Robotics and Autonomous Systems 78 (2016) 17–28

Contents lists available at ScienceDirect

Robotics and Autonomous Systems

journal homepage: www.elsevier.com/locate/robot

Extrinsic calibration of a camera and a 2D laser without overlap

Yunsu Bok, Dong-Geol Choi *, In So Kweon

Robotics and Computer Vision Lab, KAIST, Daejeon, Republic of Korea

HIGHLIGHTS

- Calibrated the extrinsic parameters of camera–laser systems without overlap.
- Proposed two methods of calculating an initial solution.
- Proposed three different cost functions for non-linear optimization.
- Analyzed poses which must be considered while capturing data.
- Evaluated the accuracy of the proposed methods using both synthetic and real data.

ARTICLE INFO

Article history:
Received 27 July 2015
Accepted 26 December 2015
Available online 2 January 2016

Keywords:
Calibration
2D laser sensor
Non-overlapping system

ABSTRACT

This paper presents a practical means of extrinsic calibration between a camera and a 2D laser sensor, without overlap. In previous calibration methods, the sensors must be able to see a common geometric structure such as a plane or a line. In order to calibrate a non-overlapping camera–laser system, it is necessary to attach an extra sensor, such as a camera or a 3D laser sensor, whose relative poses from both the camera and the 2D laser sensor can be calculated. In this paper, we propose two means of calibrating a non-overlapping camera–laser system directly without an extra sensor. For each method, the initial solution of the relative pose between the camera and the 2D laser sensor is computed by adopting a reasonable assumption about geometric structures. This is then refined via non-linear optimization, even if the assumption is not met perfectly. Both simulation results and experiments using actual data show that the proposed methods provide reliable results compared to the ground truth, as well as similar or better results than those provided by conventional methods.

1. Introduction

We study the calibration of multiple-sensor systems, especially those which consist of cameras and 2D laser sensors. Cameras and 2D laser sensors are the most commonly used sensors for robotic applications. They capture projected images and depth information, respectively, in their fields of view. Various applications using them have been studied for many decades.

Given that they have nearly opposite strengths and weaknesses, the combination of a camera and a 2D laser sensor is an effective arrangement. Although fusion sensors of cameras and 2D laser sensors are mainly used based on the assumption of 2D space, the unknown-depth limitation of cameras is complemented by 2D laser sensors. Ortín et al. [1] scanned walls using a 2D laser sensor to transform their textures into a common viewpoint. Biber et al. [2] computed the 3D geometries of indoor environments using a 2D laser sensor and textures imported from omnidirectional images. Luo et al. [3] combined a stereo-camera and a 2D laser sensor to build an indoor map containing visual signs. Gallegos and Rives [4] detected line features from omnidirectional images and estimated their 3D positions using scan data. Choi et al. [5] used image features to solve the ambiguity associated with laser-based motion estimations. Zhang et al. [6] detected line features from both images and scan data to remove noisy line segments. Several researchers tried to use the fusion sensor in 3D space. Newman et al. [7] detected closed loops by comparing images while a 2D laser sensor scanned local 3D structures for 3D SLAM (simultaneous localization and mapping). Bok et al. [8,9] estimated the motion of camera–laser fusion systems by projecting scan data onto images.

In order to utilize multiple sensors in a unified framework, it is essential to compute their relative poses, or extrinsic parameters. The extrinsic calibration of multiple-camera systems is a traditional issue in this area of research. The relative pose between non-overlapping cameras is computed by estimating the

* Corresponding author.
E-mail addresses: ysbok@rcv.kaist.ac.kr (Y. Bok), dgchoi@rcv.kaist.ac.kr (D.-G. Choi), iskweon@kaist.ac.kr (I.S. Kweon).

http://dx.doi.org/10.1016/j.robot.2015.12.007
0921-8890/

motion of each camera and solving the AX = XB problem [10], or by other methods [11,12]. Calibration of cameras and 3D laser sensors can be solved in the same way, or with the geometric constraints of objects scanned by them [13–15].

The extrinsic calibration of 2D laser sensors is more difficult than that of 3D laser sensors, because their field of view is limited to a 2D space. The most popular solution to this problem was proposed by Zhang and Pless [16]. This solution minimized the Euclidean distance between a planar pattern and the scan data. Mei and Rives [17] used a similar geometric constraint for extrinsic calibration. Li et al. [18] and Bok et al. [8] proposed line-feature-based algorithms. Kassir and Peynot [19] automatically calibrated a camera–laser system, but their method focused on the automated detection of checkerboard corners and scan data on the checkerboard, while the algorithm of extrinsic calibration is the same as that by Zhang and Pless [16]. All of them require adequate overlap between the camera and the 2D laser sensor.

