Spectral-based Image Reproduction Workflow

From Capture to Print

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***Abstract*—Metameric reproduction systems (e.g. ICC-based systems) are successfully used around the world today. For distinct applications, however, such as artwork reproduction, proofing or high accurate industrial color communication, systematic limitations avoid satisfying results. This paper discovers the systematic problems of metameric reproduction systems and introduces a spectral-based workflow that allows the solution of these problems to a large extent. The basic concepts and main modules of a spectral-based reproduction system are investigated and finally a real system is presented.**

Keywords-component; color reproduction, spectral workflow

I. Introduction

A graphic arts industry without color-management systems that colorimetrically control capture, exchange and reproduction of color information is unthinkable today. In the last decade isolated color-management systems were replaced by industrial and recently by an ISO standard (ISO 15076-1), which is based on the industrial standard of the International Color Consortium (ICC) [1]. The open system architecture of the ICC standard allows an exchange of color information independently of the computer operating systems, device and software application by so-called color profiles, which include transformation functions between color spaces and allow a device independent representation of color [2]. Modern software applications are capable to read and apply these profiles, which can also be embedded into standardized image and document-formats (e.g. JPEG, TIFF or PDF). By using today's color management applications nobody has to worry about problems of the pre-colormanagement era, such as the green on the display changes into a blue on the print. Even if there is still room for improvement, the success story of such so-called metameric color management systems is so impressive that one could believe that all color-reproduction problems can be solved in near future by simply enhancing existing systems.

This indeed is a misapprehension. There are systematic limitations of metameric image reproduction systems, which cannot be overcome. Today's professional systems are close to these limits and it is unlikely that increasing the effort of improving these systems can result in a noticeable improvement of the color reproduction. This can be seen as a diminishing returns problem of metameric reproductions.

But are today's color reproduction systems not sufficient?

Yes and no! Yes, because for the majority of applications a highly accurate color reproduction is not necessary. Other factors are more important, such as preferred aesthetic manipulations. Moreover, the original scene is mostly not available, so that a direct comparison between original and reproduction is not possible. Since color discrimination from memory is much worse than from direct comparisons the accuracy level of the metameric reproduction system is mostly within the tolerance bounds of observers. However, for some applications metameric reproduction systems are not sufficient. This is the case when color reproduction accuracy is highly important and simultaneously the viewing conditions are not known in advance or are changing. Under these circumstances the limitations of metameric reproductions are exceeded and it is unlikely that a metameric reproduction is able to meet the needs of the applications, which are for instance: artwork reproduction, proofing of print presses and highly accurate industrial color communication.

For these applications it is desired that original and reproduction match under multiple viewing conditions, ideally under all viewing conditions, which implies a spectral agreement between original and reproduction. Such a reproduction is called spectral reproduction. The structure of a spectral reproduction workflow, from image acquisition to print, will be discussed in this paper. The example of a spectral reproduction system developed at the Munsell Color Science Laboratory (MCSL) will be described including colorimetric results. In order to understand the advantages of such a system I will begin with a short investigation of systematic limitations of the typical metameric ICC workflow.

II. Limitations of the Colorimetric ICC-based Reproduction

Figure 1 shows a block diagram of a typical ICC color reproduction workflow. The systematic color reproduction errors that can typically be observed are a combination of errors that arise at each component of the system. Therefore, each component of the system will be investigated with regard to its potential error source:

1. **Camera/Scanner System**: The majority of today's camera or scanner systems is trichromatic. Capturing a continuous reflectance spectrum results in only

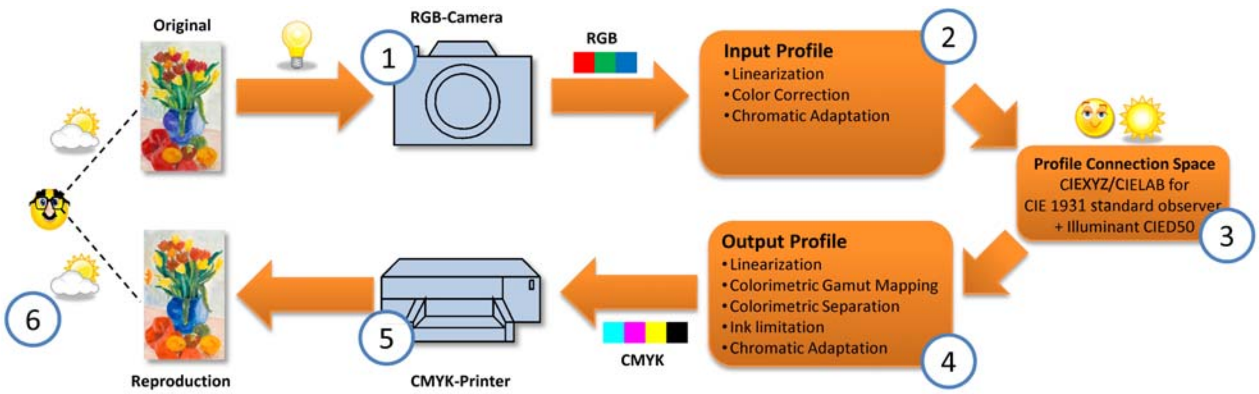

Figure 1. Metameric image reproduction workflow according ICC standard.

