Calibration and Target Signal-to-Noise Ratio Enhancement Method of Infrared Camera Array Based on Refocus

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Abstract. The accuracy of infrared (IR) camera calibration directly affects the quality of IR imaging results. Many imaging devices have been utilized in infrared dim and small target detection, which is a major research direction in infrared field. Comparing with single-lens cameras, IR camera array can improve the detection capability by adding more imaging units, and is expected to break the limitations of traditional single-lens imaging system in cost, volume and performance. The calibration methods for camera array nowadays are generally applied in visible spectrum instead of IR band. In this paper, we proposed a calibration method based on refocus for IR camera array. Furthermore, the target signal-to-noise ratio enhancement method become effective after calibration of IR camera array. As the camera parameters obtained can be used to correct image distortion and improve the quality of imaging, the calibrating process can support many subsequent tasks such as target detection. Experiments indicate that our method achieves the expected effect.

1. Introduction
In order to pursue higher imaging quality, with the development of photoelectric detection technology, the size of detector lens is showing an increasing trend. However, the larger lens requires the more rigorous processing technology and the higher cost. The camera array is proposed and applied to improve the performance of single-lens camera. The camera array uses multiple cameras at different spatial locations to collect photos with different perspectives. The supplementary information provides the possibility of many applications such as post-capture refocusing [1][2], super-resolution [3], view synthesis [4] and de-occlusion [5]. Wilburn et al.[6] used cheap cameras to build a high-performance camera array, which is utilized for high-resolution and high-dynamic-range video capture, spatiotemporal view interpolation, non-linear synthetic aperture photography etc.. Vaish et al.[7] also had relative work with the support of camera array. The camera array is calibrated by plane+ parallax, which is used to see the surface of the obscured object behind branches or people. Yang et al. [8] proposed a new type of real-time hybrid synthetic aperture imaging monitoring technology, is used to solve the blur problem caused by shooting high-speed moving objects with a small aperture in a low-light environment. Xiao et al.[9] proposed image computing refocusing method based on camera array that can focus the light field image to any depth and improve the signal-to-noise ratio of the focused image.

Inspired by relevant works, camera array can be used in IR band. The calibration of IR camera array is a primary stage for the whole process. Lens distortion is mainly divided into radial distortion and tangential distortion[10][11]. The currently widely used nonlinear model camera calibration method is proposed by Zhang. His method can easily calibrate a single-lens camera with radial
distortion by solving the maximum likelihood estimation of a nonlinear optimization problem[12]. To establish the physical world coordinates constraint of different targets, the customization of a large-FOV calibration board is an intuitive idea [13][14]. In the infrared domain, Wang et al.[15] proposed a method for subpixel corners positioning, containing edge extraction, gray centroid and curve fitting. Wang et al.[16] designed a target plan possessing high and low radiation areas with sharp boundaries which can supply feature points by sharp boundaries from different radiation areas for an infrared camera. In our works, we made a calibrating board that is appropriate for IR band. When the single camera calibrating is finished, the following work for camera array can be carried out normally.

For the purpose of improving SNR of IR images, the disparity of sub-cameras should be figured out. Zeng et al.[17] review the camera array system in space target observation which can bring about low cost, wide visual field, high resolution and high detection ability. Xia et al.[18] proposed a method of IR light field imaging based on camera array, and they can obtain a resampling image with higher SNR by blending multiple low SNR images. Wang et al.[19] bound four stages of 110mm telescopes and verify the improvement of detection ability and the SNR of image successfully. In this paper, the main work is the calibration method of IR camera array based on refocus. On this basis, we utilized the IR camera array to achieve enhancement of target SNR which can support the studies of IR target detection.

2. Proposed methods

2.1. Calibration stage

Due to the baseline difference between the sub-cameras of the camera array, there are disparities between the sub-images [20]. These sub-pixel disparities allow us to obtain more imaging information from the synchronised instant sub-images. At the same time, because the optical axis of the camera array are difficult to be completely parallel during the assembly process, systematic errors will be introduced. However, when the lens position is fixed, the system error no longer changes, we can combine it with the disparity generated during imaging. Figure 1 gives an example of disparity in IR camera array imaging.

