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Calibration of Structured Light Vision System using Multiple Vertical Planes

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Abstract – Structured light vision system has been widely used in 3D surface profiling. Usually, it is composed of a camera and a laser which projects a line on the target. Calibration is necessary to acquire 3D information using structured light stripe vision system. Conventional calibration algorithms have found the pose of the camera and the equation of the stripe plane of the laser under the same coordinate system of the camera. Therefore, the 3D reconstruction is only possible under the camera frame. In most cases, this is sufficient to fulfill given tasks. However, they require multiple images which are acquired under different poses for calibration. In this paper, we propose a calibration algorithm that could work by using just one shot. Also, proposed algorithm could give 3D reconstruction under both the camera and laser frame. This would be done by using newly designed calibration structure which has multiple vertical planes on the ground plane. The ability to have 3D reconstruction under both the camera and laser frame would give more flexibility for its applications. Also, proposed algorithm gives an improvement in the accuracy of 3D reconstruction.

Keywords: Calibration, Extrinsic calibration, Structured light vision system, 3D reconstruction

1. Introduction

Non-contact 3D measurements are feasible through various approaches according to the involved hardware including single point and laser scanners, slit scanner, pattern projection, moiré, time-of-flight systems and interferometry based systems [1]. They have diverse applications in assuring the quality of machine vision where 3D information is directly used for checking dimension or quality of the product [2]. In particular, in factory automation, the focus in machine vision has shifted from conventional 2D to 3D according to the rapid development of hardware and various 3D acquisition algorithms.

In computer vision, the conventional method for reconstructing 3D has used stereo vision system. Passive methods of stereo vision system have difficulty in finding corresponding points between two images. On the other hand, active methods use lasers or projectors instead of one camera. This makes finding matching points easy because areas hit by the laser or the projector would have distinct brightness distribution compared to other areas on the image. A structured light vision system uses either projector or laser as an active light source. In this paper, we deal with structure light vision system composed of one camera and one slit laser. A slit laser emits laser line using a point laser and a cylindrical lens.

The calibration of the structured light vision system requires two steps of camera calibration and projector calibration. Camera calibration computes the intrinsic and extrinsic parameters of the camera [3, 4]. In general, it also considers distortion caused by lenses. Intrinsic parameters usually include effective focal length, principal point, and skew coefficient. Extrinsic parameters are the position and orientation of the camera coordinate system with respect to the world coordinate system. Camera calibration is done by using known 3D world points on calibration structure and corresponding points on the image. Calibration structure with one or more than two planes was used. Projector calibration computes the equation of the light stripe plane with respect to the same world coordinate system used in the camera calibration. The plane equation of the light stripe could be determined by finding at least three non-collinear points that exist on the plane. The calibration of structured light vision system requires finding the equation of light stripe plane with respect to the camera coordinate system.

Fan and Tsai [5] used a template that is made by a laser writer having one-micron accuracy of line spacing for the calibration of the structured light stripe vision system. They found the coordinates of control points that lie on the scan plane of the laser by using moving template. They require a precise template and accurate motion of the template. Gang and Wei [6] used a calibration target that is composed of a photo-electrical aiming device and a translation stage with 3 axes. Calibration target was used to find the coordinates of control points that lie on the scan plane of the laser. It additional required specially designed hardware and accurate motion stage. Algorithms for the calibration of projector could also be used in the calibration of the laser stripe.

Huynh [7] proposed a calibration algorithm of a structured light stripe system using 4 known non-coplanar

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sets of 3 collinear world points that are located on two planes. They compute 4X3 image-to-world transformation matrix for each stripe plane using cross-ratio and homography between the light stripe and image planes. It used one projector with multiple light stripe planes. Zhou and Zhang [8] proposed an algorithm which is similar to [7] but it only uses one plane. Control points are obtained by observing a planar target under at least two different poses and they used for the determination of the plane of the light stripe. Cross-ratio used in [7] was also adopted to find the control point of the scan plane on the calibration plane.

