control the CCD exposure.[5,6] Scanner spectral sensitivity may tend to resemble traditional Status M responsivities, silver halide color paper sensitivities, or other sensitivities depending upon the particular application and the technology used.

Following scanning, the conversion of the acquired signals into printing instructions is generally the primary goal of the image processing step. A number of discrete operations are accomplished in this sequence of steps, including the functional separation of acquired red, green, and blue channel data, color correction of the data to account for specific or generic film and scanner properties, the application of the intended image rendition properties (e.g., color and tone rendition), and finally the encoding of the corrected image data in one or more useful intermediate forms. The end result of this process typically is the creation of device-specific data or operational instructions, to allow storage, transmission, or printing.

Currently, digital printing, the final step in Fig. 1, can take place via a number of different writing engines. Exposure of silver halide paper by laser writers, cathode ray tubes (CRT), or light valve technologies, is one high productivity form of printing for the photofinishing industry. In the future, inkjet printing will increase importance in low-volume applications, including minilab level operations; presently, thermal dye transfer technologies fill this lower volume segment.

Image Data Processing Path Requirements

Of paramount importance in optimizing silver halide for hybrid system image capture is determining the nature of the image processing that is operating in the system. Two different approaches to image data encoding appear to be prevalent at the present time: densitometric encoding, and colorimetric encoding.[7]

Referring again to Fig. 1, it is necessary to convert the "microdensitometric" data acquired in scanning to some form of the intermediate image data encoded signals. In the more rudimentary form of the two encoding schemes, scanner transmittances or densities are transformed into intermediary electronic signals that are color- and tone-corrected based on the properties of the input color negative or color reversal film. The digital printing system attempts to view the input film much like silver halide color paper in an optical printing system, based on effective printing densities, in some examples. Therefore, system color correction continues to rely heavily on the intrinsic printing correction properties and lab-to-lab contrast provided by the particular color film. In such printing density schemes, the intermediary color encoding metric may have no intrinsic technical value and may be discarded after usage. The end objective is to produce printer-specific writing instructions (printer code values) or device-specific display instructions (monitor code values), which may actually be used in display or may alternatively be used as a convenient, but constrained, storage metric (e.g., sRGB color space). This type of image-processing scheme appears to provide small opportunity for developing films exclusively for scanning, since the historical optical printing paradigm is imbedded in its architecture, and little deviation from optical printing film specifications appears acceptable.

An alternate scheme—colorimetric encoding—is exemplified by the KODAK PHOTO CD System.[8] In this paradigm, at least one concrete form of intermediate image-bearing electronic signal is established and it has clear colorimetric significance. The reference encoding metric could be a traditional colorimetric metric, such as CIELAB space, CIELUV space, or CIE XYZ space, or it could be a metric better designed for use in an image-processing scheme in a production computing environment. The key feature is that multiple input forms (i.e., film scans, print scans, digital still camera data, etc.) can be accepted, and their corrected data can be centrally stored and be further processed systematically to provide various output data forms.

In the PHOTO CD System, colorimetric encoding is produced by first decomposing the source raw RGB input data into unconfounded, RGB channel-independent signals. The colorimetric encoding is then performed by further transforming this refined input data, in effect, to estimate the original scene spectral power distributions. Scene light levels are calculated as if measured by a hypothetical "reference image-capture device". This reference has spectral responsivities equivalent to a set of visual color-matching functions, and it is used as an intermediary storage metric. Color and tone rendering properties can be applied (reproduction hue, chroma, and lightness adjustments), and spatial manipulations can be carried out to increase image sharpness. This adjusted original scene colorimetry is further transformed into other colorimetric encoding signals, eventually as an output storage metric. The signal processing includes both linear and nonlinear transformations of the individual RGB input signals. It is important to note that the encoded color quality produced by this approach is clearly limited by the spectral capture quality of the particular input source.

