Letter

A Distortion Self-Calibration Method for Binocular High Dynamic Light Adjusting and Imaging System Based on Digital Micromirror Device

Pei Wu, Yanjie Wang, Honghai Sun, and Zhuoman Wen

Dear Editor,

In order to realize the pixel level light adjusting control of the binocular high dynamic light adjusting and imaging system, this letter proposed a novel self-calibration method. By analyzing the optical design of the system, the causes of the distortion are given and a distortion model is established. Then, a quick and accurate self-calibration method is designed. The experiments indicate that the method can calibrate the two image sensors of the system at the same time, the average pixel deviation of the calibrated system is less than 0.5 pixels and the maximum deviation is less than 1 pixel. This method does not need external calibration template and its precision can satisfy the requirement of the system.

Introduction: Dynamic range is one of the important performance parameters of the optoelectronic imaging equipment. Currently in the application of high dynamic radiation energy scene observation, such as deep space exploration, solar observation and spacecraft launching process, the optical imaging equipment is required to have a high dynamic range of radiation energy measurement so that it can accurately observe and measure the scene. Currently, scholars have put forward many high dynamic detection methods to solve this problem [1]−[3].

We have designed a binocular high dynamic pixel level light adjusting imaging system by using the digital micromirror device (DMD) and made the dynamic range up to 180 dB [4], [5]. In this system, each pixel of the two image sensors has a corresponding micromirror on the DMD and the pixels which have the same coordinate correspond to the same micromirror. So, it can achieve pixel-level adjusting control. However in the actual system, the images captured by the system have a special distortion because of the optical structure of the system. This distortion can hardly be corrected by normal means and the distortions of the two image sensors are not the same.

In recent years, people have done a lot of researches on different optical systems in the field of distortion calibration. The calibration method proposed by Zhang is a classic method in the field of calibration [6], [7]. Rosten puts forward a camera distortion self-calibration method by using the plumb-line constraint and minimal Hough entropy [8]. Bradley uses rectification error to calibrate the distortion [9]. These calibration methods are all put forward according to their respective application background and are not fully applicable in our system.

This letter presents a novel self-calibration method for the high dynamic imaging system based on DMD. It does not require external calibration object, the system itself can correct the distortion of the two image sensors and make their pixels of the same coordinate correspond to the same micromirror.

Corresponding author: Pei Wu.

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P. Wu was with the University of Chinese Academy of Sciences, Beijing 100049, and NIO Inc. Shanghai 200000, China. He is now with Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China (e-mail: wupei210@mail.ustc.edu.cn).

Y. Wang, H. Sun, and Z. Wen are with Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun 130033, China (e-mail: wupei210@163.com; wupei210@163.com; wupei210@163.com).

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Overview of the system: Fig. 1 shows the optical design of the system. The core device of the system is DMD which is used as the spatial light modulator. The high dynamic radiation energy scene passes through the imaging objective lens and projects onto the DMD surface. The DMD modulates the scene under the control of the device and produces a bright frame and a dark frame. The two frames are projected respectively onto their corresponding image sensors through the imaging objective lens. The sensors send the collected two frames to the image processing system. The system determines the next step work by analyzing the frames according to the adjusting algorithm. If the system can not recover the high dynamic scene from the collected frames, the system will produce a new mask image to the DMD and let it modulate the scene. Otherwise, the system will produce a recovered high dynamic image of the scene. Therefore, the close loop control of the imaging system is realized.

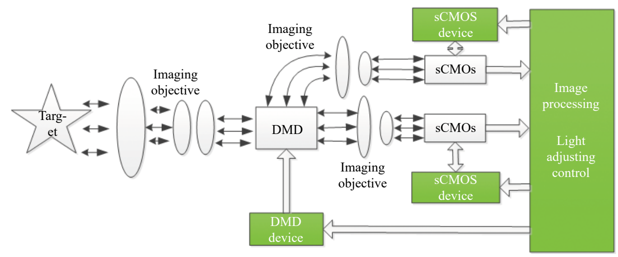
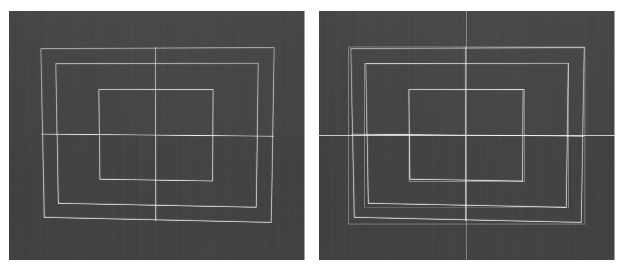


Fig. 1. The optical structure of the system.