2.1.1. Single-camera calibration

In the imaging process, we need construct a camera model to represent the mapping relationship between 3D space points and 2D image pixels. At present, camera models are usually divided into linear models and nonlinear models. Choosing an appropriate camera model plays a decisive role in
the calculation and optimization of the subsequent calibration algorithm. The linear model is currently the most classic, most commonly used and simplest camera model, also known as the pinhole model, which is widely used in various optical components. The nonlinear model considers various nonlinear distortions of the lens on the basis of the pinhole model, including radial distortion and tangential distortion. **Figure 2** shows the diagram of camera model and camera distortion.

[Image of camera model and camera distortion]

![Figure 2. The diagram of camera model and camera distortion.](image)

The single-camera calibration is required before procedure of camera array. Considering Zhang’s method [12] is flexible, since a camera can be calibrated with only a few images of the planar pattern in different orientations. According to the Zhang’s method, using black and white checkerboard can complete the distortion calibrate under the condition of visible light band. But for IR camera array, the corners of the checkerboard image cannot be captured due to the imaging band is infrared. Therefore, we made a dot array calibrate plate for IR band. With the collocation of heating apparatus, the images of calibration board show the feature points clearly, which can be detected by IR lens. **Figure 3** displays the dot array calibrate plate used in experiments.

[Image of dot array calibrate plate with heating apparatus]

![Figure 3. The dot array calibrate plate with heating apparatus.](image)

To eliminate the influence of camera distortion, Zhang’s calibration method calculates the intrinsic matrices and reprojection errors. The intrinsic matrix is given as equation (1).

$$
K = \begin{bmatrix}
\alpha f & 0 & c_x \\
0 & \beta f & c_y \\
0 & 0 & 1
\end{bmatrix} = \begin{bmatrix}
f_x & 0 & c_x \\
0 & f_y & c_y \\
0 & 0 & 1
\end{bmatrix}
$$

(1)
where $\alpha, \beta$ represent the number of pixels per unit distance on the image, then $f_x = \alpha f, f_y = \beta f$ transforms the focal length $f$ of the camera to the pixel measurement in the $x$ and $y$ directions. $(e_x, e_y)$ is the actual position of the principal point which represents the offset in the $x$ and $y$ directions.

2.1.2. Homography matrix

Inspired by transformation of intrinsic matrix and extrinsic matrix, we introduce the homographic transformation into registration of camera array. Homography is a concept in geometry. It refers to a reversible transformation from the real projective plane to the projective plane. The homography transformation can be simply understood as describing the position mapping relationship between the world coordinate system and the pixel coordinate system. The corresponding transformation matrix is called the homography matrix. The different views of imaging have different homographic transformation. Once we know the homography matrices of multi-view images to world coordinate system, then the images of different views to each other can be calculated by matrix operations.

Figure 4 illustrates the relationship among them.

Assuming that the homogeneous coordinates of the corresponding points of Image1 and Image2 are $(x', y', 1)$ and $(x, y, 1)$, the homography matrix is defined as $H = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\
 h_{21} & h_{22} & h_{23} \\
 h_{31} & h_{32} & h_{33} \end{bmatrix}$, and we get equation (2)

$$\begin{bmatrix} x' \\ y' \\ 1 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\
 h_{21} & h_{22} & h_{23} \\
 h_{31} & h_{32} & h_{33} \end{bmatrix} \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} \tag{2}$$

The Eq. (2) is equivalent to equation (3)

$$\begin{align*}
x' &= \frac{h_{11}x + h_{12}y + h_{13}}{h_{31}x + h_{32}y + h_{33}} = \frac{h_{11}'x + h_{12}'y + h_{13}'}{h_{31}'x + h_{32}'y + h_{33}'} \\
y' &= \frac{h_{21}x + h_{22}y + h_{23}}{h_{31}x + h_{32}y + h_{33}} = \frac{h_{21}'x + h_{22}'y + h_{23}'}{h_{31}'x + h_{32}'y + h_{33}'} \tag{3}\end{align*}$$

