Automatic Color Calibration Method for Multi-Camera System Connected on Network

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Abstract

We propose an automatic color calibration method for a multi-camera system by using colors of objects in the common view of the multiple cameras. We assume that at least one camera has already been calibrated a priori, and reflectance property is diffuse for the objects used as the calibration target in the common view. By this assumption, it is easily understood that the corresponding colors in each camera image should be independent of view point after the complete color calibrations for all the cameras. Therefore, by comparing the output of calibrated camera and un-calibrated camera for diffuse target colors, the color characteristic of un-calibrated camera can be automatically calibrated in our proposed technique. In this paper, we examined the proposed method by using two cameras as preliminary experiments. The experimental result shows the effectiveness of our proposed technique.

1 Introduction

Immersive visualization systems which use synthesized multiple images from cameras are useful for applications in various fields such as entertainment and remote learning. These systems provide us arbitrary viewpoint images of objects measured in remote place. For example, multiple cameras surrounding a football ground enables us to watch a game from arbitrary viewpoints[1]. An immersive telepresence system provides us high realistic sensation, and is useful for remote learning system to produce the reality in education[2].

In these multi-camera systems, geometric and color calibration are performed for all cameras to synthesize images seamlessly. Color calibration is important to synthesize the images naturally. Many cameras, however, do not exhibit consistent responses even if they measure the same object, and this individual difference causes color artifacts in synthetic images. Therefore, color calibration must be performed for all cameras, and it takes a lot of time and cost in case of large number of cameras.

The color calibration for a multi-camera system is usually performed with respect to known targets, such as a 24-sample *GretagMacbeth ColorChecker*^{TM}. By measuring images of a color target, the gains and the offsets of each color channel are calibrated for each camera. After adjusting the camera parameters, acquired images are processed to match their colors[3-4]. Other researchers have proposed to use statistical analysis and image correlations with real scenes[5-6]. These methods can produce reasonable results for the colors used for training data such as the color checker. However, they are not enough for applying to non-training colors since camera responses for natural scenes have high nonlinearity.

In this paper, we propose an accurate and efficient color calibration method for a multi-camera system. The proposed method can calibrate non-training colors accurately as well as the colors used for training data, since the model used for camera characterization is based on the fact that the responses of cameras can be described accurately by a nonlinear model using three principle components for the set of the camera responses[7-9].

In the next section, we will describe the details of the proposed method. The section 3 presents the experiment and its result. Finally, we discuss the experimental results, and conclude our method in the section 4.

2 Color calibration method

In the proposed method, a single camera is calibrated at first to be a reference camera. Other cameras are calibrated automatically by using colors of objects in the common view with the reference camera.

The proposed method consists of three main steps as illustrated in Figure 1: calibration of the reference camera; characteristic estimation of un-calibrated cameras; and color matching across all cameras. The overview of the proposed method is described in Section 2.1, and the detail of the each process is presented in the following sections.

2.1 System overview

In the first step, the reference camera is calibrated by measuring color patches generated by an image projector, as illustrated in Figure 1(a). Since it is necessary for accurate calibration to measure a lot of color patches, the projector is convenient to generate an arbitrary color. Moreover, the projection image is more useful for the color of a natural image in the reflected reproduction rather than self-luminous displays. This projector is controlled efficiently to derive the parameter of principle component analysis, such as basis vectors, coefficient and bias. The details of this process are described in Section 2.2.

In the second step, the color characteristics of un-calibrated cameras are estimated by using colors of objects in the common view with the reference camera as illustrated in Figure 1(b). The characteristics of un-calibrated cameras are obtained by minimizing the estimation errors. The details of this process are described in Section 2.3.

In the third step, color calibration of all cameras is performed by using the estimated characteristics as illustrated in Figure 1(c). The details of this process are described in Section 2.4.