Fig. 2(a) shows the image collected by one of the image sensors. In order to see the degree of the distortion, Fig. 2(b) adds the reference lines in the image which represent the theoretical position. It can be seen that each side of the boxes has a different degree of tilt and they are not on the center of symmetry.



(a) Distorted image (b) Distorted image with the reference lines

Fig. 2. Schematic diagram of image distortion.

According to the causes of distortion, the distortion can be divided into: Radial distortion, eccentric distortion, thin prism distortion and tilt distortion [10]. In our system, the first imaging objective lens and second imaging objective lens are adjusted with high precision and the precision has reached sub-pixel level. So that we can ignore the thin prism distortion and only consider the other three kinds of distortion in the system: Tilt distortion, eccentric distortion and radial distortion. It can be seen that the tilt distortion is the most obvious among them.

Proposed self-calibration method: In the field of distortion correction, scholars have done a lot of researches and established many mathematical models to express the distortion by a polynomial [11]. Neglecting higher order terms, tilt distortion δ_t, eccentric distortion δ_e and radial distortion δ_r can be expressed as follows:

$$\begin{cases}\delta_{xt} = p_0 x + p_1 y + p_2 xy + p_3 \\ \delta_{yt} = q_0 x + q_1 y + q_2 xy + q_3\end{cases} \tag{1}$$

$$\begin{cases}\delta_{xe} = s_1(3x^2+y^2)+2s_2xy \\ \delta_{ye} = s_2(x^2+3y^2)+2s_1xy\end{cases} \tag{2}$$

$$\begin{cases}\delta_{xr} = w_1x(x^2+y^2) \\ \delta_{yr} = w_2x(x^2+y^2).\end{cases} \tag{3}$$

In this letter, we introduce a novel self-calibration method based on DMD. It does not need to calibrate the internal and external parameters of the binocular cameras and does not need to use external calibration template to calibrate the system. By using the mask image projected by DMD, the system can be quickly and accurately calibrated. In our method, the mask image is used as the calibration template and its shape is known and changeable. Fig. 3 shows the calibration template, it consists of three rectangles and a cross hair. The rectangles and the cross hair are all symmetrical about the center of the image. The number of the rectangles and their sizes can be changed according to the calibration precision required. Each corner of the template are numbered in order to express the distortion correction results more intuitively in the following part. By using this template displayed by DMD, the distortion of the system can be directly observed through the image sensors and the two sensors can be calibrated at the same time.

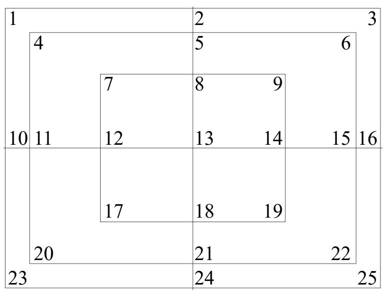


Fig. 3. The calibration template.

In order to find the proper distortion model of the system, we first only correct the tilt distortion which is the most obvious. After correction, we establish a mapping relationship between the calculated corner coordinates and their theoretical coordinates. The relationship Δ is area-related and expressed as

$$\begin{cases}\Delta_x = \sum_{i=0}^{N} k_i x^i \\ \Delta_y = \sum_{i=0}^{N} l_i y^i.\end{cases} \tag{4}$$

Then, the final distortion model is

$$\delta = \delta_t + \Delta. \tag{5}$$

Merging the same order terms and neglecting the higher order terms, (5) can be expressed as

$$\begin{cases}\delta_x = a_0x^2+a_1xy+a_2x+a_3y+a_4 \\ \delta_y = b_0y^2+b_1xy+b_2x+b_3y+b_4.\end{cases} \tag{6}$$

