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Laser pose calibration of ViSP for precise 6-DOF structural displacement monitoring

Jae-Uk Shin[**1], Haemin Jeon[**2], Suyoung Choi[1], Youngjae Kim[1] and Hyun Myung[*1,3]

[1]Robotics Program, KAIST, Daejeon 34141, Republic of Korea
[2]Department of Civil and Environmental Engineering, Hanbat National University, Daejeon, 34158, Republic of Korea
[3]Department of Civil and Environmental Engineering, KAIST, Daejeon 34141, Republic of Korea

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Abstract. To estimate structural displacement, a visually servoed paired structured light system (ViSP) was proposed in previous studies. The ViSP is composed of two sides facing each other, each with one or two laser pointers, a 2-DOF manipulator, a camera, and a screen. By calculating the positions of the laser beams projected onto the screens and rotation angles of the manipulators, relative 6-DOF displacement between two sides can be estimated. Although the performance of the system has been verified through various simulations and experimental tests, it has a limitation that the accuracy of the displacement measurement depends on the alignment of the laser pointers. In deriving the kinematic equation of the ViSP, the laser pointers were assumed to be installed perfectly normal to the same side screen. In reality, however, this is very difficult to achieve due to installation errors. In other words, the pose of laser pointers should be calibrated carefully before measuring the displacement. To calibrate the initial pose of the laser pointers, a specially designed jig device is made and employed. Experimental tests have been performed to validate the performance of the proposed calibration method and the results show that the estimated displacement with the initial pose calibration increases the accuracy of the 6-DOF displacement estimation.

Keywords: structural health monitoring; displacement measurement; visually servoed paired structured light system (ViSP); laser pose calibration

1. Introduction

Structural displacement is used to assess or evaluate the structural health and safety (Balageas *et al.* 2006). To measure the structural displacement, conventional sensors such as accelerometers, GPS, or LDVs (laser Doppler vibrometers) have been widely used. However, these sensors have drawbacks in that the accelerometer is sensitive to environmental changes such as temperature (Kim *et al.* 2007, Mita and Yokoi 2001) and the cost of GPS or LDV is very high (Psimoulis and Stiros 2008, Nassif *et al.* 2005, Meng *et al.* 2004). In efforts to ameliorate these problems, vision-based displacement estimation systems or methods have been researched (Park *et al.* 2010, Ji and Chang 2008, Lee and Shinozuka 2006, Wahbeh *et al.* 2003, Olaszek 1999, Leith *et al.* 1989,

∗Corresponding author, Professor, E-mail: hmyung@kaist.ac.kr
** These authors contributed equally to this work.

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Marecos *et al.* 1969). In most of the systems, targets are installed on the structure and the movement of the targets is monitored by a camera located on a fixed position from a considerable distance. As the distance between the camera and the target becomes relatively long, accuracy of the displacement estimation is strongly influenced by environmental changes.

In response to these issues, Myung *et al.* (2011) proposed a paired structured light (SL) system. The paired SL system is composed of two sides facing each other, each with one or two laser pointers, a camera, and a screen (Myung *et al.* 2011). The laser pointers project their beams to the screen on the opposite side and the camera near the screen captures an image of the screen. The translational and rotational displacement between two sides can be estimated by calculating the positions of the projected laser beams. Since the distance between the camera and the screen is short, it is robust to external environmental variations such as illumination changes and fog. As the screen size is limited, however, the measurable displacement range is similarly limited.

To address this problem, a visually servoed paired structured light system (ViSP) which is an advanced version of the paired SL system, was proposed by Jeon *et al*. (2011). In ViSP, the poses of laser pointers are controlled by a 2-DOF manipulator so that laser beams are always projected inside the screen boundary. By employing the manipulators, the measurable displacement range is largely expanded in comparison with the former paired SL system. The relative displacement between two sides can be estimated by calculating the positions of the three projected laser beams and rotation angles of the manipulators. To increase the computation time and reduce the accumulated error of ViSP, an incremental displacement estimation method (Jeon *et al.* 2012), a displacement estimation error back-propagation method (Jeon *et al.* 2013), and a pose-graph optimization method (Lee *et al.* 2014) have been proposed. The performance of the system with the displacement estimation algorithm has been verified from experimental tests with a steel frame building structure and a rail-way bridge (Jeon *et al.* 2014). However, it has a limitation that the performance of the displacement estimation is dependent on the initial pose of laser pointers. In deriving the kinematic equation of the ViSP, the laser pointers were assumed to be installed perfectly normal to the same side screen. In reality, however, this is very difficult to achieve due to installation errors. As inclination of the laser pointers is unavoidable, the initial pose of the laser pointers should be considered. In this paper, an initial pose calibration method for laser pointers using a specially designed jig is introduced. The ViSP is installed in the jig with a known geometry and the initial inclination angles of laser pointers about two axes are calculated. Afterwards, the 6-DOF translational and rotational displacement can be estimated with high accuracy by considering the previously calculated inclination angles of the laser pointers. The performance of the laser pose calibration method is verified through experimental tests. The rest of this paper is organized as follows. In Section 2, the ViSP is briefly introduced. The initial pose calibration method for laser pointers is proposed in Section 3. In Section 4, the performance of the proposed method is validated through experimental tests. Finally, conclusions are provided in Section 5.

