Optimization of stereo calibration parameters for the binocular camera based on improved Beetle Antennae Search algorithm

Zhaoran Wang¹*, Guochu Chen², Lisi Tan²
School of Electrical Engineering, Shanghai Dianji University, Shanghai 201306, China
*Corresponding author’s e-mail: 196001010212@st.sdju.edu.cn

Abstract. For binocular cameras, aiming at the low precision of traditional stereo calibration methods for binocular cameras, a Beetle Antennae Search (BAS) algorithm based on binocular parallel polar line constraint was proposed to improve the calibration accuracy. The internal parameter matrix and distortion parameter matrix of the left and right cameras of the binocular camera were first calculated by using the MATLAB calibration toolbox. Then the stereo calibration parameter matrix of the binocular camera was calculated. Then, using the binocular parallel polar line constraint based on the BAS algorithm establishes the objective function by taking the difference and average values of the vertical coordinates of each checkerboard corner in the left and right images after stereo correction as the objective. The stereo calibration parameters of the binocular camera are further optimized. The results show that the BAS algorithm based on binocular parallel pole constraint is stable, reliable and fast in convergence, which can realize the optimization of stereo calibration parameters of the binocular camera.

1. Introduction
With the development of artificial intelligence [1], camera calibration [2] is an essential primary link in machine vision technology, and the accuracy of camera calibration will directly affect the accuracy of the whole machine vision system. Among them, for binocular stereo ranging technology [3], the stereo calibration accuracy of the binocular camera directly impacts its ranging accuracy.

At present, the most widely used stereo calibration methods for binocular camera mainly include direct linear transformation solution [4], two-step calibration method based on radial correction constraint [5] and Zhang Zhengyou checkerboard calibration method [6]. However, the traditional calibration method for binocular camera calibration accuracy is low, making the binocular stereo vision ranging accuracy low. Therefore, the stereo calibration parameters of the binocular camera need to be optimized to meet the accuracy of binocular stereo vision ranging technology. However, the existing methods only optimize the parameters of a single camera to improve the calibration accuracy without verifying whether the optimized parameters improve the ranging accuracy. At the same time, there is no practical reference significance for optimizing stereo calibration parameters of the binocular camera to enhance the parallelism of the binocular camera, so their direct application is limited.

Since the parallelism degree of the binocular camera is determined by the stereo calibration parameters of the binocular camera, the more parallel the binocular camera is, the higher the ranging
accuracy will be. Therefore, it is necessary to optimize the stereo calibration parameters of the binocular camera to improve the parallelism degree of the binocular camera and thus improve the ranging accuracy. Therefore, this paper proposes a BAS algorithm based on binocular parallel polar line constraint to optimize the stereo calibration parameters of binocular cameras to improve the parallelism of binocular cameras to improve the ranging accuracy.

2. Binocular stereo calibration parameters
The stereo calibration of the binocular camera is to calibrate the left and right cameras, respectively, according to Zhang Zhengyou's checkerboard calibration method. Finally, the stereo calibration parameters of the binocular camera are obtained according to the calibration parameters of the left and right cameras, namely, the internal parameter matrix, the distortion parameter matrix and the external parameter matrix. The calibration plate used for stereo calibration is shown in Figure 1.

![Figure 1. calibration plate](image)

The internal parameter matrix includes the left camera internal parameter matrix and the right camera internal parameter matrix. The distortion parameter matrix consists of the left camera distortion parameter matrix and the right camera distortion parameter matrix. The external parameter matrix includes the rotation matrix and the translation matrix [7].

The internal parameter matrix expression of the left camera is

$$
\begin{bmatrix}
  f_{uleft} & 0 & u_{0left} \\
  0 & f_{vleft} & v_{0left} \\
  0 & 0 & 1
\end{bmatrix}
$$

where $f_{uleft}$ and $f_{vleft}$ are the focal lengths on the $u$ axis and $v$ axis, respectively, and $(u_{0left}, v_{0left})$ is the $O_l$ coordinate.