For applications such as robots and ground vehicles, however, sensors have different heading directions depending on their individual purposes. For example, a horizontal 2D laser sensor and a vertical camera heading to the ceiling can be combined for indoor localization. Cameras for detecting visual features may not have a common field-of-view with 2D laser sensors for scanning 3D structures. Thus far, non-overlapping camera–laser systems can be calibrated indirectly by attaching an extra sensor, such as a camera or a 3D laser sensor, whose relative poses from both the camera and the 2D laser sensor can be computed.

In this paper, we present practical solutions for the extrinsic calibration of a camera and a 2D laser sensor 'without overlap'. Direct calibration between non-overlapping sensors is important because it does not require a bridging sensor. Moreover, this technique can be utilized as an additional constraint for system calibration, even if the system can also be calibrated using conventional methods. To the best of our knowledge, this work is the first attempt to solve this problem. We present two methods which utilize reasonable assumptions about geometric features such as a plane or a line intersecting two planes. For each method, we obtain an initial solution via SVD (singular value decomposition). This is then refined via non-linear optimization, which does not require any assumptions about structures but estimates their parameters. Both simulation results and experiments using actual data provided reliable results compared to ground-truth data.

This paper is an extension of our conference paper [20]. We renewed the mathematical derivations and analyzed data dependency theoretically. We also included more experiments to evaluate the proposed methods.

2. Overview of the proposed methods

A flow chart of the proposed methods is shown in Fig. 1. It contains one method using a plane, and another using a line intersecting two planes. First, we capture a number of image–scan sets (pattern image and scan data captured simultaneously) while a camera views a planar pattern and a 2D laser sensor scans a user-defined structure. A relative pose between the structure and the planar pattern must be fixed and close to the assumption made, which will be explained in Section 3. Assuming that the camera is calibrated, the relative pose between the camera and the planar pattern may be computed easily. We then manually select the part of the scan data that overlapped the structure. This approach is widely used when calibrating systems, except for cases of self-calibration. An example of the data selection process is shown in Fig. 3(a). If we want to utilize an intersecting line, we extract a feature from the scan data via line fitting. After accumulating rows of the matrix $\mathbf{A}$ using the selected parts or features (see Section 3), its singular vector corresponding to the minimum singular value is used to compute an initial solution of the relative pose between the sensors. Finally, this is refined via non-linear optimization, whose cost function depends on the structure. The cost function for each method is designed to minimize the sum of geometric errors (see Section 4).

3. Solving a non-overlapping system

In this paper, the coordinate system of a planar pattern is set to the 'world coordinate system'. The pose of the planar pattern is defined as $z = 0$ in the world coordinate system. Camera and laser sensor have their own coordinate systems, which will be referred to as 'camera coordinate system' and 'laser coordinate system', respectively. We compute both the intrinsic and extrinsic parameters of a camera using a conventional camera calibration method [21]. Let $[\mathbf{R}\ \mathbf{t}]$ be the world-to-camera transformation (i.e., the extrinsic parameter or projection matrix).

The scanning plane of the 2D laser sensor is set equal to $y = 0$ in the laser coordinate system. A scanned point with distance d and angle ϕ is converted into a Cartesian point $\mathbf{q}_L = [x_L\ 0\ z_L]^\top$ in the laser coordinate system using (1).

$$\mathbf{q}_L = \begin{bmatrix} x_L \\ 0 \\ z_L \end{bmatrix} = \begin{bmatrix} d\cos\phi \\ 0 \\ d\sin\phi \end{bmatrix}. \tag{1}$$

Adopting an unknown laser-to-camera transformation $[\hat{\mathbf{R}}\ \hat{\mathbf{t}}]$, a point is transformed into the world coordinate system $\mathbf{q}_W = [x_W\ y_W\ z_W]^\top$.

