Optimization of Stereo Matching in 3D Reconstruction Based on Binocular Vision

Qiyang Gai

Electronic Information Engineering, Glasgow College, University of Electronic Science and Technology of China, Chengdu, Sichuan 611731, China

Email: *15511392991@163.com

Abstract. Stereo matching is one of the key steps of 3D reconstruction based on binocular vision. In order to improve the convergence speed and accuracy in 3D reconstruction based on binocular vision, this paper adopts the combination method of polar constraint and ant colony algorithm. By using the line constraint to reduce the search range, an ant colony algorithm is used to optimize the stereo matching feature search function in the proposed search range. Through the establishment of the stereo matching optimization process analysis model of ant colony algorithm, the global optimization solution of stereo matching in 3D reconstruction based on binocular vision system is realized. The simulation results show that by the combining the advantage of polar constraint and ant colony algorithm, the stereo matching range of 3D reconstruction based on binocular vision is simplified, and the convergence speed and accuracy of this stereo matching process are improved.

1. Introduction

Binocular vision is an important branch in the computer vision field [1, 2]. It refers to the shooting of the same scene or object by movement or rotation of two or more cameras at different positions. By calculating the parallax between the two images, the three-dimensional geometric description of the objects is restored and the spatial properties of objects in the scene are quantitatively determined.

1.1. The basic principle of binocular vision

![](image.png)

**Figure 1.** Geometric relation of cameras in binocular vision
According to the principle of camera imaging, the spatial point is \( L(x, y, z) \). \( L(0x, 0y) \) is the intersection point between the connection line of \( L \) and camera's optical center and camera screen. If the image points of \( L \) in the left and right camera are \( L1(x1, y1) \) and \( L2(x2, y2) \), the original space point \( L \) is located at the intersection of the extension line of the spatial ray \( O1L1 \) and of \( O2L2 \) (\( O1, O2 \) are respectively the optical center of the left and right camera.). The intersection of the spatial ray \( O1L1 \) and of \( O2L2 \) can be inverted to find the 3D coordinate of \( L \), which is shown in Figure 1. Therefore, binocular vision can be viewed as a mapping process from the image coordinates to the 3D world coordinates [3].

1.2. Binocular vision system

A complete binocular vision system can usually be divided into image acquisition, camera calibration, feature extraction, stereo matching, and depth recovery and depth interpolation.

1.2.1 Image acquisition. There are many ways to obtain images, which mainly depends on the application of the occasion and purpose, but also considers the point of view differences, lighting conditions, camera performance and scene characteristics and other factors to facilitate the three-dimensional calculation [4].

1.2.2 Camera calibration. Camera calibration is used to determine the camera location, attribute parameters, and to establish an imaging model to determine the corresponding relationship between the object points in space coordinate system and the image points in the image plane [5].

1.2.3 Feature extraction. Feature extraction is to obtain the required image feature matching. Because there is not a universally applicable theory to be applied to image feature extraction, it leads to the diversity of feature matching in stereo vision research [6].

1.2.4 Stereo matching. Stereo matching is the one-to-one correspondence between the pixels that seek the same spatial scene at different points of view [7].

1.2.5 Depth recovery. It is easy to recover 3D distance after stereo imaging model and matching parallax [8].

1.2.6 Depth interpolation. The ultimate goal of stereo vision is to restore the complete information of the visual surface of the scene. For a complete stereo vision system, the final surface interpolation reconstruction must be carried out [9].

2. Stereo matching

Stereo matching is one of the key steps of 3D reconstruction. The so-called stereo matching is to seek the corresponding relations between image pixels from the same space scene under different viewpoints [10].

In order to remove the ambiguity, and reduce the computational complexity, the polar constraint technique is used to reduce the search range of stereo matching; at the same time, due to the reduced stereo matching search range matching results bring non optimal solution, the ant colony algorithm for stereo matching calculation process optimization and optimal solution for stereo matching is used to overcome the negative effects, and to improve the computational efficiency of stereo matching [11].

