Color Measurement of Printed Textile using CCD Cameras

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Abstract

Automated visual inspection of industrial textile printing has the potential to increase the overall print quality. In this article, we investigate whether all printed colors can be detected by CCD cameras and determine the color measurement precision.Occurring deviations in color values of homogenouesly colored textile patches are explained by the dichromatic reflection model. An extra clue is given for color inspection based on body and surface reflection invariance, inspection of the color component hue is useful as it is insensitive to texture and highlights. Experimental results show that a trade-off exists between selection of the color-matching matrix: A calibrated matrix allows color detection with higher accuracy then a default transformation matrix. However, the use of such calibrated matrix prevents detection of a broad spectrum of colors.

1 Introduction

We investigate the possibility to inspect textile color printing with cyan (C), magenta (M), yellow (Y) and black (K) inks using CCD cameras. Automatic visual inspection of industrial textile printing has the potential of increasing the overall print quality by reducing the amount of second quality printed textile. Questions that are to be answered are 1) Can all printed colors composed by CMYK inks be detected with CCD cameras? 2) What is the color measurement precision? Experiments are carried out with different C, M, Y and red (R), green (G) and blue (B) color filters.

Although several textile inspection machines are already being offered commercially, the image processing methods used remain undisclosed. A number of articles [1] [2] [3] [4] is published over the years which survey publications, reports, and articles dealing with automated visual inspection for industry. Articles appearing in *open* literature concerning the inspection of color printing (Which camera and filters? Which illuminant? Which precision to detect colors? etc.) of textile are rare. Norton-Wayne, Bradshaw and Jewell [5] inspect rolls of web textile fabric using grey-level imaging. The presence of a defect causes the received signal to rise or fall momentarily, and the resultant peaks or thoughs are detected by thresholding. Sodergard, Launonen and Aikas [6] inspect paper printing. Target colorimetric CIE-values for grey balance and critical colors are determined from the image originals. Their results show that color calibration of the inspecting camera enables the system to compare the colors of the scanned image original with the printed colors.

Conventional color CCD cameras have associated color matching matrices. The use of RGBCMY filters however requires that the camera output is calibrated since no default color matching matrix exists for these filter configurations. In Section 3 we calibrate and thereby optimize the conversion from the camera output into CIELAB space. The performance of such camera configurations is then compared to color data obtained by a spectophotometer. It is then possible to determine whether all printed colors can be detected by the calibrated CCD camera and with what precision. The output of a CCD camera for a color sample depends on illumination, the spectral reflectances of the observed web and the scene geometry. In addition, the information provided is complex due to highlights and other phenomena. In order to understand how light, object and sensor create an image, an imaging system needs a model of the way light interacts with the world. Therefore, the dichromatic reflection model is discussed in Section 4.1 to explain the observed color variations in an image, while Section 4.2 reports experiments with the hue color feature which is insensitive to surface reflection properties. In Section 5, we determine whether all printed colors can be detected by a CCD camera. In a practical inspection setting, a golden standard is required specifying the reference values that the camera output is compared to. Given such synthetic representation of a color sample, an attempt is made to determine the relationship between synthetic CIELAB values and CIELAB values observed by the CCD camera. Section 6 summarizes the report.

2 Sample Image Set

256 differently colored textile samples are available which are representative for the gamut of colors realizable with CMYK inks. Two techniques are used to extract color information using CCD camera's. The sample sets obtained are refered to as set I and set II:

- Set I: A color image is created using a monochrome CCD by taking successive images while switching in optical filters having the desired transmittances. These color filters are Schott glass absorption filters, 3 mm. red (R), green (G) and blue (B), and Kodak Wratten gelatine filters, cyan 44A (C), magenta 32 (M) and yellow 12 (Y). Besides conventional RGB, the CMY filters are chosen because we will inspect colors created by CMYK inks. Camera used is 'Adimex, MX12", 1024 x 1024 pixels with build in infrared (IR) filter and extra IR suppressor Schott KG3, 3mm, with range of $0 \rightarrow 255$ per pixel.

- Set II: Another set of images is created by "Sony 3CCD, XC-003P" camera, 752 x 582 pixels with range of $0 \rightarrow 255$ per pixel.

The viewing geometry defining the angle of view relative to the angle at which the illuminating light falls on the surface is $(45/0)$, illumination is an approximation of D_{65} (average daylight).