The PHOTO CD System was especially oriented toward video display as a home image player. Therefore a suitable output video colorimetric encoding metric was created, which was termed KODAK PHOTOYCC Color Interchange Space. It had a color gamut appropriately limited to the rendering capabilities of video phosphors. But underlying it was the internal color encoding metric based on the reference image-capture device, which employed recommended color-matching functions for video primaries that provided a large color gamut: it preserved real world colors recorded by the input films, which were outside the final output video gamut of YCC space, or the common sRGB space as well. An improved device-independent colorimetric encoding scheme for intermediary storage, which is more consistent with printing system requirements, is termed RIMM, for Reference Input Medium Metric.[9]

It is useful to further illustrate colorimetric encoding with the specific example of digitization of color negative film by the PHOTO CD System.[7] An image frame is scanned creating an initial set of RGB scanner signals. The scanner transmittances or densities are subjected to a correction transform to assure a proper state of calibration. A film-specific or a generic (e.g., universal) film term is applied to the electronic image signals. This transformation first removes cross talk between the RGB signals that originates from (1) the use of imperfect image dyes with unwanted absorptions that were integrally measured during RGB scanning and (2) interlayer interimage effects that were produced in the color negative film to accomplish optical print system color correction and image sharpening. The corrected RGB signals in density form are mapped back to become exposure-representative signals by the use of an inverse film characteristic curve. A scene balance algorithm further adjusts the exposure space signals for lightness balance and color balance, and the corrected RGB signals are converted to the intermediary RGB tristimulus exposure-factor values for the reference image capture device—the colorimetric encoding of the captured scene light exposures. Next, the RGB signals are transformed nonlinearly to new intermediary values, which are transformed into luminance and chrominance space values for final transformation into PHOTOYCC space device-specific code values for video display.

Silver Halide Media Considerations

Properties of Current Films

Color negative films were originally designed as part of a two-stage system. The color negative film first performs image capture by providing long recording latitude, good signal-to-noise ratio, and respectable blue, green, and red light recording accuracy by virtue of the traditional spectral sensitizations of the silver halide grains, with high sensitivity resulting from continuing advances in silver halide emulsion quantum efficiency, component imaging chemicals, and multilayer film design.[10] During chemical processing, particularly during the color development step, color negative films accomplish chemical image processing as well.

Two chemical technologies stand out as pivotal achievements, each of which greatly advanced the field of color photography: colored masking couplers and development inhibitor releasing compounds, especially those with long-range inhibition capabilities.[11] These technologies serve to produce color correction for the imperfect image dyes hues associated with real and practicable chromophores by producing imagewise interlayer interimage effects that suppress density formation by various means; the longer range development inhibition technologies also serve to create adjacency effects resulting in printthrough sharpness increases. A fairly rigid standard has evolved around the system printing density specifications, including gammas or slopes of about 0.65 for each color record and high minimum densities in unexposed areas, which are responsible for the traditional salmon orange color of processed films.[7]

Color reversal films comprise a one-stage system wherein the created image is intended for direct viewing. This feature produces a system specification for high gamma (ca. 2.0), low minimum densities and high maximum densities. Reduced interimage is required for color correction of the single-stage system.[7] The lower recording latitude of reversal films and high maximum densities reduce their desirability as hybrid system input models.[7]

Basic Hybrid System Opportunities in Film Design

The insightful and provocative suggestion of designing a color negative film explicitly for scanning and digital image processing was recently made by Wirowski and Willsau.[12] These authors recognized, from similar considerations, that the chemical image processing carried out in conventional color negative films was potentially redundant in hybrid systems where the identical color corrections and image quality enhancements could be provided digitally, apparently indifferent as to whether they were carried out at all in the film. Colorimetric encoding was also suggested. Their analysis led them to envision the design of a simpler color negative film in terms of function, and material type and content, certainly producing lower minimum density. The existence of a commercial colorimetric image-processing paradigm, where system color correction and chemical cross talk are fully managed electronically, certainly supports their proposition.

Building upon this profound suggestion for silver halide film design, and the expansive potential capabilities of electronic signal processing, a possible opportunity exists to materially improve basic silver halide capture quality. Further increases in the accuracy of spectral capture by both color negative and color reversal silver halide films have been limited by the properties of chemical signal processing. The interlayer interimage effects produced by silver halide development, independent of processing mode (e.g., positive or negative), are nonlinear in character and limited in achievable magnitude.

Colorimetric transformations require linear space mathematical operations that are unavailable in purely chemical signal-processing environments.[7] The magnitude of the matrix terms for color correction of high accuracy capture is another obstacle in a chemical system. In addition, the presence of colored masking couplers in contemporary color negative films critically interferes with the potential light distribution requirements of colorimetric capture.