2.1. Reducing search range by epipolar constraint

As shown in Figure 2, if \( L1 \) point in the left image corresponds to \( L2 \) point in the right image, \( L1, L2, O1, O2 \) and \( L \) are located in the \( D \) plane, \( d1 \) and \( d2 \) are respectively the intersection line of the \( D \) plane and the two image planes, \( L1 \) is a point on \( D1 \), \( L2 \) is \( D2 \) the point, \( d1 \) is called polar of the point \( L2 \), \( d2 \) is called polar of the point \( L1 \), \( p1 \) and \( p2 \) are the pole. It can be seen that the projection of the corresponding point \( L \) of the \( L1 \) on the right image is always on the \( d2 \). So, \( L2 \), which is the
corresponding point of the any point \( L_1 \), can be only found in its corresponding \( d_2 \). This is the calculation logic of the polar constraint.

\[
\begin{align*}
\text{Figure 2. Pole and polar in stereo images}
\end{align*}
\]

For the two images obtained from different angles on the same target, the previous matching search method is to obtain a feature point on the first image and then find the corresponding feature point of the feature point on the other image. And the principle of polar constraint can be known: if there is no occlusion, the feature point on the first image must be located in the corresponding polar line on the second image. So, the two-dimensional search on the two-dimensional plane can be transformed into a one-dimensional search on the one-dimensional. If the distance between the image acquisition device and the target is obtained, the search range can be limited on a specific small interval of the polar line, as shown in Figure 3.

\[
\begin{align*}
\text{Figure 3. Space someone distance a rectilinear writing recorder segment pairs in the zone should the most on-line limited zone}
\end{align*}
\]

2.2 application of ant colony algorithm optimization in polar constraint

Because the ant colony algorithm has the characteristics of self-heuristic search, the ant colony algorithm is used to realize the optimal solution of the stereo matching search function under the constraint of the polar line [12].

The stereo matching search is performed in the corresponding polar lines of the left and right images. Then, the pole set of \( i \)th row in the left image is \( PL_i=\{pl_1, pl_2, \ldots, pl_n\} \) and in the right image, the pole set of \( i \)th row is \( PR_i=\{pr_1, pr_2, \ldots, pr_n\} \).

The objective of ant colony optimization is to find the pole points matching relation between the set \( PL_i \) and \( PR_i \). The ant colony algorithm is used to solve the pole matching problem on the corresponding polar line of the left and right images [13]. Its design is as follows.

- Initialize the stereo matching ant colony algorithm optimization parameters, such as setting the number of ants, the number of iterations, the total amount of pheromone and so on.
- Between the \( i \)th line pole sets \( PL_i \) of the left image and the \( i \)th line pole sets \( PR_i \) of the right image, the pole set ,which has less pole points, is used as the, and the other pole set is the search point set.
All ants are placed at the first feature point of the model point set. Each ant randomly selects a feature point of the search point set, and adds the feature point is added into each ant's marked table.

The ants are placed to the next feature point sets. According to the change rules, the feature point is selected by each ant in search point set and not in marked table. It is assigned to the feature points of the model where the ants are, that is, the selected feature points constitute a mapping with the model points of the ants. The change rules that ants follow when selecting feature points are:

- The ant a current model feature is the point i, which selects the feature point j in probability $p_{ij}^a$ to form the mapping from point j to point i. The formula of $p_{ij}^a$ is described in (1).

$$
p_{ij}^a = \begin{cases} 
\frac{(r_{ij})^\alpha (q_{ij})^\beta}{\sum_{k \in R} (r_{ik})^\alpha (q_{ik})^\beta} & i, j \in R \\
0 & \text{otherwise}
\end{cases}
$$

(1)

