A Calibration Method for Inconsistency between Different Channel Images of a High-speed Multi-channel Framing Camera

Yongwei Zhang, Yang Ding, Jin Li, and Qiang Lu

***Abstract*—Images from different channels of a high-speed multi-channel framing camera are usually inconsistent; this occurs for many reasons, including machining and installation errors of components like camera lens, beam splitters, CCDs, or other optical elements. We analyze the reasons for the inconsistencies and develop a calibration method to resolve the inconsistencies. We test our calibration method and find that the relative error between different channel images reduces greatly. This result can improve the ability of a high-speed multi-channel framing camera to perform quantitative measurements.**

***Index Terms*—Calibration method, inconsistency, multi-channel framing camera**

I. Introduction

HIGH-speed multi-channel framing cameras have been widely used to capture time-resolved, high-resolution and high-frame-rate sequence images[1],[2]. The most popular image processing methods, for high-speed multi-channel framing cameras, include the geometric distortion calibration, image pixel position arrangement, flat-field correction of the photo-response non-uniformity between the pixels in one image and the response calibration between sequential images. An optical measurement is usually completed via the morphological comparison of sequential images; however, the sequential images produced by different channels of a high-speed multi-channel framing camera are often inconsistent. This is likely because the optical signal is divided into several individual signals by the optical splitting system, but the optical elements of the optical splitting system have various machining and installation errors. The image inconsistencies mean that the corresponding points in the images produced by distinct channels are skewed. This skew may cause optical measurement errors. Many efforts have been made to resolve this problem. Some researchers try to improve image consistency by improving the optical frame division structure [3]-[6], but the machining errors and installation errors cannot be completely eliminated. Dongyao Jia proposed a novel calibration method using wavelet analysis. The novel calibration method improved the correlation value between the images taken from different channels [7].

A new calibration method is proposed in this work, based on analyzing the imaging mechanisms of a high-speed multi-channel framing camera. The outline of the paper is as follows: Sec. II presents the imaging model. Sec. III describes the experimental setup and results. Sec. IV analyzes the reasons for the inconsistency and delineates the calibration method. Sec. V describes the results of applying the calibration method and a conclusion is summarized in Sec. VI.

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II. Modeling

Fig. 1 shows the components of a high-speed multi-channel framing camera. The camera is composed of an optical splitting system, a gate-pulse generating circuit, intensified CCDs, and a control system. The optical signal is divided into several individual signals by the optical splitting system. The pulse interval is controlled by the gate-pulse generating circuit, and the electronic signals are generated by intensified CCDs.

Each intensified CCD channel has high-resolution image intensifiers and CCD sensors. The intensified CCD channels are fully individual and controlled remotely by the control system.

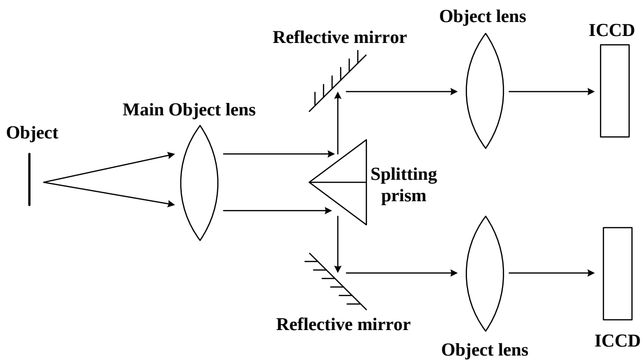

Fig. 1. Constitution of the high-speed multi-channel framing camera

The optical imaging process, using a pinhole model characterization, is shown in figure 2. In the figure, Q is a single point that denotes an object, $OXYZ$ is the camera’s coordinate system, O_1xy is the image’s coordinate system, and O_2uv is the pixel's coordinate system. The projection of Q onto the plane O_1xy is q.

