

Research on the Calibration Method of Laser Radar and Camera Extrinsic Fusion based on Checkerboard Features

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Abstract: The external parameter calibration of LiDAR and camera is the core link of multimodal perception fusion technology, and its accuracy directly determines the effectiveness of cross modal information fusion. This article proposes a method for high-precision calibration of laser radar and camera extrinsic parameters using a checkerboard calibration board based on spatial registration theory. In response to the difficulty of feature extraction caused by the sparsity of LiDAR point clouds, this method enhances feature information by accumulating multi view point clouds and combines filtering algorithms to improve feature saliency; A standardized experimental platform was built based on ROS and Matlab, utilizing the reflection intensity distribution pattern of the checkerboard point cloud to achieve accurate extraction of its three-dimensional corner coordinates. At the same time, the corresponding two-dimensional checkerboard corner points are detected in the camera image, and the relative pose transformation matrix between the LiDAR and the camera is solved by establishing an accurate matching relationship between the two-dimensional and three-dimensional corner points. The experimental results show that this method has high-precision calibration results and good repeatability, which can provide a reliable extrinsic basis for multi-sensor fusion perception systems.

Keywords: Chessboard Pattern Features; Multi-sensor Fusion; Lidar Camera Calibration; External Parameter Fusion Calibration Method.

1. Preface

Environment perception target detection is one of the key technologies of autonomous vehicle. The accuracy, reliability and robustness of perception methods are closely related to the safety and stability of vehicles. At present, obstacle detection technology based on pure vision single sensor has been developed rapidly, but the adaptability and processing ability of single sensor system in dealing with complex scenes are limited, which will affect the accuracy of the vehicle's perception of obstacles around itself. [1] In order to enable autonomous vehicles to better adapt to complex scenes, experts and scholars at home and abroad have carried out research on multi-mode data fusion environment perception technology, aiming at feature extraction and fusion by combining point cloud data collected by laser radar with RGB images collected by camera [2].

At present, multi-sensor information fusion has been widely applied in industrial production [3]. Among different fusion algorithms, LiDAR and camera are the most common combination. The first and most crucial step in fusing LiDAR point clouds and camera images is precise external calibration. Without precise calibration parameters, the texture features in the image cannot be accurately correlated with the distance information provided by the LiDAR. The calibration process between LiDAR and camera (external calibration) involves calculating an appropriate transformation matrix to align the coordinate systems of the two sensors. This process has been studied in the fields of robotics and computer vision for many years. External calibration methods can be divided into target based methods and target free methods. The focus of target based methods is to identify the corresponding features of common targets from multimodal data. The method without target objects estimates the transformation matrix by maximizing the correlation of mutual information in

multimodal data, such as the discontinuity of edges and point cloud scan lines in images [4-5], the brightness of images and the reflectivity of point clouds [6]. Among them, the calibration method based on the target object provides higher reliability and accuracy. The fusion technology of LiDAR and camera can achieve comprehensive recognition of objects in complex environments [7]. Therefore, this article chooses a checkerboard as the calibration board and proposes a laser radar camera calibration method based on the checkerboard calibration board.

2. Camera Model

Camera calibration is a crucial step in computer vision, aimed at establishing an accurate mapping relationship between three-dimensional world coordinates and two-dimensional image pixel coordinates through mathematical models. This process is achieved by solving the camera's internal parameter matrix (focal length, principal point coordinates, distortion coefficient) and external parameter matrix (rotation matrix R and translation vector), while this article uses Matlab to calibrate the camera and obtain its internal parameters.

Due to its low price and high frame rate, the camera can obtain rich color information, making it one of the best sensors for robotic arm systems to recognize and classify targets. The characteristic of the camera is that it can recognize and classify targets through its rich color and texture information. There are mainly traditional machine vision algorithms and deep learning algorithms for camera based target recognition. The shortcomings of traditional machine vision algorithms are low algorithm accuracy, relatively slow efficiency, and poor robustness in complex scenes. So we chose the fusion of cameras and LiDAR for more accurate recognition.