2. ViSP: Displacement measurement system

As shown in Fig. 1, a visually servoed paired structured light system (ViSP) is composed of two sides facing each other, each with one or two laser pointers, a camera, and a screen. The laser pointers project beams onto the screen on the opposite side and the camera nearby the screen captures an image of the screen. The projected laser beams are continuously directed onto the center of the screen by controlling the 2-DOF manipulators. The relative 6-DOF displacement between two sides can be estimated by calculating positions of the projected laser beams and rotation angles of the manipulators. The displacement estimation procedure of ViSP is shown in Jeon *et al.* (2014). The camera in each side captures an image of the screen. The camera lens distortion is corrected, and the screen boundary and the positions of the projected laser beam(s) are detected by using various image processing techniques. If the positions of the projected laser beams move outside of the screen boundary, the 2-DOF manipulator controls the pose of the laser pointers so that the beams always stay on the screen. The 6-DOF displacement can be estimated by calculating the positions of the laser beams and rotation angles of the manipulators.

Kinematics of ViSP defines a geometric relationship between observed data (positions of the projected laser beams) and 6-DOF translational and rotational displacement. Homogeneous transformation matrices are used to derive kinematics. For further details of kinematics of ViSP, please refer to Jeon *et al.* (2011).

3. Initial laser pose calibration method

Although the performance of ViSP has been verified through various experimental tests (Jeon *et al.* 2011, Jeon *et al.* 2012, Jeon *et al.* 2013, Jeon *et al.* 2014), it has a limitation that the measured displacement accuracy is dependent on the initial pose of the laser pointers. Since it is practically impossible to precisely install laser pointers normal to the plane of the screen, the initial inclination angles of laser pointers should be calibrated. In ViSP, the rotation angles of the 2-DOF manipulators are set to zeros at the beginning. In other words, it is assumed that the lasers are installed exactly perpendicular to the screen and parallel to each other. As shown in Fig. 2, however, it is hard to control the initial pose of lasers to be perfectly orthogonal to the screen. Also, the two lasers installed on side *A* cannot be perfectly aligned parallel while bolting up.

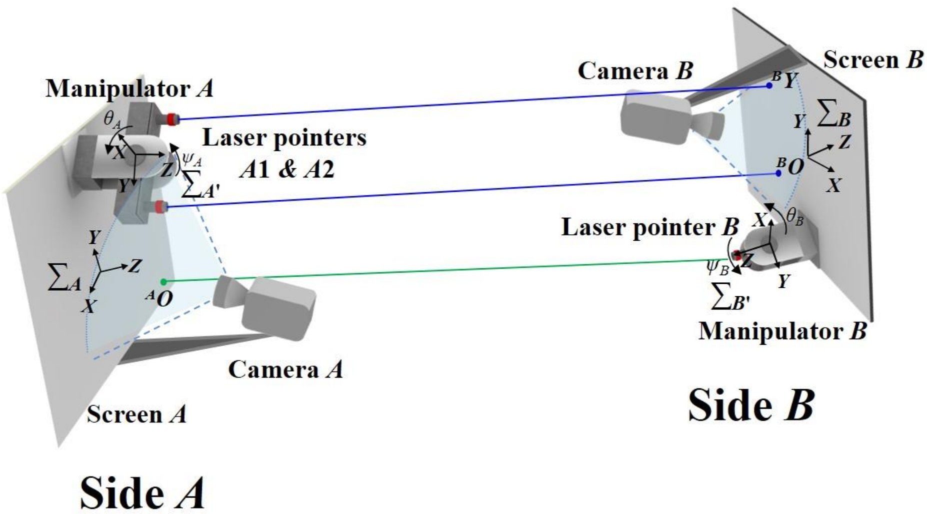


Fig. 1 Schematic diagram of a visually servoed paired structured light system (ViSP)

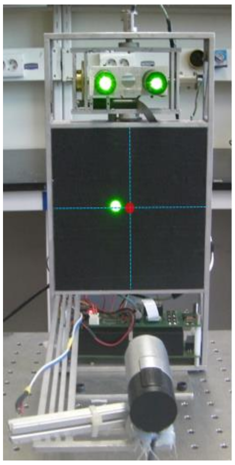


Fig. 2 An initial setup of the ViSP. A red point on the screen indicates the ideal beam location, and the green one is the actual initial point obtained

To resolve this problem, a specially designed jig is employed to calculate the initial pose of lasers. As shown in Fig. 3, a specially designed jig has been used to calculate the inclination angles of the laser pointers. The jig has been manufactured so that two sides of ViSP can be installed at a known distance *H* along *Z*-axis between two sides when they are fixed on the jig. In other words, each side of the module is installed inside the jig with a known distance such that they are facing each other, each with one or two laser pointers, a camera, and a screen.

As Fig. 3 shows, the inclination angles of the laser pointers about *X* and *Y* axes should be considered. By calculating the positions of the projected laser beams with a known geometry, the rotation angle of each laser pointer can be estimated.