Liu et al. [9] proposed an algorithm that also uses planar targets with more calibration points to improve calibration accuracy. Wei et al. [10] proposed an algorithm that uses 1D target. It computed the intersection of light stripe plane with the 1D target using the distances between known values of control points on 1D target. The equation of light stripe plane is computed using multiple points obtained under different pose. Liu et al. [11] proposed an algorithm that uses a single ball target. They compute the equation of light stripe plane by relating the cone profile on the image to known sphere under the camera coordinate system. Liu et al. [12] proposed an algorithm that uses two cylinders. They used fitted ellipse on the image that corresponds to the intersection of light stripe plane on the cylinder. They use the geometric constraint that the minor axis of the ellipse is equal to the diameter of the cylinder.

Most previous approaches could have 3D reconstruction only under the camera coordinate system. 3D reconstruction under the laser coordinate system has not been possible because they compute laser scan plane with respect to the camera frame. They require an additional step to compute relative pose of the laser with respect to the camera frame. In our previous approach [13], we have proposed a calibration algorithm of structured light vision system using calibration structure having multiple slits. A plane with multiple slits is used for the calibration. Also, it could compute the relative pose of the laser with respect to the camera. In this paper, we propose a new calibration structure that does not require slits which are rather difficult to make in precise, particularly in small scale. Proposed calibration structure only requires multiple planes to be set perpendicular to the ground plane. New calibration structure can be made more accurately with ease than the previous one. This would lead to the improvement in calibration accuracy.

Proposed algorithm has two distinct novelties compared to previous approaches. First, 3D reconstruction is possible under both the camera and laser frame. Second, calibration structure can be made accurate with ease, in the same time it gives improved calibration accuracy.

2. Proposed Approach

Proposed algorithm could compute the pose of the camera and laser with respect to the same world coordinate system on the calibration structure. Therefore, we can compute the transformation matrix between the camera and the laser coordinate system. It enables 3D reconstruction under both the camera and laser frame. The camera is calibrated using points in chessboard on the calibration structure. The pose of the laser is computed using points generated by laser scan plane when it strikes on the calibration structure.

2.1 Camera calibration

We use Tsai algorithm [3] for the calibration of the camera. For the completeness of the paper, we would briefly explain procedures of camera calibration. A pin-hole model is used for modeling the projection of a point in 3D space onto the image plane by the camera. This is shown in Fig. 1. The intrinsic and extrinsic parameters of the camera are computed through camera calibration. A 3D point $\mathbf{P}_w = (x_w, y_w, z_w)^T$ under world frame is converted into 3D point $\mathbf{P}_c = (x_c, y_c, z_c)^T$ under camera frame by extrinsic parameters as follows.

$$\mathbf{P}_c = {}^C\mathbf{R}_W \mathbf{P}_w + {}^C\mathbf{T} \tag{1}$$

${}^C\mathbf{R}_W$ is 3X3 rotation matrix from world coordinate system to camera coordinate system. ${}^C\mathbf{T}$ is 3X1 translation vector from the origin of camera coordinate system to the origin of the world coordinate system. ${}^C\mathbf{R}_W$ and ${}^C\mathbf{T}$ are called extrinsic parameters in camera calibration.

A point $\mathbf{P}_c$ in 3D is projected onto the ideal image plane a point $\mathbf{p}_u = (x_u, y_u)^T$ through perspective projection. It is represented as follows.

$$x_u = f\frac{x_c}{z_c} \quad y_u = f\frac{y_c}{z_c} \tag{2}$$

f is the effective focal length and it is the distance between the origin of the camera coordinate system and

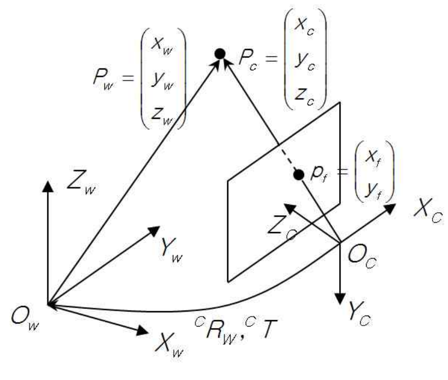


Fig. 1. The projection of a point under pin-hole camera assumption

the ideal image plane. Finally, distortion of lens and conversion factor from metric to pixel domain would be considered. There are many types of lens distortion. In computer vision, two types of lens distortion including radial and tangential distortion are typically considered. In Tsai [3] algorithm, only radial distortion is considered as follows.