The calibration board used in this article is 70x70 for better

calibration of the LiDAR. The camera collects data from the three-dimensional world and outputs two-dimensional pixel information. The camera end mainly includes four coordinate systems: world coordinate system ($O_W X_W Y_W Z_W$), camera coordinate system ($O_C X_C Y_C Z_C$), image coordinate system ($O_i X_i Z_i$), and pixel coordinate system (OUV). The relationship between the four coordinate systems is shown in Figure 1.

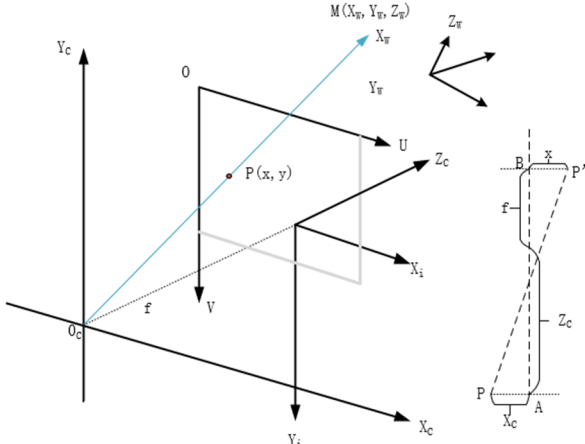


Figure 1. Schematic diagram of the coordinate system relationship of the camera

The camera imaging model is shown in Figure 2-1. A three-dimensional point P is captured on the two-dimensional imaging plane in the camera coordinate system $O_C-X_C Y_C Z_C$. xy represents the position of P in the image coordinate system xoy . Formula (1) can be derived based on the similarity triangle theorem

$$\frac{Z_c}{f} = \frac{X_c}{x} = \frac{Y_c}{y} \quad (1)$$

The conversion relationship between the camera coordinate system $O_C-X_C Y_C Z_C$ and the image coordinate system xoy can be summarized as follows:

$$x = f \frac{X_c}{Z_c}, \quad y = f \frac{Y_c}{Z_c}, \quad Z_c \neq 0 \quad (2)$$

The expression for converting the above equation into homogeneous coordinates is:

$$Z_c \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} \quad (3)$$

The conversion process is based on the ideal pinhole imaging principle, assuming that the camera achieves perspective imaging using a linear imaging model. However, in reality, due to the presence of lenses on the camera lens, distortion occurs in the imaging. The distortion of the lens can be divided into two categories: radial distortion and tangential distortion. Radial distortion refers to the distortion distributed along the radius of the lens, and the distortion becomes more pronounced closer to the edge of the image. Radial distortion mainly includes pillow distortion and barrel distortion.

In Matlab, we first distort the image and then calibrate it as shown in Figure 2

3. Lidar Model

Lidar (Light Detection and Ranging) is a non-contact optical sensor that scans and ranges target objects through a laser beam. It is widely used in intelligent driving cars and has

the function of acting as the "eyes" of the vehicle. It can help the car identify obstacles in motion and avoid collisions with pedestrians, cyclists, stationary or moving vehicles, etc.

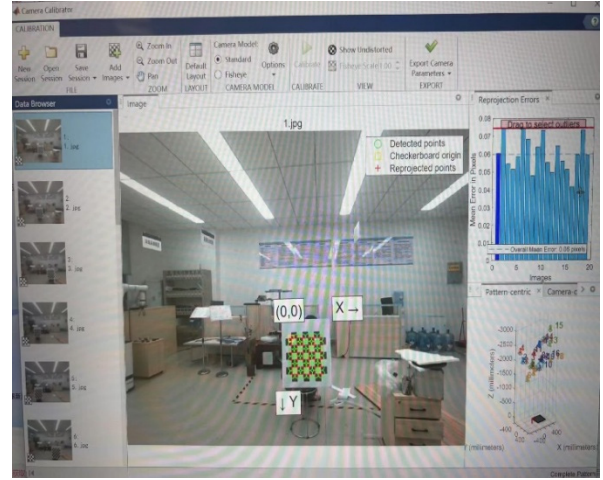


Figure 2. Schematic diagram of camera calibration

Lidar can obtain rich surface information of objects in the surrounding environment of intelligent driving vehicles. Different structured objects present different scanning results in the form of point clouds, as shown in Figure 3. The spatial coordinates and external dimensions of the scanning target object can be obtained through point clouds.