The position of the projected laser beam on side *A*, ${}^{A}O$ can be obtained as follows

$$ {}^{A}O = {}^{A}T_{B} \cdot {}^{B}T_{B'} \cdot {}^{B'}T_{B''} \cdot \begin{bmatrix} {}^{B}L_{x} & {}^{B}L_{y} & Z_{AB} & 1 \end{bmatrix}^{T} \tag{1} $$

where ${}^{B}L_x$ and ${}^{B}L_y$ are the offsets of the installed laser position from the center of screen *B* in *X* and *Y* direction and $Z_{AB} = H$ is the distance in *Z* direction between two sides. ${}^{A}T_{B}$ is the transformation matrix that transforms the coordinate frame of side *B* to side *A*, which consists of the product of the translation matrix along *X*, *Y*, and *Z* axes and the rotation matrices about *X*, *Y*, and *Z* axes. ${}^{B}T_{B'}$ is a manipulator rotation matrix on side *B* as follows

$$ {}^{B}T_{B'} = R_x(-\theta_{Benc}) \cdot R_y(\phi_{Benc}) \tag{2} $$

where $R_x(\theta)$ indicates a rotation matrix along *X*-axis with rotation angle θ; θ_{Benc} and ϕ_{Benc} are rotated angles of the manipulator on side *B* about *X* and *Y* axes, respectively, which can be obtained through encoders attached to motors. ${}^{B'}T_{B''}$ is the initial laser pose calibration matrix composed of inclination angles of the laser pointer on side *B* about *X* and *Y* axes as follows

$$ {}^{B'}T_{B''} = R_x(\theta_{BL}) \cdot R_y(\phi_{BL}) \tag{3} $$

where θ_{BL} and ϕ_{BL} are inclined angles of the laser pointer *B* about *X* and *Y* axes (see Fig. 3).

Similar to ^{A}O, the positions of the projected laser beams on side B, ^{B}O and ^{B}Y can be obtained as follows

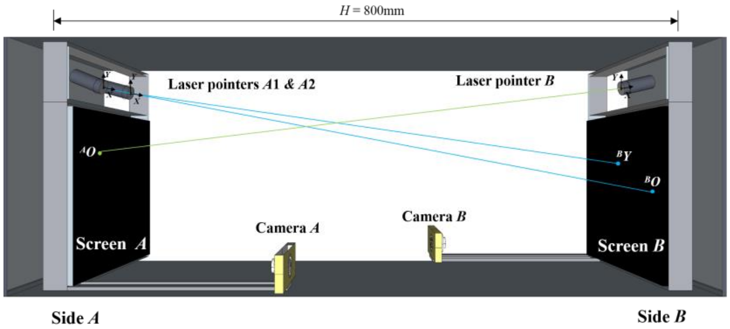
$$^{B}O = {}^{B}T_{A} \cdot {}^{A}T_{A'} \cdot {}^{A1'}T_{A1''} \cdot [\ {}^{A}L_{x} \quad {}^{A}L_{y} \quad Z_{AB} \quad 1\ ]^{T} \tag{4}$$

$$^{B}Y = {}^{B}T_{A} \cdot {}^{A}T_{A'} \cdot {}^{A2'}T_{A2''} \cdot [\ -{}^{A}L_{x} \quad {}^{A}L_{y} \quad Z_{AB} \quad 1\ ]^{T} \tag{5}$$

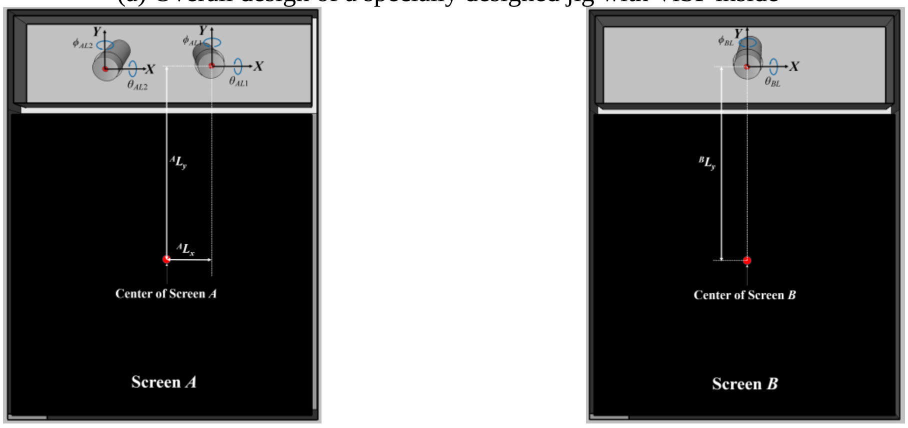
where $^{A}L_{x}$ and $^{A}L_{y}$ are the offsets of the installed laser position from the center of the screen in X and Y direction; $^{A1'}T_{A1''}$ is the initial laser pose calibration matrix composed of inclination angles of the laser pointer on the right side of screen A, $A1$, about X and Y axes as follows

$$^{A1'}T_{A1''} = R_{x}(\theta_{AL1}) \cdot R_{y}(\phi_{AL1}) \tag{6}$$

where θ_{AL1} and ϕ_{AL1} are inclined angles of the laser pointer. $^{A2'}T_{A2''}$ can be calculated in the same manner. The z components of three projected laser beams should be constrained to zero since they are projected onto the 2D screen. As the jig geometry is given *a priori*, the relative 6-DOF displacement between two sides is known. By using the constraints, the kinematics of the initial pose of laser pointers can be derived. Eq. (7) can be derived by combining Eqs. (1)-(5). Referring to Eq. (1), the projected laser point on side A, ^{A}O, can be written as follows



(a) Overall design of a specially designed jig with ViSP inside



(b) Coordinate system of laser pointers (Zoomed figure of each side in (a))