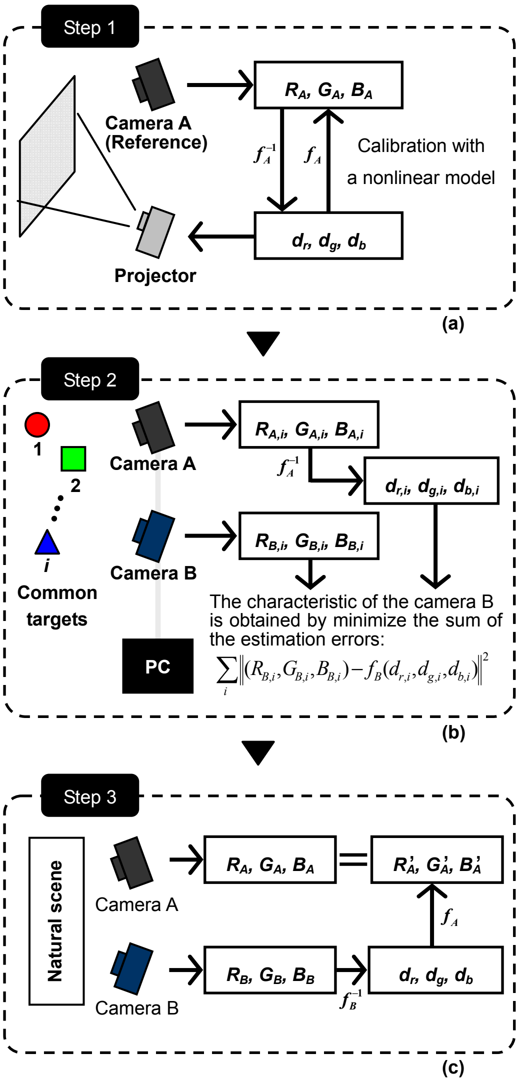

Figure 1. (a) Calibrating the reference camera by measuring color patches generated by a projector. (b) Estimation of the color characteristic of an un-calibrated camera by using common targets. (c) Color calibration of the cameras with the estimated characteristic.

2.2 Reference camera calibration

In this section, calibration of the reference camera is explained as shown in Figure 1(a). Input digital counts (0-255) for red, green and blue channels of the projector are denoted as d_r, d_g, d_b, and output signals of a camera with 8 bit are denoted as R, G, B, respectively. The distribution of R, G, B are shown in Figure 2, and when the inputs of the projector are primary colors (e.g. an input for R channel is $d_g = d_b = 0$), the responses R, G, B are distributed as shown in Figure 3. A primary principle component of the camera response with $d_g = d_b = 0$ is denoted $\boldsymbol{p_r}$ and written by following equation

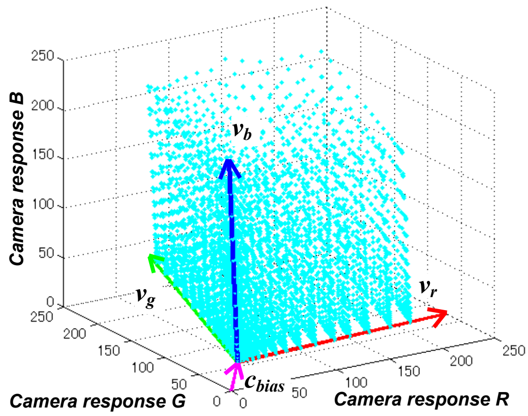

Figure 2. Distribution of camera responses.

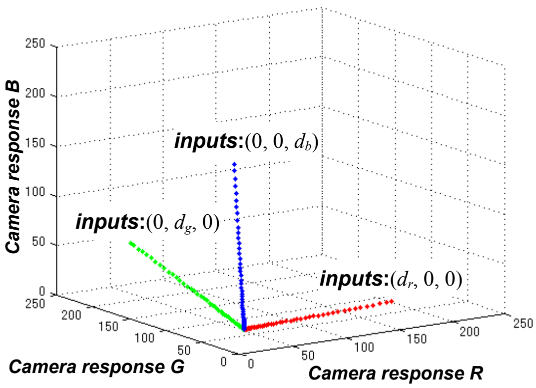

Figure 3. Distribution of the camera responses when the inputs of the projector are primary colors.

