Evaluation of a multi-spectral camera system for inline color measurement

C. Godau*[1], M. Klammer[2], T. Eckhard[3], M. Schnitzlein[2], D. Nowack[2], B. Frei[2] and P. Urban[1]

[1]Institute of Printing Science and Technology, Technische Universität Darmstadt, 64289 Darmstadt, Germany

[2]Chromasens GmbH, 78467 Konstanz, Germany

[3]Departamento de Óptica, Facultad de Ciencias, Universidad de Granada, 18071 Granada, Spain

Abstract

We evaluate a new 12-channel multi-spectral line scan camera system for full-width inline color measurements. The system provides full reflectance spectra for each pixel allowing for accurate color measurement with high spatial resolution. In our analysis, we performed measurements on three test-charts printed in our lab and by different offset printing shops in Germany. We compare the results colorimetrically and spectrally to reference measurements obtained from a conventional spectrophotometer (X-Rite i1iSis XL). In conclusion, the system is suitable for pixel-wise color measurements with an accuracy comparable to that of the human visual system or better.

1 Introduction

In-line color measurement according to industrial standards in printing and production is a challenging task. Accurate color measurements (spectral and colorimetric) are obtained with spectrophotometers, which allow for spot measurements only.

Using spot measurements to inspect a printing process might be sufficient for some application, but not for others. In packaging printing for instance, a color control stripe has to be integrated in the package design in order to allow color control via the measurement of the control stripe. The possibility to measure color spectrally with an inline imaging device would make the color control stripe redundant and further allow quality control of the entire print. For many other print applications, such as magazine, poster or picture printing, spot measurements alone are not sufficient for high fidelity color reproduction.

Apart from that, recent developments allow the characterization and calibration of printers from image content [2]. These methods have the potential to save large amounts of paper currently used for calibration and print control strips, but require in-line color measurement with high colorimetric accuracy and good spatial resolution.

State-of-the-art imaging systems currently used in print inspection applications typically use RGB cameras to acquire color information. However, color measurement with color discrimination accuracy in performance similar to the human visual system or better is currently not possible with such devices.

*godau@idd.tu-darmstadt.de

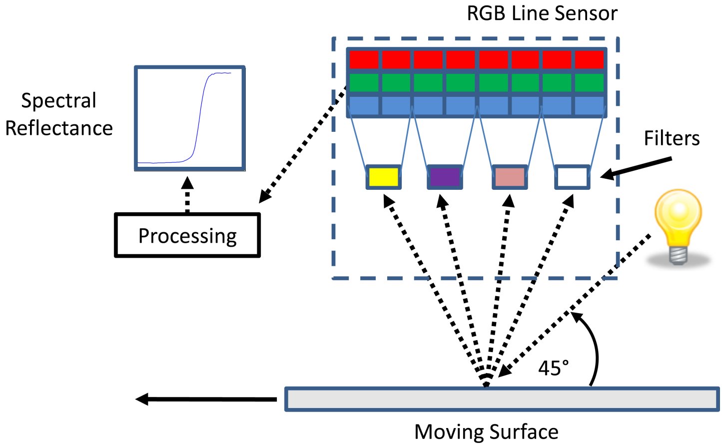


Figure 1: The camera contains one RGB line sensor with four different high-quality absorptive filters. The LED light source ist installed at a 45° angle to surface and camera. Note that the sensor and filters inside the dashed box are actually installed perpendicularly to the moving surface.

We evaluate a new 12-channel multi-spectral imaging system by Chromasens GmbH designed for full-width inline spectral reflectance and color measurements in print inspection. The camera system is suitable for high-speed inline applications with up to $30\frac{m}{min}$. For our evaluation, we adjusted the system to provide a spatial resolution of $100dpi$. Depending on the application the camera is adoptable to resolutions in the range of $30-200dpi$. Integrated in a printing machine, this camera system could solve the above mentioned problems. To the best of our knowledge this is the first high-speed in-line spectral and colorimetric imaging device adhering to industry standards for color measurement.

2 Hardware Setup

The imaging system consists of a CCD camera and an LED light source, both developed by Chromasens GmbH. The 12-channel multi-spectral camera is a Chromasens truePIXA[1] prototype based on a three-channel RGB line scan sensor with a width of 7196 pixels.