three digital counts. For this reason a lot of information is lost and different reflectances can result in the same sensor response, i.e. the acquisition system cannot discriminate these colors. The effect is called device metamerism and would be not a major problem, if the same colors could not be distinguished be a human observer. Unfortunately, nearly no device is so-called colorimetric, which means that human color matching functions (CMF) are linearly dependent from system sensitivities (see Luther-Ives condition [3, 4]). As a consequence colors that cannot be distinguished by the device are distinguishable by a human observer under the same viewing conditions. It becomes impossible to reproduce these colors accurately.

2. **Input Profile**: The input color profile describes the transformation from camera digital counts (RGB) into the profile connection space (CIEXYZ, CIELAB for illuminant CIED50 and CIE 1931 standard observer). This transformation is again not unambiguous since the acquisition illuminant (e.g. fluorescent for usual scanners) differs from CIED50 of the profile connection space (PCS). Even if the camera is colorimetric, so that a linear transformation between camera sensitivities and CMF exists, the difference in illumination could cause major problems due to illuminant metamerism. Colors that cannot be distinguished by the camera under the acquisition illuminant may be distinguishable by the CIE 1931 standard observer under CIED50 and vice versa. These issues are similar to an additional information loss in our color reproduction chain.

   A common problem frequently observed in practice is that the acquisition illuminant, for which the input profile was created, is not stable (outdoor capturing, unstable light source). Using the same input profile in such variable acquisition environment is a common error source in practical applications

3. **Profile Connection Space (PCS)**: The PCS (CIEXYZ, CIELAB) is designed for illuminant CIED50 and the CIE 1931 standard observer. It is very unlikely that a real illuminant and observer agree with this standard, so that problems related to illuminant and observer metamerism (i.e. different spectral stimuli appear similar for the CIE 1931 standard observer but can be distinguished by a real observer and vice versa) are predefined.

4. **Output Profile**: The output printer profile describes the transformation between the PCS and the control values of the printing device (CMY, CMYK, etc.). If the print has to be adjusted to the original for an illuminant different than the PCS's CIED50, similar problems related to illuminant metamerism occur as described above and an additional information loss is possible. There are a lot of colorimetric redundancies for printers with more than three colorants (e.g. CMYK), i.e. the same CIEXYZ color (for the output illuminant) can be printed using various ink combinations. The profile has to pick one of these possible ink combinations based on criteria such as gray component replacement (GCR) or under color removal (UCR). Such metameric separations (ideally) result in equal colors under the output illuminant, but correspond to different colors in case the illuminant changes. There is not enough information in a metameric workflow to pick the separation in a way that the final print mimics the original under multiple illuminants.

5. **Printing Systems**: The majority of today's printers uses CMY or CMYK inks. The set of possible colors that can be reproduced by such a device and their spectral variability is relatively small compared to all colors that can be found in our environment. Gamut mapping algorithms can reduce the perceptual difference between original and reproduction. A perfect reproduction, however, even if adjusted only to a specific illuminant and observer, is often impossible. Not to mention the small spectral variability of a CMY or CMYK ink set that generally does not allow reproductions that match under multiple illuminants.

6. **Viewing Conditions**: Metameric reproductions are adjusted to specific viewing conditions, i.e. a specific illuminant and observer. These constraints allow a (often sufficient) reproduction with a minimal

amount of means (trichromatic devices). Unfortunately, real observers differ from the CIE 1931 standard observer and the spectral power distribution of a real light source does not agree with CIED50, even if a light booth is used. Therefore, a metameric mismatch between reproduction and original is possible under real viewing conditions. Another problem is the static adjustment to single viewing conditions. If the viewing conditions are unknown in advance or are changing the metameric match falls also apart.

III. What Needs to be Changed?

The main problems of a metameric workflow result from the reduction of high dimensional spectral signals to only three dimensions. To avoid this information loss much more independent channels are required to capture the scene. The resulting multispectral camera responses have to be transformed into a device independent space (similar concept as the PCS for the ICC) to allow a reproduction or further processing without the knowledge of the input device (open system architecture). To preserve the captured information the device independent space has to have more than three dimensions as well. In addition to the regular spectral space various other spaces have been developed, such as LABPQR [5, 6] or multi-illuminant color spaces. On the printing side more colorants than the usual CMYK have to be used. This is the precondition for a large spectral gamut (all spectra that are reproducible by the printing system) and shall ensure that the acquired information can be reproduced without any loss.