3 Color-Matching Matrix Calibration

The Commission International d'Éclairage (CIE) is the primary organization responsible for standardization of color metrics and terminology. A colorimetry standard was first defined by the CIE in 1931 and continues to form the basis of modern colorimetry: Colored light is matched and therefore defined with a mixture of three fixed primary colors, called X, Y, Z. These primaries can be used to match all the colors we can see. CIE 1976 $L^*a^*b^*$ (CIELAB) space [7] is a non-linear mapping of XYZ color space. The L^* coordinate codes the "lightness", the (a^*, b^*) coordinates are opponent hue signals. This color space is perceptually uniform in that equal perceptual differences between colors do correspond to equal distances in CIELAB coordinates (which is not the case in XYZ space).

Before a comparison between colors can be made, it is necessary to have some means for quantifying perceived color differences. The camera output is therefore converted via the intermediate CIE XYZ space into the CIELAB color space in which color differences can be evaluated. For color CCD cameras, the conversion from linear RGB into XYZ is normally done using a default conversion (color matching) matrix. For images taken by a monochrome CCD camera with RGBCMY filters however, such standard conversion matrix does not exist. We therefore need to calibrate the camera configurations. The conversion matrices that are thus obtained are:

$$\begin{pmatrix} a_1 & a_2 & a_3 \\ a_4 & a_5 & a_6 \\ a_7 & a_8 & a_9 \end{pmatrix} \begin{pmatrix} R \\ G \\ B \end{pmatrix} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad (1)$$

$$\begin{pmatrix} a_1 & a_2 & a_3 \\ a_4 & a_5 & a_6 \\ a_7 & a_8 & a_9 \end{pmatrix} \begin{pmatrix} C \\ M \\ Y \end{pmatrix} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad (2)$$

$$\begin{pmatrix} a_1 & .. & a_6 \\ a_7 & .. & a_{12} \\ a_{13} & .. & a_{18} \end{pmatrix} \begin{pmatrix} R \\ G \\ B \\ C \\ M \\ Y \end{pmatrix} = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad (3)$$

For each equation, the RGBCMY and XYZ values are known from camera readout and spectrophotometer readout, respectively, while the a_i's are unknown. Color differences are evaluated according to:

$$\Delta E^*_{ab} = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (4)$$

At high values of chroma, the simple CIE 1976 color difference formula of Eq. 4 values color differences too strongly compared to experimental results of color perception [7]. An improved color difference formula was therefore recommended in 1994:

$$\Delta E^*_{94} = \sqrt{\left(\frac{\Delta L^*}{k_L S_L}\right)^2 + \left(\frac{\Delta C^*_{ab}}{k_C S_C}\right)^2 + \left(\frac{\Delta H^*_{ab}}{k_H S_H}\right)^2} \quad (5)$$

with

$$\Delta H^*_{ab} = \sqrt{(\Delta E^*_{76})^2 - (\Delta L^*)^2 - (\Delta C^*_{ab})^2} \quad (6)$$

$$\Delta C^*_{ab} = C^*_{ab,1} - C^*_{ab,2} \quad (7)$$

$$C^*_{ab} = \sqrt{(a^{*2} + b^{*2})} \quad (8)$$

The weighting functions use the geometric mean chroma of a colour-difference pair:

$$S_L = 1 \quad (9)$$

$$S_C = 1 + 0.045(C^*_{ab,1} \cdot C^*_{ab,2})^{1/2} \quad (10)$$

$$S_H = 1 + 0.015(C^*_{ab,1} \cdot C^*_{ab,2})^{1/2} \quad (11)$$

In the textile industry it is common practice to set the lightness parametric factor k_L to 2.

$$k_L = 2,\ k_C = k_H = 1 \quad (12)$$

3.1 Comparison of Calibration Matrices for Set I and Set II

A subset of six colors is taken to calibrate the camera configurations, the same color samples are used from set I and set II. Five color samples of the subset are chosen because they lie on the boundaries of the cluster of samples of the color atlas, an arbitrary sixth sample is taken because in the case of Eq. 3, six equations are required to solve $a_1..a_{18}$.