The internal parameter matrix expression of the right camera is

$$
\begin{bmatrix}
  f_{uleft} & 0 & u_{0right} \\
  0 & f_{vright} & v_{0right} \\
  0 & 0 & 1
\end{bmatrix}
$$

where $f_{uright}$ and $f_{vright}$ are the focal lengths on the $u$ axis and $v$ axis, respectively, and $(u_{0right}, v_{0right})$ is the $O_r$ coordinate.

The left camera distortion parameter matrix expression is as follows:

$$
[k_{1left} \ k_{2left} \ p_{1left} \ p_{2left} \ 0],
$$

where $k_{1left}$ and $k_{2left}$ are the radial distortion parameters of the left camera, and $p_{1left}$ and $p_{2left}$ are the tangential distortion parameters of the left camera.

The right camera distortion parameter matrix expression is as follows:

$$
[k_{1right} \ k_{2right} \ p_{1right} \ p_{2right} \ 0],
$$

where $k_{1right}$ and $k_{2right}$ are the radial distortion parameters of the right camera, and $p_{1right}$ and $p_{2right}$ are the tangential distortion parameters of the right camera.

The rotation matrix is obtained by transforming the rotation relation vector $[\omega \ \delta \ \theta]$ to Rodrigues [8]. The translation matrix is $[T_X \ T_Y \ T_Z]$.

The stereo calibration parameters of the binocular camera are summarized as follows: eight internal parameters, eight distortion parameters, and six external parameters, a total of twenty-two parameters.

3. Analysis of binocular parallel polar line constraint principle
After stereo calibration of the binocular camera, stereo correction of left and right shot images should be carried out through an algorithm [9]. Binocular parallel correction is a part of the stereo correction,
and parallel polar line correction involves a concept called epipolar constraint, and its principle is as follows:

In 3D space, the projection points of point $P$ onto the left camera imaging plane $left image$ and left camera imaging plane $right image$ are $P_l$ and $P_r$, respectively. The three points $P$, $P_l$, and $P_r$ form a plane $S$ in three dimensions. The line $L_l$ of the intersection of $S$ and $left image$ crosses the point $P_l$, and the line $L_r$ of the intersection of $S$ and $right image$ crosses the point $P_r$, where $L_l$ and $L_r$ are called polar lines. Its schematic diagram is shown in Figure 2.

**Figure 2. Schematic diagram of parallel binocular poles.**

The epipolar constraint means that the imaging point of the same point on the imaging plane of the left camera is on the left polar line. The right imaging point of the point on the imaging plane of the right camera must be on the right polar line relative to the left polar line to reduce the number of points to be matched. Taking Fig. 7 as an example, the epipolar constraint equation can be expressed by formula (1):

$$x_l^T F x_r = 0$$

Where $x_l^T$ transposes $P_l$’s three-dimensional vector $x_l$, $x_r$ is the transpose of $P_r$’s three-dimensional vector, and $F$ is a fundamental matrix $3 \times 3$ with rank 2.

The equations of both polar lines $L_l$ and $L_r$ are formula (2):

$$\begin{cases} 
  l_l = F x_l \\
  l_r = F^T x_r 
\end{cases}$$

For binocular parallel polar constraint and the left and right image points being on the corresponding left and right polar lines, respectively, and another characteristic is that the corresponding left and right polar lines are at the same height on the left and right image plane. It indicates that the height of the left and right imaging points corresponding to the left and right polar lines is the same. That is, their vertical coordinates in the pixel coordinate system are the same.

