Application of a 3-CCD color camera for colorimetric and densitometric measurements

D.Brydges[1], F.Deppner[1], H.Künzli[1], K. Heuberger[1], R.D. Hersch[2]

[1]Swiss Federal Laboratories for Materials Testing and Research (EMPA)
[2]École Polytechnique Fédérale - Lausanne (EPFL)

ABSTRACT

Video cameras have been used in the graphic arts industry primarily for quality inspection applications where one is interested only in the macro or large scale appearance defects of the print i.e. acceptable/not acceptable. CCD video cameras also have the potential for use in on-press color-type measurements. The advantages of such measurements are numerous, most notably the ability to accurately determine what has been measured. However, despite the advantages current CCD cameras are not designed to measure colors directly. One of the major drawbacks to the use of standard 3-CCD cameras for such measurements is that the spectral response of the cameras differ from standard densitometric or colorimetric responses. Additionally, the dynamic range of the CCD camera is not suitable to accurately measure the densities attainable in high quality sheet-fed printing.

This paper discusses techniques which have been used, and results obtained, in an attempt to acquire both densitometric and colorimetric measurements from a standard 8-bit 3-CCD camera for use in newspaper printing.

Keywords: CCD camera, colorimetry, densitometry, printing

1 INTRODUCTION

To improve the quality of printed materials, and the efficiency with which they are printed, methods to measure and control the important variables of the printing process are of great importance. Traditionally, the densitometer has been the main measurement tool used for gathering information for quality evaluations and control purposes, almost to the exclusion of any other instrument. However, in recent years CCD cameras have been introduced as pressroom alternatives to the densitometer for press control. Some advantages of CCD cameras for press control include:

- Ability to measure several quality attributes simultaneously.
- CCD cameras provide an image which can be analyzed to identify measurement locations for both control bar and intra-image measurements.
- Ability to detect defects within a measurement preventing erroneous press adjustments.

Despite the advantages described above, there are two important drawbacks to the use of CCD cameras for color-type measurements; 1) CCD cameras are currently not designed to *measure* colors directly, 2) The dynamic range of the camera limits the range of reflectances, or densities, that can be measured accurately. The first drawback mentioned leads to a common situation confronting the researcher: "How does one convert from RGB camera values to densitometric, and/or to colorimetric values?" The second drawback mentioned does not pose a problem in this work as this investigation is limited to newspaper printing, where the minimium reflectances, or maximium densities,

---

Electronic Imaging 98, Conf. Color Imaging: Device Independent Color, Color Hardcopy and Graphic Arts III, San Jose, SPIE Vol. 3300 (1998), 292-301

achievable are within the range of the camera. The purpose of this investigation has been to evaluate several options that may be used to obtain acceptable densitometric and colorimetric measurements from a standard 8-bit 3-CCD camera for use in newspaper printing.

2 PREVIOUS WORK

2.1 Densitometric

A review of the literature indicates that several investigations have been made concerning the use of 3-CCD cameras for direct measurements. Malmqvist [1] et al., report of a technique developed for measuring densities within the halftone dots of a halftone tint. The technique allows the determination of both solid ink density (SID) and dot area, and hence dot gain, from one measurement. The authors have reported that the density of a halftone dot is a function of tonal area, with smaller dots carrying less ink. Based on the experimental procedures used, the results may not necessarily be true, as it is well known that small dark areas (halftone dots) surrounded by lighter areas (paper) will indicate higher reflectances, lower densities, due to the additional light that is reflected into the optics from the surrounding paper areas. No numerical results are provided.

Södergård [2] et al., also report measuring densities directly, as one part of their ARGUS system for inspecting color printing. The authors have used a technique similiar to that of Malmqvist, and report that densities can be measured with this method to within an accuracy of +/- 0.05D units. No mention of the tonal area from which these results were obtained is provided.

The most ambitious work is provided by Seymour [3], who goes into detail to describe the corrections he has applied in an attempt to measure densities within an accuracy of +/- 0.05D units, and a precision of +/- 0.01D units of all densities up to 2.0. At the time of the publication the results, presented for black only, indicated that the accuracy still needed to be improved. The errors were most notable for densities above approximately 1.30D. However, recent unpublished results indicate that densities can be measured to within an accuracy of about +/- 0.03D units for a complete set of color patches: CMYK solids, 25%, 50%, 75% halftones, and red, green and blue overprints.

