Research on Calibration Method of Multi-camera System without Overlapping Fields of View Based on SLAM

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Abstract. The basis of multi-camera system measurement is the calibration of the multi-camera system. Although multi-camera system calibration has achieved certain results, there are still problems such as tedious calibration process and high calibration cost. In this paper, we propose a practical calibration method for multi-camera systems without overlapping fields of view. Firstly, a global 3D model of the scene is reconstructed using Simultaneous Localization and Mapping (SLAM). Then, each camera is calibrated using the 2D-3D correspondence between the images acquired by the multi-camera system and the 3D model. Finally, the external parameters of the multi-camera system are calibrated. In the process of using SLAM to build the model, the graph optimization is used to improve the accuracy of the modeling, and the accuracy of the calibration depends on the accuracy of the modeling. After several experiments, the experimental results show that the method is feasible.

1. Introduction
A multi-camera system has a larger field of view than a single camera, and it is often used in fields such as Advanced Driver Assistance System (ADAS)\textsuperscript{[1, 2]}, scene reconstruction\textsuperscript{[3-6]} and photogrammetry\textsuperscript{[7]}. The calibration of the multi-camera system is to obtain accurate parameters of the multi-camera system. The famous camera calibration method is Zhang’s method\textsuperscript{[8]}. In this method, the calibration target is placed in the overlapping field of view of the multi-camera system to calculate the external parameters. However, due to structural design and cost issues, some systems do not overlap the field of view (FOV) between the cameras, that leads to increased calibration difficulty. In the multi-camera system without an overlapping FOV, different cameras cannot capture images of the same target, and traditional calibration methods are no longer applicable in such cases. Therefore, a calibration method for a multi-camera system without overlapping FOVs is urgently needed.

Because some multi-camera systems lack an overlapping field of view, some researchers have addressed this problem with additional tools to create overlapping FOVs. Z. Xu et al.\textsuperscript{[9]} proposed a calibration method for multi-camera system without overlapping FOVs using a flat mirror. By adjusting the position and angle of the mirror, the relative relationship between two cameras without an overlapping field of view can be calculated. However, this method can only calibrate a pair of cameras without an overlapping FOV at a time. To simplify operation, a calibration method for a multi-camera system without overlapping FOVs using a laser rangefinder(LRF) was proposed by Z. Liu et al.\textsuperscript{[10]}. Firstly, the images of laser points projected on a flat object are capture by the camera, while LRF is used to
measure the distance between the laser projection points. Then, according to the collinear laser points collected by each camera and the distance between them, external parameters between the cameras can be calculated. However, high-precision measuring instruments are very expensive, increasing the cost of multi-camera system calibration.

In summary, the traditional multi-camera system without overlapping FOVs requires expensive measurement equipment for calibration. And many existing methods can only handle small areas and specific multi-camera systems without overlapping fields of view. To solve this problem, we propose a calibration method that can deal with various cameras distribution based on SLAM.

2. Theoretical background
We propose the calibration of multi-camera systems without overlapping FOVs based on SLAM reconstruction. The SLAM used in this paper is an improvement on orb-slam2\(^\text{[1]}\). When multi-camera system calibration is performed using the model established by SLAM, the accuracy of calibration is limited by the accuracy of the 3D model established by SLAM. Therefore, our proposed method uses graph optimization\(^\text{[2]}\) to improve the accuracy of the model, thereby improving the precision of the calibration. Graph optimization is a theory that combines nonlinear optimization with graph theory. The vertices in the graph represent the poses and key points of the camera at different times, and the edges represent the constraint relationship between the vertices. After the graph is constructed, the key points’ positions are solved using the graph optimization algorithm, so that the vertices better satisfy the constraint relationship of the corresponding edges. After non-linear optimization, more accurate camera motion trajectories and 3D maps can be obtained.

It is assumed that during the process of collecting surrounding information by the binocular camera, \(m\) \((i = 1, 2, \ldots, m)\) key frames is collected, and \(n\) \((j = 1, 2, \ldots, n)\) feature points are detected in the \(i\)-th key frame. Among them, the projection point calculated by the 3D feature point \(p_{ij}\) using the camera’s internal and external parameters is \(p_{ijp}\), and there is an observation equation:

\[
p_{ij} = f(K, R_i, t_i, D, P_i)
\]

(1)

Where \(D = [k_1, k_2, p_1, p_2, k_3]\) represents a vector of distortion coefficients. \(K, R_i, t_i\) is the intrinsic and extrinsic parameters of the binocular camera. At that time, the feature point detected in the image corresponding to \(P_i\) is \(x_{ij}\), and the objective function of the graph optimization is:

\[
\min \sum_i \sum_j \|x_{ij} - p_{ij}\|^2
\]

(2)

At this time, the graph optimization of the entire problem can be shown in the Figure 1. The circles represent 3D feature points and the triangles represent key frames. The dashed lines represent the reprojection model, the lines between circles represent the point-to-point relationship, and the lines between triangles represent the key frames motion model. After the graph model is established, the Levenberg-Marquardt (LM) algorithm is used to start iterative calculations until the end of the iteration to obtain an optimized 3D model.