$$\begin{aligned} x_u &= x_d\left(1+k_1r^2+k_2r^4+k_3r^6\right) \\ y_u &= y_d\left(1+k_1r^2+k_2r^4+k_3r^6\right) \end{aligned} \tag{3}$$

$\mathbf{p}_d=\left(x_d,y_d\right)^T$ is the distorted point on the ideal image plane through radial distortion of lens. r is the radius of the distorted point. Finally, distorted point on the ideal image plane is converted into point $\mathbf{p}_f=\left(x_f,y_f\right)^T$ on the image plane as follows.

$$\begin{pmatrix} x_f \\ y_f \\ 1 \end{pmatrix} = \begin{bmatrix} \alpha_u & 0 & u_0 \\ 0 & \alpha_v & v_0 \\ 0 & 0 & 1 \end{bmatrix}\begin{pmatrix} x_d \\ y_d \\ 1 \end{pmatrix} \tag{4}$$

α_u and α_v are the conversion parameters from the metric domain to the pixel domain along the horizontal and vertical direction. $\left(u_0,v_0\right)$ is the principle point where the z-axis of the camera coordinate system meets the image plane.

2.2. The extrinsic calibration of laser frame with respect to the camera frame

Through laser calibration, we could find the pose of laser frame with respect to world frame. Most traditional algorithms find the equation of laser scan plane under camera frame. The equation of laser scan plane could be determined by finding more than three non-linear points which lie on the scan plane. Their coordinates are represented under the camera coordinate system. Therefore, 3D reconstruction is possible only with respect to the camera coordinate system. Proposed algorithm also finds the equation of the scan plane, but we can represent them both under camera and laser coordinate system. Therefore, 3D reconstruction is possible both under the camera and laser coordinate system.

The proposed algorithm uses newly designed calibration structure as shown in Fig. 2 which has multiple vertical planes on the ground plane. If a laser stripe hits the calibration structure, some portions of them are blocked by vertical planes and non-blocked portions would hit the ground plane. Therefore, we could have multiple line segments on the calibration structure.

In Fig. 2, $\mathbf{v}_i$ represents a point that the laser line meets at the top of vertical plane. $\mathbf{h}_i$ corresponds the point that the same laser line of $\mathbf{v}_i$ hits on the ground

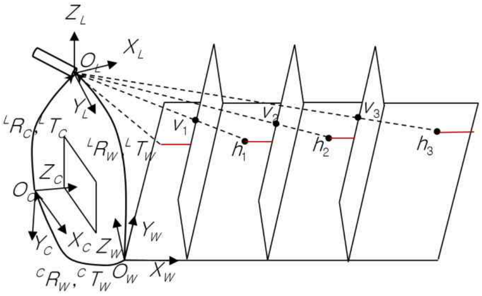


Fig. 2. Proposed calibration structure which has multiple vertical planes on the ground plane

plane. $\left\{\mathbf{O}_w,\mathbf{X}_W,\mathbf{Y}_W,\mathbf{Z}_W\right\}$, $\left\{\mathbf{O}_C,\mathbf{X}_C,\mathbf{Y}_C,\mathbf{Z}_C\right\}$, and $\left\{\mathbf{O}_L,\mathbf{X}_L,\mathbf{Y}_L,\mathbf{Z}_L\right\}$ represent the world, camera, and laser coordinate system. Proposed algorithm uses a geometric constraint which is inherent in the newly designed calibration structure. The geometric constraint is that the line which passes two points $\mathbf{v}_i$ and $\mathbf{h}_i$ would also passes the origin of the laser coordinate system. Proposed calibration structure provides multiple lines which satisfy given constraint. We could determine the origin of laser coordinate system by finding crossing points of those multiple lines.

In Fig. 2, there are three lines formed by a pair of points $\left\{\mathbf{v}_1,\mathbf{h}_1\right\}$, $\left\{\mathbf{v}_2,\mathbf{h}_2\right\}$, and $\left\{\mathbf{v}_3,\mathbf{h}_3\right\}$. The crossing point of those three lines corresponds to the origin of the laser coordinate system. The 3D coordinates of points $\mathbf{v}_i$ and $\mathbf{h}_i$ under world frame could be obtained by hand. Therefore, we could compute the location of the laser coordinate system with respect to world frame. Also, those points could be transformed into camera coordinate system by using camera calibration information.