Fig. 3 Design of a specially designed jig for laser pose calibration

$$
{}^{A}O = \begin{bmatrix} {}^{B}L_y s_{\theta_{BL}} s_{\phi_{BL}} + s_{\phi_{BL}} (H - {}^{B}L_y c_{\phi_{BL}} s_{\theta_{BL}}) / c_{\phi_{BL}} \\ {}^{B}L_y c_{\theta_{BL}} - s_{\theta_{BL}} (H - {}^{B}L_y c_{\phi_{BL}} s_{\theta_{BL}}) / (c_{\theta_{BL}} c_{\phi_{BL}}) \\ 0 \\ 1 \end{bmatrix} \quad (7)
$$

where $z_{AB} = H$ is the pre-defined distance between two sides in the jig, ${}^{B}L_x$ is set to 0, and s_{θ} and c_{θ} denote $\sin\theta$ and $\cos\theta$. As shown in the first two rows of Eq. (7), we can obtain two components from the observation of ${}^{A}O$. In a similar way, four additional components are obtained from ${}^{B}O$ and ${}^{B}Y$. By using these components, kinematic equation can be derived as follows

$$
\begin{aligned}
M &= \begin{bmatrix} {}^{A}O & {}^{B}O & {}^{B}Y \end{bmatrix}^T \\
&= \begin{bmatrix} {}^{A}O_x & {}^{A}O_y & {}^{B}O_x & {}^{B}O_y & {}^{B}Y_x & {}^{B}Y_y \end{bmatrix}^T \\
&= \begin{bmatrix} {}^{B}L_y s_{\theta_{BL}} s_{\phi_{BL}} + s_{\phi_{BL}} (H - {}^{B}L_y c_{\phi_{BL}} s_{\theta_{BL}}) / c_{\phi_{BL}} \\ {}^{B}L_y c_{\theta_{BL}} - s_{\theta_{BL}} (H - {}^{B}L_y c_{\phi_{BL}} s_{\theta_{BL}}) / (c_{\theta_{BL}} c_{\phi_{BL}}) \\ {}^{A}L_y s_{\theta_{AL1}} - {}^{A}L_x c_{\phi_{AL1}} - s_{\phi_{AL1}} (H + {}^{A}L_x s_{\phi_{[AL1}} + {}^{A}L_y c_{\phi_{AL1}} s_{\theta_{AL1}}) c_{\phi_{AL1}} \\ {}^{A}L_y c_{\theta_{AL1}} + s_{\theta_{AL1}} (H + {}^{A}L_x s_{\phi_{AL1}} + {}^{A}L_y c_{\phi_{AL1}} s_{\theta_{AL1}} / (c_{\theta_{AL1}} c_{\phi_{AL1}}) \\ {}^{A}L_y c_{\phi_{AL2}} + {}^{A}L_y s_{\theta_{AL2}} s_{\phi_{AL2}} - s_{\phi_{AL2}} (H - {}^{A}L_x s_{\phi_{AL2}} + {}^{A}L_y c_{\phi_{AL2}} s_{\theta_{AL1}}) / c_{\phi_{AL2}} \\ {}^{A}L_y c_{\theta_{AL2}} + s_{\theta_{AL2}} (H - {}^{A}L_x s_{\phi_{AL2}} + {}^{A}L_y c_{\phi_{AL2}} s_{\theta_{AL2}}) / (c_{\theta_{AL2}} c_{\phi_{AL2}}) \end{bmatrix}
\end{aligned} \quad (8)
$$

where ${}^{A}O_x$ and ${}^{A}O_y$ denote the x and y components of ${}^{A}O$, respectively. For simplification, the rotation angles of the manipulator are set to zero initially. By using the Newton-Raphson method, the initial inclination angles of the lasers, $p_L = \begin{bmatrix} \theta_{BL} & \phi_{BL} & \theta_{AL1} & \phi_{AL1} & \theta_{AL2} & \phi_{AL2} \end{bmatrix}^T$, can be estimated using the following iterations

$$
\hat{p_L}(k+1) = \hat{p_L}(k) + J_{p_L}^{\dagger}(m(k) - \hat{m}(k)) \quad (9)
$$

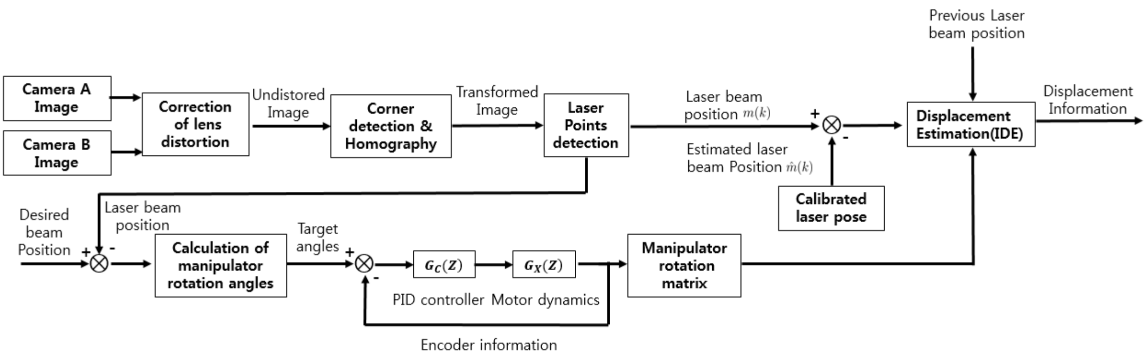
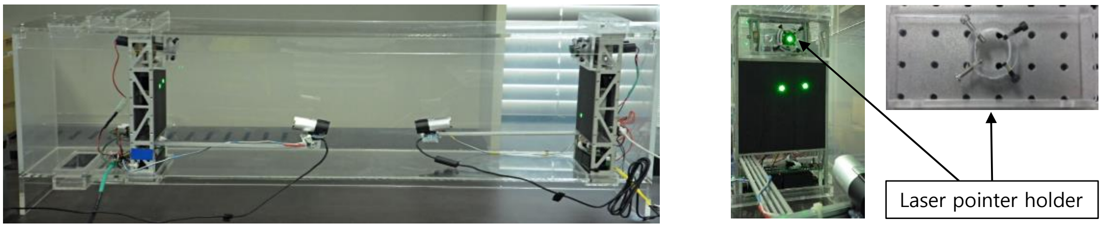