$$\boldsymbol{p}_r = c_r(d_r)\,\boldsymbol{v}_r + \boldsymbol{c}_{bias}, \qquad (1)$$

where c_r is a function of the score of the primary principle component corresponding to basis vector $\boldsymbol{v}_r$ and $\boldsymbol{c}_{bias}$ is the camera response where digital counts equal to 0, respectively. Similarly, other channels are also described as

$$\boldsymbol{p}_g = c_g(d_g)\,\boldsymbol{v}_g + \boldsymbol{c}_{bias}, \qquad (2)$$

$$\boldsymbol{p}_b = c_b(d_b)\,\boldsymbol{v}_b + \boldsymbol{c}_{bias}. \qquad (3)$$

Therefore, from Equation (1), (2), (3) and Figure 2, the responses of the camera R, G, B are described as

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = c_r(d_r)\,\boldsymbol{v}_r + c_g(d_g)\,\boldsymbol{v}_g + c_b(d_b)\,\boldsymbol{v}_b + \boldsymbol{c}_{bias}$$

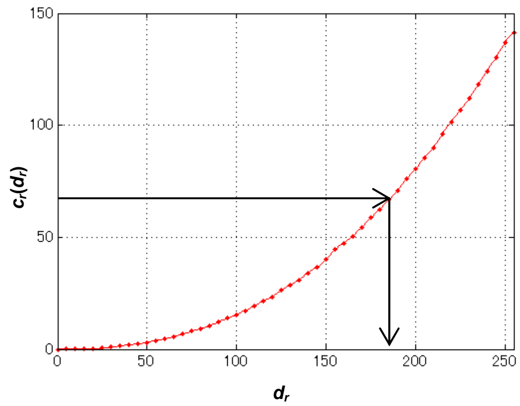

Figure 4. Primary principle component score $c_r(d_r)$ with respect to the corresponding input d_r.

$$= \mathrm{V}\begin{bmatrix} c_r(d_r) \\ c_g(d_g) \\ c_b(d_b) \end{bmatrix} + \boldsymbol{c}_{bias}, \qquad (4)$$

where $\mathrm{V} = [\boldsymbol{v}_r\ \boldsymbol{v}_g\ \boldsymbol{v}_b]$. The score $c_r(d_r)$ corresponding to an arbitrary d_r can be obtained by spline interpolation to the plot of $c_r(d_r)$, with respect to the corresponding input d_r as illustrated in Figure 4. Similarly, $c_g(d_g)$, $c_b(d_b)$ can be obtained. The inverse transform is written as

$$\begin{bmatrix} c_r(d_r) \\ c_g(d_g) \\ c_b(d_b) \end{bmatrix} = \mathrm{V}^{-1}\left(\begin{bmatrix} R \\ G \\ B \end{bmatrix} - \boldsymbol{c}_{bias}\right). \qquad (5)$$

where d_r, d_g, d_b are obtained from Figure 4.

2.3 Characteristic estimation

As illustrated in Figure 1(b), training data for an un-calibrated camera are obtained by measuring common targets. It is noted that the characteristic of the un-calibrated camera is obtained by estimating the basis vectors, the score curves and the bias. These are denoted as model parameters. The responses of the reference camera are transformed to corresponding inputs of the projector $d_{r,i}$, $d_{g,i}$, $d_{b,i}$, where i represents the ith common target. The corresponding response of the un-calibrated camera is denoted as R_i, G_i, B_i, and estimated R_i, G_i, B_i from $d_{r,i}$, $d_{g,i}$, $d_{b,i}$ are denoted as $\hat{R}_i$, $\hat{G}_i$, $\hat{B}_i$, respectively. The inputs of the projector $d_{r,i}$, $d_{g,i}$, $d_{b,i}$ can be regarded as invariant in both cameras. Therefore, the characteristic of the