Next, we show a procedure for computing extrinsic parameters of laser under world frame. A 3D line which passes two points $(x_1,y_1,z_1)^T$ and $(x_2,y_2,z_2)^T$ is represented as

$$\begin{aligned} &\frac{x-x_1}{l}=\frac{y-y_1}{m}=\frac{z-z_1}{n} \\ &\left(l=x_2-x_1, m=y_2-y_1, n=z_2-z_1\right) \end{aligned}. \tag{5}$$

$\left(l,m,n\right)$ is a direction vector of the line. From a pair of point, we obtain two equations for computing the location of laser frame. The crossing point of multiple lines is computed by least-squares estimation to cancel out error caused by during the selection of control points and by laser itself. The crossing point is computed by solving following equation.

$$\begin{bmatrix} m_1 & -l_1 & 0 \\ 0 & n_1 & -m_1 \\ & \vdots & \\ m_n & -l_n & 0 \\ 0 & n_n & -m_n \end{bmatrix}\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} m_1x_1^1-l_1y_1^1 \\ n_1y_1^1-l_1z_1^1 \\ \vdots \\ m_nx_1^n-l_1y_1^n \\ n_ny_1^n-l_nz_1^n \end{bmatrix} \tag{6}$$

$(x_1^i, y_1^i, z_1^i)^t$ is the coordinate of first point in the i-th point pairs which forms a line. $(l_i, m_i, n_i)^T$ is the direction vector of the i-th line.

By solving Eq. (6), we could obtain the location of laser frame with respect to world frame and it corresponds to the translation component in extrinsic parameters. Next, we compute the remaining rotation components in extrinsic parameters. Let the rotation matrix from world frame to laser frame be

$$ {}^{L}\mathbf{R}_W = \begin{bmatrix} r_{11} & t_{12} & r_{13} \\ r_{21} & t_{22} & r_{23} \\ r_{31} & t_{32} & r_{33} \end{bmatrix}. \tag{7}$$

${}^{L}\mathbf{R}_W$ is a 3X3 rotation matrix from the world coordinate system to the laser coordinate system. We could fit a plane which passes all point pairs $\{\mathbf{v}_i, \mathbf{h}_i\}$ in Fig. 2. Point pair $\mathbf{v}_i$ and $\mathbf{h}_i$ exist on different ground and vertical plane, therefore we could use them in plane fitting. The normal of the fitted plane corresponds to the normal of laser scan plane.

The coordinate of each point is represented under world frame, therefore the normal is also under world frame. We could set it as the z-component of rotation matrix from world frame to laser frame. The unit plane normal corresponds to (r_{13}, r_{23}, r_{33}) in rotation matrix ${}^{L}\mathbf{R}_W$.

Next, we fit a line which passes points on the ground plane. The normalized direction vector of fitted line can be set as (r_{11}, r_{21}, r_{31}) which is the x-component in rotation matrix ${}^{L}\mathbf{R}_W$. The remaining y-component in rotation matrix can be computed by the cross product of z-component and x-component in rotation matrix. We have computed the extrinsic parameters of laser frame with respect to world frame by using proposed calibration structure. Camera is calibrated using the same world frame used in the extrinsic calibration of the laser. The pose of camera and laser is obtained under the same world frame. Extrinsic parameters of the camera and laser with respect to the world coordinate system are represented as

$$\begin{aligned} \mathbf{P}_L &= {}^{L}\mathbf{R}_W \mathbf{P}_W + {}^{L}\mathbf{T} \\ \mathbf{P}_C &= {}^{C}\mathbf{R}_W \mathbf{P}_W + {}^{C}\mathbf{T} \end{aligned}. \tag{8}$$

$\mathbf{P}_W$, $\mathbf{P}_L$, and $\mathbf{P}_C$ represent a 3D point under the world, laser, and camera coordinate system. ${}^{L}\mathbf{R}_W$ and ${}^{L}\mathbf{T}$ is the rotation matrix and translation vector from the world coordinate system to the laser coordinate system. ${}^{C}\mathbf{R}_W$ and ${}^{C}\mathbf{T}$ is the rotation matrix and translation vector from the world coordinate system to the camera coordinate system. From Eq. (8), we could compute relative pose between a camera and laser coordinate system as follows.