Fig. 4 The procedure of the displacement estimation



(a) (b)

Fig. 5 Initial laser pose calibration with a specially designed jig. (a) Installation of ViSP on the jig and (b) the laser pointer is fixed by the laser pointer holder

where k is the iteration step, $J_{p_L} = \partial M / \partial p_L$ is the Jacobian of the kinematic equation M with respect to the variable p_L, $J_{p_L}^{\dagger}$ is the pseudo-inverse of the Jacobian, and $m(k)$ and $\hat{m}(k)$ are the measured and estimated observations, respectively. In other words, $m(k) = [\, ^{A}O \;\; ^{B}O \;\; ^{B}Y \,]^T$ is the observed data, and $\hat{m}(k)$ is the estimated observation given by M in Eq. (8). To estimate six unknowns of the laser pose, p_L, at least three observation data are needed because each observation contains two equations describing x and y coordinate points. In case there are uncertainties in the measurement, the extended Kalman filter (EKF) method can be applied. For the formulation of EKF, we can follow the same framework introduced in Jeon *et al.* (2011).

The overall procedure of the displacement estimation is shown in Fig. 4. As shown in the figure, the cameras capture the images of the screens and the boundary of each screen is calculated. Afterwards, the laser beams are detected and the centers of gravity of the projected laser beams are calculated with calibrated laser pose from a special jig as shown in Fig 5. By using the calculated positions of the projected laser beams and rotation angles of the manipulators, the 6-DOF displacement can be estimated.

4. Experimental validation

To verify the performance of the proposed laser pose calibration method, experimental tests have been conducted. As shown in Fig. 5(a), each side of the ViSP is installed inside of a specially designed jig with a manufacturing tolerance of 0.01 mm to calibrate the initial pose of the laser pointers. Both sides are facing each other, each with one or two laser pointers, a camera, a manipulator, and a screen. The laser pointers project their beams onto the screen on the opposite side, and the camera situated closer captures the image of the screen. The distance between the two sides in the jig device, H, is set to 800 mm and the offsets of the installed laser position, $^{A}L_x$, $^{A}L_y$, $^{B}L_x$, and $^{B}L_y$ are set to 22.75 mm, 119.50 mm, 0, and 119.50 mm, respectively. The poses of laser pointers are fixed by using specially designed laser pointer holders, as shown in Fig. 5(b). After applying (9), the calibration results of initial inclinations of the laser pointers are obtained as follows: θ_{AL1} = -0.0478, ϕ_{AL1} = -0.0015, θ_{AL2} = -0.0553, ϕ_{AL2} = -0.0035, θ_{BL} = 0.0635, and ϕ_{BL} = -0.0245, where all units are in radians. Fig. 6 shows the estimation of initial inclination angles of the laser pointers by using the Newton-Raphson method described in (9). The estimation results converged in about 10 iterations.