Four lenses in front of the sensor each project an image onto a separate part of the RGB line sensor. They are oriented to provide the same field of view (further: FOV). By placing different color glass filters in front of the lenses, the effective spectral responsivity of the RGB line sensor can be altered independently for each of the 4 parts. The high-quality absorptive glass filters were selected to be optimal for the spectral and colorimetric measurement task.

The light source is a prototype LED line scan illumination [2] with adjustable spectral power distribution (SPD). Tuning the SPD is achieved through independent control of the LED currents for each of the 4 different types of LEDs in the light source. Active cooling ensures a

[1] http://chromasens.de/en/truepixa-spectral-camera
[2] http://chromasens.de/en/corona-ii-led-line-scan-camera-illumination

stable SPD, and a diffuser improves the spatial homogeneity. The spectral adjustability allows for color measurement close to measurement condition M1 and M2 of norm ISO 13655 (*Graphics technology: Spectral measurements and colorimetric computations for graphic arts images*) [5]. In accordance with the M3 measurement condition defined in ISO 13655, optional polarizing filters are available for the illumination and camera system. The SPD of the illumination and the spectral responsivities of the camera system are illustrated in Figure 2.

The whole system (camera and illumination) is set up in a bidirectional $45^\circ/0^\circ$ measurement geometry. The optical axis of the camera is perpendicular to the measurement plane (0°) and the illumination is installed at 45° from the optical axis. Figure 1 illustrates this configuration, the geometry is also specified in the norm ISO 13655 [5]. For this work, the camera system was set up in a laboratory environment and mounted on a linear scanning table.

3 Calibration and Processing

The raw data of the truePixa consists of 3-channel images with 4 projected FOVs of the same area. A geometric calibration procedure is required to create a 12-channel image from the raw data. In addition, a so-called color calibration step is performed to obtain spectral reflectance data from the 12-channel images. The following subsections describe these procedures.

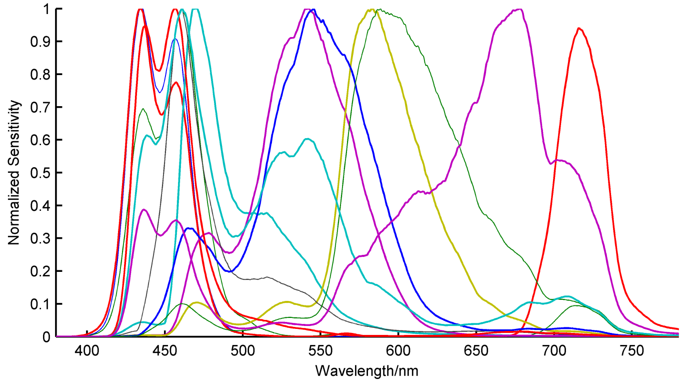
3.1 Geometric calibration

During geometric calibration, a raw image of the RGB camera sensor is divided into its 4 sub-image parts and FOVs corresponding to each lens are spatially registered. Following this division and registration, the 4 parts of the raw 3-channel RGB image are appended to form a 12-channel image. The geometric calibration process uses a free-form registration model. This sub-pixel accurate model performs the channel registration and a lens-dependent image distortion correction. The size of the 12-channel image is 1400 pixels, which in our $100dpi$-system corresponds to a usable measurement width of around $35cm$. Figure 3 illustrates the image formation process leading from a raw 3-channel to a registered 12-channel image.

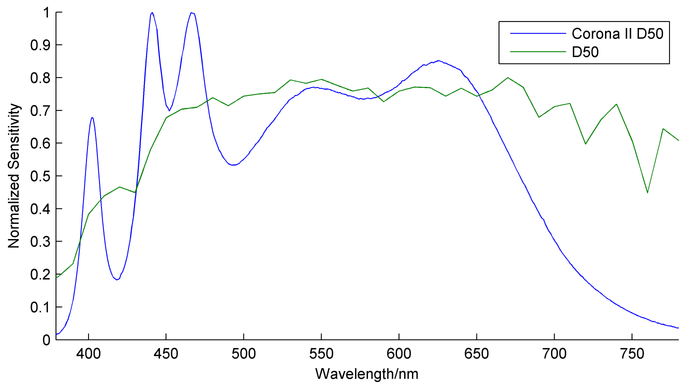
3.2 Color calibration

We designed our system to estimate spectral reflectance spectra, which we then use for colorimetric calculations. A number of image preprocessing steps significantly facilitate the subsequent spectral estimation. First, subtraction of a dark image reduces the image noise and removes stray light influences. Second, we use a full-width white reference to correct for shading. This accounts for spatial non-uniformity of the light source and local variations in the sensitivity of the camera sensor. For in-line applications, it is possible to integrate the white reference into the system housing.