It should be noted that in practice a trade-off between spectral reproduction accuracy and system complexity is necessary. Due to the higher dimensionality of spaces (device dependent and independent) the inter-space transformations cannot be practically described by ICC-like color lookup tables since the memory usage to store the lookup tables increases exponentially with the domain space dimension. For this reason, the intention is to satisfy the colorimetric and spectral accuracy needs of the given application with only a minimal number of colorants and camera channels. Much research was already conducted to find the optimal number of channels and to determine the spectral characteristics of camera spectral sensitivities [7] or ink sets [8, 9]. In case the set of input reflectances is known a priori, e.g. the output of an offset-press in a spectral proofing application, these parameters can be adjusted to the special application. For some applications the number of necessary channels is very high (e.g. reproduction of artwork that includes many different pigments). In this case the number of necessary channels for input and output devices is simply too high for a universal spectral reproduction system. Therefore, some of the systematic problems may only be reduced and not completely solved. Particularly, the limited spectral gamut of printing devices (even if a large variety of colorants is used) does generally not allow an error-less reproduction.

IV. The Spectral End-to-End Reproduction Workflow

Figure 2 shows the general concept of a spectral end-to-end reproduction system. The basic difference of the spectral workflow compared to the metameric workflow is the processing of much higher-dimensional signals, which requires completely different algorithms for characterization, separation or gamut mapping.

A. *Multispectral Cameras*

There are many ways to increase the channel number of acquisition devices. Using a filter wheel or a liquid crystal filter in front of a sensor are two possible ways for capturing still scenes. For video capturing other approach are more appropriate such as replacing the color filter array with an array that utilizes more than three filters or to use a direct image sensor. Another way is to utilize a beam splitter that allows the usage of multiple sensor/filter combinations simultaneously. Combinations of these methods are also in practical use. For high resolution scanning a diffraction grating can be used to disperse a scan-line onto a rectangular CCD, capturing spatial information in one dimension and spectral information in the other.

B. *Camera Response Processing*

Starting with a multichannel acquisition the linearized camera responses have to be transformed into a high dimensional device-independent space (e.g. a spectral or multi-illuminant space). Various methods have been developed for this purpose, which can be classified into two basic categories: Target-based methods and model-based methods. The basic strategy of all these methods is to use as much information as possible of the underlying capture process. Target-based methods use captured colors with known reflectances in order to construct a response-to-reflectance transformation and apply this transformation on other captured images [10, 11, 12]. The training target needs to be chosen very carefully and has to include representative spectra of the processed images. The main advantage of this class of methods is that a prior knowledge of the acquisition illuminant and device model parameters is not necessary. The main drawback is the high dependency of the spectral and colorimetric accuracy on the target choice [13].

Model-based methods use the mathematical model of the input device and the acquisition illuminant to calculate response-to-reflectance transformations. The model is a predicting function from reflectance space to camera responses and needs to be inverted. Unfortunately, this is an ill-posed problem even for acquisition systems utilizing many channels, since continuous reflectance curves have to be estimated from discrete cameraresponses. Additional assumptions need to be utilized to improve the spectral and colorimetric accuracy of the pure mathematical Pseudoinverse solution. Such assumptions can be a low dimensional liner [14] or non-linear model [15] of reflectances, smoothness properties of natural reflectances [16, 17, 18] or the distribution of reflectances and noise as used by