$$\begin{aligned}\begin{bmatrix} \mathbf{q}_W \\ 1 \end{bmatrix} &= \begin{bmatrix} \mathbf{R} & \mathbf{t} \\ \mathbf{0}^\top & 1 \end{bmatrix}^{-1} \begin{bmatrix} \hat{\mathbf{R}} & \hat{\mathbf{t}} \\ \mathbf{0}^\top & 1 \end{bmatrix} \begin{bmatrix} \mathbf{q}_L \\ 1 \end{bmatrix} \\ &= \begin{bmatrix} \mathbf{R}^\top & -\mathbf{R}^\top\mathbf{t} \\ \mathbf{0}^\top & 1 \end{bmatrix} \begin{bmatrix} \hat{\mathbf{R}} & \hat{\mathbf{t}} \\ \mathbf{0}^\top & 1 \end{bmatrix} \begin{bmatrix} \mathbf{q}_L \\ 1 \end{bmatrix}.\end{aligned} \tag{2}$$

We define $\mathbf{r}_\alpha$ and $\hat{\mathbf{r}}_\alpha$ ($\alpha \in \{x, y, z\}$) as the column of the rotation matrices $\mathbf{R} = [\mathbf{r}_x\, \mathbf{r}_y\, \mathbf{r}_z]$ and $\hat{\mathbf{R}} = [\hat{\mathbf{r}}_x\, \hat{\mathbf{r}}_y\, \hat{\mathbf{r}}_z]$, respectively. From (2), the elements of $\mathbf{q}_W$ can be expressed by the multiplication of known 10×1 vectors $\mathbf{v}_x$, $\mathbf{v}_y$, and $\mathbf{v}_z$ and the unknown 10×1 vector $\mathbf{x}$.

$$\begin{aligned}\mathbf{q}_W &= \begin{bmatrix} \mathbf{r}_x^\top & -\mathbf{r}_x^\top\mathbf{t} \\ \mathbf{r}_y^\top & -\mathbf{r}_y^\top\mathbf{t} \\ \mathbf{r}_z^\top & -\mathbf{r}_z^\top\mathbf{t} \end{bmatrix} \begin{bmatrix} \hat{\mathbf{r}}_x & \hat{\mathbf{r}}_y & \hat{\mathbf{r}}_z & \hat{\mathbf{t}} \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x_L \\ 0 \\ z_L \\ 1 \end{bmatrix} \\ &= \begin{bmatrix} x_L\mathbf{r}_x^\top\hat{\mathbf{r}}_x + z_L\mathbf{r}_x^\top\hat{\mathbf{r}}_z + \mathbf{r}_x^\top\hat{\mathbf{t}} - \mathbf{r}_x^\top\mathbf{t} \\ x_L\mathbf{r}_y^\top\hat{\mathbf{r}}_x + z_L\mathbf{r}_y^\top\hat{\mathbf{r}}_z + \mathbf{r}_y^\top\hat{\mathbf{t}} - \mathbf{r}_y^\top\mathbf{t} \\ x_L\mathbf{r}_z^\top\hat{\mathbf{r}}_x + z_L\mathbf{r}_z^\top\hat{\mathbf{r}}_z + \mathbf{r}_z^\top\hat{\mathbf{t}} - \mathbf{r}_z^\top\mathbf{t} \end{bmatrix} \\ &= \begin{bmatrix} x_L\mathbf{r}_x^\top & z_L\mathbf{r}_x^\top & \mathbf{r}_x^\top & -\mathbf{r}_x^\top\mathbf{t} \\ x_L\mathbf{r}_y^\top & z_L\mathbf{r}_y^\top & \mathbf{r}_y^\top & -\mathbf{r}_y^\top\mathbf{t} \\ x_L\mathbf{r}_z^\top & z_L\mathbf{r}_z^\top & \mathbf{r}_z^\top & -\mathbf{r}_z^\top\mathbf{t} \end{bmatrix} \begin{bmatrix} \hat{\mathbf{r}}_x \\ \hat{\mathbf{r}}_z \\ \hat{\mathbf{t}} \\ 1 \end{bmatrix} \\ &\equiv \begin{bmatrix} \mathbf{v}_x^\top \\ \mathbf{v}_y^\top \\ \mathbf{v}_z^\top \end{bmatrix} \mathbf{x}.\end{aligned} \tag{3}$$

In this section, we provide two methods: one using a plane and the other using a line intersecting two planes. Both methods provide a unique solution to the relative pose $[\hat{\mathbf{R}}\ \hat{\mathbf{t}}]$ using (3). Although any axis of the world coordinate system may be utilized for the proposed method, we derive equations only for y-axis in the rest of this paper. Equations for x- and z-axes can be derived in the same manner as those for y-axis. It should be noted that y-axis examples have no relation with the assignment of the laser coordinate system ($y = 0$).