In order to realize the pixel-level light adjusting control, a mapping relationship between the micromirror and the pixels of the collected images is needed and the corresponding pixel coordinates of the same micromirror in the two image sensors must be the same. Assuming the distortion image collected by the sensor 1 is $f_1(x_1,y_1)$ and the ideal image is $g_1(u_1,v_1)$ and the distorted image of sensor 2 is $f_2(x_2,y_2)$, the ideal image is $g_2(u_2,v_2)$. The ideal image is $g(u,v)$, the coordinates of the same control point in the images before and after correction are (x_1,y_1), (x_2,y_2) and (u_1,v_1), (u_2,v_2). The relationship between them can be expressed as

$$\begin{cases}u_1 = h_1(x_1,y_1) \\ v_1 = h_2(x_1,y_1) \\ u_2 = h_3(x_2,y_2) \\ v_2 = h_4(x_2,y_2).\end{cases} \tag{7}$$

Normally, the relationship can be approximated by polynomial, that is, the distortion model. Equation (7) can be expressed as

$$\begin{cases}u_1 = a_0x_1^2+a_1x_1+a_2y_1+a_3x_1y_1+a_4 \\ v_1 = b_0y_1^2+b_1x_1+b_2y_1+b_3x_1y_1+b_4 \\ u_2 = c_0x_2^2+c_1x_2+c_2y_2+c_3x_2y_2+c_4 \\ v_2 = d_0y_2^2+d_1x_2+d_2y_2+d_3x_2y_2+d_4\end{cases} \tag{8}$$

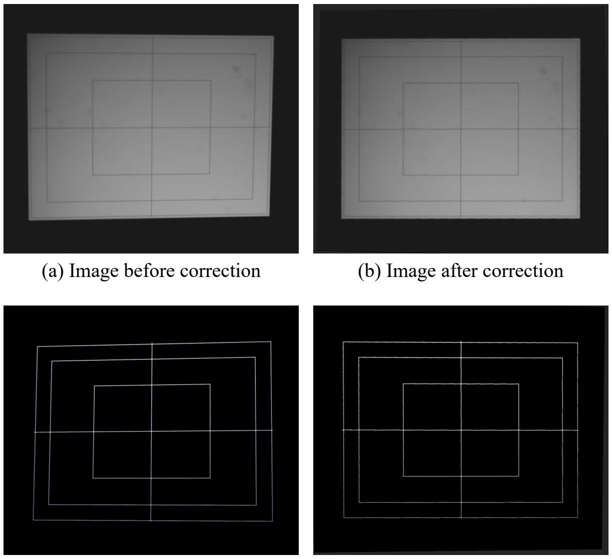
where a_i, b_i, c_i and d_i are called the distortion coefficients, a_i is the distortion coefficient of x-coordinate in sensor 1, $b_i$is the distortion coefficient of y-coordinate in sensor 1, c_i is the distortion coefficient of x-coordinate in sensor 2 and d_i is the distortion coefficient of x-coordinate in sensor 2. It only needs five sets of distorted coordinates and their corresponding theoretical undistorted coordinates to get the distortion coefficients. But there may be some errors during the process of corner extraction and different sets of points may get different coefficients. Therefore, we take 25 corner points into account and use the least square method to obtain the optimal solution [12]. The process of correcting the distortion image is traversing each point (x,y) in the distortion image to obtain its corresponding point (u,v), then assigning its gray value to (u,v) according to (8). However, in this method, the relationships between the points in the two images are not one to one. There may be two or more points in the distorted image mapped to the same point after correction, which makes some points of the corrected image being assigned for several times while some not being assigned. In the proposed method, we exchange the ideal image and the distortion image, which means we regard the ideal image as the new distortion image and the distortion image as the new ideal image. The distortion image is produced by the ideal image after distortion. Neglecting higher order terms, the final distortion model can be expressed as

