An Improved Method for Calibration Between a 2D Lidar and a Camera Based on Point-Line Correspondences

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Abstract. The paper depicts an improved method for calibration parameters, which is a 2D homography, using point-line correspondences. The correspondences are the edge lines of the board provided by camera and the intersection points obtained by lidar. Particularly, a data preprocessing method is put forward and exploited to dramatically reduce the lidar’s measurement error. Afterwards, we use a triangular board to establish constraints. At least 8 correspondences are employed to compute the initial value, and the final result is optimized by L-M algorithm. Massive experimental results show that proposed method has about 1 pixel improvement, compared with the previous methods.

1. Introduction
Light detection and ranging sensors (Lidars) and visual sensors are widely used in robotic perceptor, particularly simultaneous localization and mapping (SLAM). A 2D lidar is capable of providing high-accuracy point clouds, whilst the visual sensors are able to acquire the rich environmental information, such as the colour, shape and texture information of objects. Through fusing above two kinds of sensors, a 2D map in SLAM system, containing richer information, can be achieved [1]. The primary problem of data fusion is the united calibration. In fact, united calibration is a process that estimates mapping relations between point clouds and images. Generally, this problem can be divided into two parts, camera intrinsic calibration and extrinsic calibration of both sensors. In the term of intrinsic calibration, Zhang developed a method which is the most popular approach now to obtain the camera’s intrinsic parameters [2]. In the aspect of extrinsic calibration, there are many calibration methods based on distinct geometric features. In this paper, an approach based on Kiho’s and Daniel’s method [3] is enhanced by two improvements. One improvement is a data preprocessing method which is proposed to decrease the ranging error according to distribution property of the lidar measurement [4]. Another improvement is that we estimate 2D homography directly without calculating the intrinsic and extrinsic parameters in advance.

2. Problem Formulation
As figure 1 shows, \(O_C - X_CY_CZ_C\) is the camera coordinate system and \(O - UV\) is the pixel coordinate system [5]. In addition, \(O_L - X_LY_LZ_L\) is the lidar coordinate system. The extrinsic parameters represent the rotation and translation from \(O_L - X_LY_LZ_L\) to \(O_C - X_CY_CZ_C\). The intrinsic parameters denote the transformation from \(O_C - X_CY_CZ_C\) to \(O - UV\). According to pinhole camera model, the projection from lidar coordinate \(P_L = (x_L, y_L, z_L)^T\) to pixel coordinate \(P_{uv} = (u, v)^T\) satisfies:
\[ s \begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = K \begin{pmatrix} R & t \\ 0 & 1 \end{pmatrix} \begin{pmatrix} x_L \\ y_L \\ z_L \end{pmatrix} \]  

(1)

Where \( K \) is a 3 \( \times \) 3 matrix that represents camera intrinsic parameters, \( R \) is a 3 \( \times \) 3 matrix that represents rotation, \( t \) is a 3 \( \times \) 1 matrix that represents translation and \( s \) is a scale factor.

While the pose of lidar and camera are fixed, the extrinsic parameters \((R, t)\) will be a definite constant matrix. Moreover, 2D lidar can only provide two dimensions information, so we assume \( z_L = 0 \). The Eq. (1) is rewritten as follows:

\[ \begin{pmatrix} u \\ v \\ 1 \end{pmatrix} = H \begin{pmatrix} x_L \\ y_L \\ 1 \end{pmatrix} = \begin{pmatrix} h_1 & h_2 & h_3 \\ h_4 & h_5 & h_6 \\ h_7 & h_8 & h_9 \end{pmatrix} \begin{pmatrix} x_L \\ y_L \\ 1 \end{pmatrix} \]  

(2)

Where \( H \) is a 2D homography that represents the transformation from lidar scanning plane to image pixel plane. It is a 3 \( \times \) 3 matrix and has 8 DOF.

Obviously, the united calibration parameter is a 2D homography. In order to estimate the 8-DOF homography, we need at least 8 pairs of the correspondences and each triangular board pose can provide two correspondences. Thus, at least 4 distinct triangular board poses are required to compute \( H \).