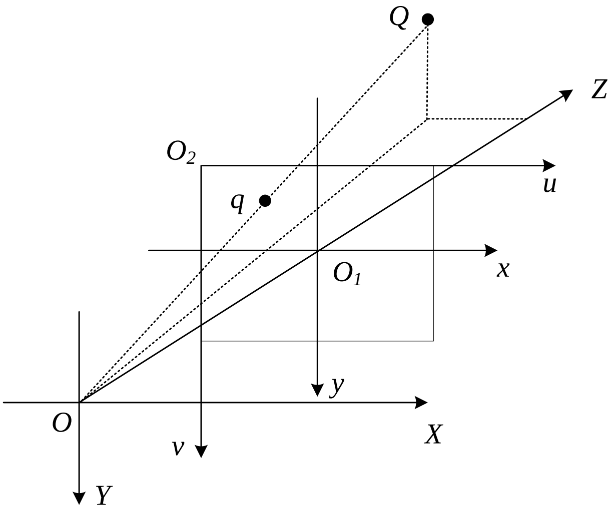

Fig. 2. Schematic of the optical imaging process

The coordinates (X,Y,Z) represent a point Q in the camera's coordinate system and the coordinates (x,y) correspond to the point q in the image. The relationship between the coordinate systems is represented by

$$Z\begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} f & & \\ & f & \\ & & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{1}$$

where f is the focal length.

The pixel coordinates (u,v) and the image coordinates (x,y) of point q have the relationship

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} 1/dx & & u_0 \\ & 1/dy & v_0 \\ & & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{2}$$

where dx and dy are the number of pixels per world unit in the x and y direction, (u_0, v_0) represent the optical center in pixels.

Substituting (2) into (1), we obtain

$$Z\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} 1/dx & & u_0 \\ & 1/dy & v_0 \\ & & 1 \end{bmatrix} \begin{bmatrix} f & & \\ & f & \\ & & 1 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = K \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \tag{3}$$

where K is the camera intrinsic matrix.

It can be known from (3) that there is one pixel coordinate corresponding to a static point in the world coordinate system, however, the corresponding pixel coordinates of different channels of the high-speed multi-channel framing camera are often different.

III. Experiment

The high-speed multi-channel framing camera we used in the experiment is shown in figure 3. This experiment is designed to show the image consistency problem. The camera has 8 channels, can record events at a rate $2*10^8$ fps and produces a maximum of 8 images in a single shot.

The method to find the relative pixel error between images taken using different channels is described next: First, we shoot a stationary checkboard pattern using the high-speed multi-channel framing camera to get 8 channel images. Second, we extract the internal corner coordinates for each coordinate system of the 8 channel images. Third, we get relative pixel errors between different channel images by comparing the internal corner coordinates of different channel images. Fourth, we repeat the previous steps and calculate the statistical results.

Fig. 3. The high-speed multi-channel framing camera

Fig. 4 shows the experimental setup used in our experiment. The system consists of a computer workstation, a high-speed multi-channel framing camera, a checkboard, a pulsed xenon lamp and a synchronous controller. The synchronous controller ensures that the shooting and flashing processes of the pulsed xenon lamp are synchronized. Forty-five photography processes were enacted. A total of 360 images of the checkerboard pattern at different orientations relative to the camera were taken.

