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Calibration of a multiple axes 3-D laser scanning system consisting of robot, portable laser scanner and turntable

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ABSTRACT

A multiple axes 3-D laser scanning system consisting of a portable 3-D laser scanner, a industrial robot and a turntable is demonstrated. By using a criterion sphere, a robot tool center point (TCP) calibration approach is proposed to calibrate the relation between the laser 3-D scanner and the robot end-effector. In this approach, two different translational motions of robot are first made to determine the rotation part, and then at least three different rotational motions are made to determine the translation part. Meanwhile, by using the criterion sphere, a turntable approach is proposed to calibrate the pose of the turntable relative to the robot. In this approach, several rotational angles of turntable and two different heights of the sphere are made to determine the rotational axis of turntable. Experiment is performed on a portable laser scanner mounted on an industrial robot ABB IRB4400 with a turntable. The experiment results show that the two proposed calibration algorithms are stable and flexible. The application of 3-D measurement is also given to demonstrate the effectiveness and stability of the multiple axes 3-D laser scanning system.

1. Introduction

Structured-light-based 3-D measurement technique has many advantages such as non-contact operation, fast acquisition speed, simple optical arrangement, low cost and good stability. Now it has been widely applied to the measurement of surfaces and molds, as well as to medicine, rapid prototyping, and reverse engineering, etc. [1–3]. Recently, with the development and progress in optical, microelectronic and automation technologies, compact and portable 3D laser scanners have received much interest and attention. It can be combined with an industrial robot for acquiring the 3-D information of the object's surface from multiple angles and directions, and thus the problem of occlusion, shadowing, and insufficient data can be overcome [4,5]. However, when these 3D acquisition systems of small depth-of-view are applied to measure the object of large size and complicated profile, one has to edit multiple scanning paths and register the scanning data to obtain the entire 3D surface information, and the process of multiple paths' editing and scanning is time-consuming and the process of data registering will reduce the measurement accuracy. Aiming this problem, we have extended the depth-of-view of a portable 3D laser scanner by tilting the image plane successfully and proposed a new segmental calibration method to calibrate the tilted scanning system accurately [6]. However, the scanning range of these scanning systems is still not enough for some large-scale objects due to the limited working area of robot manipulator. This problem can be solved by adding a turntable surrounding the robot [7]. Before using such a scanning system for measurement, usually three kinds of calibration need to be performed. The first is camera and projector calibration to determine the intrinsic and extrinsic parameters of camera describing the mapping between 3-D world coordinates and 2-D image coordinates [8]. The second is robot TCP calibration to determine the placement of the portable 3-D laser scanner head on the robot end-effector (also called tool-zero coordinate frame or Tool0) [9]. The third is turntable calibration to determine the pose of the turntable relative to the robot.

In this paper, a multiple axes 3-D laser scanning system is constructed by a portable 3-D laser scanner, an industrial robot and a turntable. By using a criterion sphere with known diameter as calibration object, a robot TCP calibration approach is proposed to calibrate the pose of the laser 3-D scanner relative to the robot. We first translate the robot to two different positions and make the laser scanner shoot at the sphere to determine the rotation matrix. Then by using the determined rotation part and making at least three different rotational motions, the translation vector is determined. This approach has three advantages: (1) calibration grid is not needed and thus the complicated process of tracking correspondence points is also not needed; (2) the camera extrin-

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sic parameters are not needed to be recalibrated for each robot motion, which can decrease the calibration error brought by camera calibration; (3) this approach makes use of the differences of different robot positions in calculations, which can decrease the calibration error brought by robot positioning error. Meanwhile, by using the criterion sphere, a turntable approach is proposed to calibrate the pose of the turntable relative to the robot. In this approach, several rotational angles of turntable and two different heights of the sphere are made to determine the rotational axis of turntable. Experiment is performed on a portable laser scanner mounted on an industrial robot ABB IRB4400 with a turntable. The experiment results show that the two proposed calibration algorithms are stable and flexible. The application of 3-D measurement is also given to demonstrate the effectiveness and stability of the multiple axes 3-D laser scanning system.

2. Structure of the multiple axes scanning system and its calibration model

The schematic structure of the multiple axes scanning system, shown in Fig. 1, is based on a portable laser scanner mounted on an absolute positioning industrial robot with a turntable. By the cooperation of the three parts, the 3-D surface information of the object placed on the turntable can be obtained from multiple angles and directions. Before such a system being used, the following calibration procedures have to be performed.

(1) Camera and projector calibration.
(2) Robot TCP calibration.
(3) Turntable calibration.

For simplicity and clarity, we defined some parameters, as listed in Table 1.