Color Capture Accuracy in Media and Devices

Figure 2 illustrates the massive differences between contemporary, high-quality color negative film spectral sensitivities and potentially realizable tristimulus values of special color-matching function forms. It is necessary to make an assumption that better spectral sensitivity resemblance to color-matching function tristimulus values will result in superior, lower-error color recording. Commonly, color-matching functions are comprised of one or more tristimulus values with negative responsivities. Such functions are appropriate for describing the color properties of real objects in psychophysical color-matching experiments, and those functions are not appropriate as models for real systems because negative responses cannot be physically manifested. The all-positive color-matching functions of Fig. 2 were published by Ohta as recommendations for colorimeter responsivities.[13] They are potentially reasonable specifications for real physical devices, and possibly media. The all-positive color-matching functions are characterized by extensive overlap between the red and green channels, and a slight overlap between the blue and green channels; the wavelength of maximum response for the red channel is shifted hypsochromically below 600 nm. In contrast, the spectral sensitivities of the red, green, and blue channels of the color negative film are well separated with minimal overlap, and the peak red sensitivity occurs above 620 nm.

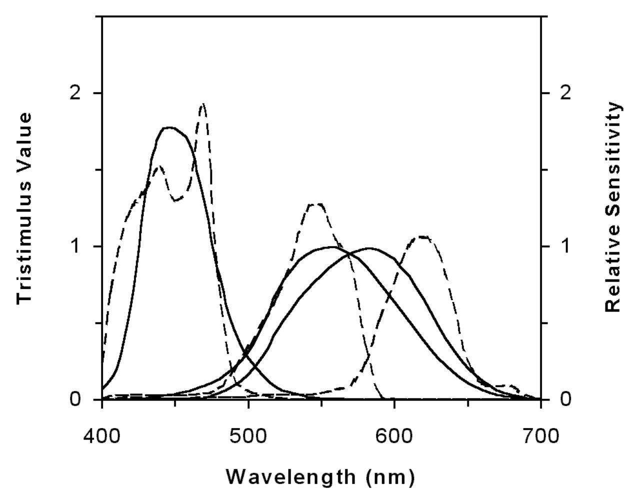

Figure 2. Color-matching function tristimulus values (solid line) compared with CNF relative spectral sensitivity (dashed line).

A colorimetric image-processing path clearly derives high-value from direct colorimetric input, such as a digital still camera in principle will provide.[7,14,15] In order to assess such trends in digital still camera device technology, the literature was surveyed for published measurements. In Table 1, the red and green responsivities of all-positive color-matching functions (CMF), digital still cameras (DSC), and representative color negative films (CNF) and color reversal film (CRF) are compared. The wavelength of maximum green and red response, the wavelength of equal red and green sensitivity, and the percent of peak red sensitivity that occurs at green equality are shown (a gauge of green and red response overlap). The wavelength of the blue channel maximum sensitivity was basically similar for all entries; it is the wavelength of the peak red sensitivity and the degree of green-red channel overlap that most affect object color metamerism errors or illuminant metamerism errors during scene capture. These data were typically derived from relatively coarse, plotted 10-nm increment spectral responses; the interpolated data were rounded up or down to the nearest five-nm increment.

Table 1. Green And Red Spectral Responsivities.

Entry	Type	G λ-max (nm)	R λ-max (nm)	R-G λ-equal (nm)	Relative R Sen. (%)
1.	CMF[13]	555	580	570	95≤
2.	CMF[16]	540	580	570	95≤
3.	CMF[17]	540	580	570	95≤
4.	DSC[18]	525	580	555	50
5.	DSC[19]	530	595	565	40
6.	DSC[20]	520	585	565	70
7.	DSC[21]	525	595	570	45
8.	CNF	550	620	585	25
9.	CNF	550	650	585	15
10.	CRF	570	650	585	25

Striking class behavior is evident in the data of Table 1, despite the modest precision of the gathered data. While the details of all-positive color-matching function tristimulus value responsivity do vary significantly, the gross features are essentially identical. These eye-like responsivities all show enormous green-red overlap. The group of digital still cameras shows behavior intermediate between all-positive color-matching functions and traditional films, suggesting a considerable improvement in the accuracy of color capture, though not necessarily in overall system color reproduction.[22] The peak red sensitivity falls at or below 600 nm and the green-red overlap is substantial: at green-red equality, the red sensitivity is 40–70% of peak sensitivity. A recent color negative film with relatively excellent capture accuracy shows peak red sensitivity just at about 620 nm, and even more bathochromic 650-nm peak sensitivity is still common; the green-red overlap is only about 15–25% of peak red sensitivity as a result.[23] Bathochromic red capture produces significant color capture metameric hue error, particularly with certain blue and purple colors, and lightness errors with red colors.