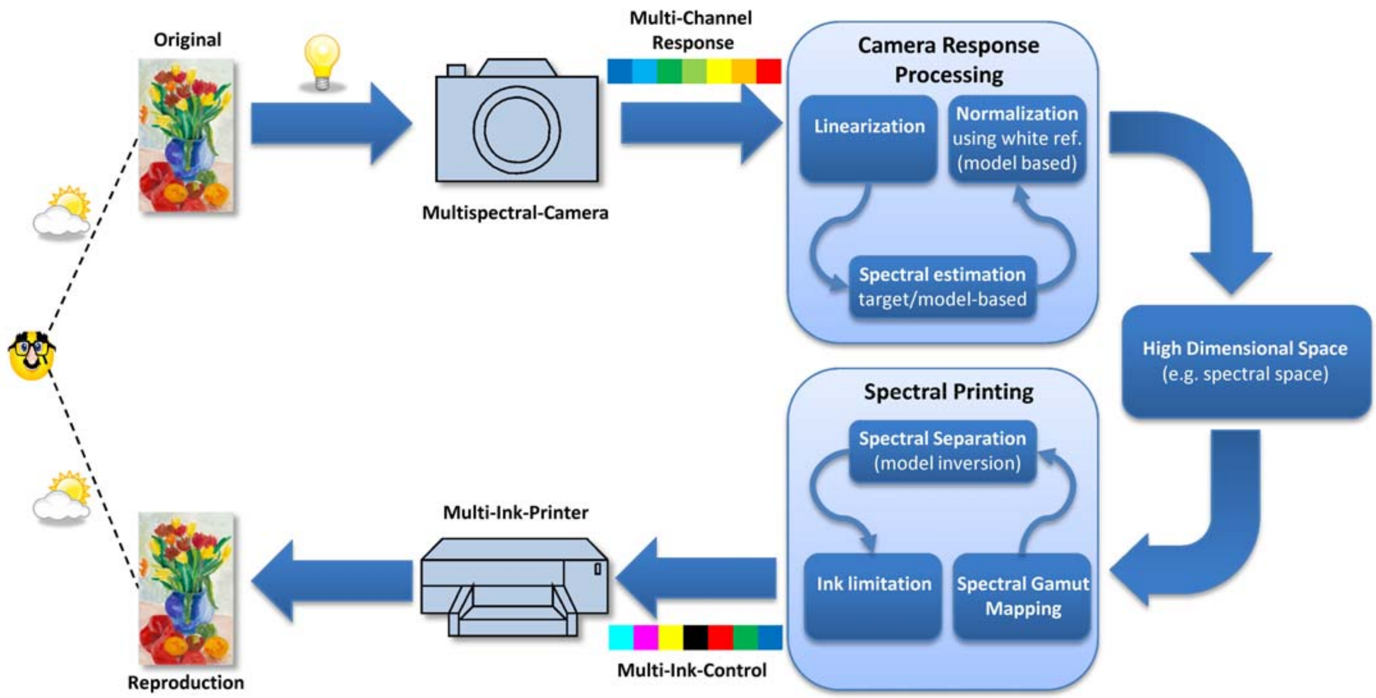

Figure 2.Concept of a spectral image reproduction workflow

the reflectance estimating Wiener filter. Also additional spectral spot measurements of the original using a spectrophotometer can be used [19] or the knowledge that the original is a print produced by a known printer [20, 21]. A relatively new approach is to utilize the correlation of neighboring pixel/reflectance for spectral estimation [22, 23].

In case the acquisition illuminant is unknown, model-based methods require an additional normalization step. The reconstructed spectra need to be normalized to illuminant CIE E (equal-energy radiator) using a captured and spectrally known white reference.

C. Spectral Printing

The transformation from spectral reflectances to printer control values can be divided into three main parts: 1. Spectral gamut mapping, 2. Spectral printer model inversion and 3. Ink limitation.

1) Spectral gamut mapping

Spectral gamut mapping describes the transformation of non-reproducible reflectances into the spectral printer gamut. Such a transformation has to consider properties of human color vision in order to minimize the perceptual difference between original and reproduction subject to device limits. In contrast to a metameric workflow, perceptual image differences have to be minimized under multiple illuminants and for different observers. The main problem is the size of the spectral printer gamut, which is many dimensions smaller than the space of natural reflectances (a lower bound can be determined through analysis of various spectral databases [24]). Therefore, nearly each given reflectance is out of spectral gamut and need to be modified in order to become printable.

A fundamental problem is the definition of an appropriate objective function that has to approximate the perceptual difference in a space that has many more dimensions than the three-dimensional cone response space of the observer. One approach is to define metrics in spectral space [25, 26]. Another one is to use a lower dimensional representation of spectra, so that the first three dimensions agree with a perceptual space (for a specific observer and illuminant) and the remaining dimensions describe the metameric black space [5, 27, 6, 28]. A spectral gamut mapping within such a space is a perceptual mapping (traditional gamut mapping [29]) within the first three dimensions and a spectral mapping within the metameric black space [30]. In a recent approach multiple perceptual spaces (for different illuminants and a specific observer) are combined to a multi-illuminant perceptual space. For the three dimensions corresponding with the application’s most important illuminant a traditional gamut mapping is performed. For all other illuminants colors are mapped onto metamer mismatch spaces (see [31]) by means of colorimetric criteria [32, 33].

2) Spectral Printer Model Inversion

The result of the spectral gamut mapping is a reproducible distorted image. In order to print this image device control values have to be calculated from the spectral data. This so-called spectral-based separation requires the fast inversion of a spectral printer model, which is a predicting function from control value space to spectral space. Many different spectral printer models have been developed in the past. An overview