Thus, each pair of points from Image1&2 gives us two equations. We make a transformation to $H$, then we get equation (4)

$$H' = \frac{1}{h_{33}} H = \begin{bmatrix} h_{11}' & h_{12}' & h_{13}' \\
 h_{21}' & h_{22}' & h_{23}' \\
 h_{31}' & h_{32}' & h_{33}' \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} & h_{13} \\
 h_{21} & h_{22} & h_{23} \\
 h_{31} & h_{32} & h_{33} \end{bmatrix} \tag{4}$$

It can be seen that the homography matrix has only 8 degrees of freedom, that is, there are 8 unknowns. Therefore, it requires 4 different pairs of non-collinear points to solve the equation set.

The homography matrices of 3 images to planar surface are $H_1, H_2, H_3$. Then we get equation (5)

$$\begin{Bmatrix} P = H_1 I \\
P = H_2 I \\
P = H_3 I \end{Bmatrix} \tag{5}$$

From the properties of matrix, the homography matrices from Image1 to Image2 is $H_2' H_1$. And the similar relationship goes for other images.

2.1.3. IR camera array calibration

The 2×2 IR camera array provides 4 views of data simultaneously. To simplicity, we number the four cameras from I to IV in a clockwise circle and select the camera I as the reference camera. The homography matrices in Section 2.1.2 are utilizing in reprojection transformation. The images captured
from camera II, III, IV are reprojected to the imaging focal plane of reference camera. The disparity of 4 sub-images is only related to the imaging distance.

We assuming that the point coordinate on the checkboard plane $\Pi$ is $(x_{w}, y_{w}, 0, 1)$, which is the focusing plane. The points on plane $\Pi$ can be projected to the pixels position on reference camera I. Meanwhile, the points on reference camera I can back project to the plane $\Pi$. Then the other sub-cameras plane can reproject to the focal plane. The plane $\Pi$ is parallel to the reference camera plane. Therefore, the normal vector of the focusing plane in reference camera coordinates can be expressed as $\vec{n} = (0,0,1)$. At the same time, the point on the z-axis can be selected as a point on the focusing plane to fix the focusing plane. For example, select $(0,0,z_{i})$ as a point on the focusing plane. Then the focusing plane in the reference camera coordinate system can be described as $z = z_{i}$. Notice that the absolute value of $z_{i}$ is the distance between the camera and the focusing plane. Therefore, by changing the value of $z_{i}$, the image can be refocused to the plane at any distance from the reference camera.

2.2. SNR improvement stage
The infrared imaging system is composed of many system units, and each system unit introduces noise. Therefore, there are many forms of noise. The spatial noise of infrared images is mainly background noise, amplifier noise and detector noise, as well as uniformity correction residual noise and A/D conversion noise. In the focal plane detector noise, most noises basically obey the Gaussian distribution, with the exception of the salt and pepper noise caused by the correspondingly large or small individual pixels, the inherent noise of the image caused by the inconsistent response of each pixel of the detector itself, and the non-uniformity noise caused by image uniformity correction.

The camera array can make multiple observations of the current scene. After calibration, the array synthetic image can be obtained, which can effectively suppress background noise and enhance the signal-to-noise ratio. For camera array imaging, we get equation (6)

$$I_{k} = B_{k} + t_{k} + n_{k}, k = 1, 2, \cdots, K$$

(6)

where, $I_{k}$ is the image obtained by $k^{th}$ sub-camera, $B_{k}$ is the background of $I_{k}$, $t_{k}$ is the target of $I_{k}$, $n_{k} \sim N(0, \sigma^{2})$ is the noise in $I_{k}$, K is the number of sub-camera. We assume that the noise between the sub-cameras is independent and obeys Gaussian distribution. Then the array synthetic image satisfying equation (7)

$$\bar{T} = \sum_{k=1}^{K} I_{k} = \bar{B} + \bar{T} + \bar{n}, k = 1, 2, \cdots, K$$