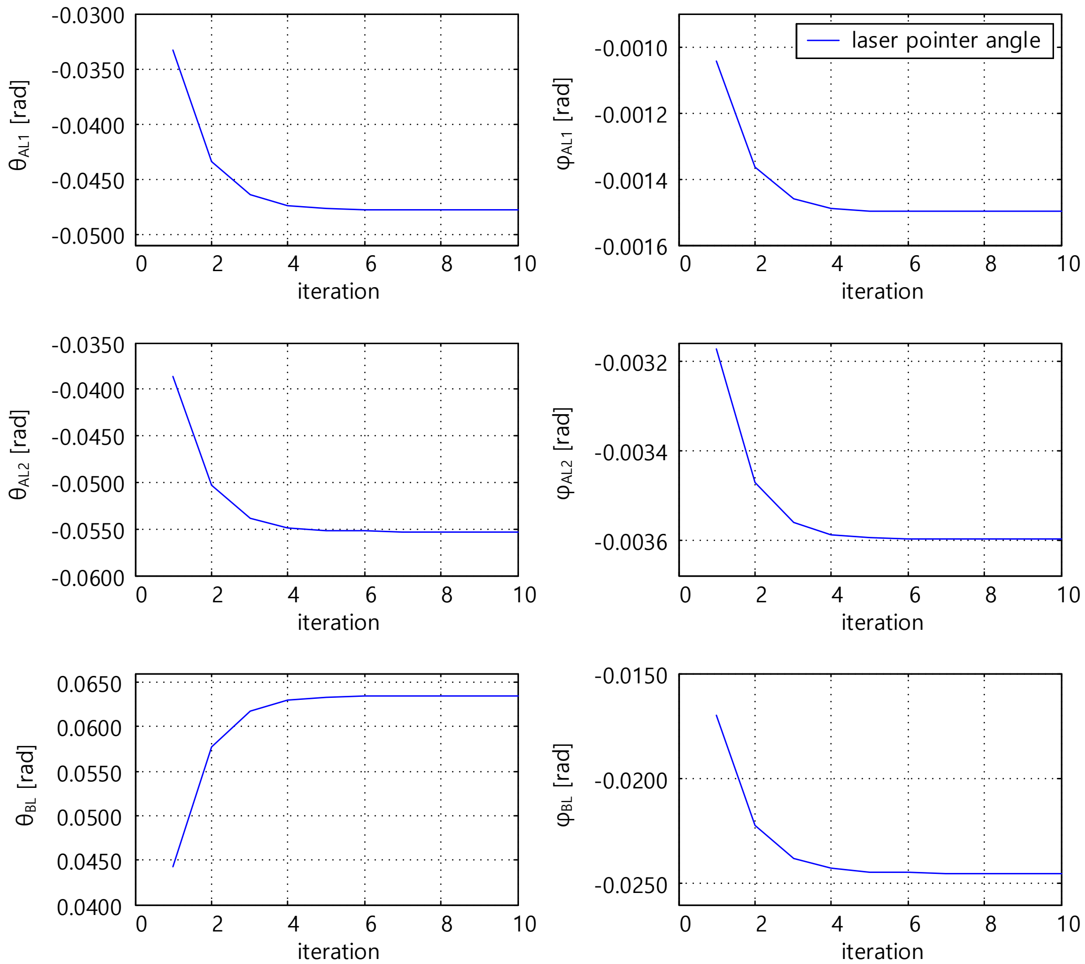


Fig. 6 Calibration result of initial inclinations of the laser pointers

After calibration of the initial poses of the laser pointers, each side of ViSP is installed as shown in Fig. 7. One of two sides is laid on a fixed table, and the other is on a motorized motion stage (Thorlabs Inc., 2011). The motion stage is a tool that can control the translational and rotational displacement along *X*-axis and about *Y*-axis with a resolution of 0.0001 mm and 0.0001°, respectively. Artificial translational and rotational movements between two sides are generated from the motion stage. The estimated displacements are compared with the results from the motion stage that can be considered as the ground truth. The distance between two sides is set to 2.00 m or 5.00 m or 10.00 m.

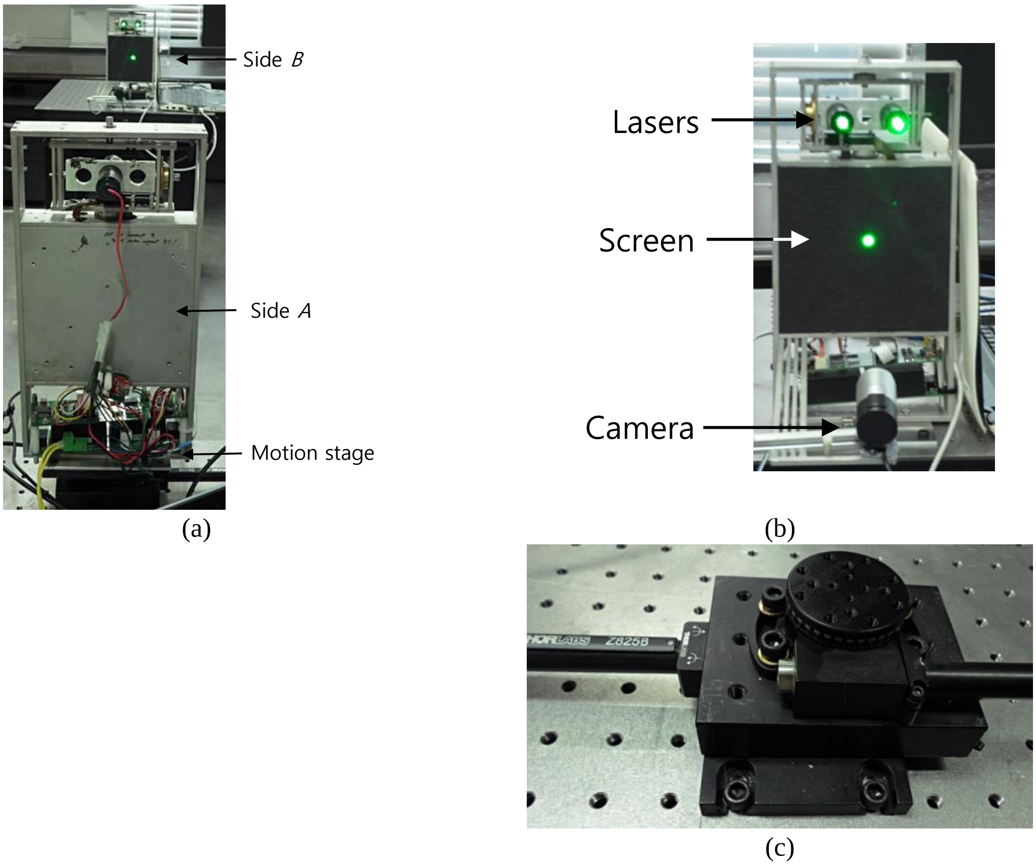


Fig. 7 Experimental setup with a motorized motion stage. (a) Overall experimental setup, (b) a front view of side *B*, and (c) a motorized motion stage

The estimated displacements for the case where the maximum translational displacement is 20 mm in *X*-axis and rotational displacement is 3^{o} about *Y*-axis with a distance of 2.00 m are shown in Figs. 8 and 9, respectively. As shown in the figures, the estimated displacements with the proposed initial laser pose calibration method provide better results than those obtained without the proposed method. The estimated displacements for the case where the maximum translational displacement is 20 mm in *X*-axis and rotational displacement is 1^{o} about *Y*-axis with a distance of 5.00 m are shown in Figs. 10 and 11, and with a distance of 10.00 m are shown in Figs. 12 and 13, respectively.