2.2 Colorimetric

Many techniques have been presented in the literature for transforming between RGB values and XYZ tristimulus values. There also exists a small body of work done on conversions from RGB to reflectance or density spectra. A good overview of the techniques and results achieved is provided by Seymour [4]. Therefore, only a brief overview of the results pertinent to this work are provided here.

Södergård, et al. [2] applied polynomial modelling to halftone printing on newsprint (34 l/cm). They determined that a 14 term polynomial was sufficient and obtained an average deviation between measured and calculated of $\Delta E^*_{ab} = 5.77$, Std. deviation = 2.80, and Max. $\Delta E^*_{ab} = 30.70$. In their work gray balanced RGB values were used, without compensation for camera noise. The fitting was performed over all patches (236) of the Kodak Q-60 Test Target.

Kang [5] applied a similiar method as Södergård, however, to xerographic and thermal transfer prints, in addition to color films. The results obtained for a model with equal number of terms were signifigantly better than those reported by Södergård. This is most likely due to the significant difference between the two media i.e. newsprint, as compared to coated paper. One of the more interesting aspects of this work was the results reported concerning the generality of the transforms, over different media. The comparison was made over three different paper and colorant combinations. The results indicate that a unified transformation existed for the three different media which produced results within one ΔE^*_{ab} of the results produced from the individual transforms.

Seymour [4] performed a more extensive investigation to determine if color transforms really work, and the generality of the transforms. Performing the calibration for both first and second-order polynomials on 27 CMY combinations, the transfer matricies were then used to convert the calibration set and three other sets of color patches to XYZ tristimulus values. Seymour was able to obtain mean ΔE^*_{ab} values between 3.4-6.3 for the first-order matrix, and between 1.4-2.4 for the second-order matrix. One interesting note concerning this work was that for the first-order matrix the calibration set had the largest mean ΔE^*_{ab} value of the four data sets, while for the second-order matrix the calibration set had the smallest mean ΔE^*_{ab} value. This would indicate that while the second-order produces more accurate results, it is less general than the first-order matrix.

The results of the work of Kang and Seymour concerning the generality of the transforms is encouraging in this work for two main reasons: 1) Frequent recalibrations for variations in paper and ink to maintain an acceptable level of accuracy are expensive and time consuming, 2) As the solid ink density varies throughout the press run, so will the gamut of colors contained within the initial calibration. Hence, the ability to accurately extrapolate beyond the color coordinates of colors not specifically included in the initial calibration data set is very desirable.

As an alternative to polynomial modelling and multidimensional LUT's, Viggiano & Wang [6] proposed an analytical approach to characterizing color digitizing scanners based on use of the Beer-Bouger-Lambert model and Principal Component Analysis (PCA). Using a flat-bed scanner, and a Kodak Q60C transmission target the authors obtained a mean $\Delta E^*_{ab} = 4.10$ over 236 patches of the target. The authors suggest that the large deviations between measured and predicted may be due to an inadequate amplitude response function for converting RGB scanner values to RGB densities, and the broadband nature of the spectral sensitivities of the scanner, which are assumed to be narrow under the assumptions of Beer-Bouger-Lambert. This technique is of interest due to the spectral nature of the prediction model. Although ink/paper prints do not behave according to the Beer-Bouger-Lambert model, it is believed, and also suggested by the authors, that this technique could be adapted for use under such conditions.

2.3 Densitometry or Colorimetry

Within the graphic arts industry, densitometry has been the main measurement method for measuring and controlling the colors produced by the printing press. Densitometers are used to measure such attributes as SID, dot area, trapping, etc.. Although the densitometer is well suited for measurements pertaining to the relative strength of an ink film, and hence well suited for process control, the densitometer is not suitable for measuring color in a manner which relates to the visual sensation of color. This is primarily a result of the differences between the spectral products of the densitometer and the spectral products of the colorimeter (CIE standard observer/Illuminant combination). The question then becomes which measurement response should be used? We believe that both responses are necessary, with the choice of response depending on the purpose of the measurement. For example, if a press operator is interested in a quantitative assessment of the appearance of some aspect of the print, say a three-color neutral, colorimetry is clearly the better response. If the press operator is interested in adjusting the colors of the print to bring the three-color neutral back to neutrality, densitometric information is necessary as the controls available to adjust the flow of ink are in terms of densities. Within this work we have investigated methods that will allow for the acquisition of both densitometric and colorimetric information allowing the press operator to select the desired response, and possibly also acting as a training aid to acquire some "feel" for what the relationship may be between densitometric and colorimetric values.