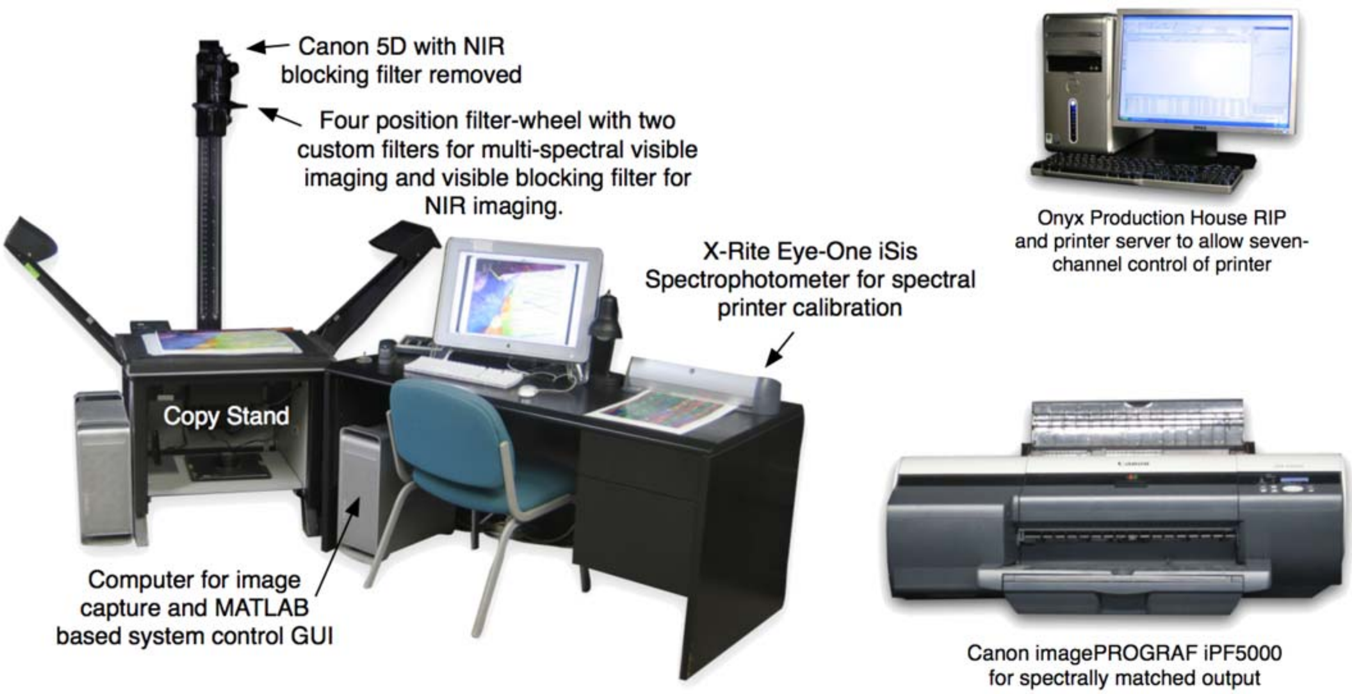

Figure 3. Spectral end-to-end reproduction system developed at the Munsell Color Science Laboratory.

of physical, empirical or hybrid models is given by Wyble and Berns [34]. A widely used printer model is the Yule-Nielsen Spectral Neugebauer (YNSN) model [35, 36, 37] and its cellular extension [38] the cellular Yule-Nielsen spectral Neugebauer (CYNSN) model. This particular model is of practical interest because it combines simplicity and accuracy with a reasonable effort of necessary measurements to fit the model to the actual printer. Many modifications are proposed to improve the model's accuracy or to decrease the number of measurements [39, 40]. Since an analytical inversion of the model is not possible, standard mathematical optimization methods were used [41, 42, 43] or inversion techniques were developed, which are especially adapted to the problem [44, 45, 46]. It has to be noted that a pixel-wise treatment of the optimization can result in some problems due to spectral redundancies [47]. Nearly similar neighboring reflectances can result in completely different control values and as a consequence to undesired color shifts in the final print. Therefore, it is important to add spatial constraints to the optimization.

Another approach is to limit the number of overprints of an multilink printer. A printer that uses the CMYK ink set and is limited to three overprints for instance, can be seen as the combination of 4 printers with the ink sets: CMY, CMK, CYK and MYK. To model a six-channel printer Tzeng and Berns [48] used this approach by restricting the maximal number of overprints to four including the black ink, which results in ten ink subsets. Fitting ten 4-dimensional submodels requires much less measurements than fitting a 6-dimensional model with similar spectral and colorimetric accuracy. Based on this idea a separation method has been developed that combines the spectral gamut mapping and model inversion in a single step [32]. The method utilizes the color just noticeable distance (JND) of the human visual system (HVS) as well as the high quantization of typical printing devices [49] to perform a discrete optimization within the union of all ink subsets. The objective is the selection of ink combinations that fulfill colorimetric criteria in a multi-illuminant perceptual space.