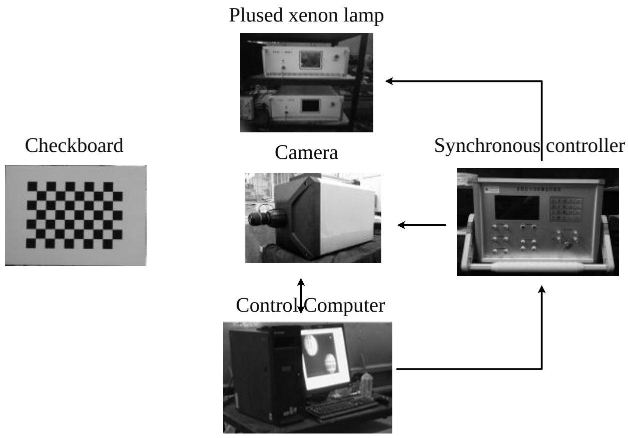

Fig. 4. Schematic of the experimental setup

We use the images taken by channel 1 and channel 2 as an example. An image taken by channel 1 is shown in figure 5, and the corresponding image from channel 2 is shown in figure 6. The comparison between the internal corner coordinates of the image produced by channel 1 and those produced by channel 2 is shown in figure 7. Figure 7 shows that there are evident relative pixel errors between the internal corner coordinates of the channel 1 image and the internal corner coordinates of the channel 2 image. The statistical data of 45 set images from channel 1 and channel 2, which is listed in table I, indicates that the mean value of the lateral pixel error is 3.33 pixels, while the max value is 16.81 pixels, and the standard deviation value is 3.98 pixels. The mean value of the longitudinal pixel error is 6.63 pixels, while the max value is 21.84 pixels, and the standard deviation value is 4.70 pixels. The statistical results indicate that the relative pixel error between images produced by different channels is large. The non-uniformity between images taken from different channels will be analyzed in next part.

TABLE I
STATISTICS FROM 45 SET IMAGES

	Mean/pixel	Max/pixel	Std.Dev./pixel
Lateral pixel error	3.33	16.81	3.98
Longitudinal pixel error	6.63	21.84	4.70

