This paper proposes a new color calibration method for multi-camera systems with a novel omnidirectional color checker. The designed cylindrical color checker contains a periodic array of color patches, and is visible for all the cameras without manual adjustment. For color calibration, accurate global correspondences are first generated by local descriptors and area-based correlation methods. Then, the multi-camera color calibration problem is formulated as an overdetermined linear system, in which the dynamic range shaping is incorporated to ensure the high contrasts of captured images. The cameras are calibrated with the parameters obtained by solving the linear system. According to experimental results on a real multi-camera system, the proposed method shows high performance in achieving inter-camera color consistency and high dynamic range.

Index Terms— Color calibration, multi-camera system, color checker, color consistency, dynamic range

1. INTRODUCTION

High quality multi-camera imaging demands consistent color responses of cameras. Vedula et al. [1] point out the artifacts for view interpolation if the colors of multi-camera images are not consistent. This inconsistency is mainly due to aperture and fabrication variations, electrical noises, and so on. Therefore, color (or radiometric) calibration is required to ensure the inter-camera color consistency. However, less attention has been paid to color calibration than to geometric calibration for multi-camera systems [2, 3].

A common method is to self-calibrate each camera using gain and white balance adjustment algorithm with the help of a standard color checker, such as the 24-patch GretagMacbeth ColorChecker™ chart[4]. Joshi et al. [5] propose the first inter-camera color calibration method using the color checker for their light field camera array system. Based on that, Ilie et al. [6] develop an iterative closed-loop on-camera calibration method by minimizing the color differences among cameras, followed by a post-processing refinement. Both the two methods can achieve inter-camera color consistency, but are mainly developed for planar systems, e.g., the light field multi-camera arrays, in which a planar color calibration target is visible for all the cameras. To realize the inter-camera color consistency for non-planar multi-camera systems, Unal et al. [7] combine the multi-view stereo technique with camera calibration (geometric and color calibration). However, this method mainly considers the estimation of distortion parameters of cameras, and does not give enough results for color calibration. Yamamoto et al. [8] also try to realize inter-camera color consistency for non-planar multi-camera systems without the standard color checker. This method only focuses on post-processing after acquisition, and does not involve on-camera adjustment. Moreover, human intervention is required to choose one reference camera so that the other cameras can be corrected to have similar colors with the reference camera.

In this paper, we propose a novel color calibration method using a designed omnidirectional color checker for multi-camera systems. Accurate global correspondences are first generated by local descriptors and area-based correlation methods. Then, the multi-camera color calibration problem is formulated as an overdetermined linear system. The proposed method achieves inter-camera color consistency and high contrasts of all the cameras simultaneously.

The remainder of this paper is structured as follows: Section 2 describes the designed omnidirectional color checker, and Section 3 details our automatic color calibration method. Validation experiments and results are presented in Section 4. The paper is concluded in Section 5.

2. THE OMNIDIRECTIONAL COLOR CHECKER

The GretagMacbeth ColorChecker™ chart with 24 patches [4] is widely used in color calibration for a single camera or a planar multi-camera array. However, for non-planar multi-camera systems, cameras cannot be calibrated simultaneously because the color patches on the color checker are not visible for all the cameras. Therefore, human intervention is needed to change the direction of the color checker, and each camera is calibrated separately as a single camera without the inter-camera color consistency.
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<th>123</th>
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<td>53</td>
<td>31</td>
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</tr>
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Table 1: Color values of patches on the color checker.

Fig. 1: Omnidirectional color checker.

To calibrate multi-camera systems (not limited to planar multi-camera arrays) without manual operations, we design a novel omnidirectional color checker, which is simultaneously visible for all the cameras. As shown in Fig. 1, 160 (8 × 20) patches are printed on a paper, which is rolled into a cylinder. The diameter of the cylinder can be flexibly adjusted. This checker has a moderate red background and Lambertian reflectance. Each column contains eight patches, seven of which are printed with achromatic colors (gray scales) to avoid the color cast. The 8th patch (bluish green) is reserved for future work. The color values of the color patches are detailed in Table 1.

3. PROPOSED COLOR CALIBRATION METHOD

In our method, global correspondences of color patches are first established by an automatic feature detecting and matching method. Then, given the global correspondences for all the cameras, the color calibration problem is formulated as an overdetermined linear system to ensure the inter-camera color consistency and high dynamic range.

3.1. Automatic Establishment of Global Correspondences

Feature detection is important in finding the correspondences among multi-view images. In our method, the robust Scale-Invariant Feature Transform (SIFT) local descriptors [9] and the area-based correlation methods are first used to detect and match the feature regions in pairs. Then, global correspondences are generated by threading the pair-by-pair matches.

