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Abstract. Structured light stripe systems are widely used in industrial applications for acquiring three-dimensional (3-D) information. Calibration is the first necessary step and traditional algorithms compute the 4×3 transformation matrix from image to world. Therefore, 3-D information can be obtained with respect to the camera's coordinate system, and it cannot be transformed into the laser coordinate system. We propose a new calibration algorithm of a structured light system that can compute the relative pose of the laser coordinate system with respect to the camera coordinate system. We can convert 3-D information either to the laser coordinate system or to the camera coordinate system. The proposed algorithm uses two planes where one plane with multiple slits is set perpendicular to the other plane. We can easily compute the position and rotation of the laser coordinate system using proposed calibration structure. Also, we can solve the extrinsic calibration using just one shot of an image while conventional algorithms require more than two images under different poses. Experiments under various configurations show the feasibility of proposed algorithm. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.52.1.013602](https://doi.org/10.1117/1.OE.52.1.013602)]

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1 Introduction

Three-dimensional (3-D) sensing capability can expand its application areas in industrial automation. Many approaches have been proposed for 3-D sensing.¹ The typical approach is to use a stereo system consisting of two cameras. In stereo, it has difficulty in finding correspondence between images because brightness values depend heavily on the reflectivity of material, the characteristics of camera and the illumination. A structured light stripe system has an advantage in finding correspondence because active lighting by laser makes finding correspondence easy. Therefore, it has preference over stereo system in industrial automation.

The first necessary step for 3-D acquisition using a structured light stripe system is to find the relative pose between camera and laser. It is usually called extrinsic calibration. Chen and Kak² proposed an algorithm that gives the 4×3 transformation matrix that converts points on the image plane into corresponding 3-D coordinates with respect to the camera. They use known world lines and corresponding image points to compute the transformation matrix, and it requires at least six world lines. Leid³ extended Chen and Kak's algorithm using known world plane and image point correspondence. Huynh⁴ proposed a method using the invariance of cross-ratio of four points to compute world points on the light stripe plane, and it uses two orthogonal planes. Zhou and Zhang⁵ further extended Huynh's algorithm by partially automating the computation of control points on image, and they use one plane.

All these methods compute the transformation matrix from image to camera coordinate. 3-D information is computed only with respect to the camera because they cannot compute the pose of the laser with respect to the camera

directly. In this paper, we propose a calibration algorithm that can compute the relative pose of the laser with respect to the camera using two planes where one has multiple slits. 3-D information is computed by finding cross point of camera ray and laser stripe plane.⁶ We can convert 3-D coordinates from camera to laser because we know the relative pose between them. It can have flexibility in applications where a structured light stripe system is used attached on a robot's arm because we can convert 3-D information with respect to the coordinate system we want.

2 Extrinsic Calibration Using Plane with Slits

Our proposed method uses two planes where one plane with multiple slits is set perpendicular to the other plane as shown in Fig. 1. $\{^L O, ^L X, ^L Y, ^L Z\}$ represents the laser coordinate system and $\{^C O, ^C X, ^C Y, ^C Z\}$ corresponds to the camera coordinate system. $\{^W O, ^W X, ^W Y, ^W Z\}$ corresponds to the world coordinate system.

We attach chessboard pattern on both planes. Control points on two planes are used for the calibration of the camera using Tsai algorithm.⁷ After camera calibration, we can convert 3-D coordinate of a point with respect to the world coordinate system into the camera coordinate system.

The laser stripe plane that passes through slits on the vertical plane would form separated lines on each plane. In Fig. 1, four lines formed by point pairs $\{A, A'\}$, $\{B, B'\}$, $\{C, C'\}$ and $\{D, D'\}$ would meet at a point that corresponds to the origin of the laser. We manually select their positions with respect to the world coordinate system. Then, we convert them into the camera coordinate system using camera's calibration information. The relative location of the laser origin with respect to the camera coordinate system can be

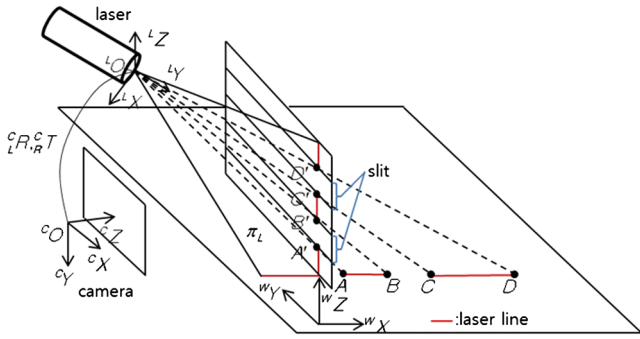


Fig. 1 Proposed calibration algorithm using two planes where the perpendicular one has multiple slits.

computed by finding the crossing point of lines. Lines will not meet at one point due to the error during manual selection. Therefore, we compute the cross point using least-square estimation.