### 4. Principle analysis of BAS algorithm based on binocular parallel polar line constraint

The BAS algorithm based on binocular parallel epipolar constraint algorithm [10] is similar to the genetic algorithm (GA) [11], particle swarm optimization algorithm (PSO) [12], simulated annealing algorithm (SA) [13], and other intelligent optimization algorithms. The function to be optimized by this algorithm has no specific form and gradient information. Compared with the above algorithm, the BAS algorithm only needs one individual, which dramatically reduces computation. Meanwhile, the algorithm can be used for the optimization of any dimensional function. The principle of the BAS algorithm based on binocular parallel epipolar constraint is as follows:

The simplified model of the longicorn is shown in Figure 3.
For a longicorn, $x_l$ and $x_r$ are located on the centroid $x$'s left and right, respectively, where $x$ is a 22-dimensional vector $[f_{\text{left}} u_{\text{left}} v_{\text{left}} k_1\text{left} \ k_2\text{left} \ p_1\text{left} \ p_2\text{left} \ f_{\text{right}} u_{\text{right}} v_{\text{right}} k_1\text{right} \ k_2\text{right} \ p_1\text{right} \ p_2\text{right} \ \omega \ \delta \ \theta \ \tau_{X\omega} \ \tau_{Y\omega} \ \tau_{Z\omega}]$ composed of 22 stereo calibration parameters of the binocular camera, namely, a 22-dimensional variable to be optimized. The formula of the ratio of the step length $\text{step}$ to the distance $d_0$ between the two whiskers:

$$\text{step} = c \times d_0$$  \hspace{1cm} (3)

Where $c$ is a constant, according to the characteristic that the head of the longicorn is arbitrary, the direction vector of the right whisker to the left whisker of the longicorn is also arbitrary, so the direction vector $\text{dir}$ is expressed by formula (4):

$$\text{dir} = \text{rands}(22,1)$$  \hspace{1cm} (4)

$rands(22,1)$ represents a twenty-two-dimensional direction vector. Normalized the direction vector to obtain the normalized direction vector $\text{dir}_1$:

$$\text{dir}_1 = \frac{\text{dir}}{\text{norm}(\text{dir})}$$  \hspace{1cm} (5)

Where $\text{norm}(\text{dir})$ is the Euclidean distance of $\text{dir}$. The difference between $x_l$ and $x_r$ is $d$ can be expressed as:

$$d = x_l - x_r = d_0 \times \text{dir}$$  \hspace{1cm} (6)

$x_l$ and $x_r$ can also be represented by $d_0$:

$$\begin{align*}
x_l &= x + d_0 \times \frac{\text{dir}_1}{2} \\
x_r &= x - d_0 \times \frac{\text{dir}_1}{2}
\end{align*}$$  \hspace{1cm} (7)

According to search for food by a comparison of the two, Sawyer feels about food taste value size to determine the direction. The movement characteristics of smell value, namely for optimal function value $f$ for each board a corner in the three-dimensional imaging points around the image after the correction in pixel coordinates ordinate difference and average, the smaller the value, the higher the degree of parallel binocular camera. The vertical coordinates of the left and right imaging points corresponding to each corner in the pixel coordinate system are $v_{l1}$, $v_{l2}$, $v_{l3}$, ..., $v_{ln}$, and $v_{r1}$, $v_{r2}$, $v_{r3}$, ..., $v_{rn}$. $f$ can be expressed as:

$$f = \sum_{k=1}^{n} (v_{lk} - v_{rk})$$  \hspace{1cm} (8)

Each iteration will result in two new parameters $x_{ln}$ and $x_{rn}$, and $n$ is the number of current iterations. $f_{ln}$ and $f_{rn}$ can be obtained through formula (9). The smallest value of $f_{ln}$ and $f_{rn}$ can be determined by comparing it with the smallest value of $f_{l(n-1)}$ and $f_{r(n-1)}$ in the previous generation. It determines whether to keep the variable corresponding to the minimum value of the previous generation or the variable corresponding to $f_{ln}$ and $f_{rn}$'s minimum value in the current generation. The judgment expressions are respectively:
\[ \begin{align*} 
&x_{n}, \ f_{n} < f_{n-1} \\
&x_{r(n-1)}, f_{n} > f_{n-1} \\
&x_{n-1}, f_{n} = f_{n-1} 
\end{align*} \]

(9)