2.1. Camera and projector calibration

Camera calibration is a method to find a mathematical model of the transformation matrix between I and L resulting from the image formation process. The parameters can be divided into three categories [6]: (a) extrinsic parameters (the elements of $\boldsymbol{R}_w$, $\boldsymbol{T}_w$), which contain the pose of C with respect to L; (b) intrinsic parameters, which contain the information about the optical characteristic of the camera, including the pixel scale factors (f_x, f_y), and location of the image center (x_0, y_0); (c) distortion parameters (k_1, k_2, k_3, p_1, p_2) which describe the geometric non-linearities of the lens. Many methods for camera calibration can be found in literature, which can be classified into four categories: linear techniques [10], nonlinear optimization techniques [11], two-step techniques (e.g. Tsai [12] and Weng et al. [13]), and self-calibration techniques [14]. The accuracy of two-step techniques, having good compromise between accuracy and simplicity, is fast in data processing [15]. In this paper, we still use the large depth-of-view 3D laser scanning system in Ref. [6]. Therefore, the nonlinear segmental two-step calibration method is adopted to determine the camera parameters [6]. For line laser scanning system, projector calibration is to determine the parameters $[a, b, c, d]$ of the laser stripe plane, which can provide an additional equation to transform the 2D image coordinates $\boldsymbol{X}_I$ to the 3D world coordinates $\boldsymbol{X}_l$ [16]. However, the scanning range is limited if the relative position of the scanner and the object is fixed, and thus the scanner has to be combined with a translation device, i.e., a robot manipulator.

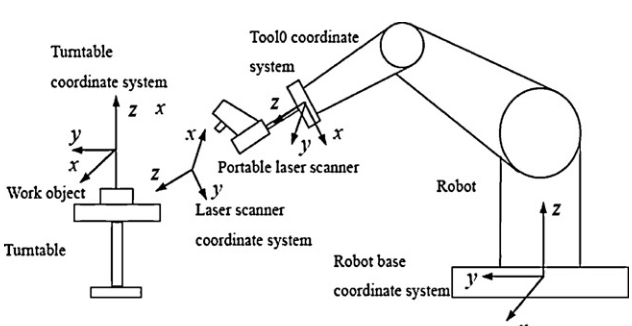

Fig. 1. Schematic structure of the multiple axes laser scanning system.

Table 1
Notations used in calibration.

C	Camera coordinate frame
I	Computed image coordinate frame
L	Laser coordinate frame
Base	Robot base coordinate frame
T	Turntable coordinate frame
Tool0	Robot end-effector coordinate frame
$\boldsymbol{R}_w$	Rotation matrix from C to L
$\boldsymbol{T}_w$	Translation vector from C to L
$\mathbf{R}_s$	Rotation matrix from L to Tool0
$\mathbf{T}_s$	Translation vector from L to Tool0
$\mathbf{R}_0$	Rotation matrix from Tool0 to Base
$\mathbf{T}_0$	Translation vector from Tool0 to Base
$\mathbf{R}_t$	Rotation matrix from T to Base
$\mathbf{T}_t$	Translation vector from T to Base
$\mathbf{R}_a$	Rotation matrix when the turntable is rotated
$\mathbf{X}_I$	2-D position $(x_I, y_I)^{\mathrm{T}}$ of space point in I
$\mathbf{X}_l$	3-D position $(x_l, y_l, z_l)^{\mathrm{T}}$ of space point in L
$\mathbf{X}_b$	3-D position $(x_b, y_b, z_b)^{\mathrm{T}}$ of space point in Base

2.2. Robot TCP calibration

Robot TCP calibration is to determine the transformation matrix from L to Tool0. When the tool is camera, robot TCP calibration also can be considered as robot hand-eye calibration. The traditional robot hand-eye calibration is to solve a homogeneous equation **AX** = **XB** or **AX** = **YB**, where **X** and **Y** are the unknown hand-to-camera rigid transformation and the robot-to-world rigid transformation, respectively. **A** and **B** are the movements of the hand and camera, respectively. Several close-form solutions including linear solution [17–20] and nonlinear solution [21,22] were reported in literature to solve for **X** or **Y**. In these approaches, at least a pair of robot and camera motion is needed. For each robot motion, the camera extrinsic parameters have to be recalibrated by tracking the corresponding featured points between a calibration grid and its image, which will introduce much camera calibration and robot positioning errors into the final results. Compared to the conventional single or dual camera in robot vision, the laser scanner has an additional tool of projector, which offers us an approach to simplify the calibration process and increase the calibration accuracy.

By using a criterion sphere mounted on the turntable as the calibration object, we propose a new robot TCP calibration approach which can be divided into the two following steps.

Step 1. Calibration of $\mathbf{R}_s$

Assuming that there is a virtual reference point P_0 fixed relatively to B, the 3D positions of the point in Base and L satisfy the following equation:

$$\begin{pmatrix} \boldsymbol{X}_b \\ 1 \end{pmatrix} = \begin{pmatrix} \boldsymbol{R}_0 & \boldsymbol{T}_0 \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \boldsymbol{R}_s & \boldsymbol{T}_s \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \boldsymbol{X}_l \\ 1 \end{pmatrix}. \quad (1)$$

By moving the robot to two different Tool0 positions and making the scanner reconstruct the fixed point P_0 twice, the following two equations can be obtained from Eq. (1),

$$\boldsymbol{X}_{b1} = \boldsymbol{R}_{01} \cdot \boldsymbol{R}_s \cdot \boldsymbol{X}_{l1} + \boldsymbol{R}_{01} \cdot \boldsymbol{T}_s + \boldsymbol{T}_{01}, \quad (2)$$