A 3-D line that passes through two points $(x_1, y_1, z_1)^t$ and $(x_2, y_2, z_2)^t$ can be represented as:

$$\frac{x - x_1}{l} = \frac{y - y_1}{m} = \frac{z - z_1}{n}, \quad (1)$$

where (l, m, n) is direction vector of the line. The crossing point by multiple lines can be obtained by solving following equation:

$$\begin{bmatrix} m_1 & -l_1 & 0 \\ 0 & n_1 & -m_1 \\ \vdots & \vdots & \vdots \\ m_n & -l_n & 0 \\ 0 & n_n & -m_n \end{bmatrix} \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} m_1 x_1^1 - l_1 y_1^1 \\ n_1 y_1^1 - l_1 z_1^1 \\ \vdots \\ m_n x_1^n - l_n y_1^n \\ n_n y_1^n - l_n z_1^n \end{bmatrix}, \quad (2)$$

where $(l_i, m_i, n_i)^t$ is the direction vector of the i 'th line and $(x_1^i, y_1^i, z_1^i)^t$ is the coordinate of the i -th point with respect to the camera coordinate system.

Up to now, we computed the position of laser origin with respect to the camera coordinate system. We obtained the translation, ${}^c_L T$, of the laser coordinate system with respect to the camera coordinate system.

Next, we compute the rotation, ${}^c_L R$, of the laser coordinate system with respect to the camera coordinate system. In Fig. 1, two planes are perpendicular so that the laser lines on different plane would have the same property. We select two lines from each plane and set them as the two axes of laser coordinate system. For example, we select the two lines \overline{AB} and $\overline{A'B'}$ in Fig. 1 as the two axes, ${}^L X, {}^L Y$, of the laser coordinate system. The coordinate of each point on line is obtained with respect to the camera coordinate system using camera's calibration information. Third axis, ${}^L Z$, of the laser coordinate system can be computed by cross product of two axes.

In Fig. 1, two planes are perpendicular so that laser lines on different plane would have the same property. We select two lines from each plane and set them as the two orthogonal axes of laser coordinate system. For example, we select two lines \overline{AB} and $\overline{A'B'}$ in Fig. 1 as the two axes, ${}^L X, {}^L Y$, of the

laser coordinate system. Coordinates of each point are set manually on the image. The coordinate of each point on line is obtained with respect to the camera coordinate system using camera's calibration information. The length of each is normalized to have one. Third axis, ${}^L Z$, of the laser coordinate system can be computed by cross product of two axes. Throughout this, we obtained three orthogonal axes with respect to the camera coordinate system that correspond to the rotation, ${}^c_L R$, between the camera and laser coordinate system.

Finally, we can compute the relative pose of the rotation and translation, ${}^c_L R, {}^c_L T$, of the laser coordinate system with respect to the camera coordinate system. Also, we can represent the laser scan plane with respect to the camera coordinate system. 3-D coordinates of laser points on the image are computed by finding the crossing point of camera ray and laser stripe plane.⁶

It is convenient if one axis of the laser coordinates is aligned with the center of laser scan plane in the real application. Two axes on the laser scan plane that are obtained by the proposed algorithm do not coincide with the center of laser stripe plane. They correspond to two axes on the calibration structure as shown in Fig. 1. In Fig. 2, green axes represent the two axes computed after extrinsic calibration and the two red axes are desirable ones for the application.

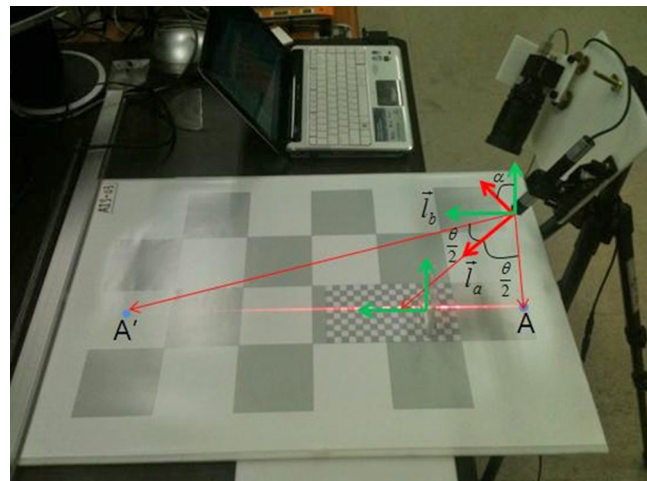


Fig. 2 Laser coordinate adjustment (red coordinate is aligned with the center of laser scan plane and green coordinate is computed one through camera and laser calibration).