Obstacles To Colorimetric Recording With AgX

Some obstacles to colorimetric capture have been removed by suggesting the use of a hybrid system with colorimetric image processing provided computationally, and by adopting the Wirowski-Willsau scan film composition. But significant problems still remain. First and foremost, producing the required light capture distribution in a silver halide multilayer film structure appears daunting. It is prudent to assume a simplification: it seems reasonable that a hybrid system can derive substantial color accuracy benefits by targeting spectral sensitivities that are intermediate between all-positive color-matching functions and contemporary film spectral sensitivities, much as these digital still cameras appear to have done. Nonetheless, solid-state capture devices have a significant advantage over traditional silver halide film structures in even this situation. As shown in Fig. 3, a typical image sensor is configured in a planar array, with individual RGB pixels (ca. 10 x 10 μm) regularly placed in side-by-side repeating units, bordered by vertical and horizontal registers to conduct electrical current transfers. For traditional silver halide spectral sensitivities, this configuration appears inefficient, because a given picture element in a single spatial location can record only one of the three primary colors, which suggests a waste of incident light and overall reduced capture efficiency. However, when colorimetric capture is the objective, this configuration is entirely efficient, because the green and red channels are competing for much of the same impinging visible radiation.

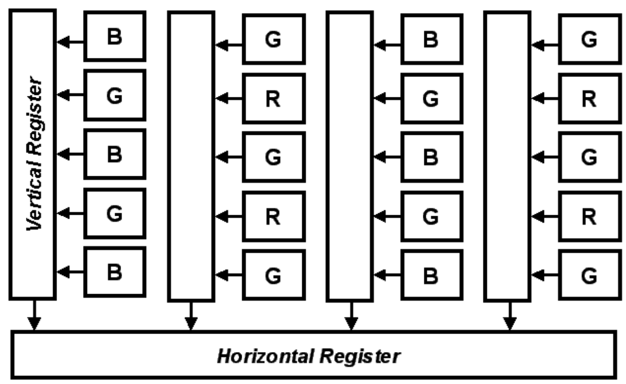

Figure 3. Segment of a typical solid state CCD capture sensor in a planar array, viewed from top-down as exposed.

In contrast, a portion of a stacked silver halide multilayer color film is shown in Fig. 4. With traditional film spectral sensitivities, a stacked array offers very high light collection efficiency, because a particular picture element location can capture and record each channel of incident RGB visible radiation.

But with colorimetric capture, film green record shielding of the red record (which now also records *green* light) could be problematic. In addition, sustained advances in film performance have been founded on the continued addition of layers (i.e., subdivision especially of the green and red records into three and four layers for precise imagewise control of light capture and development effects), and high-density crystal packing for reduced image granularity and net improvements in signal-to-noise ratio.[4]

Another critical, if less obvious, difficulty with colorimetric capture by either CCD sensor or film is image noise amplification. Linear space processing with the necessary high matrix coefficient values produces high channel mixing and large increases in image noise (graininess).[24,25] Reducing silver coverage in multilayer color films in order to enable colorimetric recording by addressing layer shielding issues would likely prove counterproductive if it results in significant granularity increases.

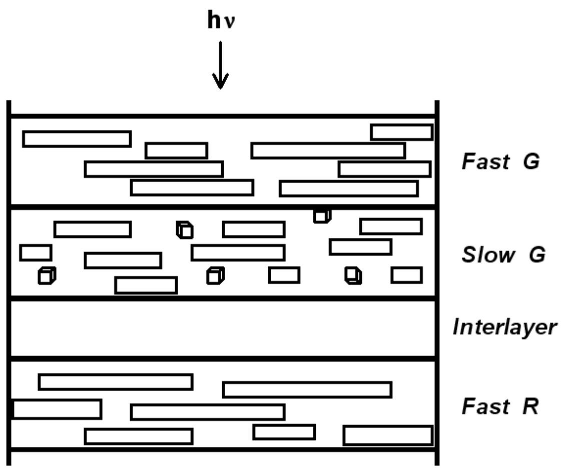

Figure 4. High-density crystal packing in a segment of a modern color negative film, as viewed in cross-section.