The final 12-channel images allow an estimation of spectral reflectance data for each pixel. The estimated spectra have a wavelength range of 380nm to 730nm with 10nm resolution. A related previous study reports that out of the many existing spectral estimation algorithms, least-square regression (linear or kernel-based) performs best with this hardware configuration [4]. Regression approaches belong to the class of learning-based algorithms in which a relation between camera responses and reflectance spectra is established based on empirical data. We use a pseudo-inverse approach to directly estimate a linear transformation from camera responses to reflectance spectra, minimizing the spectral root mean square error on the



(a) Normalized responsivities of our 12-channel camera based on one RGB sensor with four different filters.



(b) Normalized spectral power distribution of the LED-based illumination (Corona II D50) compared to standard illuminant D50.

Figure 2: The spectral sensitivities (left) and illumination spectral power distribution (right) of the camera system.

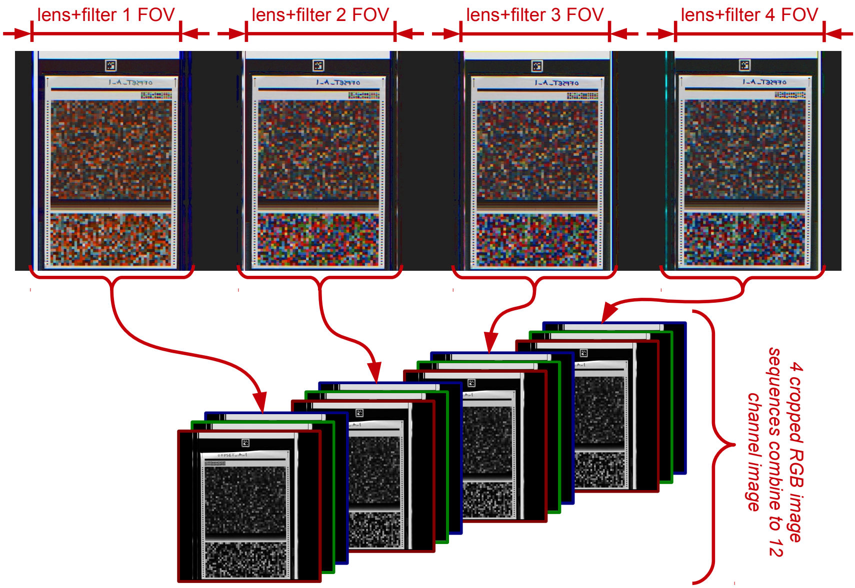


Figure 3: Raw data processing: the RGB image is cropped into 4 parts corresponding to the same area projected onto the sensor by the individual lenses. The four 3-channel RGB images are registered and combined to form the final 12-channel image.

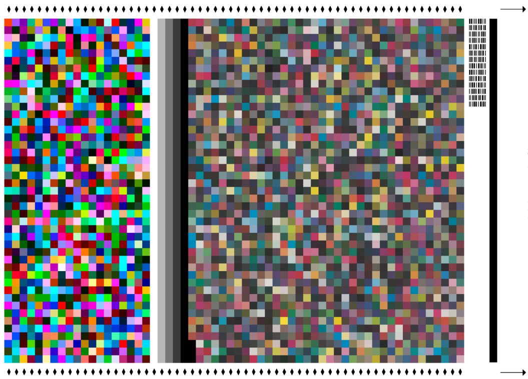


Figure 4: Test chart used for evaluation of the multi-spectral system performance in color measurement. The three areas from left to right: a selection of highly saturated patches, five gray lines ranging from white to black, 1618 colors from an IT8 test and calibration chart [6]. We evaluate the system using the IT8 patches only.

training data. This approach is not to be confused with use of the pseudo-inverse in inverting a linear image formation model, which is highly susceptible to noise and typically leads to much larger errors.

To achieve an optimal color calibration of the system, we designed custom color charts that we printed on a wide gamut inkjet printer (HP Designjet Z3100) using 7 different inks (cyan, magenta, yellow, black, red green, blue). We measured the spectral reflectances of each of the 2700 spots on the charts using an X-Rite i1iSis XL spectrophotometer [3].