The ant a selects the search j as the path to the model i in this iteration. The pheromone $r_{ij}$ is accumulated on the search. $\eta_{ij}$ is the heuristic information that maps the search feature point j to the feature point i of the model set, $\eta_{ij}=1/S_{ij}$. $S_{ij}$ is the search function for selecting the search j to reach the model i, which is equivalent to the search length from j to i, and the $S_{ij}$ calculation is determined by the specific line constrained geometric model. $\alpha$ and $\beta$ represent the different effects of the accumulated pheromone $r_{ij}$ and the heuristic information $\eta_{ij}$ in the process of ants select the search set point. R denotes a set of feature points that the ant a can currently select from a set of search points, which does not include the points in the marked table. The above process is cycled until all the ants walk through all the feature points in the model points, that is, all the ants find the mapping from the feature points in the search point to the feature points in the set of model point.

The pheromone updates when an iteration is completed. Only the pheromone on the optimal search is adjusted. The sum of the search lengths $W$ ($W = \Sigma S_{ij}$) is compared in the search for each ant in this iteration. The pheromone on the search for an ant with minimal W is updated as follows:

$$
r_{ij}(t+1) = \rho r_{ij}(t) + \delta r_{ij}^\text{best}(t), \rho \in (0, 1)
$$

(2)

Where $r_{ij}(t+1)$ and $r_{ij}(t)$ are respectively the pheromones on the search j on the model i at the (t+1)th iteration and the tth iteration. $\delta r_{ij}^\text{best}$ Represents the pheromone increment of the current an iteration of the ants in this search. $\sum r_{ij}^\text{best}(t) = Q / S^\text{best}$ is the total length of each search for the current iteration's optimal ant. $Q$ is the total amount of pheromones of ants, and $\rho$ is the pheromone residual coefficient.

If the iteration termination condition is satisfied, the iteration ends; otherwise, empty the marked table and turn to the step c. At the end of the iteration, the ant with the minimum length of S is chosen to achieve the global optimal matching solution of the stereo matching under the constraint condition of the polar constraint.

3. Design of stereo matching process based on ant colony algorithm under polar constraint

The optimization workflow design of stereo matching in the 3D reconstruction based on the ant colony algorithm under polar constraint is as follows, shown in Figure 4.
Establish binocular vision geometry model
Introduce the polar constraint method
Reduce the dimension of 3D space
Introduce Ant Colony Algorithm for Global Optimization of Artificial Intelligence
Set up the application model of ant colony algorithm with stereo matching

Figure 4. The optimization workflow design of stereo matching in the 3D reconstruction based on the ant colony algorithm under polar constraint

3.1 Establish binocular vision geometry model
The spatial target points are locked by the left and right visual sources, and the geometric relation is used to gradually establish the geometric plane of the spatial target points in the left and right views.

3.2 Introduce the polar constraint method
The concept of polar line is defined according to the feature points projected from the space target point to the left and right planes, and the geometric calculation method is constructed to realize the polar constraint range of the space target point.

3.3 Reduce the dimension of 3D space
According to the searching range of polar lines, the work of the 3D to 2D and 2D to 1D is implemented. The complexity of the algorithm is reduced by the simplified work, in order to define the search range and simplify the analysis process of the stereo matching data.

3.4 Introduce Ant Colony Algorithm for Global Optimization of Artificial Intelligence
In order to avoid the incompleteness of data information caused by polar constraint, ant colony algorithm is introduced to realize the optimal solution of global information of stereo matching.

3.5 Set up the application model of ant colony algorithm with stereo matching
According to the geometric information of the spatial target points in the binocular vision system, the number of ants, the number of iterations and the total amount of pheromone are set up to realize the automatic optimization of stereo matching.

4. Simulation and analysis

4.1 Simulation environment
In order to verify the stereo matching optimization process in the binocular vision system using the "polar constraint + ant colony algorithm" combination mode, the simulation environment is set as follows.