Where \( f_{n\min} \) is the minimum value in \( f_{n} \), and \( f_{r(n-1)} \). \( x_{n-1} \) is the variable corresponding to the minimum value in \( f_{(n-1)} \) and \( f_{r(n-1)} \) of the previous generation, \( x_{n} \) and \( x_{r(n)} \) are the parameters after the left and right movement of the previous generation, respectively, and the expressions of \( x_{n} \) and \( x_{r(n)} \) are as follows:

\[ \begin{align*} 
&x_{n} = x_{n-1} + eta \times step \times dir_{1} \\
&x_{r(n)} = x_{n-1} - eta \times step \times dir_{1} 
\end{align*} \]

(10)

\( eta \) is the variable step-size coefficient.

\[ x_{n} = \begin{cases} 
\lfloor x_{\min}, f_{n\min} < f_{(n-1)\min} \\
\lfloor x_{n-1}, f_{n\min} > f_{(n-1)\min} 
\end{cases} \]

(11)

\( x_{n\min} \) variable corresponds to the minimum value of this generation, and \( x_{n} \) is the variable finally determined in this generation after two judgments. Finally, the minimum optimal function value is obtained through \( n \) iterations, and the corresponding optimal variable is the optimal parameter.

5. Experimental analysis

In the experiment, the DSL-3079-HE camera of ChuRui Technology Co., Ltd. was used to shoot the calibration images. The camera adopted Sony IMX179 sensor, and the image resolution was 640 pixels \( \times \) 480 pixels. The size of each grid of the checkerboard is 25mm \( \times \) 25mm (length \( \times \) width), and the checkerboard corner point is taken as the marking point, with a total of 88 marking points. Five sets of calibration image sets were taken, and each set of calibration image sets included 12 pairs of left and right images, with a total of 120 images. The MATLAB calibration toolbox calibrated five groups of calibration image sets to obtain five groups of binocular stereo calibration parameters. As shown in Tables 1, 2 and 3.

| Table 1 Left camera parameter matrix | Left camera distortion parameter matrix |
|--------------------------------------|----------------------------------------|
| Left camera internal parameter matrix | Left camera distortion parameter matrix |
| [517.74247 0.00000 322.60294 0.00000 518.23530 322.59702 0.00000 0.00000 1.00000] | [0.12316 −0.11190 −0.00130 −0.00001 0.00000] |
| [517.38003 0.00000 323.66303 0.00000 517.58820 324.54091 0.00000 0.00000 1.00000] | [0.11691 −0.08309 −0.00023 0.00002 0.00000] |
| [520.32472 0.00000 322.97005 0.00000 520.74186 324.68547 0.00000 0.00000 1.00000] | [0.13119 −0.16947 −0.00094 0.00007 0.00000] |
| [518.85991 0.00000 322.18730 0.00000 519.56053 324.81648 0.00000 0.00000 1.00000] | [0.12444 −0.12276 −0.00013 −0.00025 0.00000] |
| [516.93666 0.00000 322.90410 0.00000 517.40709 324.76845 0.00000 0.00000 1.00000] | [0.13995 −0.19373 −0.00248 −0.00013 0.00000] |

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Table 2 Right camera parameter matrix

| Right camera internal parameter matrix | Right camera distortion parameter matrix |
|----------------------------------------|------------------------------------------|
| 1                                      | [0.13624 -0.17425 0.00011 0.00066 0.00000] |
| 2                                      | [0.14213 -0.20923 -0.00213 -0.00090 0.00000] |
| 3                                      | [0.15904 -0.23684 -0.00115 0.00188 0.00000] |
| 4                                      | [0.14350 -0.23337 -0.00114 -0.00228 0.00000] |
| 5                                      | [0.14510 -0.21445 -0.00127 0.00013 0.00000] |

Table 3 External parameter matrix of binocular camera

| Rotation matrix | Translation matrix |
|-----------------|--------------------|
| 1 [−0.00784 0.00871 0.00203] | [−105.69467 0.15943 2.83075] |
| 2 [−0.01413 0.00668 0.00198] | [−105.41144 0.22767 3.21702] |
| 3 [−0.00931 0.00756 0.00195] | [−105.37882 0.03876 −6.82599] |
| 4 [−0.01321 0.00756 0.00195] | [−105.59194 0.16024 0.37719] |
| 5 [−0.00838 0.00838 0.00184] | [−105.64356 0.30242 3.17143] |