The average red, green, blue, cyan, magenta and yellow values of the color samples are combined with the corresponding XYZ values which are obtained a spectrophotometer. Using Singular Value Decomposition [9] (SVD), the three color matching matrices are determined as specified in Eq. 1, 2, 3.

For each type of color matching matrix, the parameters a_i are fitted by SVD. To determine the goodness-of-fit, the maximum standard deviation is given in Table 1, as well as the the mean color difference over 6 samples. We note from Table 1 that

- Color differences show a decreasing trend when evaluated by the E^*_{94} color difference formula. This becomes understandable when one looks into the details of Eq. 5. In the ΔE^*_{94} formula, high changes of chroma are reduced by the factor of $1 + 0.0045 \cdot C^*_{ab}$.

- The use of 6 samples leads to an overdetermined system of equations when solved by SVD for Eq. 1 2 and to an exact solution when solved for Eq. 3. An errorless transformation from RGBCMY to XYZ is thus possible when evaluated for ΔE^*_{76} and ΔE^*_{94}, here the color differences between spectrophotometer and camera output are zero. The difference in variances of the fitted parameters a_j is significant however. In the case of three color bands, the standard deviation is an order 20 smaller than in the case that six color bands are used. In the case that color bands RGB are used, the performance is an order 6 better than the case that CMY is used.

- The results of the Adimex RGB configuration (Camera Adimex, Eq. 1) are of the same order of magnitude as those with the Sony camera (Camera Sony, Eq. 1).

Camera	Eq.	σ_{max}	$\overline{\Delta E}^*_{76}$	$\overline{\Delta E}^*_{94}$
Adimex	1	0.027	3.4	5.0
Adimex	2	0.035	17.1	31.6
Adimex	3	0.674	0.0	0.0
Sony	1	0.009	6.1	4.1

Table 1: *For different camera types, the transformation matrices of Eq. 1, 2, 3 are computed using SVD. Shown are the standard deviation σ of a_j and mean color difference for the six calibration samples of the resulting matrices. The transformation using RGB (Eq. 1) performs better than the one using CMY (Eq. 2). An errorless transformation is possible using RGBCMY.*

Cam.	Eq.	Matr.	$\Delta E^*_{76,max}$	$\Delta E^*_{94,max}$
Adim.	1	SVD	6.5	5.6
Adim.	2	SVD	16.4	4.5
Adim.	3	SVD	105.5	65.4
Sony	1	SVD	2.9	2.6
Sony	1	NTSC	3.2	2.5

Table 2: *Color differences ΔE^*_{76} and ΔE^*_{94} are calculated for each combination of minimum quantization steps $\pm\Delta R$, $\pm\Delta G$, $\pm\Delta B$, $\pm\Delta C$, $\pm\Delta M$, $\pm\Delta Y$. Results are given for the calibrated (SVD) and default (NTSC) color matching matrices. The digital steps $\Delta RGBCMY$ are set to one. The matrix obtained for Eq. 1 shows to be the least sensitive for quantization errors, the matrix for Eq. 3 performs worst. Quantization errors for the Sony camera with default conversion matrix NTSC are of same order of magnitude as for color matching matrix determined by SVD.*

3.2 Quantization Errors

The theoretical minimum of ΔE that can be obtained by color measurements with a CCD camera is determined as follows: The color gamut is first placed within the smallest rectangular box. The edges of the box are chosen parallel to the axes of the color space being quantizised [8]. The three dimensions of the box define the ranges of the axes to be quantized in order to catch any color within the gamut. The assumed quantization defines a uniform grid of color points in the CIELAB space. Each digital step from one point of the grid to one of the neighbors produces a color difference. By converting the grid of an arbitrary color space into CIELAB coordinates, the color difference can be calculated in ΔE_{ab} or ΔE_{94} units.

When switching digitally from one quantized value of an axis to the next, or when doing the same at two or three axes altogether, one diagonal step will produce the maximum color difference. With the assumed dimensions of the quantization box put around the computer representable color gamut, this results in the maximum $\Delta E_{ab} = \sqrt{(\frac{100}{2^8})^2 + 2 \cdot (\frac{256}{2^8})^2} = 1.47$ for a *single* pixel.

To verify the performance of the calibrated matrices and the default National Television Systems Committee (NTSC) matrix (which is valid for the Sony camera only), the color differences are calculated for each combination of quantization steps. According to Table 2, the RGB configuration performs best. If we assume that quantization errors occur uniformly distributed however, the *averaged* ΔE_{ab} and ΔE_{94} could well be equal to zero.