4 Methods

In this work, we evaluate the suitability of the presented camera system for accurate color measurement in offset printing. We base our evaluation on a custom made test chart with 2700 color patches shown in Figure 4. There are three different regions on the chart. The right part consists of 1618 colors from an IT8 test and calibration chart [6]. In the middle, five lines are filled with gray ramps from white ($CMYK = [0,0,0,0]$) to black ($CMYK = [0,0,0,1]$). The left part consists of highly saturated patches that include colors outside of the range of colors specified in the IT8 dataset. We evaluate the system using the IT8 patches only.

We used 3 different versions of this chart, the first produced using one desktop inkjet printer and the other 2 ordered from 2 regular printing shops in Germany. From now on, we will refer to these charts as "Inkjet", "Offset A" and "Offset B".

The spectral reflectance data of each of the 3 charts was measured using the X-Rite i1iSis XL. Figure 5 shows a sample reflectance spectrum from the 3 different printed test charts. The overall quality and visual appearance of the printed charts differ significantly. Image reference data for the chart was defined explicitly in CIELAB color values, the differences are due to various inks and color conversion or printer settings used during the production of each chart.

[3] `https://www.xrite.com/product_overview.aspx?id=894`

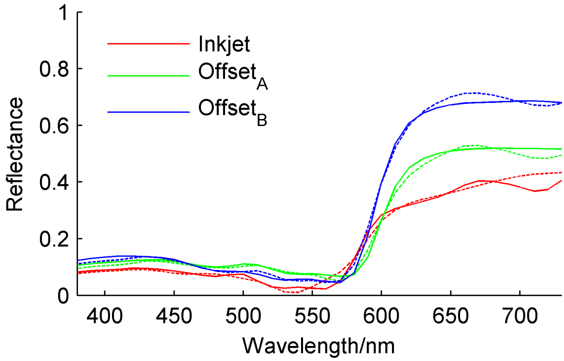


Figure 5: A sample reflectance spectrum from the test charts produced by different printers. The solid lines show the reference spectra measured using the X-Rite iSis XL, the dashed lines are spectra estimated using our system.

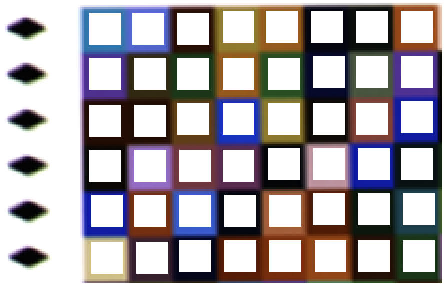


Figure 6: A closeup view of some patches with the corresponding central areas shown in white.

We evaluated the colorimetric and spectral accuracy of our system by comparing our results to the reflectance data measured using the X-Rite i1iSis XL. The X-Rite i1iSis XL measures spectral data for a central area of each patch in the chart, while our system measures pixel-wise spectral data with a resolution of 100dpi. To obtain comparable measurments we therefore extracted average camera responses for the central area of each patch in the chart. Figure 6 shows a closeup view of some patches with the corresponding central areas.

We evaluated the colorimetric accuracy using two common color difference formulas. CIE-ΔE_{76} [10] is the simplest and most widely accepted metric in the graphic industry. The color difference between a reference color $[L_1^*, a_1^*, b_1^*]$ and its estimated counterpart $[L_2^*, a_2^*, b_2^*]$ is their Euclidean distance

$$\Delta E_{76} = \sqrt{(L_1^* - L_2^*)^2 + (a_1^* - a_2^*)^2 + (b_1^* - b_2^*)^2}. \tag{1}$$

The latest recommendation for color measurements by the International Commission on Illumination (CIE) is the CIE-ΔE_{00} [3], we therefore also include results for this more complex color difference formula.

Spectral accuracy is evaluated using the root mean square error (further: RMSE). For a reference spectral reflectance r of dimension m and its estimated counterpart r', the RMSE is

$$RMSE = \sqrt{\frac{\sum_{i=1}^{m}(r_i - r'_i)^2}{m}}. \tag{2}$$

5 Results and Discussion

Tables 1,2, and 3 illustrate median, mean, 90th percentile and maximum deviations from the reference (X-Rite i1iSis XL) for the colorimetric and spectral metrics of each printed test chart.

Table 1: Deviation from reference (X-Rite i1iSis XL) for each chart type: CIE-ΔE_{76}.

	Median	Mean	90th percentile	Max
Inkjet	0.77	0.85	1.14	2.61
Offset A	1.02	1.07	1.43	3.61
Offset B	1.47	1.48	2.01	4.14

Table 2: Deviation from reference (X-Rite i1iSis XL) for each chart type: CIE-ΔE_{00}.