To evaluate the proposed BAS algorithm based on binomial parallel polar line constraint, the particle swarm optimization algorithm (PSO) and annealing simulation algorithm (SA) is improved accordingly. The proposed algorithm, particle swarm optimization algorithm based on binocular parallel poles constraint and simulated annealing algorithm based on binocular parallel poles constraint, is used to optimize binocular cameras' stereo calibration parameters. The optimization results are shown in Table 4 and Table 5, respectively. Because the algorithm name is too long, the algorithm proposed in this paper and the two improved algorithms are called BAS, PSO and SA.

Table 4 Optimization results of stereo parameters of binocular camera based on three algorithms of binocular parallel polar line constraint

| $f_{origin}$ | BAS $f_{optimize}$ | PSO $f_{optimize}$ | SA $f_{optimize}$ |
|--------------|------------------|--------------------|------------------|
| $f_{origin}$ | $f_{optimize}$ | difference value | $f_{optimize}$ | difference value | $f_{optimize}$ | difference value |
| 1 0.43328    | 0.23184 0.20144 | 0.44230 -0.00902 | 0.39937 0.03391 |
| 2 0.49498    | 0.31955 0.17543 | 0.42208 0.07290 | 0.40095 0.09403 |
| 3 0.84067    | 0.39033 0.45034 | 0.54350 0.29717 | 0.57682 0.26385 |
| 4 0.35928    | 0.35268 0.00066 | 0.36405 -0.00477 | 0.44942 -0.09014 |
| 5 0.41370    | 0.29948 0.11422 | 0.61981 -0.20611 | 0.37741 0.03629 |
| average value | 0.50838 0.31878 | 0.18960 0.48239 | 0.02599 0.44079 | 0.06759 |
Table 5 Average optimization results of stereo parameters of the binocular camera by three algorithms based on binocular parallel polar line constraint

| Optimization Algorithm | Average Optimization Value | Average Optimization Percentage |
|-------------------------|-----------------------------|---------------------------------|
| BAS                     | 0.18960                     | 37.29%                          |
| PSO                     | 0.02599                     | 5.11%                           |
| SA                      | 0.06759                     | 13.30%                          |

For the three algorithms based on binocular parallel pole constraint, it can be seen from Table 4 that the optimization results of BAS for each of the five groups of binocular stereo calibration parameters are better than those of PSO and SA. At the same time, both PSO and SA appear to be either superior or inferior, such as Group 1, Group 4 and Group 5 of PSO and Group 4 of SA. Meanwhile, it can be seen from Table 5 that the average optimization results of BAS for the five groups of binocular stereo calibration parameters are better than those of PSO and SA. In conclusion, BAS has a significant optimization effect on optimizing the stereo calibration parameters of the binocular camera, thus effectively improving the parallelism of the binocular camera. At the same time, the binocular camera cannot reach the ideal parallel state due to the inevitable technological errors in the production of the camera, the inability to make the camera with the same parameters and the possible errors when the left and right cameras are placed parallel manually.

6. Conclusion

This article is based on the BAS algorithm based on the binocular parallel polar line constraint of the binocular stereo camera calibration parameters optimization method. The MATLAB toolbox won a stereo binocular camera calibration parameter. As an optimization algorithm of the initial value, the BAS algorithm is based on the binocular parallel polar line constraint of all parameters of binocular cameras’ iterative optimization. This algorithm is a very complex multi-dimensional optimization problem without a specific objective function. It has the advantages of fast convergence and is not easy to fall into the optimal local solution. The results show that the BAS algorithm based on binocular parallel pole constraint can improve the stereo calibration accuracy of the binocular camera quickly and effectively. The algorithm is simple and easy to implement. When solving multi-dimensional problems, the parameters will not affect each other, the convergence is fast, and it is suitable for engineering practice.

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