3 MEASUREMENT METHODS

3.1 Colorimetric: Transformation

Polynomial Modelling

Based on the amount of literature utilizing empirical color transformations, the polynomial approach appears to be a very common method of obtaining XYZ tristimulus values from RGB values. The polynomial transformation is very simple requiring only measurements of XYZ tristimulus values and the corresponding RGB values for some number of color patches. A transformation matrix is obtained that provides a best agreement between the two measurements in a least-squares sense. For this work we have chosen to obtain a transformation from RGB camera values to reflectance spectra. Calculating a reflectance spectrum enables us to acquire both tristimulus and densitometric values by applying the appropriate weighting functions to the predicted spectrum. This method has been tested using a first-order model (RGB values), and a second-order model (RGB, squared terms, and cross products).

Spectral Decomposition

As indicated in the literature review (Section 2.2), several modifications could be made to the procedures used by

Viggiano & Wang to improve the results for photographic media, and for applying the technique to ink/paper printing conditions. We have decided to evaluate this technique, applying the corrections suggested by the authors. The corrections and procedures are presented below.

The Beer-Bouger-Lambert model states that the density spectrum (above base) of a point is linearly related to the dye concentrations. Therefore, the density spectrum of a point can be computed from knowledge of the density spectra of the base, the primary dyes at unit strength (basis vectors), and the density above base at three wavelengths of the point. However, because CMYK prints do not behave according to the Beer-Bouger-Lambert model, due to proportionality (first surface reflections, light scattering, etc.) and additivity failures (ink trapping), the density spectra of the primaries (CMYK) at unit strengths do not add linearly to produce the spectrum of a point. It is however possible by performing a PCA on the density spectra of the calibration set, once the paper has been subtracted, to obtain a family of independent basis spectra such that all the color patches of our calibration set are a linear combination of the basis spectra. The number of basis spectra needed to reconstruct the spectra is strongly dependent on the ink/substrate combination. In the case of photographic media, three vectors typically carry 99.96% of the information of the calibration set. For an ink/newsprint combination 4 or 5 vectors are more likely needed to carry the same amount of information. Using the basis spectra and the spectra of the calibration patches the concentrations can be determined, from which the calibration spectra can be reconstructed.

To predict the spectrum of a color measured with the CCD camera, the RGB camera values are first converted to densities, using the procedures described in the experimental section. The RGB densities are then related to the concentrations via a transformation. The estimated concentrations are then used with the basis spectra to reconstruct the density spectrum of the color. For materials obeying the Beer-Bouger-Lambert law and RGB integral densities measured with narrowband filters a simple 3 X 3 linear transformation can be used to convert from integral to analytical densities. Because of the broadband nature of the CCD camera filters, and the fact that we are working with integral reflection densities, from which no linear transformation to analytical densities exists due to the non-linear relationship between reflection and transmission densities, a simple 3 X 3 linear transformation between integral RGB camera densities and concentrations will not suffice. We have therefore evaluated in addition to the simple 3 X 3 transformation the ability of several alternatives using second-order polynomials of both six-terms (RGB, squared terms), and nine-terms (RGB, squared terms, cross products), to obtain an acceptable transformation.

The accuracy of the results obtained from this method are dependent on both the number of basis spectra extracted, and the order of the transformation between RGB camera densities and concentrations. Therefore, several combinations have been evaluated.

Model Evaluation

Each of the models discussed above has been evaluated using three different procedures. The procedures are designed to evaluate the models for both accuracy and generality or robustness. The three procedures are described below.

Procedure 1: **Sample Specific Characterization:** A *sample print* specific transformation is determined for each sample sheet, which consists of 24 color patches, within a single press run. The calibration and testing data sets are the same.