3) Ink Limitation

Exceeding a paper-dependent physical threshold of ink coverage results in visual artifacts such as ink bleeding. Therefore, ink limitation is an important part of the multi-ink printing process where the theoretical maximum ink coverage (which is n¢100% for a n-ink printer) is usually far above the physical threshold. Various ink limitation strategies have been developed and included in metameric printing solutions, which can also be used for the spectral workflow. Such ink limitation techniques can be part of the printer model [39] or can be performed outside the separation process [50], as shown in figure 2. In order to dissociate the ink limitation part from the separation process the printer model has to be fitted on already ink limited target colors. Hence, from the perspective of the printer model, the physical threshold of ink coverage agrees with the theoretical maximum ink coverage and the output of the separation need to be ink limited in a similar way as the targer colors, e.g. by a multi-linear approach [50].

V. An Example of a Spectral End-to-End Reproduction System

In order to reproduce artwork a spectral end-to-end reproduction system was developed at the Munsell Color Science Laboratory (MCSL), which is part of the Rochester Institute of Technology (NY, USA). Commercial devices were used to the greatest extent to keep costs low. Figure 3 shows the setup of the system for a Canon 5D camera and a Canon imagePROGRAF iPF5000 printer. The camera was modified by removing the NIR blocking filter and by mounting a filter wheel with two custom filters (blue and yellow) in front of the lens. These modifications result in six different channels within the visible wavelength range. The printer was controlled by the Onyx ProductionHouse RIP as a seven-channel CMYKRGB-printer (no custom inks were used). As printing medium Felix Schoeller's proofing paper (H74261) was used, which does not include optical brightener.

The maximal number of overprints was set to four including the black ink, so that 20 CYNSN-submodels were used to model the printer. 7725 training colors were printed and measured using the X-Rite Eye-One ISIS (approx 30 min.) to fit all submodels with an average spectral RMS accuracy of 2% and an average CIEDE2000 error below 1 for multiple illuminants.

The reproduction software was written in MATLAB and in C++ and allows a simple plug in of image registration, spectral estimation and separation methods. Since the artists' paint palette was known approximately, a target approach for reflectance estimation was used [11]. Spectral gamut mapping and spectral-based separation were performed according Urban et al. [32]. Figure 4 shows a painting juxtaposed with its reproduction under two different illuminants. The table shows some quantitative colorimetric results for the Color Checker (CC) and for a target (T100) utilizing 100 different pigment-combinations (this target was also used by the spectral estimation method).

The MCSL-system is a trade-off between accuracy and complexity. With only six input channels and seven output channels a perfect spectral reproduction is generally impossible. Nevertheless, it improves colorimetric results of metameric reproductions significantly and demonstrates that a multiple-illuminant-match is achievable utilizing today's commercial devices with marginal modifications. Due to the open system architecture other input and output devices can be used for the reproduction, e.g. a modified Sinarback 54 digital camera or the HP Designjet Z3100 Photo printer. For this specific setup, results can be found in Berns et al. [33] containing a detailed analysis of each submodule.

Figure 4. A painting and its spectral reproduction compared under two different illuminants.

TABLE I. CIEDE2000 RESULTS

Target	CIE D65			CIE A		
	Mean	***Std***	***Max***	***Mean***	***Std***	***Max***
T100	2.0	0.8	3.7	2.7	1.0	5.8
CC	1.7	0.8	4.1	2.2	1.2	5.9

T100=Target with 100 different pigment combinations; CC=Color Checker

VI. Conclusion

Color management according to the ICC-standard is used successfully in many imaging applications worldwide. For distinct applications, however, where the viewing conditions are unknown or are changing in time, such as artwork reproduction, proofing or highly accurate industrial color communication, metameric reproduction systems are insufficient. The reasons are systematic problems related to device, illuminant and observer metamerism, which are directly related to the information lost corresponding with trichromatic devices and a three-dimensional profile connection space.

The solution of these problems is spectral reproduction, which requires the use of more dimensions throughout the whole reproduction chain and completely new algorithms for characterization, separation and gamut mapping. The spectral reproduction workflow is typically a trade-off between accuracy and complexity. Starting with the image acquisition using a multi-spectral camera the sensor responses have to be transformed into a higher-dimensional device independent space (e.g. a spectral space or a multi-illuminant perceptual space) in order to allow a reproduction independent of the knowledge of the input device (Open System Architecture). From this space the data need to be transformed into the spectral gamut of the printer by a spectral gamut mapping method and further processed by a separation and ink limitation algorithm in order to obtain suitable control values for the multi-ink printer.

A prototype developed at the Munsell Color Science Laboratory shows a spectral end-to-end reproduction system based on slightly modified commercial devices. Within the limits of the devices this system allows a reproduction that matches with the original under multiple illuminants.

Many modules of such a reproduction system are still an active research field, particularly the spectral gamut mapping. Therefore, improvements not only on the device side can be expected in future.

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References

[1] [1] ICC. File Format for Color Profiles. http://www.color.org, 4.0.0 edition, 2002.