$$\begin{cases}x_1 = \alpha_0u_1^2+\alpha_1u_1+\alpha_2v_1+\alpha_3u_1v_1+\alpha_4 \\ y_1 = \beta_0v_1^2+\beta_1u_1+\beta_2v_1+\beta_3u_1v_1+\beta_4 \\ x_2 = \gamma_0u_2^2+\gamma_1u_2+\gamma_2v_2+\gamma_3u_2v_2+\gamma_4 \\ y_2 = \omega_0v_2^2+\omega_1u_2+\omega_2v_2+\omega_3u_2v_2+\omega_4\end{cases} \tag{9}$$

where α_i, β_i, γ_i and ω_i are the new distortion coefficients. We traverse each point (u,v) in the ideal image to obtain its corresponding point (x,y) in the distortion image and assign the gray value of (x,y) to (u,v) according to (8). This method can guarantee every point of the ideal images can be assigned. In the process of distortion correction, the obtained coordinates are often not integers. In order to obtain the proper gray value, the gray interpolation method is often used to assign the value. Commonly used methods are nearest neighbor interpolation method, bilinear interpolation method, three spline interpolation method, etc. [13]. Nearest neighbor interpolation method is the simplest method but it has the worst accuracy; bilinear interpolation method is an improved method of nearest neighbor interpolation method; three spline interpolation method takes the change rate of the gray value into account which makes the edges smoother and has a higher accuracy. In this letter, we use three spline interpolation method to calculate the gray value.

Experiments: A beam of parallel light is illuminated in the system and the calibration template is displayed by the DMD, then we can get the distortion images of the two cameras. According to the distortion model, we acquire the distortion parameters of the two cameras and achieve the accuracy of correction. The result is shown in Fig. 4. Fig. 4(a) is collected by image sensor 1 and Fig. 4(c) is collected by image sensor 2. It can be seen that there are very serious distortions in the two pictures. The top cornerstone has very distinct tilt distortion and the images have eccentric distortion. Figs. 4(b) and 4(d) show the correction results.

In order to accurately analyze the correction result, we obtain the corner coordinates of the four images and do the error analysis with the ideal coordinates. Assuming the coordinate before correction is (x,y) and the coordinate after correction is (x',y'), the deviation between the two coordinates can be expressed as



(a) Image before correction (b) Image after correction

(c) Image before correction (d) Image after correction

Fig. 4. Distortion correction results.

$$deviation = \sqrt{(x-x')^2+(y-y')^2}. \tag{10}$$

The average deviation before and after correction of the two cameras are shown in Table 1.

Table 1. Pixel Deviation Before and After Correction of Each Camera

	Camera 1	Camera 2
Average deviation before correction	8.06	9.1
Average deviation after correction	0.75	0.73

It is can be seen that the average pixel deviations of the distortion image are about 8.06 and 9.1 pixels. After correction, the average deviation decreases to 0.75 and 0.73, they are less than 1 pixel. In order to verify the matching accuracy of the two corrected sensors, the average deviation between Figs. 4(b) and 4(d) is shown in Table 2. The average deviation of the two corrected sensors is 0.48 pixels and the maximum deviation is less than 1 pixel.

Conclusion: This letter presented a novel self-calibration method for binocular high dynamic light adjusting and imaging system based on DMD. This system can observe the high dynamic range scene and achieve different light adjusting control to targets with different brightness at the same time. A distortion model was established and a self-calibration template was designed according to the imaging characteristic of the system. Compared with other traditional calibration methods, this method can quickly and exactly complete the calibration without using external calibration template. By using the template, the distortion of the system and the effect of calibration can be easily observed. The results indicate that the average deviation of the calibrated sensors is less than 1 pixel and the deviation between the two sensors is better than 0.5 pixels. The calibration accuracy meets the requirement of the system. This self-calibration method is only applicable to the imaging system with spatial light modulator.

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Table 2. Pixel Deviation of the Two Corrected Cameras

No.	Deviation	No.	Deviation
1	0.04	14	0.51
2	0.93	15	0.28
3	0.12	16	0.85
4	0.62	17	0.45
5	0.90	18	0.99
6	0.15	19	0.21
7	0.83	20	0.14
8	0.02	21	0.16
9	0.79	22	0.35
10	0.59	23	0.81
11	0.20	24	0.74
12	0.15	25	0.52
13	0.61		
Average deviation		0.48	

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