![Figure 1. Graph optimization diagram.](image)

The auxiliary camera calibration method is a common calibration method for multi-camera systems without non-overlapping FOVs. In order to verify the accuracy of the proposed method, it is used to
compare the calibration method proposed in this paper. In the method of adding auxiliary cameras, when there is no overlapping field of view between the cameras to be calibrated, the auxiliary cameras are used to establish a connection between the cameras to be calibrated, and the calibration between the cameras to be calibrated is completed. Firstly, place one calibration target in the FOV of each camera to be calibrated. And Fix one auxiliary camera which can view all targets. Secondly, each camera takes a few images of the targets in its FOV. And the relative extrinsic parameters between cameras to be calibrated and auxiliary camera are calculated. Finally, the extrinsic parameters of each camera relative to the reference coordinate system are obtained using the redundant data based on the result of the previous step. The calibration method of auxiliary camera is completed.

3. The Propose Calibration Method
As shown in Figure 2, the method proposed in this paper is divided into two parts: 3D model construction and multi-camera system calibration, and the two parts are relatively independent. Firstly, a binocular camera SLAM platform was used to reconstruct a 3D model of the scene. Then, the 2D-3D correspondence between the image collected by the camera to be calibrated and the 3D model formed in the previous step is calculated, and the external parameter of the multi-camera system without overlapping FOVs is calculated. This paper refers to the camera in the multi-camera system that needs to be calibrated as the query camera. In the previous part, we introduced SLAM to construct a high-precision 3D model using nonlinear optimization.

Figure 2. Schematic diagram of the proposed method.

3.1. Camera Localization
Using the SLAM system proposed above, a high-precision 3D model of the scene is reconstructed.

The external parameters of each camera relative to three-dimensional model can be obtained by locating each camera to be calibrated in the 3D model, using the reconstructed high-precision 3D model as a reference object. This paper uses key frames matching, and the location images are the images collected by the query camera. Firstly, K key frames are found as candidate frames that are close to the location image using the bag of words (BoW). Then for each candidate frame, N-1 key frames with similar poses are added separately to form K clusters, and each cluster has N key frames. Finally, the matching of each cluster with the feature points of the location image is calculated separately, and the cluster with the highest total matching score is selected. In the last step, Random Sample Consensus (RANSAC) is used to geometrically verify the correspondence between points to reduce mismatches.

This paper uses the 2D-3D point correspondence obtained above to calculate the camera pose of the location images through the Efficient Perspective-n-Point (EPnP) algorithm. By repeatedly calculating, the camera pose corresponding to each location image can be calculated, that is the pose of each camera in the multi-camera system relative to the 3D model.

3.2. Multi-camera System Calibration
In this section, the single-camera projection model described earlier is extended to a projection model of a multi-camera system. Without loss of generality, we use a four-camera system as an example (as shown in Figure 3). As shown in the figure, the four cameras are installed at the front, rear, left, right, and left positions of the vehicle, respectively, and there is little or no overlapping FOVs between the
cameras. In a multi-camera system, a camera is selected as the main camera (assuming the camera Cam1 in front of the vehicle in Figure 3), and the main camera coordinate system is the global coordinate system.

![Figure 3. Model of multi-camera system.](image)

From the previous section, the pose of each camera relative to the 3D model in the multi-camera system is known as the external parameters. Suppose \( P_i \) represents the coordinates of a 3D point in a 3D model. \( P_1^c, P_2^c, P_3^c, \) and \( P_4^c \) represent the coordinates of \( P_i \) corresponding in the camera Cam1 coordinate system, camera Cam2 coordinate system, camera Cam3 coordinate system, and camera Cam4 coordinate system, respectively. The results of the previous section can be expressed as:

\[
P_i^c = [R_{ni} \ t_{ni}]P_s
\]

(3)