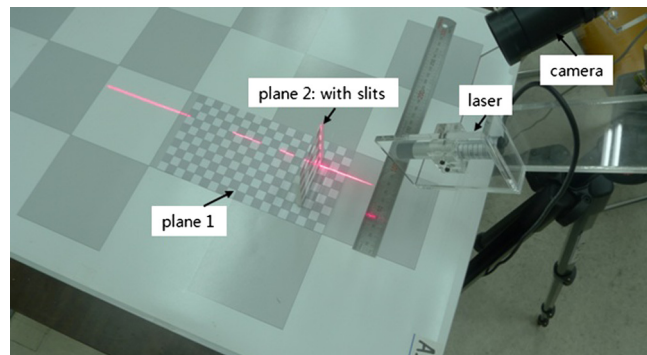


Fig. 3 Calibration setup consisting of camera, laser, and two planes.

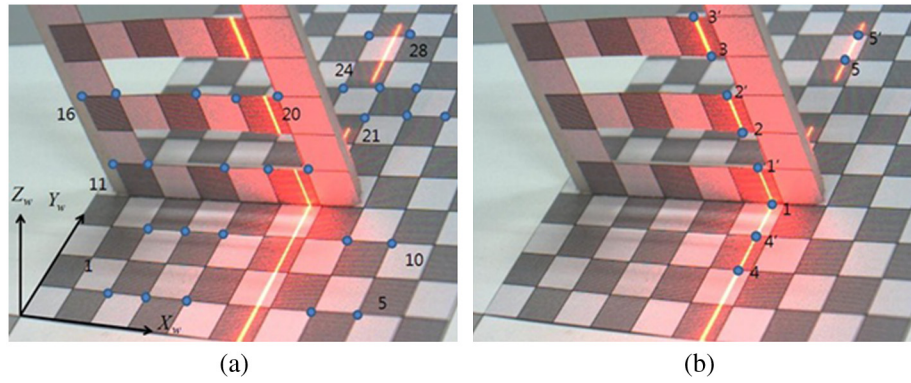


Fig. 4 Control points used in (a) camera calibration (b) evaluation of 3-D accuracy.

There is rotation, α , between two coordinate systems as shown in Fig. 2. It can be recovered if we know the scan angle of laser and the coordinate of one point of two end points of laser stripe plane with respect to the world coordinate system. If we know the position of A that is one end point of laser, then we can compute the direction vector \vec{l}_a using known scan angle of laser. The rotation angle α between the two coordinate system can be computed using the two direction vectors of \vec{l}_a and \vec{l}_b .

3 Experimental Results

In our experiments, extrinsic calibration of the camera and slit laser system is done several times by changing the relative pose of the camera and the laser. Figure 3 shows the calibration setup for experiments consisting of camera, laser, and calibration structure. The plane with slits is placed perpendicular to the ground plane. A chessboard pattern is attached on each plane as shown in Fig. 4(a) where we attach chessboard to avoid blocking the slit area on the vertical plane.

A chessboard pattern is attached on each plane. Figure 4(a) shows control points for the calibration of the camera. Two-dimensional (2-D) coordinates of control points on the image are refined into subpixel accuracy.

Three pairs of points are used for the determination of the location and orientation of the laser coordinate system with respect to the camera coordinate system. The coordinate of each point is measured manually with respect the world coordinate and it is converted into camera coordinate using camera's calibration information.

Table 1 shows computed extrinsic parameters of rotation and translation between camera and laser by proposed algorithm. Number 1 to 3 is the result under similar mechanical configurations. We tried to locate the camera and laser at the same position as much as possible whenever we assembled them. We can notice that results of three configurations have a similar value. Number 4 to 6 is the result after changing the relative pose of camera and laser. We reduced the field of view of camera so that the relative position of the camera has been changed. Those changes can be verified in the result of extrinsic calibration.