The input consists of \( N \) images, \( \{I_n\}_{1 \leq n \leq N} \), captured by \( N \) cameras. The SIFT method is first employed to extract features from each camera image. Then, a feature is considered to be invalid if it is not located within the color patches on the omnidirectional color checker. Specifically, an invalid feature is determined by examining the color homogeneity (with a certain tolerance) of the \( r_1 \times r_2 \) block centered at the feature. After removing the invalid features, we obtain a set of local descriptors \( D_n = \{d_n^i\}_{1 \leq i \leq L_n} \) for the image \( I_n \), where \( d_n^i \) is the descriptor of the \( i \)th feature, and \( L_n \) is the number of the retained features. As suggested in [9], the Best-Bin-First (BBF) algorithm [10] is used to match the features for each image pair. Specifically, given the set of SIFT descriptors \( D_n \) for the image \( I_n \), we match each element of \( D_n \) with the sets of features extracted from the two adjacent camera images. For each feature \( d_n^i \), the matching method will assign a matched feature in \( D_m \) (\( m \) is an adjacent view of \( n \)), if the Euclidean distance between their invariant descriptor vectors is minimum. In order to remove the outliers in the matches, the Zero-mean Normalized Cross-Correlation (ZNCC) criteria is used to remove improper matches that have low correlation scores between \( r_2 \times r_2 \) blocks.

After matching the features across all \( N \) camera images, we thread the pair-by-pair matches into global correspondences \( E = \{e_m\}_{1 \leq m \leq M} \), where \( M \) is the number of obtained global correspondences. Each global correspondence \( e_m \) is represented as \( \{(\gamma_i, P_{\gamma_i}^m)\}_{1 \leq i \leq N_m} \), where \( \gamma_i \) denotes the associated camera index, \( P_{\gamma_i}^m \) the pixel location of \( e_m \) in the image \( \gamma_i \), and \( N_m \) the number of associated cameras in the correspondence \( e_m \).

3.2. Multi-camera Color Calibration

3.2.1. Inter-camera Color Consistency

The sensor response of a camera can be approximated by a linear model with a multiplicative gain \( g \) and an additive offset \( b \) [11]. The goal of the multi-camera color calibration is to find proper parameters, i.e., \( g_n \) and \( b_n \), \( n \in \{1, 2, \ldots, N\} \), to make the color responses of all the cameras consistent. If the color responses of the calibrated cameras are consistent, the color values of the global correspondence \( e_m \) in all associated camera images will be equal to their average value after calibration. For each associated camera \( \gamma_k \) in the global correspondence \( e_m \), we have

\[
g_{\gamma_k} I_{\gamma_k}^m + b_{\gamma_k} = \frac{\sum_{\gamma_i \in \Gamma_m} (g_{\gamma_i} I_{\gamma_i}^m + b_{\gamma_i})}{N_m},
\]

where \( \Gamma_m = \{\gamma_i\}_{1 \leq i \leq N_m} \) is the set of associated camera indices and \( I_{\gamma_i}^m \) denotes the color value at the pixel location \( P_{\gamma_i}^m \) in the associated camera image \( \gamma_i \).

The linear equation Eq. (1) formulates the color consistency requirement for the camera \( \gamma_k \) in the global correspondence \( e_m \). Similarly, the other associated cameras in the global correspondence \( e_m \) also have their corresponding linear equations, forming the simultaneous linear equations \( A_m x = 0 \). Stacking all the equations for \( M \) global corre-
spondences, we have the following linear system:
\[
\begin{pmatrix}
A_1^T & A_2^T & \cdots & A_M^T
\end{pmatrix}^T x = 0,
\]
(2)
in which the number of equations, \(\sum_{m=1}^M N_m\), is significantly larger than the number of unknowns, \(2N\), for typical multi-camera systems. Therefore, it is an overdetermined linear system.

3.2.2. Dynamic Range Shaping

Although the linear system given in Section 3.2.1 ensures the inter-camera color consistency for all the cameras, the new captured multi-view images may have a low dynamic range. In order to ensure proper dynamic range for the captured images, a dynamic range shaping process is incorporated into the linear system.