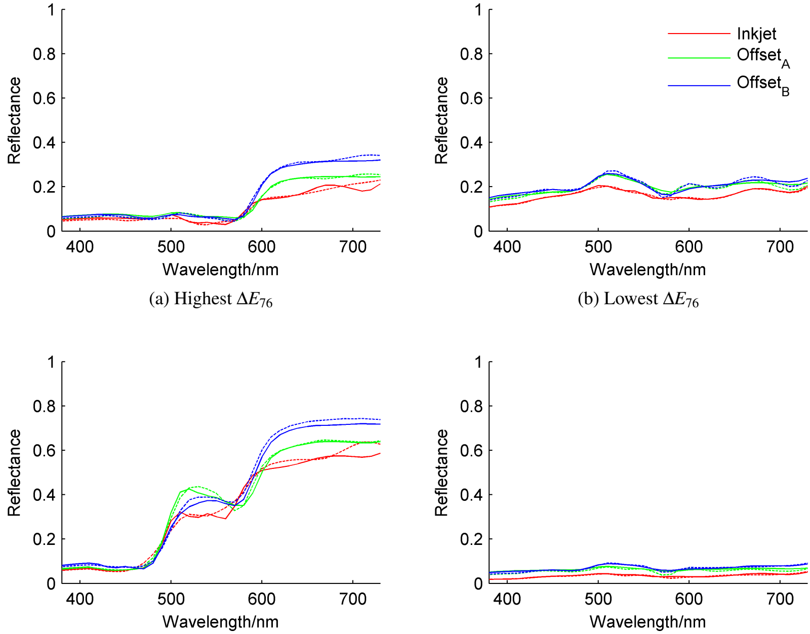
	Median	Mean	90th percentile	Max
Inkjet	0.61	0.66	0.88	1.97
Offset A	0.76	0.83	1.10	3.48
Offset B	1.05	1.04	1.39	2.83

Table 3: Deviation from reference (X-Rite i1iSis XL) for each chart type: $RMSE$.

	Median	Mean	90th percentile	Max
Inkjet	0.0090	0.0102	0.0137	0.0261
Offset A	0.0085	0.0092	0.0114	0.0240
Offset B	0.0091	0.0099	0.0122	0.0292

Figure 7 shows the spectra with best/worst estimation results according to $RMSE$ and ΔE_{76} for each chart. It seems clear from these figures that there is only a weak correlation between $RMSE$ and ΔE_{76} in our results. This result is confirmed in Figure 8, which shows a scatter plot of $RMSE$ against ΔE_{76} for all samples. Obviously, there is no strong correlation between the error metrics.

Previous studies on inter-instrument agreement of spectrophotometers have shown surprisingly large deviations even within instruments using identical measurement geometries.



(a) Highest ΔE_{76} (b) Lowest ΔE_{76}

(c) Highest *RMSE* (d) Lowest *RMSE*

Figure 7: Spectra with best/worst reconstruction results according to *RMSE* and ΔE_{76} for each chart. The solid lines indicate reference spectra (X-Rite i1iSis XL), the dashed lines are spectra reconstructed using our system.

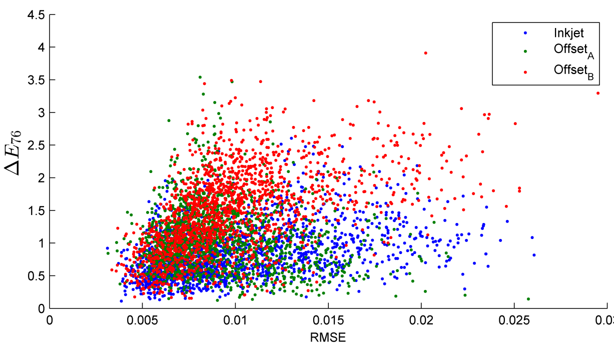


Figure 8: Scatter plot of *RMSE* against ΔE_{76} for all samples, which confirms that there is only a weak correlation between these norms.

Wyble and Rich [11] (therein Table IV) report average deviations between different bidirectional spectrophotometers of $\Delta E_{76} = 0.54$ to 2.88 for printed inks, with maximum deviations of $\Delta E_{76} = 0.9$ to 6.03. The deviations of our results from the reference instrument (X-Rite i1iSis XL) were in a similar range, which indicates that overall performance for printed samples is similar to typical handheld spectrophotometers.