3.3 Comparison of Default vs. Calibrated Transformation Matrices for Set II

For 99 images of set II, independent samples are taken in a 3x3 neighborhood, for which the mean $\overline{\Delta} E$ and standard deviation is computed. Table 3 summarizes the *relative* CIELAB ΔE error for different conversion matrices, individual CIELAB pixel values are compared to the average CIELAB value.

The top row shows the mean $\overline{\Delta} E_{ab}$ using the default NTSC conversion matrix. Applying the calibrated transformation matrix, $\overline{\Delta} E_{ab}$ and $\overline{\Delta} E_{94}$ drop to 3.5 and 2.2, respectively, as is shown in the bottom row. We conclude from Table 3 that

- The structure and texture of textile causes fluctuations in the intensity of the image. However, $\overline{\sigma}_{\Delta L^*}$, $\overline{\sigma}_{\Delta H^*}$ and $\overline{\sigma}_{\Delta C^*_{ab}}$ are of equal order of magnitude (ΔH^*_{ab} is *not* an angular measure). Color differences ΔE seem to be equally dependent in variances of chroma and lightness. This can be explained looking at the way L^* is computed (See [7]): Variation in L^* is reduced by $L^* \approx Y^{1/3}$, where the Y tristimulus value is correlated to intensity.
- The mean ΔE's shown in the bottom row may well depict the maximum performance of the CCD camera when calibrated assuming a linear transform exists between RGB and XYZ. The standard deviation σ is due to the texture of the material.

Table 4 shows similar results as Table 3, this time the results are obtained by comparison of pixel CIELAB values with the *absolute* CIELAB values measured by a spectophotometer. The spectophotometer values are considered as ground-truth. Again, applying the calibrated transformation matrix show a decreasing trend of ΔE. The fluctuations in intensity due to the textile texture is reduced by setting the lightness parametric factor k_L to 2.

4 Body and Surface Reflection Invariance

In the previous section, we observed that the $\sigma_{\Delta E^*}$ is caused by the texture of the textile samples. We therefore investigate color features that are invariant of surface reflection properties.

4.1 Dichromatic Reflection Model

The dichromatic reflection model applies to inhomogeneous dielectric materials and models that light reflected from an object is the sum of two components: the "body" component and the "surface" component. The terms "body" and "surface" reflection refer to different physics processes, the first being a result of phenomena which occur after penetration of the light to the material ("body"), where as the second refers to processes involving the reflection that takes place on the surface. The color term of the "body" component is a function of the spectral characteristics of the object and current illumination, and is modeled as the color of the object, where as the color term of the "surface" component is assumed to be the illuminant color. The "body" component has the diffusional characteristic of the exciting light and is usually represented by means of the Lambertian model. Lambertian surfaces are matte surfaces that remit equal luminance to all directions. The "surface" component is the specular (shiny) part of the reflected flux and is describable by a function with a sharp peak around the angle of perfect mirror reflection. [11] present experimental data to show that the model is quite reasonable for textile surface. In this paper, we focus on body reflection.

More precisely, consider an image of an infinitesimal matte (the specular term is not considered here) surface patch. Using the red, green and blue sensors with spectral sensitivities given by $f_R(\lambda)$, $f_G(\lambda)$ and

	$\overline{\Delta E}^*_{76}$	$\overline{\sigma}_{\Delta E^*_{76}}$	$\overline{\sigma}_{\Delta L^*}$	$\overline{\sigma}_{\Delta H^*_{ab}}$	$\overline{\sigma}_{\Delta C^*_{ab}}$	$\overline{\Delta E}^*_{94}$	$\overline{\sigma}_{\Delta E^*_{94}}$
NTSC	4.8	4.1	3.7	2.7	3.7	2.6	2.3
calibrated	3.5	3.1	2.8	2.0	2.4	2.2	1.9

Table 3: *Relative color differences and standard deviations for components of color difference averaged over the 99 color samples of Set II. ΔL^* denotes "lightness" difference, ΔH^*_{ab} denotes the hue difference, ΔC^*_{ab} denotes the chroma difference. Results are given for default (NTSC) vs. calibrated color matching matrix.*