[2] B. Hill. (R)evolution of Color Imaging Systems. In CGIV, pages 473–479, Poitiers, France, 2002. IS&T.

[3] R. Luther. Aus dem Gebiet der Farbreizmetrik. Zeitschrift f¨ur technische Physik, 8:540–558, 1927.

[4] H. E. Ives. The transformation of color-mixture equations from one system to another. J. Franklin Inst., 16:673–701, 1915.

[5] Th. Keusen. Multispectral color system with an encoding format compatible with the conventional tristimulus model. Journal of Imaging Science and Technology, 40:510–515, 1996.

[6] M.W. Derhak and M.R. Rosen. Spectral Colorimetry using LabPQR - An Interim Connection Space. Journal of Imaging Science and Technology, 50:53–63, 2006.

[7] M.J. Vrhel and H. J. Trussell. Optimal color filters in the presence of noise. IEEE Trans. Image Processing, 4:814–823, 1995.

[8] D.-Y. Tzeng and R. S. Berns. Spectral-Based Ink Selection for Multiple-Ink Printing I. Colorant Estimation of Original Objects. In IS&T/SID, pages 106–111, Scottsdale Ariz., 1998.

[9] D.-Y. Tzeng and R. S. Berns. Spectral-Based Ink Selection for Multiple-Ink Printing II. Optimal Ink Selection. In IS&T/SID, pages 182–187, Scottsdale Ariz., 1999.

[10] F. H. Imai and R. S. Berns. Spectral estimation using trichromatic digital cameras. In Intl. Sym. Multispectral Imaging and Color Reproduction for Digital Archives, pages 42–49, Chiba University, 1999.

[11] Y. Zhao and R. S. Berns. Image-based spectral reflectance reconstruction using the matrix R method. Color Research and Application, 32(5):343–351, 2007.

[12] C. Li and M. R. Luo. A novel approach for generating object spectral reflectance functions from digital cameras. In IS&T/SID, pages 99–103, Scottsdale Ariz., 2005.

[13] M. Mohammadi, M. Nezamabadi, R. Berns, and L. Taplin. Spectral imaging target development based on hierarchical cluster analysis. In IS&T/SID, 12th Color Imaging Conference, pages 59–64, Scottsdale Ariz., 2004.

[14] L. T. Maloney and B. A. Wandell. Color constancy- A method for recovering surface spectral reflectance. Optical Society of America, Journal, A: Optics and Image Science, 3:29–33, 1986.

[15] J. M. DiCarlo and B. A. Wandell. Spectral estimation theory: beyond linear but before Bayesian. Journal of the Optical Society of America A, 20(7):1261–1270, 2003.

[16] C. Li and M. R. Luo. The estimation of spectral reflectances using the smoothness constraint condition. pages 62–67, Scottsdale Ariz., 2001.

[17] V. Cheung, S.Westland, C. Li, J. Hardeberg, and D. Connah. Characterization of trichromatic color cameras by using a new multispectral imaging technique. Journal of the Optical Society of America A, 22(7):1231–1240, 2005.

[18] P. Morovic and G. D. Finlayson. Metamer-set-based approach to estimating surface reflectance from camera RGB. Journal of the Optical Society of America A, 23(8):1814–1822, 2006.

[19] Y. Murakami, K. Ietomi, M. Yamaguchi, and N. Ohyama. Maximum a posteriori estimation of spectral reflectance from color image and multipoint spectral measurements. Applied Optics, 46(28):7068–7082, 2007.

[20] G. Sharma. Targetless scanner color calibration. Journal of Imaging Science and Technology, 44:301–307, 2000.

[21] G. Sharma. Set theoretic estimation for problems in subtractive color. Color Research and Application, 25:333–348, 2000.

[22] Y. Murakami, K. Fukura, M. Yamaguchi, and N. Ohyama. Color reproduction from low-SNR multispectral images using spatio-spectral Wiener estimation. Optics Express,16(6):4106–4120, 2008.

[23] R. S. Berns P. Urban, M. R. Rosen. A Spatially Adaptive Wiener Filter for Reflectance Estimation. In IS&T/SID, 16th Color Imaging Conference, Portland, Oregon (to appear), 2008.

[24] J. Y. Hardeberg. On the spectral dimensionality of object colours. In CGIV, pages 480–485, Poitiers, France, 2002. IS&T.

[25] F. H. Imai, M. R. Rosen, and R. S. Berns. Comparative study of metrics for spectral match quality. In CGIV, pages 492–496, Poitiers, France, 2002. IS&T.

[26] J. A. S. Viggiano. Metrics for evaluating spectral matches: A quantitative comparison. In CGIV, pages 286–291, Aachen, Germany, 2004. IS&T.