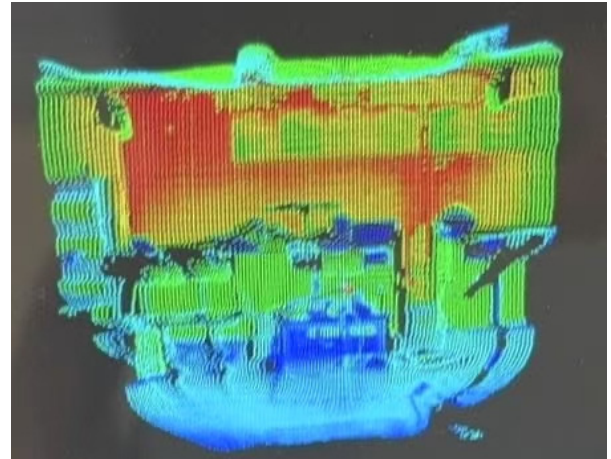


Figure 3. Point cloud maps of different types of obstacles scanned by LiDAR

Lidar can scan the environmental information around vehicles with high-resolution 3D point clouds. Compared with camera sensors, it is not affected by light intensity and has the advantages of long detection distance and strong anti-interference ability. Taking mechanical LiDAR as an example, it mainly consists of a laser transmitter, a laser receiver, a scanning system, and a signal processing unit. The high-speed rotating laser transmitter continuously emits pulsed laser beams at a certain angle to the outside. After projecting them onto the surface of the object, the receiver receives the reflected echo signal. The signal processing unit is used to extract information from the echo. Based on the laser propagation speed, emission angle, and other information, the distance of the target can be calculated. Combined with the spatial installation position of the LiDAR, the direction and angle of laser scanning can determine the location of the target.

The principle of laser radar ranging mostly uses time-of-

flight (TOF) method, which obtains the distance between the target and the radar through the flight time difference of light pulses. According to equation (5), the distance d between the LiDAR and the target object can be calculated.

$$d = v \times \frac{t_2 - t_1}{2} \quad (4)$$

4. Lidar Camera Joint Calibration Model and Calibration Method

4.1. Joint Calibration Model of LiDAR Camera

To achieve joint calibration between the camera and the LiDAR, the calibration board needs to be placed within the joint observation range of the LiDAR and camera. The 3D laser point cloud coordinates and image pixel coordinates corresponding to the corner points of the calibration board are collected separately by the LiDAR and camera, and an equation system is constructed to solve the joint calibration matrix. The joint calibration model between the camera and the 3D LiDAR is shown in Figure 4.



Figure 4. Joint calibration model between camera and 3D LiDAR

The transformation relationship between the motion camera coordinate system and the LiDAR coordinate system is

$$\begin{pmatrix} X_C \\ Y_C \\ Z_C \end{pmatrix} = \mathbf{R} \begin{pmatrix} X_W \\ Y_W \\ Z_W \end{pmatrix} + \mathbf{T} \quad (5)$$

The joint calibration of cameras and LiDAR is to achieve spatial matching of the coordinate systems of the two sensors. Lidar and camera are installed in different positions on autonomous vehicles, each with its own independent coordinate system. To achieve spatial matching between the two sensors, it is necessary to unify them into the same coordinate system. The unified coordinate system can be achieved by converting the coordinate systems of the two sensors themselves. Therefore, it is necessary to establish the coordinate conversion relationship between the two sensors. The coordinate conversion process between the camera and LiDAR is shown in Figure 5.