Specifically, the average of the color values of each global correspondence in all the associated camera images is first computed before calibration. Then, the average values for all the global correspondences are sorted in an ascending order. Finally, the first and the last \(\frac{t}{100}\) percentage of the sorted global correspondences are chosen as black level and white level, the target colors of which are set at \(l_b\) and \(l_w\), respectively. Suppose \(\Lambda_b\) and \(\Lambda_w\) are the index sets of the global correspondences chosen as black level and white level, respectively. If a global correspondence \(e_{\lambda}, \lambda \in \Lambda_b\), is chosen as a black level, all the associated cameras in \(e_{\lambda}\) are expected to output \(l_b\) for the corresponding pixel locations after calibration. These constraints are described as
\[
g_{\gamma}r^\lambda_{\gamma} + b_{\gamma} = l_b, \gamma \in \Gamma\lambda. \quad (3)
\]
Denote Eq. (3) as \(C_\lambda x = l_b\), where \(l_b\) is a \(N_\lambda \times 1\) vector, all elements of which are \(l_b\). Stack all the equations for selected global correspondences. Then, we have the black level constraint described in Eq. (4a). Similarly, the white level constraint is given in Eq. (4b).
\[
\begin{pmatrix}
C_1^T & C_\lambda^T & \cdots & C_{|\Lambda_l|}^T
\end{pmatrix}^T x = l_b, \quad (4a)
\]
\[
\begin{pmatrix}
C_1^T & C_\lambda^T & \cdots & C_{|\Lambda_w|}^T
\end{pmatrix}^T x = l_w, \quad (4b)
\]
where \(|\Lambda_b|\) and \(|\Lambda_w|\) are the number of elements in \(\Lambda_b\) and \(\Lambda_w\), respectively.

The color consistency requirements (Eq. (2)) and the dynamic range shaping (Eq. (4)) are concatenated into a single linear system. The resulting overdetermined linear system can be solved by the Kaczmarz method [12]. This linear system formulation method is applied to three color channels independently. Consistent color responses of all the cameras can be achieved by configuring the cameras with the obtained parameters. Because the employed sensor response model \(gF+b\) does not perfectly coincide with the real physical characteristics of cameras, the color consistency may not reach a satisfactory level. Therefore, we iteratively calibrate the cameras by capturing a new set of images and solving the corresponding linear system, until no improvement can be obtained. Experimentally, the procedure converges within at most five iterations.

4. EXPERIMENTAL RESULTS

In this section, we evaluate the performances of the proposed color calibration method on a real multi-camera system. In our experiments, we set \(t = 2\), i.e., 2\% of the sorted global correspondences are chosen as black level or white level. Block sizes \(r_1\) and \(r_2\) used in the area-based correlation methods are set at 11 and 17, respectively. Considering the nonlinearity at the lower end and upper end of the sensor response curve, \(l_b\) and \(l_w\) are set at \(0.05 \times 255 \approx 12\) and \(0.95 \times 255 \approx 242\), respectively.

In our multi-camera dome system, twenty Point Grey Flea2 cameras are placed in an approximately circular arrangement around the center of the scene. The employed cameras are capable of capturing up to 30 frames per second at 1024 \(\times\) 768 resolution. The color checker is placed in the center of the dome system to reduce the influence of radiometric falloff.

The original images captured by the multi-camera system before color calibration are shown in Fig. 2(a). The captured images are arranged in a raster scan order (from left to right and top to bottom) according to the camera index, which is shown at the bottom-left corner in each image. For the space reason, \(512 \times 512\) patches instead of whole images are shown here. It can be seen that the color responses of the 20 cameras are different. Especially, Camera 7 and Camera 8 are two adjacent cameras while they have entirely different brightness levels and contrasts. The inconsistency of the color responses would be problematic in many applications.

In order to calibrate the cameras to have consistent color responses and the high contrasts, our color calibration method is applied by iteratively adjusting the settings of cameras. The calibration method converges after four iterations. Fig. 2(b) shows the captured images after color calibration. The new captured multi-view images have consistent color responses and high contrasts. For example, the images captured by Camera 7 and Camera 8 present very consistent color with high contrasts after calibration. The same phenomenon can also be observed in the other images. This confirms that our color calibration method has a strong capability in ensuring inter-camera color consistency and high dynamic range for real multi-camera systems, thanks to the elegant design of the color calibration framework. The iterative software-hardware calibration minimizes the errors brought by the non-ideal responses of electronic devices and the algorithm is able to converge within a few iterations.
5. CONCLUSION

This paper proposes an automatic color calibration method for multi-camera systems. We design an omnidirectional color checker, which is visible for all the cameras without human intervention. The multi-camera color calibration problem is formulated as an overdetermined linear system. We evaluate the performances of the proposed method on a real multi-camera system. Experimental results demonstrate that the proposed color calibration method not only achieves inter-camera color consistency for all the cameras, but also ensures a high contrast. Due to the flexibility of the designed color checker and the generality of the linear system formulation, the proposed color calibration framework can be used in various multi-camera systems.

References