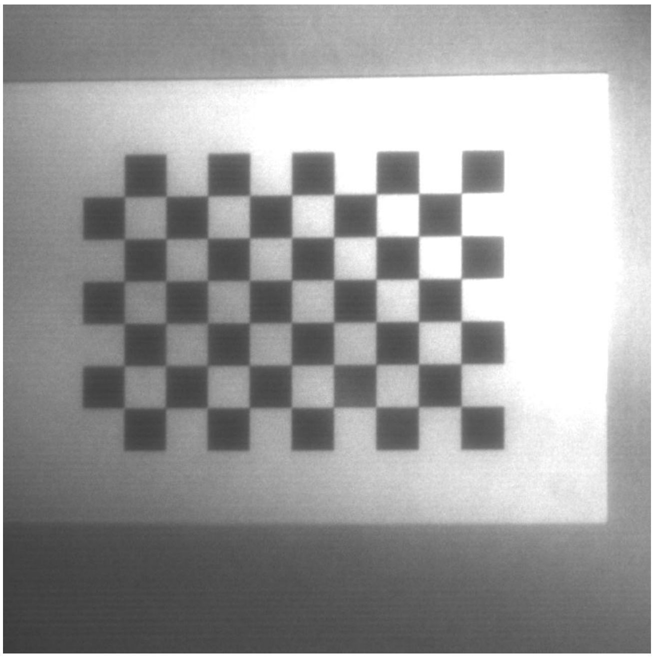

Fig. 5. The image of channel 1

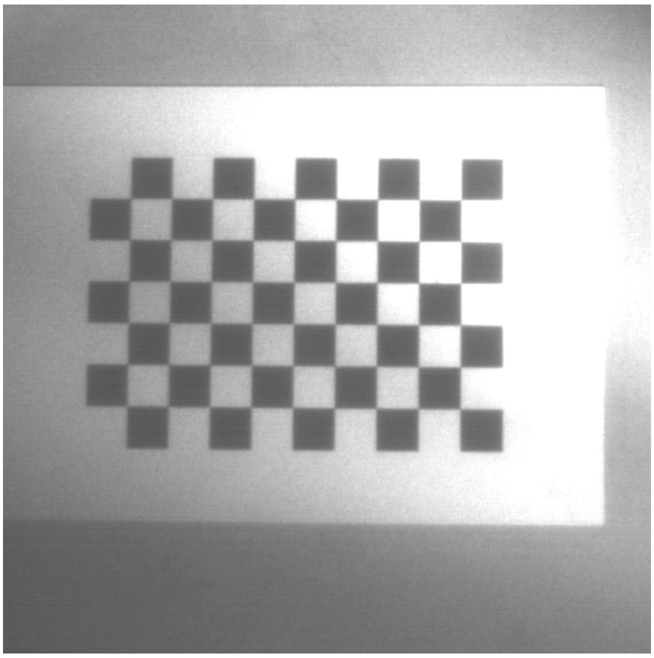

Fig. 6. The image of channel 2

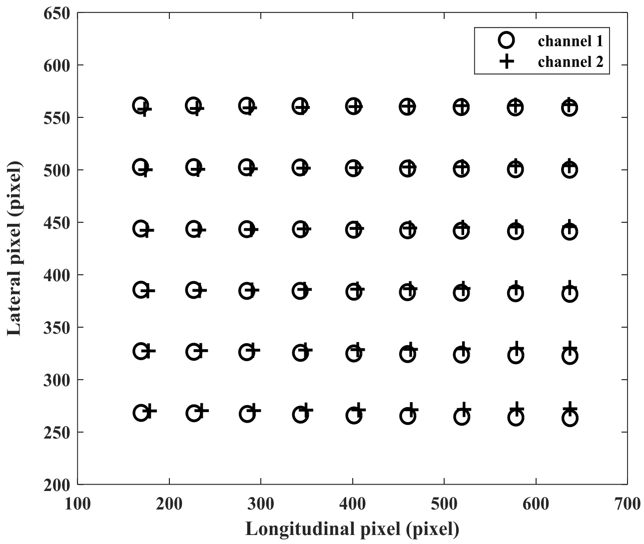

Fig. 7. Comparison between the internal corner coordinates of the channel 1 image and the internal corner coordinates of the channel 2 image

IV. METHODOLOGY

The reason for the non-uniformity between different channel images will be analyzed by studying the construction and working principles of high-speed multi-channel framing cameras.

The high-speed multi-channel framing camera is considered as 8 single channel cameras, then the reasons for non-uniformity between different channel cameras are divided into two classes:

1) Every channel camera has radial and tangential distortions. The radial and the tangential distortion coefficients of a channel camera are often distinctive, which results in distinctive image distortions.

The ideal image point is denoted by $q_d(x_d, y_d)$ and the distorted image point is denoted by $q_c(x_c, y_c)$.

The ideal image point and the distorted image point of a radial distortion are related by the expression

$$\begin{cases} x_c = x_d(1+k_1r^2+k_2r^4) \\ y_c = y_d(1+k_1r^2+k_2r^4) \end{cases} \quad r=\sqrt{x_d^2+y_d^2} \tag{4}$$

where k_1 and k_2 are the radial distortion coefficients.

The ideal image point and the distorted image point of a tangential distortion can be characterized by

$$\begin{cases} x_c = x_d + 2p_1y_d + p_2(r^2+2x_d^2) \\ y_c = y_d + 2p_2x_d + p_1(r^2+2y_d^2) \end{cases} \quad r=\sqrt{x_d^2+y_d^2} \tag{5}$$

where p_1 , p_2 are the tangential distortion coefficients.

In the case where there are both radial and tangential distortions, the relation between the ideal and distorted image point can be written as

$$\begin{cases} x_c = x_d(1+k_1r^2+k_2r^4) + 2p_1y_d + p_2(r^2+2x_d^2) \\ y_c = y_d(1+k_1r^2+k_2r^4) + 2p_2x_d + p_1(r^2+2y_d^2) \end{cases} \tag{6}$$

We can see from (6) that the image produced by the channel 2 camera is different from the image produced by the channel 1 camera when the radial and tangential distortion coefficients are different according to the channel that is used.

2) The installation errors of camera components like the lens, beam splitters and CCDs will lead to translation and rotation errors in the images taken from different channels.