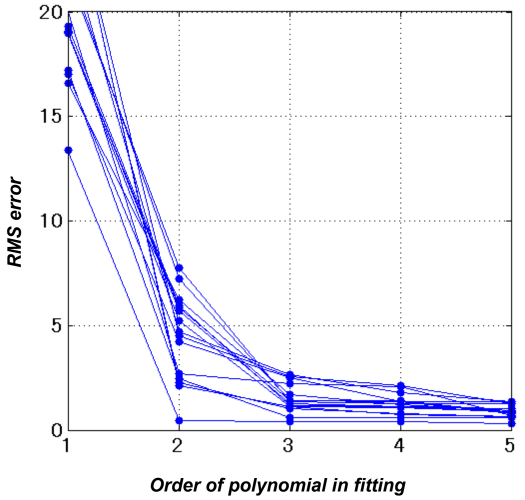

Figure 5. The RMS errors between the measured score curves and the fitted curves.

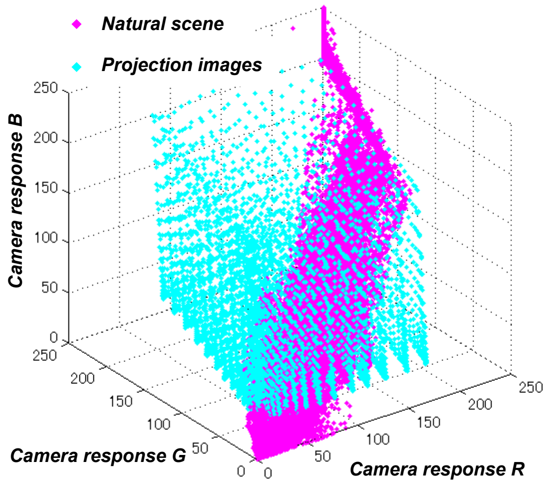

Figure 6. Distribution of camera responses.

un-calibrated are obtained by minimizing the sum of the estimation errors as follows

$$\sum_i \left\| \begin{bmatrix} R_i \\ G_i \\ B_i \end{bmatrix} - \begin{bmatrix} \hat{R}_i \\ \hat{G}_i \\ \hat{B}_i \end{bmatrix} \right\|^2 ,$$

$$\begin{bmatrix} \hat{R}_i \\ \hat{G}_i \\ \hat{B}_i \end{bmatrix} = \mathrm{V} \begin{bmatrix} c_r(d_{r,i}) \\ c_g(d_{g,i}) \\ c_b(d_{b,i}) \end{bmatrix} + \boldsymbol{c}_{bias} . \qquad (6)$$

The optimization to minimize Equation (6) is performed for the model parameters under the following constraints and assumptions to obtain a better result easily:

- The differences of the model parameters are assumed to be small between the reference camera and an un-calibrated camera. Therefore, the parameters of the reference camera are used as an initial estimation values.
- The norms of basis vectors are 1 (i.e. $\|\boldsymbol{v}_r\| = \|\boldsymbol{v}_g\| = \|\boldsymbol{v}_b\| = 1$).
- The score curves are monotonically increasing functions.
- Each element of basis vector $\boldsymbol{v}_r$, $\boldsymbol{v}_g$, and $\boldsymbol{v}_b$ is a positive number.
- The score curve showed in Figure 4 can be approximated by a polynomial.

We used cubic functions for the approximation. Figure 5 shows the RMS errors between the measured curves and the fitted curves. It is also assumed that $c_r(0) = c_g(0) = c_b(0) = 0$, then the score curves are given as

$$c_r(d_r) = s_r d_r^3 + t_r d_r^2 + u_r d_r , \qquad (7)$$

$$c_g(d_g) = s_g d_g^3 + t_g d_g^2 + u_g d_g , \qquad (8)$$

$$c_b(d_b) = s_b d_b^3 + t_b d_b^2 + u_b d_b , \qquad (9)$$

where s, t and u denote constant numbers.