Table 2 shows the accuracy of estimated 3-D points by the laser and camera system. A 3-D coordinate is obtained by finding the cross point between camera ray and laser stripe plane. We compute 3-D coordinates of ten control points that are chosen manually as shown in Fig. 4(b). We compute the

length between two points and compare it with the true one. Absolute and relative error is computed. We have 3-D accuracy with less than 5% relative error in all configurations. We have consistent results through the whole experiment.

We also applied the proposed calibration algorithm in the application of the alignment of two parts using four 3-D sensing systems as shown in Fig. 5. We used the same

Table 1 Result of extrinsic calibration between camera and laser.

	Rotation (deg) (R_x, R_y, R_z)	Translation (mm) (T_x, T_y, T_z)
No. 1	(-130.2, -38.9, -59.9)	(-63.7, 0.0, 163.3)
No. 2	(-131.3, -40.3, -60.7)	(-73.5, -2.2, 162.2)
No. 3	(-144.4, -50.4, -43.9)	(-70.0, 4.7, 163.4)
No. 4	(-138.5, -46.6, -50.6)	(-63.7, 1.1, 243.8)
No. 5	(-129.8, -40.8, -62.1)	(-67.8, 0.3, 233.2)
No. 6	(-134.4, -45.3, -54.8)	(-81.6, 4.2, 343.6)

Table 2 The accuracy of estimated 3-D points by laser and camera system.

	Absolute error (mm) (mean/std)	Relative error (%) (mean/std)
No. 1	0.34/0.23	3.37/2.31
No. 2	0.34/0.14	3.36/1.40
No. 3	0.35/0.18	3.46/1.76
No. 4	0.09/0.11	1.83/2.30
No. 5	0.11/0.14	2.10/2.77
No. 6	0.10/0.07	2.03/1.34
mean	0.22/0.15	2.69/1.98

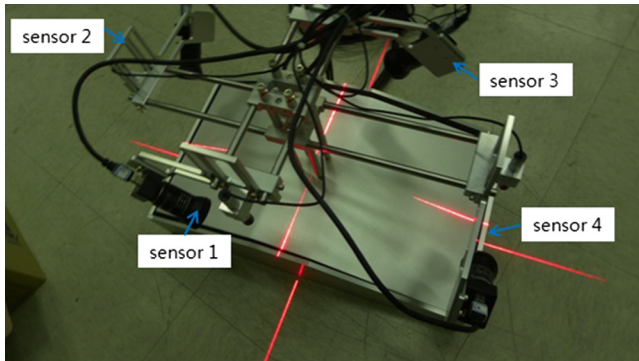


Fig. 5 Alignment application using four 3-D sensing systems of camera and slit laser.

Table 3 Result of extrinsic calibration of four sensing systems.

	Rotation (deg) (R_x, R_y, R_z)	Translation (mm) (T_x, T_y, T_z)
Sensor 1	(-143.3, -27.5, -57.6)	(-117.6, 2.8, 113.8)
Sensor 2	(-143.4, -27.6, -58.2)	(-119.1, 3.1, 106.5)
Sensor 3	(-143.1, -27.3, -58.2)	(-118.3, 3.1, 111.0)
Sensor 4	(-143.8, -27.4, -57.9)	(-122.0, 4.7, 109.0)

Table 4 The accuracy of estimated 3-D points of four sensor systems.

	Absolute error (mm) (mean/std)	Relative error (%) (mean/std)
Sensor 1	0.14/0.08	2.90/1.63
Sensor 2	0.13/0.08	2.69/1.50
Sensor 3	0.10/0.07	2.09/1.49
Sensor 4	0.07/0.05	1.39/0.96
mean	0.11/0.07	2.27/1.40

kind of camera and laser for the configuration of four 3-D sensing systems. We used the proposed algorithm for the extrinsic calibration of each 3-D sensing system. Table 3 shows the result of extrinsic calibration of each system. We tried to configure each system to be the same as possible. But, there could be small differences introduced during the assembly of camera and laser. The results of our extrinsic calibrations of four sensor systems gives similar values. The accuracy of four sensor systems is evaluated as the same procedure using the previously mentioned method. 3-D reconstruction accuracy of four sensor systems have

also similar tendencies as shown in Table 4. We can conclude that proposed algorithm gives a consistent result.

4 Conclusion

In this paper, we presented a new algorithm for the extrinsic calibration of a camera and slit laser system using a calibration structure consisting of two perpendicular planes where one has multiple slits. Our proposed algorithm can work using just one shot of an image while previous algorithms require more than two images acquired under different poses. Also, our proposed algorithm can compute the relative pose of the laser with respect to the camera.

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