Procedure 2: **Test Run Specific Characterization:** A *test run* specific transformation is determined from one sample print within the test run that is representative of *normal printing conditions*. This transformation is then applied to the RGB values of the color patches of the remaining 24 sample prints within the specific test run.

Procedure 3: Procedure 3 is similiar to Procedure 2 as a *test run* specific transformation is calculated from one print that is representative of *normal printing conditions*, however, in this procedure the transformation is used to convert the RGB values of the color patches from a different test run.

3.2 Densitometric: Direct Measurement

The spectral response of a traditional densitometer is defined by the spectral sensitivities of the photodetector, and the spectral transmittance of the optics, and filters. Densitometric standards for reflection densitometry [7] specify not the spectral response, but the spectral product, which is the product of the spectral response and the influx spectra (illumination). For a CCD camera to measure the density of a sample directly, in correspondence with a traditional densitometer, the spectral products of both instruments would have to be similiar. The Status E spectral product, and the approximate spectral product of a typical 3-CCD camera are illustrated in Figure 1.

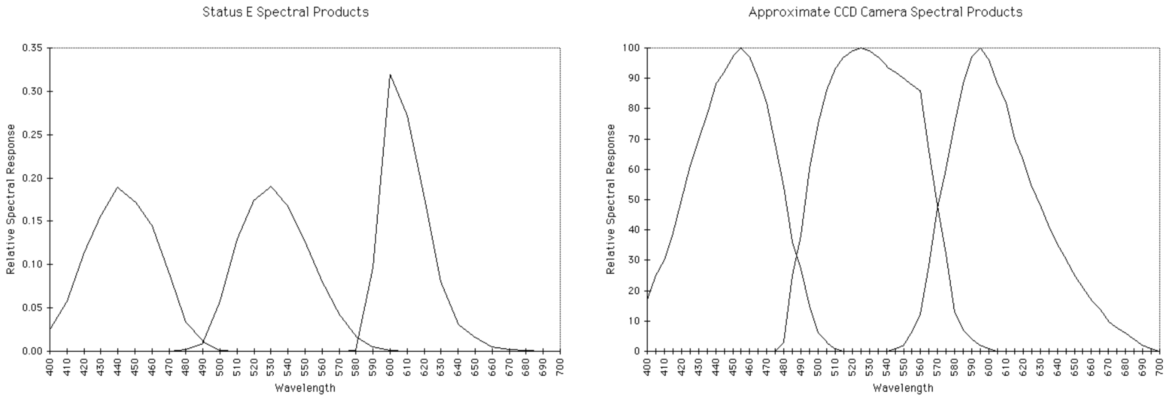

Figure 1: Status E spectral products (left), Approximate camera spectral product (right)

Although the camera and Status E responses are similiar, there are differences in both the positions of the peak sensitivities and the bandwidths. These differences would not be significant if we were only measuring neutral objects however, we are measuring colored inks whose spectra vary throughout the visible spectrum. To illustrate the resulting effect, the Status E and camera red channel spectral products along with the spectral reflectance of a cyan ink are presented in Figure 2 (left). In the wavelength region where the camera is “seeing” the sample, and the densitometer is not (540 - 580nm), the spectrum of the ink is decreasing, and will therefore increase the mean reflectance, or decrease the mean density, of the values obtained with the camera. Our results indicate that this effect does decrease the “wanted” densities to some degree through each of the channels. This effect is even more pronounced in the “unwanted” densities. From Figure 2 (right), it can be seen that in the region between 540 - 580nm the spectrum of the magenta ink is rapidly increasing, which produces a large decrease in the mean reflectance, or increased density, in the magenta ink red filter density. These errors in the “unwanted” densities are of concern in the calculation of trapping values.

3.3 Densitometric: Transformation

The densitometric transformation approach is essentially a result of predicting spectra from the color transformations rather than XYZ tristimulus values. The results presented under this method are simply the densities calculated from the spectra obtained from the color transformations presented in section 3.1.