2.4 Color matching for natural scenes

In this section, color matching across cameras is explained as illustrated in Figure 1(c). By using the estimated characteristic in the previous section, colors of the cameras are calibrated. The responses of the characterized camera are transformed to the inputs of the projector, $d_{r,i}$, $d_{g,i}$, $d_{b,i}$. The calibrated image can be obtained by using the characteristic of the reference camera.

The proposed method can match the colors inside the region showed in Figure 2. This region represents the responses of the reference camera corresponding to projection images. However, camera responses corresponding to natural scenes have wider range in the color space as shown in Figure 6. Therefore, by using the characteristic of the reference camera, the colors out of the region are approximated by the nearest colors which minimize the estimation error E as follows

$$E = \left\| \begin{bmatrix} R \\ G \\ B \end{bmatrix} - \mathrm{V} \begin{bmatrix} c_r(d_r) \\ c_g(d_g) \\ c_b(d_b) \end{bmatrix} + \boldsymbol{c}_{bias} \right\|^2 . \qquad (10)$$

3 Experiments and its results

In our experiment, two different cameras are used. One is a 3CCD camera (JK-TU52H, TOSHIBA) and another is a CMOS camera (LU170C, Lumenera). The *GretagMacbeth ColorChecker*^{TM} is used as the common target.

First, we calibrated the 3CCD camera with a projector (EMP-TW200H, EPSON) for a reference. The model parameters are obtained by measuring 154 colors, where the inputs of the projector d_r, d_g, d_b are from 0 to 255 in 5 interval.

Next, we evaluate the accuracy of the calibration for the CMOS camera with a natural scene image including the color checker. Figure 7(a) shows the image of the reference 3CCD camera. The characteristics of the CMOS camera are estimated by using only nine training data on the color checker. These colors are white, black, red, green, blue, yellow, magenta, cyan and gray (neutral 6.5). It is assumed that the positions of the color patches are known. Figure 7(b), (c) show the images of the CMOS camera before or after the color calibration.

The results showed that the proposed method could calibrate color patches which are not used for the calibration as well as the nine training data. Figure 7(d), (e) show the color differences ΔE^*_{94} of all patches on the color checker, the average color difference and the maximum color difference before or after the color calibration. The results showed that the average color difference is 2.1. In general, the empirically acceptable average color difference is approximately 2.5, and the maximum color difference is approximately 3.0 in printing industry [10-11]. Moreover, the colors around the color checker were also calibrated accurately since the estimated basis vectors, the score curves and the bias describe these colors accurately.

4 Conclusions

In this paper, we proposed an accurate and effective color calibration method for a multi-camera system. By measuring the color patches generated by a projector, a reference camera is calibrated accurately with a nonlinear model using three principle components for the set of the camera responses. The score plots for the primary principle components in red, green and blue channels are approximated by cubic functions to simplify the estimation of characteristics in un-calibrated cameras. Then, the un-calibrated cameras are characterized by minimizing the estimation errors of camera responses of objects in the common view with the reference camera. The proposed method can calibrate non-training colors accurately as well as the colors used for estimation by estimating the parameters of the model.

The proposed method was examined by using two different cameras, and the average color difference ΔE^*_{94} was 2.1. The result indicated that the proposed method could calibrate cameras with enough accuracy.

The limitation of this work is that cameras except the reference have to be calibrated again when the lighting conditions change dramatically. The proposed method does not consider spectral information which can not be described by three principle components. Therefore, it is necessary for calibrating all colors under arbitrary environments to use multiband camera and so on.