Where \([R_{ni} \ t_{ni}]\) is the external parameters from the 3D model coordinate to the camera Cami coordinate system. The camera Cam1 coordinate system is selected as the global coordinate system of the multi-camera system. The external parameters of Cam4 can be obtained according to the above formula:

\[
P_i^c = [R_{mi} \ t_{mi}]P_s = [R_{ci} \ t_{ci}]P_i^c = [R_{ci} \ t_{ci}] [R_{ni} \ t_{ni}]P_s
\]

(4)

Calculated from the previous equation:

\[
\begin{align*}
R_{ci} &= R_{ni} \cdot R_{ni}^{-1} \\
t_{ci} &= t_{ni} - R_{ci}t_{ni}
\end{align*}
\]

(5)

Where \([R_{ci} \ t_{ci}]\) represents the external parameters of camera Cam1 coordinate system to camera Cam4 coordinate system. In the same way, you can find \([R_{ci2} \ t_{ci2}]\) and \([R_{ci3} \ t_{ci3}]\) to complete the calibration of the multi-camera system.

4. Results and discussion

Our proposed method is divided into two independent parts: accurate 3D reconstruction and localization, calibration of multi-camera systems. The 3D reconstruction part uses the binocular camera SLAM. The binocular camera uses the Xiaomi binocular camera, which has a resolution of 640 * 400.

4.1. Feasibility of calibration method

Without loss of generality, this section uses a four-camera system without overlapping FOVs to verify the proposed calibration method. In order to verify the feasibility of the calibration method proposed, we performed experiments on different scenarios (including indoor scenario and parking lot scenario). This paper uses a binocular camera SLAM to collect scene images. Reconstruction experiments were repeated many times to determine that the reconstructed 3D model of the binocular SLAM system can
meet the requirements of multi-camera system calibration. The method proposed is used to locate the query camera, calculate the pose of the query camera, and position the multi-camera system in the 3D map (see Figure 4).

As shown in the Figure 4, the method proposed in this paper can successfully locate a multi-camera system in a three-dimensional model, which verifies the feasibility of the method proposed in this paper. From Figure 4, the pose of the 3D model reconstructed by the camera can be directly observed. It can be seen that the camera pose calculated by the method proposed in this paper is visually consistent with the pose when the camera captures the image.

![Figure 4. Positioning results in 3D mapping: (a) parking lot scenario; (b) indoor scenario.](image)

4.2. Precision of calibration method

To testify the accuracy of the proposed method, the proposed method will be used to calibrate a binocular camera in this section. In order to obtain accurate comparison results in the experiments, we evaluated the accuracy of the Matlab toolbox. The reprojection error of the checkerboard corners was less than 0.2 pixels. Therefore, the calibration results of the Matlab toolbox have high accuracy and it can be used as a standard for testing algorithms. As shown above, the auxiliary camera calibration method is a common calibration method for multi-camera systems without non-overlapping FOVs. Now it is used to compare the calibration method proposed in this paper. Calibration results such as Table 1.

| External Parameters | Matlab Toolbox | proposed Method | Auxiliary camera calibration method |
|---------------------|----------------|----------------|-----------------------------------|
| Rotation matrix     | 0.9936 −0.0421 −0.1050 | 0.9943 −0.0422 −0.1059 | 0.9948 −0.0419 −0.0923 |
|                     | 0.0582 0.9862 0.1550 | 0.0586 0.9863 0.1553 | 0.0559 0.9864 0.1544 |
|                     | 0.0970 −0.1601 0.9823 | 0.0950 −0.1592 0.9830 | 0.0846 −0.1588 0.9837 |
| Translation vector  | −179.5633 17.7617 120.4801 | −179.9566 20.9546 121.5569 | −182.9164 23.6372 116.4195 |

Experimental results show that the average rotation error of the auxiliary camera calibration method is 0.00503rad, and the average rotation error of the method proposed in this paper is 0.00047rad. In addition, the average translation error of the auxiliary camera calibration method is 4.4297mm. In contrast, the average translation error of the method proposed in this paper is 1.5543mm.
5. Conclusions
There are some multi-camera systems in tasks without overlapping FOVs, making it difficult to calculate external parameters of the multi-camera systems. In order to solve one of the problems, we propose an efficient multi-camera system calibration method without overlapping FOVs. Method proposed is easy to operate and can be calibrated to various distributed multi-camera systems. Firstly, the SLAM with graph optimization is used to reconstruct high-precision 3D model of scene. Then, the location of the query camera on the 3D model is calculated. Finally, according to the result of the previous step, the external parameters of the multi-camera system are calculated. Experiments show that the method proposed in this paper has good feasibility to calibrate multi-camera systems without overlapping fields of view.

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