Let R denote the rotation matrix between the channel 2 camera and the channel 1 camera, while let T denote the translation matrix. Then, the relationship between the coordinate of a point in the image produced by the channel 2 camera and the corresponding coordinate of the point in the channel 1 camera can be characterized by

$$\begin{bmatrix} X_2 \\ Y_2 \\ Z_2 \end{bmatrix} = R \begin{bmatrix} X_1 \\ Y_1 \\ Z_1 \end{bmatrix} + T \tag{7}$$

where (X_1,Y_1,Z_1) is the coordinate of a point in the channel 1 camera and (X_2,Y_2,Z_2) is the corresponding coordinate of the point in the channel 2 camera.

Substituting (1) into (7), we obtain

$$\begin{bmatrix} x_2/f_2 \\ y_2/f_2 \\ 1 \end{bmatrix} = R \begin{bmatrix} x_1/f_1 \\ y_1/f_1 \\ 1 \end{bmatrix} Z_1/Z_2 + T/Z_2 \tag{8}$$

where (x_1,y_1) is the coordinate of a point in the image produced by using the channel 1 camera and (x_2,y_2) is the coordinate of the point in the image produced by using the channel 2 camera. We denote f_1 as the focal length of the channel 1 camera and f_2 as the focal length of the channel 2 camera.

We can see in (8) that the translation and rotation coefficients, associated to the different channel cameras, results in a translation and rotation between the coordinate of a point in the image produced by channel 1 camera and the coordinate of the point in image produced by channel 2 camera.

We introduce a calibration method to correct the relative errors between various images produced from distinct channel cameras according to the root cause of the non-uniformity between the different channel images. Our calibration method has two steps:

1) Correct the radial and the tangential distortions of every channel camera. The Zhang camera calibration method is used to determine the radial and the tangential distortion coefficients [8].

Substituting (2) into (6), we obtain

$$\begin{cases} (u_c-u_0)dx = (u_d-u_0)dx(1+k_1r^2+k_2r^4)+2p_1(v_d-v_0)dy \\ +p_2(r^2+2((u_d-u_0)dx)^2) \\ (v_c-v_0)dy = (v_d-v_0)dy(1+k_1r^2+k_2r^4)+2p_2(u_d-u_0)dx \\ +p_1(r^2+2((v_d-v_0)dy)^2) \end{cases} \tag{9}$$

Therefore, we can determine the distorted pixel coordinate (u_c,v_c) corresponding to the ideal pixel coordinate (u_d,v_d) using (9). Then, we can find the corrected image by letting the gray value of the ideal pixel coordinate $I(u_d,v_d)$ equal the gray value of the distorted pixel coordinate $I(u_c,v_c)$. This relationship is characterized by the expression below

$$I(\mathrm{u}_d,\mathrm{v}_d) = I(\mathrm{u}_c,\mathrm{v}_c) \tag{10}$$

2) Next, we correct the relative image error caused by installation errors.

We substitute (2) into (8) to obtain

$$\begin{bmatrix} (\mathrm{u}_2-\mathrm{u}_{02})\mathrm{dx}/f_2 \\ (v_2-v_{02})\mathrm{dy}/f_2 \\ 1 \end{bmatrix} = R \begin{bmatrix} (\mathrm{u}_1-\mathrm{u}_{01})\mathrm{dx}/f_1 \\ (v_1-v_{01})\mathrm{dy}/f_1 \\ 1 \end{bmatrix} Z_1/Z_2 + T/Z_2 \tag{11}$$

where (u_1,v_1) is the pixel coordinate of a point in the image produced by the channel 1 camera, (u_{01},v_{01}) is the pixel coordinate of the optical center of the channel 1 camera, (u_2,v_2) is the pixel coordinate of the point in the image produced by the channel 2 camera and (u_{02},v_{02}) is the pixel coordinate of the optical center of the channel 2 camera.