Similar to the experimental results with the distance of 2.00 m between two sides, the estimated displacements with the calibration method show better performance in all cases.

The results of experimental tests with different distances between two sides, 2.00 m, 5.00 m, and 10.00 m, are summarized in Table 1. The estimated displacement results are evaluated based on the root mean square error for translation and rotation ($RMSE_T$ and $RMSE_R$). As shown in the results, the translational and rotational errors are significantly reduced by using the proposed laser pose calibration method in comparison with the results from the original ViSP.

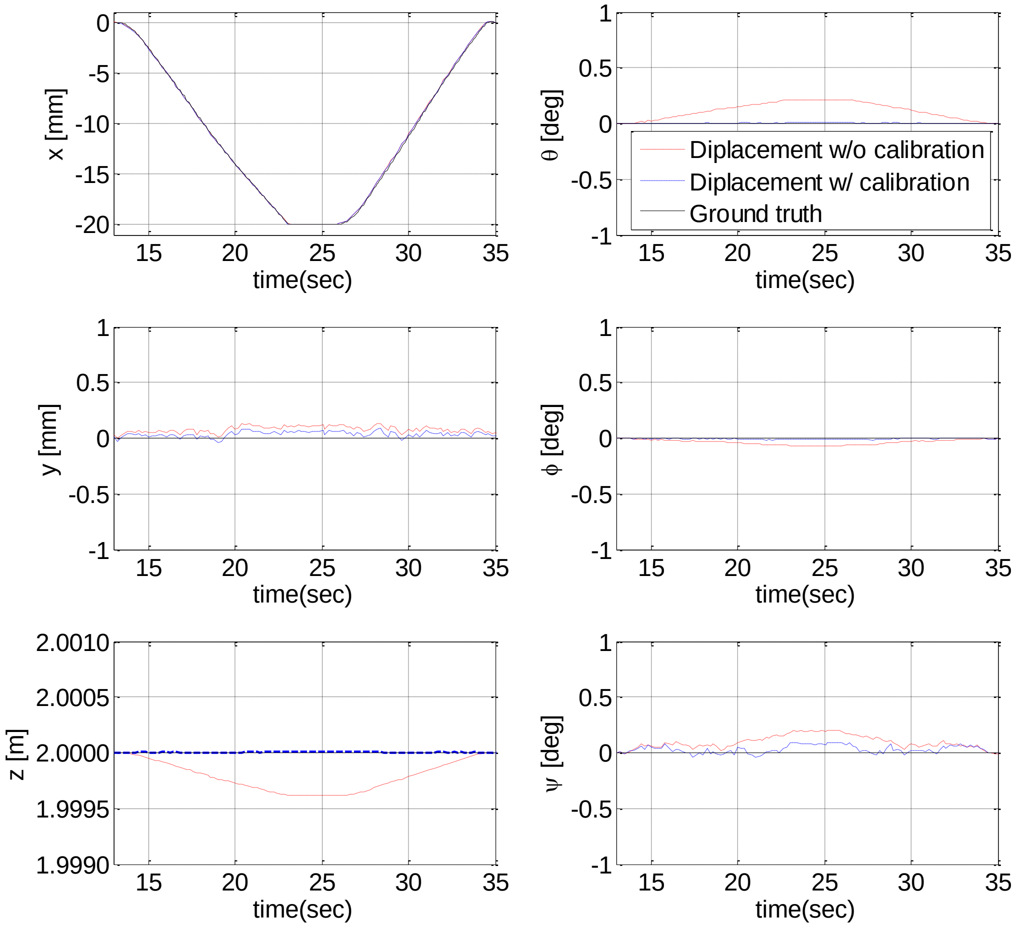


Fig. 8 Experimental result at a distance of 2.00 m. Estimated displacement for dynamic translation along *X*-axis. Solid line: result from the motion stage. Dash-dotted line: estimated displacement by using ViSP without the proposed calibration method. Dashed line: estimated displacement by using ViSP with the proposed calibration method