**Figure 1.** Lidar-Camera calibration system

**Figure 2.** Triangular calibration board used for united calibration: The red lines, left(\( l_l \)) and right(\( l_r \)) represent the line features that are extracted in the images and the red points, left(\( p_l \)) and right(\( p_r \)) describe the intersection points that are acquired from laser scanning

### 3. Method description

#### 3.1. Data Collection and Preprocessing

The correspondences adapted in proposed method are the point-line features. As is shown in figure 2, the intersection points are provided by 2D lidar, depicted as their homogeneous form \( p_l = (x_l, y_l, 1)^T \) and \( p_r = (x_r, y_r, 1)^T \). The edge lines are exacted from images manually and formulated as \( l_l = (a_l, b_l, c_l) \) and \( l_r = (a_r, b_r, c_r) \).

The calibration system is composed of a HOKUYO UST-10LX single line lidar and a HIKVISION DS-2CS55D0B-NA colour camera with the resolution 640 \( \times \) 480. Above all, the edge lines in images are exacted manually. By selecting 5 points on each line, the line parameters are fitted by least square
method. What is more, the intersection points are exacted by using lidar scanning data. With above edge lines and intersection points, the corresponds are explored to estimate 2D homography. However, the ranging error of the lidar is within 40mm. This error along the direction of the laser beams can be not ignored and it will lead to an imprecise calibration consequence. As an example, figure 3(a) presents 5 group of random scanning points, lying on calibration board, are collected at the same pose and the ranging error of scanning sequences reaches±20mm. Intuitively, the accuracy of intersection points, directly using only one group of scanning data, is not adequate. Thus, a preprocessing method is exploited to reduce the ranging error, and it is depicted as follows:

1. Repeat sampling the scanning points lying on calibration board for n times. Let m be the quantity of the scanning sequences lying on board and the sequences are denoted as \(\{q_1, \cdots, q_i, \cdots, q_m\}\). Each sequence \(q_i\) has n ranging values, which is described as \(\{q_{i1}, \cdots, q_{ik}, \cdots, q_{in}\}\).

2. For each sequence, find the maximum value \(q_{i\text{max}}\) and minimum value \(q_{i\text{min}}\) among n measurements. From \(q_{i\text{min}}\) to \(q_{i\text{max}}\), take the step of 1mm and count the times of every value. Then, a scatter plot is drafted with above information. The horizontal axis of the plot is the values from \(q_{i\text{min}}\) to \(q_{i\text{max}}\) and the vertical axis is the statistic times of every value. For instance, after 1000 measurements of one sequence, the plot in figure 3(b) exhibits the characteristic of a Gaussian curve. So we regard the mean of the Gaussian distribution as this sequence’s true distance value.

3. For every sequence, repeat step 1 and 2. Take the means of the Gaussian distribution as their true values. With this method using in the same scenario of figure 3(a), the true point clouds are fitted as the figure 3(c):

![Figure 3](image.png)

**Figure 3.** The preprocessing used to reduce ranging error; (a) the scanning points lying on calibration board with noise; (b) the distribution of a laser sequence’s ranging values (n=1000); (c) the points lying on calibration board after data preprocessing

Some experiments are conducted to validate the effect of the data preprocessing. As figure 4 shows, we mount the lidar-camera system and a rectangular board onto an optical platform. The ground truth
of the distance between lidar and rectangular board is acquired by more precise measurement, which is a high-accuracy range finder. Compared with the ground truth, the measurement error after data preprocessing decreases to ±5mm.