	$\overline{\Delta E}^*_{76}$	$\overline{\sigma}_{\Delta E^*_{76}}$	$\overline{\Delta E}^*_{94,k_{L=2}}$	$\overline{\sigma}_{\Delta E^*_{94,k_{L=2}}}$	$\overline{\Delta E}^*_{94,k_{L=1}}$	$\overline{\sigma}_{\Delta E^*_{94,k_{L=1}}}$
NTSC	14.8	22.9	8.0	2.2	11.3	3.0
calibrated	7.3	9.7	4.3	2.0	5.2	2.4

Table 4: *Absolute color differences and standard deviations for components of color difference averaged over 99 color samples of Set II. Results are given for default (NTSC) vs. calibrated color matching matrix.*

$f_B(\lambda)$ respectively, to obtain an image of the surface patch illuminated by a spectral power distribution of the incident light denoted by $e(\lambda)$, the measured sensor values will be given by Shafer [10]:

$$C = m_b(\vec{n}, \vec{s}) \int_\lambda f_C(\lambda) e(\lambda) c_b(\lambda) d\lambda \qquad (13)$$

for $C = \{R, G, B\}$ giving the Cth sensor response of a matte, dull surface patch. Further, $c_b(\lambda)$is the albedo reflectance, λ denotes the wavelength, $\vec{n}$ is the surface patch normal and $\vec{s}$ is the direction of the illumination source. Geometric term m_b denotes the geometric dependency on the body reflection.

Considering dichromatic reflectance and "white" illumination, then $e(\lambda) = e$. The measured sensor values are then:

$$C_w = e m_b(\vec{n}, \vec{s}) k_C \qquad (14)$$

for $C_w \in \{R_w, G_w, B_w\}$ giving the red, green and blue sensor response under the assumption of a white light source. $k_C = \int_\lambda f_C(\lambda) c_b(\lambda) d\lambda$ is a compact formulation depending on the sensors and the surface albedo.

In the next section, we consider this reflection model to study invariant properties of color.

4.2 Color Inspection by Hue Metric

The purpose of [12] is to arrive at viewpoint invariant segmentation results, which are also insensitive to shadows, illumination intensity and surface reflection properties. To that end, various color features intensity (I), saturation (S) and hue (H) were theoretically analyzed for standard reflection models. It was shown that H is independent of camera viewpoint, object orientation, and direction and intensity of the illumination assuming Lambertian body reflection. Thus, assuming that light reflection of textile is in accordance with the dichromatic reflection model, the hue is an invariant for matte surfaces. This can be seen as follows. Let hue be defined by the following standard expression:

$$H = \arctan\left(\frac{\sqrt{3}(G - B)}{(R - G) + (R - B)}\right) \qquad (15)$$

computed from the red, green and blue channels of a color camera. Then hue H is an invariant for matte, dull surfaces as follows from substituting Eq. 14 in Eq. 15:

$$H(R_w, G_w, B_w) =$$
$$\arctan\left(\frac{\sqrt{3} e m_b(\vec{n}, \vec{s})(k_G - k_B)}{e m_b(\vec{n}, \vec{s})((k_R - k_G) + (k_R - k_B))}\right) =$$
$$\arctan\left(\frac{\sqrt{3}(k_G - k_B)}{(k_R - k_G) + (k_R - k_B)}\right) \qquad (16)$$

Note that the essential singularity of hue is at the origin of the RGB-color cube i.e. at R=G=B=0. Further, the hue becomes unreliable when the distance to the achromatic axis is decreased, small input variations will generate major output variations. The achromaticity can be deduced from both saturation and intensity: Low saturation implies a small distance to the achromatic axis, low intensity implies a small distance to the black point. Being undefined (R=G=B=0) or unreliable (S <threshold or I <threshold), the (almost) achromatic points cannot contribute to any analysis based upon hue as a metric.

We therefore experimented by calculating the hue under saturation and intensity imposed constraints. The results are given in Table 5, where mean hue values are given for different threshold levels. In order to compare the standard deviations of intensity (range $0 \rightarrow 255$), saturation (range $0 \rightarrow 1$) and hue (range $0 \rightarrow 359$), the deviations are scaled to $0 \rightarrow 100$. The standard deviation of hue is small, 2.3 vs. 5.1 vs. 7.3, compared to the corresponding deviations in intensity and saturation, respectively.