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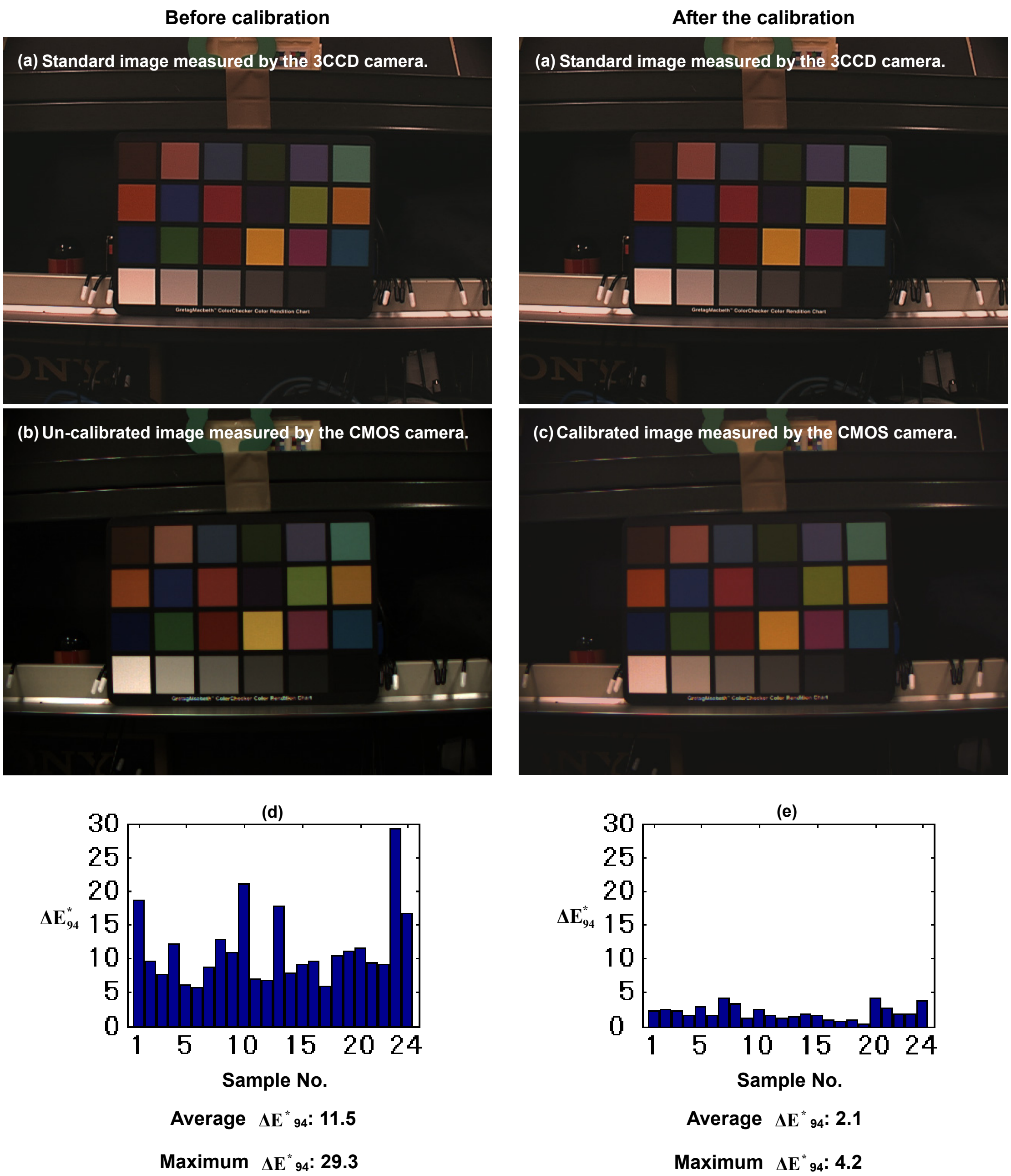

Figure 7. (a) The color checker image of the reference 3CCD camera. (b) The image of the CMOS camera before color calibration. (c) The image of the CMOS camera after the color calibration. (d) The color differences ΔE^*_{94} of all patches on the color checker, the average color difference and the maximum color difference before color calibration. (e) The color differences ΔE^*_{94} of all patches on the color checker, the average color difference and the maximum color difference after the color calibration.

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