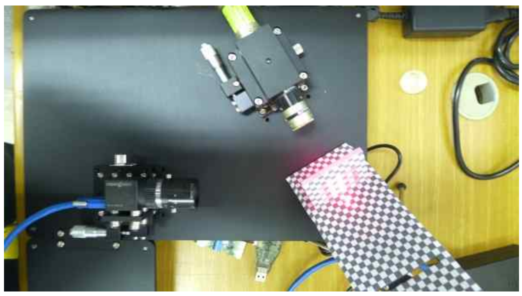
$$\begin{aligned} \mathbf{P}_L = {}^{L}\mathbf{R}_C \mathbf{P}_C + {}^{L}\mathbf{T}^* \quad where\ {}^{L}\mathbf{R}_C = {}^{L}\mathbf{R}_W\, {}^{C}\mathbf{R}_W^{-1}, \\ {}^{L}\mathbf{T}^* = -{}^{L}\mathbf{R}_W\, {}^{C}\mathbf{R}_W^{-1}\, {}^{C}\mathbf{T} + {}^{L}\mathbf{T} \end{aligned} \tag{9}$$

${}^{L}\mathbf{R}_C$ and ${}^{L}\mathbf{T}^*$ are a rotation matrix and translation vector from the camera coordinate system to the laser coordinate system. Using these extrinsic parameters, we could convert 3D reconstruction under camera frame into 3D reconstruction under laser frame.

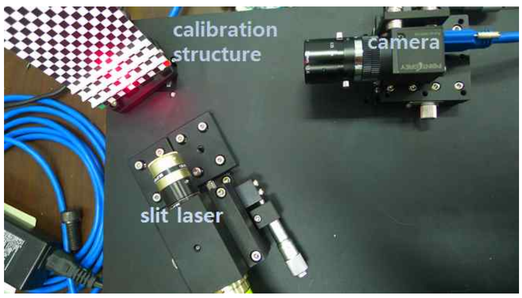
After the calibration of camera and laser, 3D reconstruction of a point is possible. The computation of a 3D coordinate of a point by structured light stripe vision system is done by finding the crossing point of a line and a laser scan plane. The line is obtained by back projecting a point on the image into the space using camera calibration information. This line meets the laser scan plane. The crossing point of back-projected line with laser scan plane corresponds to the 3D coordinate of a point. More details could be found in [14].

3. Experimental Results

In experiments, we present results including the comparison of proposed algorithm to our previous algorithm [13] which uses calibration structure having multiple slits. The accuracy of calibration is evaluated by comparing 3D distance between two points to known ground truth. In experiments, we use a structured light stripe system having a camera and a line laser which emits a line. It is shown in Fig. 3. Flea 3 (Model: FL3-U3-13S2C-CS) camera by Point Grey is used. Laser macro line generator by Schafter+



(a)



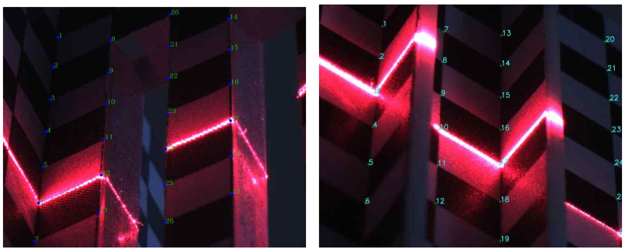
(b)

Fig. 3. Experimental setup of structured light stripe system configuration with a camera, a slit laser and a calibration structure: (a) calibration structure with multiple slits; (b) calibration structure with multiple vertical planes

Kirchhoff having 14 μm line width is used. The field of view of the camera is approximately 35mm(H)X30mm(V).