4 EXPERIMENTAL

Two trial press runs were conducted to generate prints for use in the experimental investigations. Each trial press run was conducted at WIFAG, Bern. The press runs were performed on separate occasions to produce test sets that would be representative of day to day variations that may be experienced in a production environment. Typical day to day variations are considered to be those variations resulting from slight changes in printing conditions, and batch to batch, or lot to lot changes in ink and paper. During the test printing the registration was first adjusted to within an acceptable level. The densities were then adjusted to 0.90D (CMY) and 1.10D (K). These densities were obtained using a densitometer with Status E response and a polarizing filter as specified by IFRA. From this *normal printing condition* each color was systematically adjusted to achieve 6 different inking (density) levels. This produced a range

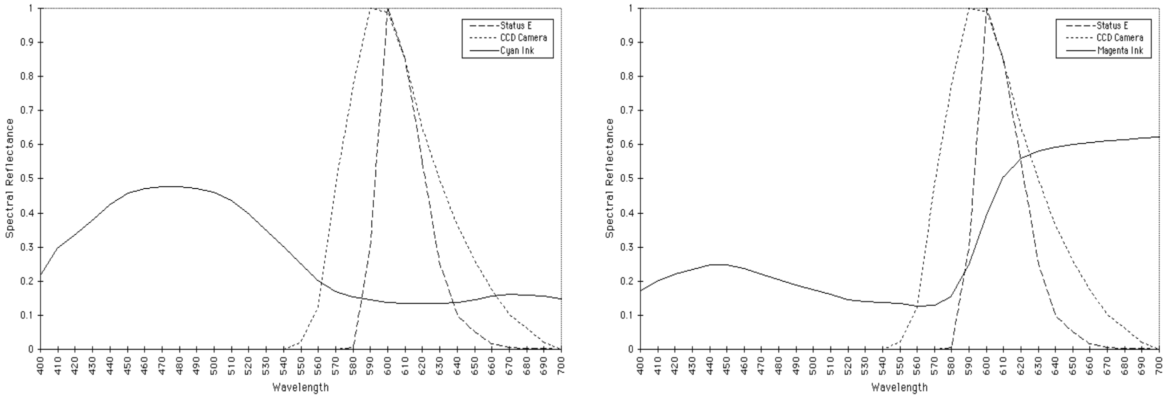

Figure 2: Red channel spectral products of Status E and camera, Cyan Ink (left), Magenta Ink (right)

of densities for each color of approximately 0.20D. After each inking level adjustment, the press was allowed to run for approximately 150 impressions before 20 sample prints were collected. From each inking level one sample print from the 20 collected was removed for evaluation producing a total of 25 sample prints (6 inking levels, 4 colors, 1 normal printing condition) from each press run.

For each print the spectral reflectance factor of the calibration set, which contains paper, CMYK solid and 25%, 50% and 75% halftone tints, RGB solid and 50% halftone overprints, and three-color solid and mid-tone overprints were measured using a Gretag SPM 100-II spectrophotometer. This instrument has 45/0 geometry, a circular 3.5mm aperture, a daylight filtered tungsten source, and a 10nm half-height bandwidth. The measurements were made over a black matte backing. One measurement was made on each color patch producing a spectrum from 380-730nm. Tristimulus values were calculated using ASTM tristimulus weights [8] under the conditions of CIE 1931 standard observer, and D50 illumination. Status E densities were calculated using ISO weights [7].

The RGB values were obtained from a standard 8-bit 3-CCD camera mounted onto a standard microscope. The camera white point was adjusted until a pressed barium sulphate tablet yielded gray level values that were approximately equal for each channel, and in the range of 225 - 235. The raw RGB values were transferred to a frame grabber from which the output was obtained via an Adobe Photoshop Plug-In. The raw RGB camera values were converted to reflectances according to equation 1. Density values measured directly with the camera were obtained by taking the negative logarithm base 10 of the reflectances obtained from equation 1. All calculations were performed by programs written in MATLAB. The use of equation 1 assumes that the gamma of the camera is unity (linear response). Cameras for scientific applications are typically designed to produce output that is linear with respect to reflectance. However, in many cases the camera response will only be linear over some range of reflectances. The linearity of the camera RGB values with respect to reflectance over the range of reflectances experienced in newspaper printing was confirmed prior to this investigation.

$$R = \frac{Dc - Df}{Dp - Df} \tag{1}$$

where: Dc = measured camera value
Df = dark frame (camera noise)
Dp = measured camera paper value
R = computed reflectance value

5 RESULTS AND DISCUSSION

5.1 Colorimetric

The results of the color transformations are presented in terms of the mean and maximum ΔE^*_{ab} values. The CIELAB values used in the ΔE^*_{ab} calculations were calculated from the XYZ tristimulus values relative to the paper. Thus the XYZ tristimulus values of the paper are represented as Xn, Yn, Zn, in the calculations.