[27] M.R. Rosen and M.W. Derhak. Spectral Gamuts and Spectral Gamut Mapping. In Spectral Imaging: Eighth International Symposium on Multispectral Color Science, San Jose, CA, 2006. SPIE.

[28] S. Tsutsumi, M.R. Rosen, and R.S. Berns. Spectral Reproduction Using LabPQR: Inverting the Fractional-Area-Coverage-to-Spectra Relationship. In ICIS, pages 107–110, Rochester, NY, 2006. IS&T.

[29] J. Morovic. Color Gamut Mapping. John Wiley & Sons, 2008.

[30] S. Tsutsumi, M. R. Rosen, and R. S. Berns. Spectral Gamut Mapping using LabPQR. Journal of Imaging Science and Technology, 51(6):473, 2007.

[31] G. Wyszecki and W.A. Stiles. Color Science: Concepts and Methods, Quantitative Data and Formulae. John Wiley & Sons, inc., 2 edition, 2000.

[32] P. Urban, M. R. Rosen, and R. S. Berns. Spectral Gamut Mapping Framework Based on Human Color Vision. In CGIV, pages 548–553, Barcelona, Spain, 2008.

[33] R. S. Berns, L. Taplin, P. Urban, and Y. Zhao. Spectral Color Reproduction of Paintings. In CGIV, pages 484–488, Barcelona, Spain, 2008.

[34] D. R. Wyble and R. S. Berns. A Critical Review of Spectral Models Applied to Binary Color Printing. Color Research and Application, 25:4–19, 2000.

[35] H. E. J. Neugebauer. Die theoretischen Grundlagen des Mehrfarbenbuchdrucks. Zeitschrft f¨ur wissenschaftliche Photographie, Photophysik und Photochemie [translation in [51]], 36:73–89, 1937.

[36] J. A. C. Yule andW. J. Nielsen. The penetration of light into paper and its effect on halftone reproduction. In Tech. Assn. Graphic Arts, volume 4, pages 65–76, 1951.

[37] J.A.S. Viggiano. The Color of Halftone Tints. In TAGA Proceedings, pages 647–661, 1985.

[38] K. J. Heuberger, Z. M. Jing, and S. Persiev. Color transformations from lookup tables. In TAGA Proceedings, pages 863–881, 1992.

[39] Y. Chen, R. S. Berns, and L. A. Taplin. Six color printer characterization using an optimized cellular Yule-Nielsen spectral Neugebauer model. Journal of Imaging Science and Technology, 48:519–528, 2004.

[40] T. Bugnon, M. Brichon, and R.D.Hersch. Simplified ink spreading equations for CMYK halftone prints. In Proceedings of SPIE, volume 6807, page 680717. SPIE, 2008.

[41] S. Zuffi and R. Schettini. Spectral-Based Printer Characterization. In CGIV, pages 598–602, Poitiers, France, 2002. IS&T.

[42] L. A. Taplin. Spectral Modeling of a Six-Color Inkjet Printer, MSc. thesis. RIT, NY, 2001. MSc. thesis. RIT, NY, 2001.

[43] D.-Y. Tzeng. Spectral-Based Color Separation Algorithm Developed for Multiple-Ink Color Reproduction. PhD thesis.

[44] P. Urban and R.-R. Grigat. Spectral-Based Color Separation using Linear Regression Iteration. Color Research and Application, 31:229–238, 2006.

[45] P. Urban, M. R. Rosen, and R. S. Berns. Accelerating Spectral-Based Color Separation within the Neugebauer Subspace. Journal of Electronic Imaging, 16:043014, 2007.

[46] P. Urban, M. R. Rosen, and R. S. Berns. Fast Spectral-Based Separation of Multispectral Images. In IS&T/SID, 15th Color Imaging Conference, pages 178–183, Albuquerque, New Mexico, 2007.

[47] M. R. Rosen, E. F. Hattenberger, and N. Ohta. Spectral redundancy in a six-ink ink jet printer. Journal of Imaging Science and Technology, 48:194–202, 2004.

[48] D.-Y. Tzeng and R. S. Berns. Spectral-Based Six-Color Separation Minimizing Metamerism. In IS&T/SID, pages 342–347, Scottsdale Ariz., 2000.

[49] G. Gonzalez, T. Hecht, A. Ritzer, A. Paul, J.-F. Le Nest, and M. Has. Color management: How accurate need it be? Recent Progress in Color Management and Communications, pages 24–29, 1998.

[50] P. Urban. Reproduktion von Multispektralbildern mit autotypischer Farbmischung. In 13. Workshop Farbbildverarbeitung, pages 31–42, Koblenz, Germany, 2007.

[51] H. E. J. Neugebauer. The Theoretical Basis of Multicolor Letterpress Printing (Translated D. Wyble and A. Kraushaar). Color Research and Application, 30:322–331, 2005.