We can see from (11) that the existence of translation and rotation mismatches between the channel 1 camera and channel 2 camera results in a distortion of the pixel coordinates. If we define the image produced by using the channel 1 camera as ideal, then the image produced by the channel 2 camera can be seen as distorted. Therefore, the coordinates of a pixel in the image produced by the channel 2 camera can be seen as ideal if we define a transformation

$$\begin{bmatrix} (\mathrm{u}_d-\mathrm{u}_{02})\mathrm{dx}/f_2 \\ (v_d-v_{02})\mathrm{dy}/f_2 \\ 1 \end{bmatrix} = R \begin{bmatrix} (\mathrm{u}_c-\mathrm{u}_{01})\mathrm{dx}/f_1 \\ (v_c-v_{01})\mathrm{dy}/f_1 \\ 1 \end{bmatrix} \mathrm{Z}_1/\mathrm{Z}_2 + T/\mathrm{Z}_2 \tag{12}$$

Therefore we can correct the image produced by the channel 2 camera by letting the gray values of the ideal pixel coordinates $I(x_d,y_d)$ equal to the gray values of the distorted pixel coordinates $I(x_c,y_c)$. Then we can eliminate the influence caused by the translation and rotation of the image produced by the channel 2 camera.

V. Results

The images are corrected by using our proposed calibration method. We use the Zhang camera calibration method [8] to find the intrinsic matrix of each channel camera. The intrinsic matrix K_1 of the channel 1 camera and the intrinsic matrix K_2 of the channel 2 camera are shown as follows:

$$K_1 = \begin{bmatrix} 3633.75 & 0 & 0 \\ -5.93 & 3620.89 & 0 \\ 699.49 & 480.60 & 1 \end{bmatrix} \tag{13}$$

$$K_2 = \begin{bmatrix} 3545.92 & 0 & 0 \\ 11.57 & 3556.47 & 0 \\ 784.99 & 210.67 & 1 \end{bmatrix} \tag{14}$$

The rotation and translation matrices between the channel 2 camera and the channel 1 camera are, respectively, determined by using a stereo matching algorithm [9]. The rotation and translation matrices are

$$R = \begin{bmatrix} 0.9998 & -0.0032 & 0.0220 \\ 0.0053 & 0.9953 & -0.0965 \\ -0.0216 & 0.0966 & 0.9951 \end{bmatrix} \tag{15}$$

$$T = \begin{bmatrix} 3.24 \\ 1.45 \\ -2.82 \end{bmatrix} \tag{16}$$

Then the images of the channel 1 camera and the channel 2 camera are corrected by the proposed calibration method. The corrected channel 1 image is shown in figure 8, and the corrected channel 2 image is shown in figure 9. The comparison between the internal corner coordinates of the corrected channel 1 and 2 images is shown in figure 10. Figure 10 shows that the relative pixel errors between the internal corner coordinates of channel 1 and 2 images are small. The statistical data of 45 set images from channel 1 and channel 2, listed in table II, indicates that the mean value of the lateral pixel error is -0.01 pixels, while the max value is 0.95 pixels, and the standard deviation value is 0.27 pixels. The mean value of the longitudinal pixel error is -0.03 pixels, the max value is 1.71 pixels, and the standard deviation value is 0.46 pixels. The statistical results indicate that the calibration method can reduce the relative error between channel images greatly.

TABLE II
STATISTICS FROM 45 SET CORRECTED IMAGES

	Mean/pixel	Max/pixel	Std.Dev./pixel
Lateral pixel error	-0.01	0.95	0.27
Longitudinal pixel error	-0.03	1.71	0.46