Among them, $\mathbf{R}$ is a 3×3 orthogonal unit rotation matrix, $\mathbf{T}=[t_x, t_y, t_z]^T$, Convert it to its secondary coordinates as shown in the following equation:

$$\begin{bmatrix} X_C \\ Y_C \\ Z_C \\ 1 \end{bmatrix} = \begin{bmatrix} \mathbf{R} & \mathbf{T} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} X_L \\ Y_L \\ Z_L \\ 1 \end{bmatrix} \quad (6)$$

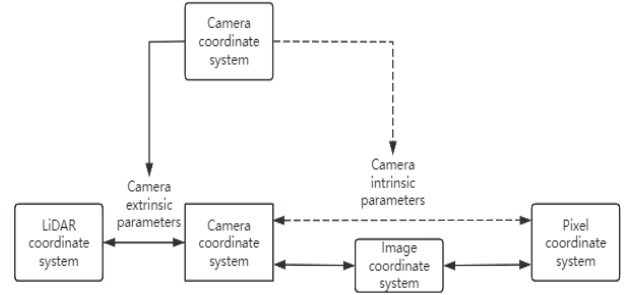


Figure 5. Coordinate Conversion Process between Camera and Lidar

The translation operation between the camera and the LiDAR coordinate system is the process of translating the origin O_L of the LiDAR coordinate system to the origin O_C of the camera coordinate system to achieve the coincidence of the two coordinate system origins. The rotation operation between the camera and the LiDAR coordinate system is the process of aligning the X_L, Y_L, Z_L axes with X_C, Y_C, Z_C by rotating around the X-axis, Y-axis, and Z-axis

The essential problem of joint calibration of cameras and LiDAR is to use the three-dimensional coordinates of the laser point cloud corresponding to the corner points of the calibration plate and the two-dimensional pixel coordinates of the image to solve the spatial coordinate rotation matrix and translation matrix. Therefore, it is necessary to establish the conversion relationship between the three-dimensional laser point cloud and the two-dimensional pixel points of camera imaging to achieve the fusion of laser point cloud and image data. The conversion model from LiDAR coordinate system to pixel coordinate system is as follows:

$$\begin{bmatrix} u \\ v \\ 1 \end{bmatrix} = \begin{bmatrix} f_x & 0 & u_0 & 0 \\ 0 & f_y & v_0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} \mathbf{R} & \mathbf{T} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} X_L \\ Y_L \\ Z_L \\ 1 \end{bmatrix} = \mathbf{K} \times \mathbf{M} \times \begin{bmatrix} X_L \\ Y_L \\ Z_L \\ 1 \end{bmatrix} \quad (7)$$

4.2. Joint Calibration Method of LiDAR Camera

In the previous section, a camera model was first built, followed by a LiDAR model. Finally, they were combined to propose a LiDAR camera information fusion calibration method based on ROS and Matlab environment. The joint data packet was decomposed into photo and pointcloud using Python in ROS, and the point cloud range was manually cut and the calibration board was selected in Matlab, while retaining suitable data. The accuracy of this method was then demonstrated by mapping the point cloud to the camera image in ROS.

5. Experimental Results and Analysis

5.1. Collection Synchronization Experimentr Coordinate

Using the built-in multi-sensor time synchronization mechanism Time Synchronizer in ROS to perform time

registration between LiDAR and camera, first subscribe to the LiDAR point cloud data topic and the camera image data topic through message_filters:: subscribers respectively. Use Time Synchronizer to define the time synchronizer, which is used to receive the published data of LiDAR and camera, and synchronously process the data in the callback function to achieve synchronous acquisition of LiDAR point cloud data and camera image data.

5.2. Joint Calibration Test

The joint calibration of cameras and LiDAR can be performed using Lidar Camera Calibrator in Matlab. Activate the camera and LiDAR, use the Rosbag tool to record data packets. During the recording process, the experimenter faces the LiDAR and holds a black and white checkerboard calibration board with a grid edge length of 70cm and an internal vertex parameter of "7 × 7" in front of them, ensuring that the calibration board is within the camera's field of view and can be fully scanned by the radar. In the camera's field of view, the calibration board is placed in three positions from near to far: forward, upward, downward, left offset, and right offset. Decompose the bag package into photo and pointcloud data using Python in ROS, and then manually adjust the calibration range and data in MATLAB. Finally, select the photos and pointclouds with small errors and retain them, delete the data with large errors, and continuously adjust them to obtain the calibration results shown in Figure 6. The left side shows the camera calibration, and the right side shows the LiDAR calibration. The obtained bar chart is the result, and the external parameters of the joint calibration are retained. In Figure 7, it can be seen that the calibration accuracy is relatively accurate, which verifies the feasibility of this method.