(7)

where, $\bar{n} \sim N\left(0, \frac{\sigma^{2}}{K}\right)$. It can be seen that using the camera array to perform synthetic imaging of the current scene can theoretically suppress the variance of the noise to the original $1/K$. $\bar{B}$ is the background mean value, which is the low-frequency component of the spatial domain, which can be suppressed by background suppression methods (such as mean filtering), and $T$ is the superposition of targets in images of different views.

The SNR is defined as equation (8)

$$\text{SNR} = \frac{E_{t}}{E_{n}}, E_{t} = \sum_{\text{set } T} |I_{\text{res}}(i)| / |T|, E_{n} = \sum_{\text{set } U \cap \text{set } T} |I_{\text{res}}(i)| / (|U| - |T|)$$

(8)

where, $E_{t}$ is the energy of target, $E_{n}$ is the energy of noise, $I_{\text{res}}$ is the residual image after background suppression, $T$ is the set of pixels occupied by the target, and $U$ is the set of all pixels in the image. $|U|$ and $|T|$ represent the number of pixels in the set respectively. Due to $\bar{n}$ obeys Gaussian distribution, calculating the spatial average value of noise energy can be equivalent to calculating the expectation value of noise energy. The mathematical proceeding is given in equation (9)

$$E_{n} = \sum_{\text{set } U \cap \text{set } T} |I_{\text{res}}(i)| / (|U| - |T|) = E(|\bar{n}|) = \int_{-\infty}^{\infty} |x| \sqrt{\frac{K}{2\pi\sigma}} e^{-\frac{kx^{2}}{2\sigma}} dx = \sqrt{\frac{2K}{\pi\sigma}} \int_{0}^{\infty} xe^{-\frac{kx^{2}}{2\sigma}} dx = \sqrt{\frac{2}{K\pi}} \sigma = \frac{C_{t}}{\sqrt{K}}$$

(9)
where, $C_i$ is a constant. It can be seen from Eq. (9) that the noise energy is inversely proportional to the 0.5 power of the number of cameras. And the target energy remains constant during the synthetic imaging process, so we get equation (10)

$$\text{SNR} = \frac{E_i}{\sqrt{K E_c}} = \frac{1}{C_i}$$

(10)

Therefore, the SNR of the array synthetic image is proportional to the 0.5 power of the number of cameras.

3. Experimental results and analysis

3.1. Calibration process

Experiments are conducted on real IR image captured by a camera array. In the calibration process, the calibration plate we utilized has a circular array through hole. The distance between the centres of two adjacent circles is 6cm and the radius is 1cm. Among them, there are 5 large circles with a radius of 2cm are distributed in four directions near the periphery is used to distinguish the orientation of the plate in the infrared image. We use electric heating wire to generate heat. Due to the radiation intensity difference brought by the film covering at the through hole of the board and the other part of the board, the through holes are imaged as highlight areas in the IR camera array.

3.1.1. Single-camera calibration

The images obtained from IR camera array exist distortion, which is influential in follow-up procedure. Therefore, the calibration aims at single-camera is utilized. We choose 10 images of dot array calibrate plate shot from different point of views as Figure 5 shows. There are 40 images in total because 4 sub-cameras imaging simultaneously. Figure 6 presents the array images with disparity. Figure 7 shows the reprojection error bar chart of 4 sub-cameras. The horizontal axis represents the serial number of the images. The overall reprojection error of the calibration result is marked by a dotted blue line, which is less than 0.5 pixels in all 4 cameras. It means that the camera array achieved a high accuracy. Thus, the undistorted images can be used for the calibration of camera array.