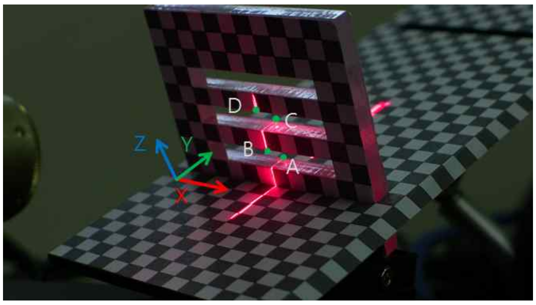
Fig. 3-(a) shows the configuration having a calibration structure of multiple slits. Fig. 3-(b) represents the configuration having a calibration structure of multiple vertical planes. Chessboard patterns are printed and attached on the plane and they are used in the calibration.

Fig. 4 shows points which are used for camera calibration and they are represented as a circle on an image. The camera is calibrated using points on a plane using Tsai algorithm [3]. In Fig. 4, the size of each rectangle on the chessboard is 5mmX5mm. Points used in the calibration are chosen by hand and sub-pixel processing is not applied. We could notice brighter spots on an image due to the glaring effects of the laser in Fig. 4. Also, we could notice the blurring of laser line on image which causes the thickness of laser line to have much larger thickness than specified one in a catalog.

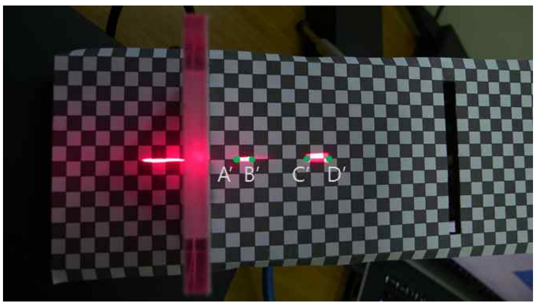


(a) (b)

Fig. 4. Points used in the camera calibration: (a) calibration structure with multiple slits; (b) calibration structure with multiple vertical planes



(a)



(b)

Fig. 5. Control points used for the laser calibration in calibration structure having multiple slits: (a) from vertical planes; (b) from the ground plane

Fig. 5 shows control points used for finding laser extrinsic parameters on calibration structure having multiple slits. Fig. 5-(a) shows the location of control points in the vertical plane. Fig. 5-(b) shows the corresponding location of control point on the ground plane. They are chosen by hand and their coordinates are obtained with respect to world frame.

Fig. 6 shows control points used for finding laser extrinsic parameters on calibration structure having multiple vertical slits. Vertical planes are set perpendicular to the ground plane. The thickness and height of the vertical plane are 1mm and 5mm, in respect. In Fig. 5, we could obtain four sets of point pairs where each point pair forms a line which passes the origin of the laser. In Fig. 6, we can obtain three sets of point pairs. In Fig. 5 and Fig. 6, green circle shows the location of control points on an image. The crossing point of multiple lines is the origin of the laser with respect to the world frame on the ground plane.

Table 1 shows the result of camera calibration and values of extrinsic parameters between camera and laser by our previous [13] and proposed algorithm. In both cases, the same camera and laser and the same configuration are

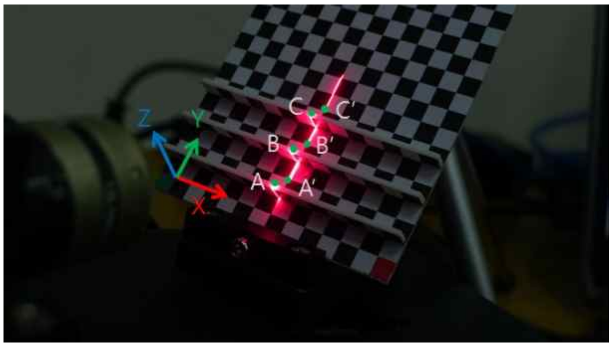


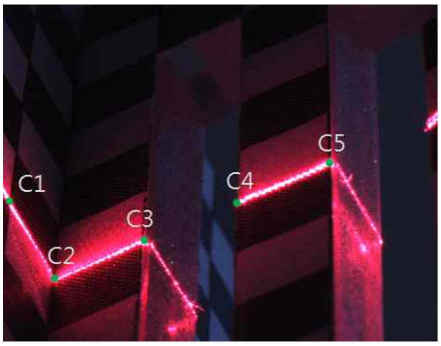
Fig. 6. Control points used for the laser calibration in calibration structure having multiple vertical planes

Table 1. The result of camera calibration and extrinsic parameters from camera to laser by proposed and our previous [13] algorithm