The experiment is repeated for hue in CIELAB color space, $h^*_{ab} = \arctan(\frac{b^*}{a^*})$. Under the constraint that $C^*_{ab} > 25$ and scaled to $0 \rightarrow 100$, the resulting

	$I(\vec{x}) > 10\%$	$I(\vec{x}) > 20\%$
$S(\vec{x}) > 10\%$	14.7	11.6
$S(\vec{x}) > 20\%$	12.7	8.2

Table 5: $\overline{\sigma}_H$ *in range of* $0 \rightarrow 359$. *Moving away from the achromatic axis by increasing saturation and intensity requirement reduces the standard deviation* σ_H *to 8.2*^{o}.

value is $\overline{\sigma}_{h^*_{ab}}$ is 2.5, which is comparable to the standard deviation of the hue in RGB sensor space. We therefore conclude that inspection of hue is useful because it is insensitive to texture and highlights.

5 Results

5.1 Can all Printed Colors be Detected by CCD Camera's?

As the optimized color matching matrix is known, it is now possible, by computation of the inverse matrix, to determine if all color samples from the color atlas can be transformed back into linear RGB values. 20 samples of the color atlas require RGB values not occurring in the lookup table. All samples have $L^* > 75$, while the hue is in the range of $5^o \rightarrow 96^o$ (orange and yellow colors).

By repeating the experiment for the inverse NTSC matrix, all CIELAB values occurring in the color atlas can be represented in the RGB color space. There is thus a trade-off between selection of the transformation matrix: A calibrated matrix allows color detection with higher accuracy then usage of a default matrix. However, a number of colors can not be represented in RGB color space using the calibrated matrix, while this problem does not occur for the default matrix.

5.2 Indication of Precision of Color Measurement using CCD cameras

Following the procedure of Sec. 5.1, it is also possible to obtain an indication of the precision of color measurement with the calibrated Sony camera. Three pairs of the textile samples and two triples of textile samples map on the same RGB value, and thus can not be distinghuised. A comparison between synthetic and spectophotometer CIELAB values is given in Table 6. As the table shows, color differences ΔE_{ab} greater then 0.6 can be detected using a calibrated transformation matrix.

5.3 Prediction of sensor CIELAB values by synthetic CIELAB specification

In a practical inspection setting, a golden standard is required specifying the reference values that the camera output is compared to. To acquire such reference to be used for color inspection, a mapping function needs to be determined which translates synthetic CIELAB values to corresponding values that will be observed by the CCD camera. However, such translation is not necessarily linear. Using SVD, a transformation matrix is determined for XYZ$_{synthetic}$ and RGB$_{measured}$. Synthetic CIELAB values can now be converted to expected RGB values. The measured RGB's are then translated using the calibrated matrix for the Sony camera, after which $\overline{\Delta}E_{94}$ between CIELAB$_{measured}$ and CIELAB$_{synthetic}$ is computed. This results in an average $\overline{\Delta}E_{94}$ of 16.6. This indicates that synthetic CIELAB values can be converted to the CIELAB values that will be measured by the CCD camera, although not very precise, because such conversion is apparantly not linear.

sample	synth. ΔE_{ab}	spect. ΔE_{ab}
95, 96	1.4	0.2
104, 105	1.4	0.6
109, 110	1.0	0.4
90, 115	1.0	0.4

Table 6: *Left column: Color blocks mapping on equal RGB values. Middle column: Color difference of blocks in synthetic representation. Right column: Color difference of blocks measured by spectophotometer.*

6 Discussion

We investigated the possibility to inspect textile printing using CCD cameras. Experiments with RGBCMY color filters to inspect colors printed by CMYK show that the RGB camera configuration outperforms those using CMY and RGBCMY filter combinations. There exists a trade-off between the type of transformation matrix to go from RGB to XYZ: A calibrated matrix allows color detection with higher accuracy then a default matrix. However, a number of colors can not be represented in RGB space using the calibrated matrix, while this problem does not occur for the default matrix. It was further shown that the hue provides an additional clue in color verification, as it is photometric invariant to texture and highlights. Finally, it was shown that determining a mapping function from synthetic CIELAB values onto CCD observed CIELAB values using SVD gives poor results, thereby indicating that no linear transformation exists.

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