3.1.2. IR camera array calibration

The 40 images are divided into 10 groups according to the time line, and each group provides 3 homographic matrices so that we can reproject the images to reference camera. We took them into consideration and use the average matrix to calibrate the camera array. The 3 average matrices are given as equation (11).

$$H_{21} = \begin{bmatrix} 1.0194 & -0.0087 & -19.5984 \\ 0.0133 & 1.0090 & -26.7995 \\ 0.0000 & 0.0000 & 1.0000 \end{bmatrix},
H_{31} = \begin{bmatrix} 0.9929 & 0.0017 & -36.0138 \\ -0.0042 & 0.9926 & -15.2070 \\ 0.0000 & 0.0000 & 1.0000 \end{bmatrix},
H_{41} = \begin{bmatrix} 1.0128 & -0.0010 & -55.7329 \\ 0.0052 & 0.9998 & -23.5580 \\ 0.0000 & 0.0000 & 1.0000 \end{bmatrix}$$

(11)
With the change of \( z_i \), we can obtain synthetic images of camera array focused on different planes as the **Figure 8** shows.

We set the step size to 1, starting from \( z_i=-7 \) to \( z_i=7 \). The result in Fig. 8 shows that when the focal plane coincides with the image plane of camera I, the synthetic image of camera array is clearly. In the case of \( z_i \) taking other values, the disparities of sub-cameras between each other are fixed. In this way, we consider the camera array is calibrating successfully.

### 3.2. Target SNR enhancement results

In this section, the experiment is design to demonstrate that the array synthetic image gets a SNR gain compare with the sub-camera image. Experiment is built on real IR camera array images. The images contain the part of the process that an airliner take off from Changsha Huanghua International Airport and they are obtained using an uncooled \( 2 \times 2 \) IR camera array with a resolution of \( 640 \times 512 \). The background including a sunny weather (Scene 1), cloudy weather (Scene 2).

![Reprojection Error Bar Chart](image)

Figure 7. The reprojection error bar chart of 4 sub-cameras
3.2.1. Evaluation indicator

In the experiments, the variation of noise $\sigma^2$, the energy of noise $E_n$, the energy of target $E_t$ and the signal-to-noise ratio $SNR$ are calculated to evaluate the image quality improvement.

3.2.2. Experimental results

During the experiment, we used IR camera arrays to shoot two scenes separately to enhance the robustness of the results. The images obtained from reference camera (Camera 1) are regarded as reference image. The experimental results are shown in Figure 9.

![Figure 8. Refocus results of different $z_i$.](image)

![Figure 9. (a1)(a2) are the image array; (b1)(b2) are the target amplification area of 4 sub-cameras; (c1)(c2) are the array synthetic image and background suppress image.](image)
Table 1. Comparison of Evaluation Indicator

| Scene 1 | Scene 2 |
|---------|---------|
| Reference image | Array Synthetic image | Reference image | Array Synthetic image |
| $\sigma^2$ | 1.381 | 1.133 | 1.935 | 1.695 |
| $E_n$ | 1.016 | 0.849 | 1.529 | 1.265 |
| $E_t$ | 3.843 | 6.273 | 10.960 | 19.360 |
| SNR | 3.784 | 7.388 | 7.169 | 15.307 |

We compared the evaluation indicator between reference image and array synthetic image in Table 1. The theoretical value of SNR gain (GSNR) of $2 \times 2$ camera array is 2 and the result in Table 1 had almost reached the ideal result. Therefore, the information obtained from other sub-cameras (except reference camera) have contribution to the target SNR enhancement. In summary, the method of array synthesis imaging can suppress the random noise in the image to some extent so that the SNR of the target is enhanced.

4. Conclusions and discussions
This paper presents a calibration method for IR camera array based on refocus. Experiment results demonstrate that the consequence of calibration is effective enough for the improvement of work in the matter of target detection. Because of the enhancement for target signal-to-noise ratio, the IR camera array is able to extend the detection range in case of dim and small target situation. It is even expected to break the limitations of traditional single lens imaging in cost, volume and performance, by means of more but cheaper small aperture lens to reach a higher performance in detection task.

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