The results of the polynomial transformations are presented in Table 1. The most suprising result is how well the first- order transform performed. Although the maximium values are slightly higher than desired, the mean ΔE^*_{ab} values are quite good. The second-order transform performed, as expected, better than the first-order with a mean ΔE^*_{ab} within measurement error. A comparison of the results between Procedures 1 & 2 indicate a similiar type of trend as reported by Seymour [4]. The first-order matrix achieved the same mean ΔE^*_{ab} value for both procedures, while the second-order matrix results under Procedure 2 are significantly higher than Procedure 1, although they are both quite acceptable.

Condition	Stats.	Procedure 1	Procedure 2	Procedure 3	Q-60 Target
First-order	Mean	1.90	1.90	1.76	2.00
	Max.	6.86	7.04	5.99	5.11
Second-order	Mean	0.77	1.21	1.24	1.58
	Max.	3.77	6.33	4.94	4.04

Table 1: Results of polynomial transformations

One would expect that the more terms used the better the results should be. Intuitively this is true, however, by adding too many terms one now has a calibration describing the calibration set very well, but one which is unable to predict the color values of prints that are not of the same type. The results of Procedure 3 are also quite encouraging as there is little increase in mean ΔE^*_{ab} between procedures 2 & 3 for the second-order model, with the mean actually decreasing for the first-order model. This would indicate that the transformation is robust enough to handle day to day changes in operating conditions and recalibration is therefore only necessary when major changes are introduced into the process.

In each of the three procedures used to evaluate the color transformations only the color patches contained within the calibration set have been used as test patches. If we were only interested in measurements of the primary colors (CMYK) and their various overprint combinations this evaluation would be sufficient. However, if a CCD camera is to be used for intra-image color measurements, colors outside the calibration set must also be accurately predicted or the calibration set must be enlarged. To evaluate the ability of the models to predict colors outside the initial calibration set 221 patches of a Kodak Q-60 target have been measured according to the procedures described in the experimental section. Each model was calibrated on the same sample print, which was used in Procedure 2 (Test run 1, normal printing conditions). The results are presented in the last column of Table 1. The first-order model mean ΔE^*_{ab} increases by only 0.10, while the second-order model increases by 0.34. Both of the results are quite acceptable, and further present the generality of the model/calibration set combinations.

		3-Term Model			6-Term Model			9-Term Model		
# Basis	Stats	P1	P2	P3	P1	P2	P3	P1	P2	P3
3	Mean	1.71	1.97	1.77	2.15	2.62	2.57	2.11	2.55	2.53
	Max.	4.20	4.86	5.12	7.32	7.24	7.35	8.19	12.79	9.03
4	Mean	1.57	1.85	1.69	1.09	1.51	1.46	1.10	1.69	1.62
	Max.	3.65	4.75	5.13	4.41	5.98	6.29	4.50	8.01	5.52
5	Mean	1.57	1.85	1.69	1.04	1.44	1.35	0.86	1.44	1.40
	Max.	3.66	4.78	5.17	4.36	5.82	6.08	3.93	7.20	5.26
6	Mean	1.57	1.85	1.69	1.03	1.42	1.33	0.82	1.41	1.36
	Max.	3.66	4.78	5.17	4.43	5.89	5.71	3.99	7.26	5.10