Conclusion

The high fundamental value of colorimetric recording merits serious exploration of its compatibility with silver halide capture as the major design benefit of future hybrid systems for scan films. The commercial precedent of film colorimetric encoding and linear space signal processing encourages attempts to improve silver halide capture accuracy using color print films lacking conventional chemical signal processing. Digital still capture is already highly advanced in colorimetric recording capability.

References

1. James Owens and Bradley VanSant, Image Quality Verification in the Development of Hardware and Media for the KODAK Digital Lab System, *Proc. PICS*, pg. 86 (1999).
2. Hiroaki Nakamura, Digital Image Processing for the Frontier 350 Digital Minilab, *Proc. PICS*, pg. 96 (1999).
3. Hiromichi Enomoto, Hybrid Imaging Systems, *Proc. IS&T 50th Annual Conference*, pg. 230 (1997).
4. Allan Sowinski, Thomas Brust, and Richard Wheeler, High-Speed Technologies of KODAK GOLD MAX Film, *Proc. ICPS'98*, pg. 206 (1998).
5. Mark Shafer and Joel DeCaro, LED/Area Array CCD Multiformat Film Scanner for Digital Photofinishing, *Proc. PICS*, pg. 90 (1999).
6. White Paper, Advantages of Kodak LED Illumination Technology, www.kodak.com, (1999).
7. Edward Giorgianni and Thomas Madden, *Digital Color Management Encoding Solutions*, Addison-Wesley, Reading, MA, 1998.
8. Edward Giorgianni and Thomas Madden, *Color for Science, Art and Technology*, Kurt Nassau Ed., Elsevier, Amsterdam, 1998.
9. Kevin Spaulding, Geoffrey Woolfe, and Edward Giorgianni, Reference Input/Output Medium Metric RGB Color Encodings (RIMM/ROMM RGB), *Proc. PICS*, pg. 155 (2000).
10. Tadaaki Tani, AgX Image Capture, *Proc. IS&T 50th Annual Conference*, pg. 223 (1997)
11. Joachim Lohmann and Johannes Willsau, *J. Imaging Sci. Technol.*, **43**, 550 (1999).
12. R. Wirowski and J. Willsau, Scan Film: Combining the Best of Analog and Digital Imaging, *Proc. PICS*, pg. 101 (1999).
13. Norboru Ohta, *Color Res. Appl.*, **7**, 53 (1982).
14. Jack Holm, A Strategy for Pictorial Digital Image Processing (PDIP), *Proc. 4th CIC*, pg. 194 (1996).
15. Hitoshi Urabe, Makoto Tsugita, and Kouji Ichikawa, *Recent Progress in Color Management and Communication*, IS&T, Springfield, VA, 1998, pg. 182.
16. M. Pearson and J. Yule, *J. Color Appearance*, **2**, 30 (1973).
17. D. MacAdam, *J. Opt. Soc. Am.*, **43**¸ 533 (1953).
18. Rudolf Gschwind and Giovanna Di Petro, Metamerism in Colour Imaging Systems and "Reverse" Colour Reproduction, *Proc. ICPS'98*, pg. 11 (1998).
19. Hiroaki Sugiura, Tetsuya Kuno, Narihiro Matoba, and Hiroaki Ikeda, A Measurement Method for Spectral Responsivity of Digital Cameras Considering Negative Lobes, *Proc. ICPS'98*, pg. 358 (1998).
20. Michaela Ritter and Dietmar Wueller, Colour Characterization of Digital Cameras by Analysing the Output Data for Measuring the Spectral Response, *Proc. PICS*, pg. 149 (1999).
21. Norboru Sasaki, Recent Progress on Full-Color Silver Halide Photographic Materials, *Proc. ICPS'98*, pg. 212 (1998).
22. Paul Hubel, Color Image Quality in Digital Cameras, *Proc. PICS*, pg. 153 (1999).
23. Steven Link, Spectral Sensitization of Emulsions for Improved Color Reproduction and Reduced Illuminant Sensitivity of Color Negative Films, *Proc. ICPS'98*, pg. 219 (1998).
24. Andrew Juenger, Color Sensitivity Selection for Electronic Still Cameras Based on Noise Considerations in Photographic Speed Maximization, *Proc. PICS*, pg. 79 (1998).
25. Paul Hubel, Jack Holm, Graham Finlayson, and Mark Drew, Matrix Calculations for Digital Photography, *Proc. 5th CIC*, pg. 105 (1997).

Biography

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