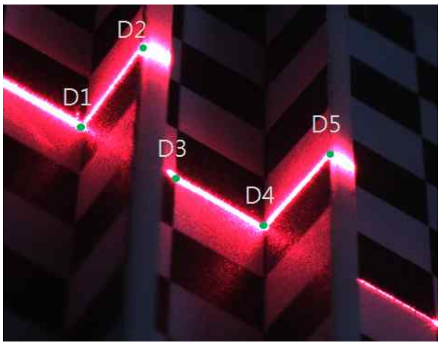
	Our previous algorithm [13]	Proposed algorithm
f [mm]	42.784	39.940
Distortion coeff. κ_1 [1/mm^2]	7.517e-004	7.650e-004
Intrinsic parameters $(\alpha_u, \alpha_v, u_0, v_0)$	(11786.1, 11786.1, 616.5, 496.5)	(11002.8, 11002.8, 380.8, 174.0)
Translation (t_x, t_y, t_z) [mm]	(9.674, -18.453, 173.915)	(4.256, -83.466, 125.615)
Rotation $(\theta_x, \theta_y, \theta_z)$ [deg]	(-164.46, -25.23, 59.55)	(-156.55, -12.06, 30.34)
Length between camera and laser [mm]	175.158	150.877

used. The same value of relative pose between camera and laser and camera iris setting is used in both cases. Therefore, in an ideal case, result from both cases should have the same value. However, result in Table 1 shows there is a considerable difference in camera calibration result and pose value between camera and laser. In particular, the pose between the camera and laser shows a clear difference. Nevertheless, we could obtain 3D reconstruction with a small error in both cases. The cause of this difference would require further research.

After calibration, we could obtain 3D reconstruction



(a)



(b)

Fig. 7. Points used in evaluating 3D reconstruction accuracy: (a) calibration structure with multiple slits; (b) calibration structure with multiple vertical planes

Table 2. The comparison of the accuracy of 3D reconstruction by proposed algorithm and our previous algorithm [13]

	Points for evaluation	Ground truth [mm]	Computed distance [mm]	Relative error [%]
Our previous algorithm (Fig 7-(a))	C1↔C2	5	4.77	4.52
	C2↔C3	5	5.00	0.12
	C3↔C4	5	4.95	0.99
	C4↔C5	5	5.01	0.18
	mean			1.46
Proposed algorithm (Fig. 7-(b))	D1↔D2	5	4.93	1.34
	D2↔D3	7.07	6.99	1.13
	D3↔D4	5	4.96	0.78
	D4↔D5	5	5.01	0.24
	mean			0.87

along the contour of the laser on an image. We evaluate the accuracy of calibration by comparing the 3D reconstruction to the known ground-truth value. Fig. 7 shows the location of points on an image which are used in the evaluation of the accuracy of 3D reconstruction. They are represented by green circles in Fig. 7. For each point, 3D reconstruction is done. We compute the distance between adjacent points where the ground truth-value is known. Table 2 shows the comparison result using control points in Fig. 7. Proposed algorithm gives 40% improvement in relative error compared to the previous algorithm.

Proposed algorithm which uses calibration structure of multiple vertical planes gives slightly better result than our previous algorithm with calibration structure of multiple slits in accuracy. Proposed calibration structure with multiple vertical planes could be made more easily and accurately than our previous one with multiple slits. It is, in particular, helpful in making small calibration structure to have 3D reconstruction under a small field of view.

The accuracy of control points needs further improvement to have more accurate 3D reconstruction. We manually selected the location of control points on an image by zooming and they are used in camera and laser calibration. The accuracy of location of control points on an image has a direct impact on the calibration result. Automatic detection of those control points on the image is necessary to improve the calibration accuracy and to automate the calibration process. Further study will focus on the automatic detection of control points.

4. Conclusion

In this paper, a new calibration algorithm for the structured light vision system is proposed. The proposed algorithm uses newly designed calibration structure which has multiple vertical planes on the ground plane. Thereby proposed calibration structure can be made with ease and accurately. Proposed algorithm enables the calibration of structured vision system just using one shot of image. Also, it is possible to have 3D reconstruction under both the camera and laser frame with improved accuracy.

Acknowledgements

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