6 Conclusions

We performed color measurements on three test charts (with 1618 patches each) printed using different offset and inkjet processes. Color Calibration was performed using inkjet-printed charts. It is therefore not surprising that the system performed best (in terms of color difference) for the test chart printed with inkjet, although the two inkjet printers were not identical. We nevertheless obtained good accuracy in our color measurements on the offset-printed test charts as well.

The median deviations from the reference spectrophotometer (X-Rite i1iSis XL) in terms of ΔE_{76} were 0.77 (Inkjet), 1.02(Offset A) and 1.47(Offset B). The corresponding spectral *RMSE* deviations were 0.0090 , 0.0085 and 0.0091 respectively. This is in line with inter-instrument deviations for printed samples between different spectrophotometers previously reported in the literature [11, 9].

Our measurements are optimized for spectral accuracy. If colorimetric accuracy is the primary concern, the pseudo-inverse spectral reconstruction could be replaced by an alternative that minimizes the colorimetric error under specified viewing conditions. Examples of such methods are the matrix R method proposed by Zhao and Berns [12], reconstruction based on the combined spectral and colorimetric metric by López-Álvarez *et al.*[7], and the weighted principle component reconstruction by Agahian *et al.* [1]. If agreement with a particular device is important, an additional regression-based characterization may lead to improvements [8].

We observed some variation in performance for test targets from different printers. This is most likely due to differences in the printing process (printer type and settings), paper types and potential differences in the spectral composition of the inks used. It is possible to adapt the color calibration for a specific printing technology and ink combination in order to further increase performance.

We are planning to install the system into an industrial machine that uses offset, flexographic and gravure printing for further analysis of the measurement performance. In this production-like setup we can for example perform measurements on wet or drying ink to evaluate usage of this system in inline printing applications.

In our evaluation, we performed all spectral reference measurements according to the ISO13655 M2 measurement norm, which does not account for fluorescence caused e.g. by optical brighteners. Several recently released spectrophotometers adhere to the M1 and M3 standards. We are planning an evaluation of the measurement performance of the system according to these standards in the near future.

References

[1] Farnaz Agahian, Seyed Ali Amirshahi, and Seyed Hossein Amirshahi. Reconstruction of reflectance spectra using weighted principal component analysis. *Color Research &*

Application, 33(5):360–371, 2008.

[2] T. Bugnon and R.D. Hersch. Constrained Acquisition of Ink Spreading Curves From Printed Color Images. *Image Processing, IEEE Transactions on*, 20(2):513–522, 2011.

[3] CIE. Improvement to industrial colour-difference evaluation. Technical report, CIE Pub. No. 142-2001, 2001.

[4] Timo Eckhard, Eva M. Valero, and Javier Hernández-Andrés. A comparative analysis of spectral estimation approaches applied to print inspection. In *18. Workshop Farbbildverarbeitung*, 2012.

[5] ISO 13655:2009 Graphic technology - Spectral measurement and colorimetric computation for graphic arts images, 2009.

[6] ISO 12641:1997 Graphic technology – Prepress digital data exchange – Colour targets for input scanner calibration, 1997.

[7] MA López-Álvarez, J Hernández-Andrés, EM Valero, and JL Nieves. Colorimetric and spectral combined metric for the optimization of multispectral systems. In *Proceedings of the 10th Congress of the International Colour Association (AICŠ05)*, pages 1685–1688. Association Internationale de la Couleur, 2005.

[8] Peter Nussbaum, Jon Y Hardeberg, and Fritz Albregtsen. Regression based characterization of color measurement instruments in printing applications. In *IS&T/SPIE Electronic Imaging*, pages 78661R–78661R. International Society for Optics and Photonics, 2011.

[9] Peter Nussbaum, Aditya Sole, and Jon Y Hardeberg. Analysis of color measurement uncertainty in a color managed printing workflow.

[10] Noboru Ohta and Alan Robertson. *Colorimetry: Fundamentals and Applications*. The Wiley-IS&T Series in Imaging Science and Technology, 2006.

[11] David R Wyble and Danny C Rich. Evaluation of methods for verifying the performance of color-measuring instruments. part ii: Inter-instrument reproducibility. *Color Research & Application*, 32(3):176–194, 2007.

[12] Yonghui Zhao and Roy S Berns. Image-based spectral reflectance reconstruction using the matrix r method. *Color Research & Application*, 32(5):343–351, 2007.