Table 2: Results obtained from spectral decomposition

The results of the spectral decomposition for different combinations of number of basis spectra and order of terms in the RGB density to concentration transformation are presented in Table 2. In all cases the results indicate that the mean ΔE^*_{ab} values decrease, or stay the same, with increasing number of basis spectra. The difference between 5 and 6 basis is negligible. The difference between 4 and 5 vectors is quite small for Procedure 1, but slightly larger for Procedures 2 & 3. Either 4 or 5 basis spectra can be used to obtain sufficient accuracy. For Procedure 1, with the exception of the 3 basis condition, the mean ΔE^*_{ab} values decrease with increasing number of model terms as expected, with the minimium ΔE^*_{ab} an acceptable 0.82. The results from Procedures 2 & 3 indicate a similiar trend as seen in the results of the polynomial modelling. While a six-term model improves the results over a three-term model, which would be expected based on the broadband spectral responses of the camera, and use of integral reflection densities, a further increase in terms actually increases the mean ΔE^*_{ab} values particularly for Procedure 3. This result indicates that although a higher order, or higher term, model improves the results for the calibration set, the generality of the transformation will be less than a transformation with fewer terms and slightly less accuracy for the calibration set. In this work the generality of the model to typical production variations in ink/paper combination is an important criterion.

This result is also seen to a larger extent when the above conditions are used to predict colors outside the initial calibration set. The results of color predictions for the 221 color patches of a Q-60 target previously described are presented in Table 3. The same trends can be seen as in Procedures 2 & 3, however, they are more pronounced. Based on the results, we conclude that a six-term RGB density to concentration transformation and 5 basis spectra produce an acceptable level of accuracy and robustness. The spectra obtained under this condition will be used in the following discussions on densitometric transformations.

# Basis	Stats.	3-Term Model	6-Term Model	9-Term Model
3	Mean	2.35	2.63	2.73
	Max.	5.88	5.60	7.10
4	Mean	2.35	2.08	2.33
	Max.	5.88	4.24	5.71
5	Mean	2.35	1.95	2.14
	Max.	5.88	4.31	5.45
6	Mean	2.35	1.92	2.12
	Max.	5.88	4.30	5.47

Table 3: Results of spectral decomposition applied to Q-60 color patches

5.2 Densitometric

To evaluate the ability of the camera to calculate densities in correspondence with a densitometer (Status E), the densities obtained from the negative logarithm base 10 of equation 1 were compared with the corresponding Status E densities calculated as described in the experimental section. For each ink (CMYK) the mean deviation of the absolute values between measured and calculated for each set of patches (25%, 50%, 75%, solid) was used as a measure of goodness. The results are presented in Table 4.

Color	DR	DG	DB	DV
Cyan	**0.008**	0.032	0.010	0.096
Magenta	0.067	**0.022**	0.028	0.169
Yellow	0.006	0.008	**0.013**	0.016
Black	0.023	0.026	0.036	**0.032**

Table 4: Densitometric results obtained from direct measurements

The results indicate that the CCD camera is capable of measuring the densities of the primary inks through the corresponding complementary filter, visual filter for black, in correspondence with a traditional densitometer, and within the specifications for newspaper printing. However, this is not the case for the densities of the primary inks measured through non-complimentary filters. Evaluations of the raw data indicate that the errors are similiar to those which would be expected based on the differences in spectral products as discussed in section 3.3. Similiar results have been reported by Seymour [3], who used a polynomial fit between densities calculated with the CCD, and a densitometer to alleviate this problem. One of the clear advantages of measuring densities directly with a standard camera is the need to only acquire two measurements (white point and dark frame) to calibrate the instrument. Because we are also interested in obtaining colorimetric values, which as previously discussed require an empirical transformation, we have decided to use the results of the color transformations (section 3.1) to also calculate densities. The results obtained from the spectra of first-order, second-order, and spectral decomposition models are presented in Table 5.

	First-order				Second-order				Spectral Decomp.			
Color	DR	DG	DB	DV	DR	DG	DB	DV	DR	DG	DB	DV
Cyan	**0.034**	0.017	0.007	0.006	**0.006**	0.005	0.006	0.005	**0.004**	0.004	0.005	0.006
Magenta	0.019	**0.018**	0.010	0.006	0.005	**0.007**	0.006	0.005	0.003	**0.005**	0.005	0.004
Yellow	0.016	0.012	**0.009**	0.006	0.004	0.005	**0.006**	0.005	0.005	0.004	**0.006**	0.004
Black	0.021	0.027	0.035	**0.025**	0.013	0.012	0.014	**0.013**	0.012	0.011	0.007	**0.009**