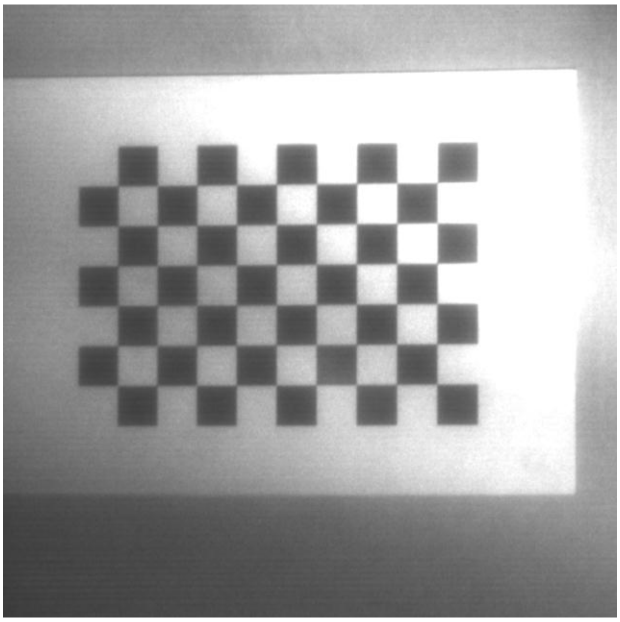

Fig. 8. The corrected channel 1 image

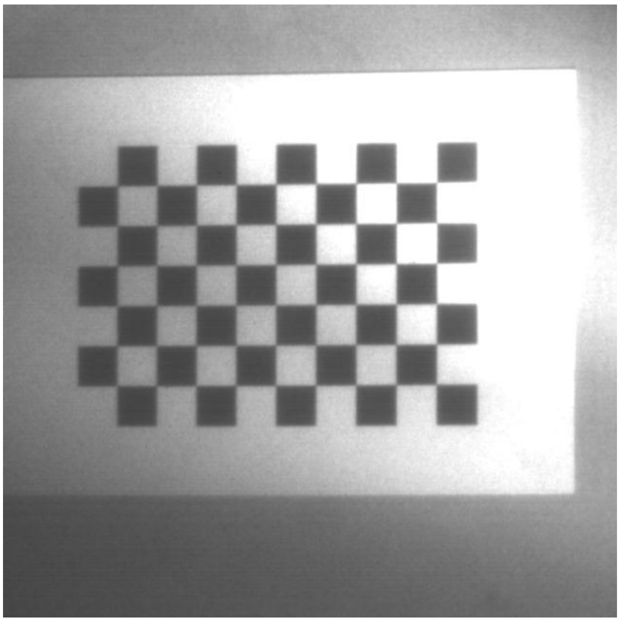

Fig. 9. The corrected channel 2 image

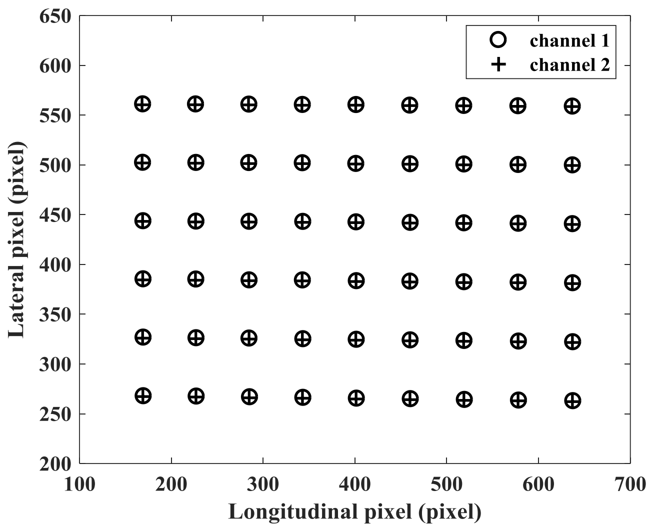

Fig. 10. Comparison between the internal corner coordinates of the corrected channel 1 image and the corrected channel 2 image

VI. CONCLUSION

Experimental results indicate that there are relative pixel errors between different channel images of a high-speed multi-channel framing camera. The analysis of the non-uniformity types between different channel images indicates that there are two causes of non-uniformity between different channel images: 1) every channel camera has a unique radial and tangential distortion; 2) installation errors of the optical elements lead to a translation and rotation between different channel images.

A calibration method is developed to correct the relative error between different channel images based on our analysis. The calibration result indicates that the calibration method can reduce the relative error between different channel images greatly.

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