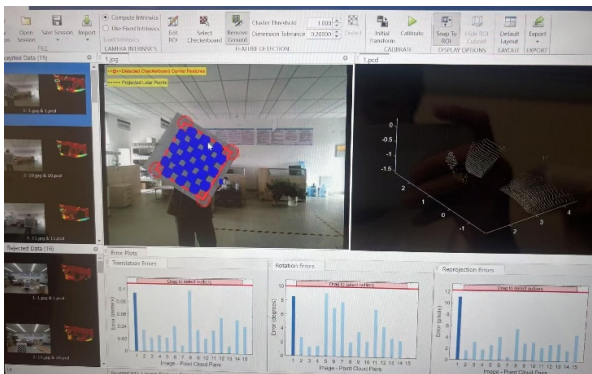


Figure 6. Joint Calibration Results of Camera and Lidar

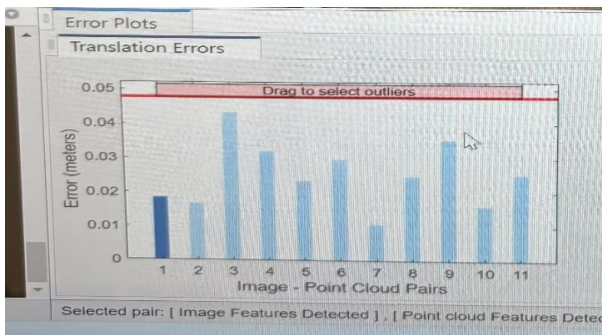


Figure 7. Camera and LiDAR Joint Calibration Accuracy Chart

5.3. Mapping Test

After obtaining the intrinsic parameters of the camera and the extrinsic parameters of the camera and LiDAR from the previous camera model and camera LiDAR joint model, a

mapping of the image and point cloud map is required to demonstrate the accuracy and feasibility of this calibration method.

In ROS, the intrinsic parameters of the camera and the joint extrinsic parameters of the camera LiDAR are combined using Python, and the point cloud map is mapped onto the image and simplified through filtering processing. Finally, the experimental results are obtained. To verify the feasibility of this method, multiple experiments were conducted from over 30 sets of data, and the mapping results are shown in Figure 8

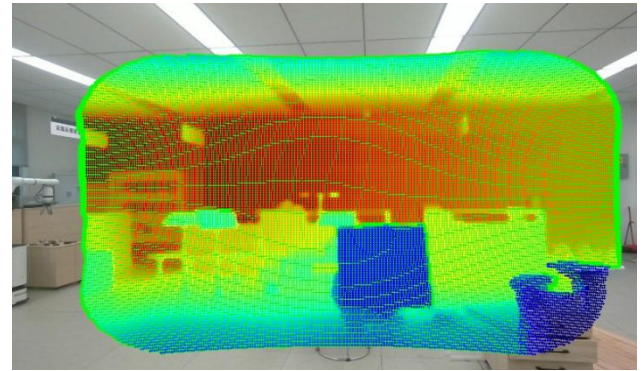


Figure 8. Joint Mapping Results of Camera and Lidar

6. Summary

In recent years, autonomous driving technology has developed rapidly, and the mainstream trend is to ensure stable perception in autonomous driving scenarios through multi-sensor fusion solutions. Among them, the complementarity between LiDAR and cameras is strong, and fusing their data can obtain richer information [8-12]. So this article mainly introduces the calibration task of LiDAR and camera. In order to achieve synchronous data acquisition of the two sensors, this article first synchronizes the time of LiDAR and camera. Then, based on the camera internal parameter calibration mentioned earlier, the camera and LiDAR are jointly calibrated. The initial value of the joint calibration of LiDAR and camera is calculated through the relationship between the three-dimensional coordinates of the laser point cloud and the two-dimensional coordinates of the image pixels. The joint calibration effect is verified through experiments.

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