- Space range V = length * width * height = 2 * 1 * 1.5 (m^3);
- Number of space target points: 50;
- Maximum length of polar line: 1 m;
Training sample (ants) Number: 200;
Number of iterations: 100;
Pheromone value: (0, 1];

It is assumed that the spatial information of 50 target points is known. There are four cases of three-dimensional matching effect comparison, as shown in Figure 5.

Case 1: there is no polar line constraints and no ant colony algorithm to participate in the three-dimensional match.
Case 2: Stereo matching is only realized under polar constraint.
Case 3: Stereo matching is only realized under ant colony algorithm.
Case 4: both polar constraint and ant colony algorithm are involved in the stereo matching.

By using the method of polar constraint in stereo matching, the initial iterative stage effect is obvious. Because the polar constraint is simplified to a one-dimensional search range, reduce the amount of data to be processed, the initial growth rate of the stereo matching curve is higher. Through constant iterative process of stereo matching with ant colony algorithm, on the one hand, it's faster to achieve the stereo matching final state; on the other hand, the degree of stereo matching is improved. Therefore, the stereo matching using ant colony algorithm can be faster and higher to achieve the matching state in the middle and late stages of the stereo matching curve.

5. Conclusion
The algorithm model and workflow design of stereo matching in 3D reconstruction based on binocular vision provide a feasible theoretical basis for the experimental simulation.

Through the experimental simulation, it proves the technical advantages of the combination of the polar constraint and the ant colony algorithm. On the one hand, the stereo matching range of 3D reconstruction under binocular vision is clarified; on the other hand, the convergence speed and accuracy of the stereo matching process are improved.

References
[1] Sedlackova A, Szczecinski N S, Quinn R D. Binocular Vision Using Synthetic Nervous Systems [M]// Biomimetic and Biohybrid Systems. 2017.
[2] Ciuffreda K J. Binocular vision in the twenty-first century. [J]. Journal of Optometry, 2017, 10(3):139-140.

[3] Lin Y H, Shou K P, Huang L J. The initial study of LLS-based binocular stereo-vision system on underwater 3D image reconstruction in the laboratory [J]. Journal of Marine Science & Technology, 2017(3):1-20.

[4] Koprowski R. Image Acquisition [M]/ Processing of Hyperspectral Medical Images. Springer International Publishing, 2017.

[5] Godding R, Hornberg A. Camera Calibration [M]/ Handbook of Machine and Computer Vision: The Guide for Developers and Users. Wiley - VCH Verlag GmbH & Co. KGaA, 2017.

[6] Zhu J, Narabu Y, Tanaka T, et al. Manufacturing feature extraction system of 3D-model for process planning [J]. Proteomics, 2017, 11(19):3779.

[7] Liu J, Yu L, Li X, et al. Research on Joint Segment Optimization and Stereo Matching [J]. Iet Communications, 2017.

[8] Chen C, Hai X P, Pavlovic V, et al. Using 3D Face Priors for Depth Recovery[J]. Journal of Visual Communication & Image Representation, 2017.

[9] Wang Y, Yan P. Depth image interpolation algorithm based on confidence map [J]. Proceedings of the Spie, 2017, 255:102550D.

[10] Oh J, Lee C. Extraction of digital elevation model using stereo matching with slope-adaptive patch transformation [J]. Ksce Journal of Civil Engineering, 2017, 20(7):1-8.

[11] Ohyama J, Ohta N, Oagwa N. Correct correspondence selection between points on two asteroid images using epipolar constraint[C]/ Jpgu-Agu Joint Meeting. 2017.

[12] Alaya I, Solnon C, Ghédira K. Ant Colony Optimization for Multi-Objective Optimization Problems[C]/ IEEE International Conference on TOOLS with Artificial Intelligence. IEEE, 2017:450-457.

[13] Sammoud O, Solnon C, Ghédira K. Ant Algorithm for the Graph Matching Problem [J]. Lecture Notes in Computer Science, 2017, 3448:213-223.