![Figure 4](image-url)

The experimental platform designed to validate the accuracy of the ranging data

3.2. Establish Constraints

In this section, we describe the intersection points and their correspondent pixel coordinate as \( p_i = (x_i, y_i)^T \) and \( q_i = (u_i, v_i, 1)^T \). The edge lines are represented as \( l_i = (a_i, b_i, c_i)^T \). Obviously, the points lie on its correspondent edge lines.

\[
l_i^T q_i = 0
\]  
(3)

And the \( q_i = (u_i, v_i, 1)^T \) can be denoted by \( p_i = (x_i, y_i)^T \) and \( H \) via Eq. (2), which is \( u_i = h_1 x_i + h_2 y_i + h_3 \) \( v_i = h_4 x_i + h_5 y_i + h_6 \). \( h_7 x_i + h_8 y_i + h_9 \)

So Eq. (3) can be denoted as follows:

\[
A_i h^T = 0
\]  
(4)

Where \( h = (h_1 \ h_2 \ h_3 \ h_4 \ h_5 \ h_6 \ h_7 \ h_8 \ h_9)^T \),

\( A_i = (a_i x_i \ a_i y_i \ a_i \ b_i x_i \ b_i y_i \ b_i \ c_i x_i \ c_i y_i \ c_i) \).

Since the homography \( H \) has 8 DOF, at least 8 correspondences are needed to solve \( H \). Namely, we need to find \( i \geq 8 \) point-line correspondences. The initial value of \( H \) with closed form can be computed by SVD method.

3.3. Optimization

The homography \( H \) is estimated optimally by minimizing the distance between the intersection points and corresponding edge lines projected onto image plane. Given \( i \) pairs different corresponding features, the \( i \)th distance formula \( f_i(l, q) \) satisfies:

\[
f_i(l, q) = [a_i x_i + b_i y_i + c_i] \over \sqrt{a_i^2 + b_i^2}
\]  
(5)

Projected scanning points \( p_i \) onto image plane \( q_i \), Eq. (5) is rewritten as:

\[
f_i(l, p) = [A_i h^T] \over \sqrt{a_i^2 + b_i^2} \over (x_i h_7 + y_i h_8 + h_9)
\]  
(6)

The error function, defined as the square sum of these distance over \( n \) pairs of features, is

\[E(h) = \sum_{i=1}^{n} f_i^2(l, p)\]  
(7)

The optimal \( h \) is available by minimizing the error function \( E(h) \), which is:

\[\min_{h} E(h) = \min_{h} \sum_{i=1}^{n} f_i^2(l, p)\]  
(8)

Obviously, Eq. (8) is a non-linear least square problem without the closed-form solution. It can be minimized by Levenberg-Marquardt algorithm, which is a generally iterative optimization algorithm. The L-M algorithm needs an initial estimation, which can be calculated by SVD method in section 3.2.
4. Experiments and results
In this section, we use a set of 26 scan/image pairs to optimize $H$. 4 pairs are used to calculate initial value and $H$ is optimized by another 22 pairs. Since we are lack of the ground truth, we compare the proposed method with Zhou’s method [6] which lacks data preprocessing. Let $H_1$ represent the homography obtained by proposed method and $H_2$ represent the homography obtained by Zhou’s method. Both $H_1$ and $H_2$ are computed by the same 26 scan/image pairs. To conduct these experiments, we collect another 30 scan/image pairs according to the distance range and the objects’ shapes. The distance between lidar and object ranges from 0.5m to 3m, and the objects are the triangular or rectangle boards. Then, we project the scanning points onto image using $H_1$ and $H_2$, respectively. The results show $H_1$ and $H_2$ are almost similar. Nevertheless, for the sake of brevity, two samples in figure 5 presents that proposed method has about 1 pixel improvement at the boundaries.

![Figure 5](image)

**Figure 5.** Two samples of the experimental results: laser scanning points projected onto image by Zhou’s method (yellow circles) and proposed improved method (red dots)

5. Conclusion
In this paper, an improved method for united calibration between a 2D lidar and a colour camera is addressed. In this method, the point-line correspondences are exploited to establish constraints. In contrast to the previous work, we put forward a data preprocessing method to enhance the accuracy of laser scanning points. The experimental results show this method can improve about 1 pixel in calibration system. Since we estimate the homography directly without obtaining the intrinsic parameters in advance, not only triangular board, but V-shape, rectangular board and so on, all of them can be used as calibration tools in proposed method, which makes the method more flexible.

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