Table 5: Densitometric results obtained from color transformations (Procedure 1)

The densities calculated from the first-order spectra are in general better than those obtained from the camera directly, but still not acceptable. The densities calculated from the second-order transformation and the spectral decomposition are quite good, with deviations only above 0.01D for the black ink. The densities reported in Table 5 were calculated from the spectra obtained from application of Procedure 1. While the results indicate that this method works quite well for the calibration set, it must also calculate densities accurately for inking levels not contained within the calibration data set. The results of densities calculated from application of Procedure 3 to the spectra obtained from the second-order polynomial and the spectral decomposition are presented in Table 6. Although the results are higher than those of Procedure 1, they are quite acceptable.

	Procedure 2				Procedure 3			
Color	DR	DG	DB	DV	DR	DG	DB	DV
Cyan	**0.015**	0.009	0.007	0.010	**0.012**	0.008	0.005	0.009
Magenta	0.009	**0.012**	0.008	0.008	0.012	**0.013**	0.005	0.007
Yellow	0.011	0.010	**0.011**	0.011	0.012	0.012	**0.009**	0.012
Black	0.018	0.014	0.014	**0.012**	0.017	0.013	0.014	**0.012**

Table 6: Densitometric results obtained from second-order and spectral decomposition models

6 CONCLUSIONS

Several methods have been evaluated for converting the RGB camera values from a standard 8-bit 3-CCD camera to densitometric and colorimetric values. The results of the color transformations indicate that while both the first and second-order polynomial models performed well, the second-order produced the lowest mean ΔE^*_{ab} value for all three evaluation procedures, and the results are well within published tolerances. The spectral decomposition method produced results close to those of the second-order polynomial when a six-term second-order model was used to relate camera RGB densities to concentrations, and five basis spectra. The results also indicate that while higher-order, or higher term, polynomials can predict the calibration set more accurately, they are less general then lower order, lower term, models for predicting colors outside the calibration set.

Of the two methods used for calculating Status E densities, the more desirable method (Direct measurement) was able to measure the densities of the primary inks through the complimentary filters accurately, however, this was not the case for the primary ink densities measured through the non-complimentary filters, which are necessary for calculating attributes such as trapping. The second method which is a direct result of the color transformations, was able to accurately measure the densities of all primary colors through all filters accurately when either the second-order polynomial or spectral decomposition method was used for the color transformation.

The results of the color transformations applied to both colorimetric and densitometric values indicate that the second-order polynomial and the spectral decomposition methods are robust with respect to day-to-day variations that may be experienced in a production environment, and therefore may only require recalibration when significant changes have been introduced into the process.

References

[1] Malmgvist, K., Bergman, L., Buck, H., Malmqvist, L., "The 3-colour CCD camera as a densitometer for measuring density of cyan, magenta and yellow in printed solid areas and in screen areas", *Proceedings of the 22nd IARIGAI Research Conference, Munich, Germany, 1993*, pp. 342-351

[2] Södergård, Caj, Lehtonen, T., Launonen, R., Äikäs, J., "A System for Inspecting Colour Printing Quality", *1995 TAGA Proceedings*, pp. 620-634

[3] Seymour, John, "The why and the how of video based on-line densitometry", *IS&T's Fourth Technical Symposium on Prepress, Proofing, and Printing*, 1995

[4] Seymour, John, "Why do color transforms work", *IS&T's 49th Annual Conference*, 1996

[5] Kang, Henry R., "Color Scanner Calibration of Reflected Samples", *1992 SPIE Color Hardcopy and Graphic Arts SPIE Vol.1670*, pp. 468-477

[6] Viggiano, J.A.S., Wang, J., "A Novel Method for Colorimetric Calibration of Color Digitizing Scanners", *1993 TAGA Proceedings* pp. 143-160

[7] 1993 *International Organization for Standardization - Photography - Density measurements - Part 3: Spectral Conditions*, Item of Work 110.2 ISO/TC 42

[8] "Standard test method for computing the colors of objects by using the CIE system ", ASTM Designation:E308, American Society for Testing Materials, Philadelphia, Pennsylvania (1990)