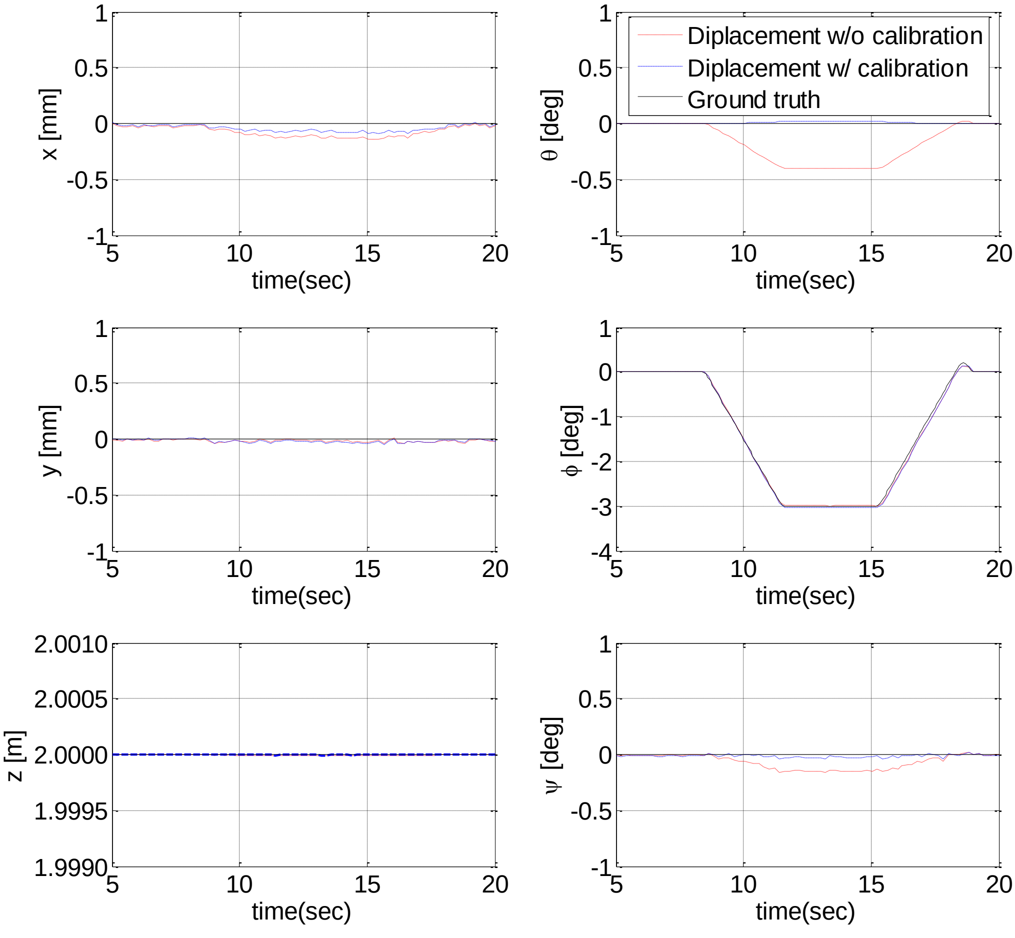


Fig. 9 Experimental result at a distance of 2.00 m. Estimated displacement for dynamic rotation about *Y*-axis. Solid line: result from the motion stage. Dash-dotted line: estimated displacement by using ViSP without the proposed calibration method. Dashed line: estimated displacement by using ViSP with the proposed calibration method

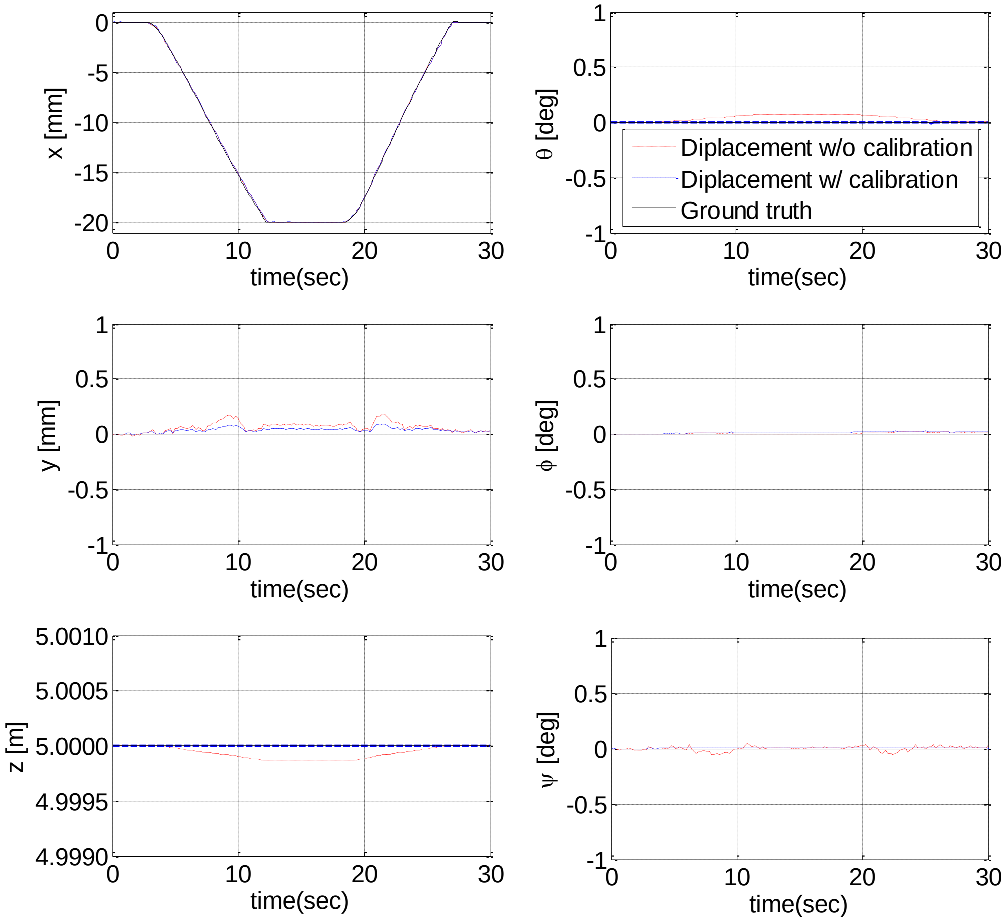


Fig. 10 Experimental result at a distance of 5.00 m. Estimated displacement for dynamic translation along X-axis. Solid line: result from the motion stage. Dash-dotted line: estimated displacement by using ViSP without the proposed calibration method. Dashed line: estimated displacement by using ViSP with the proposed calibration method

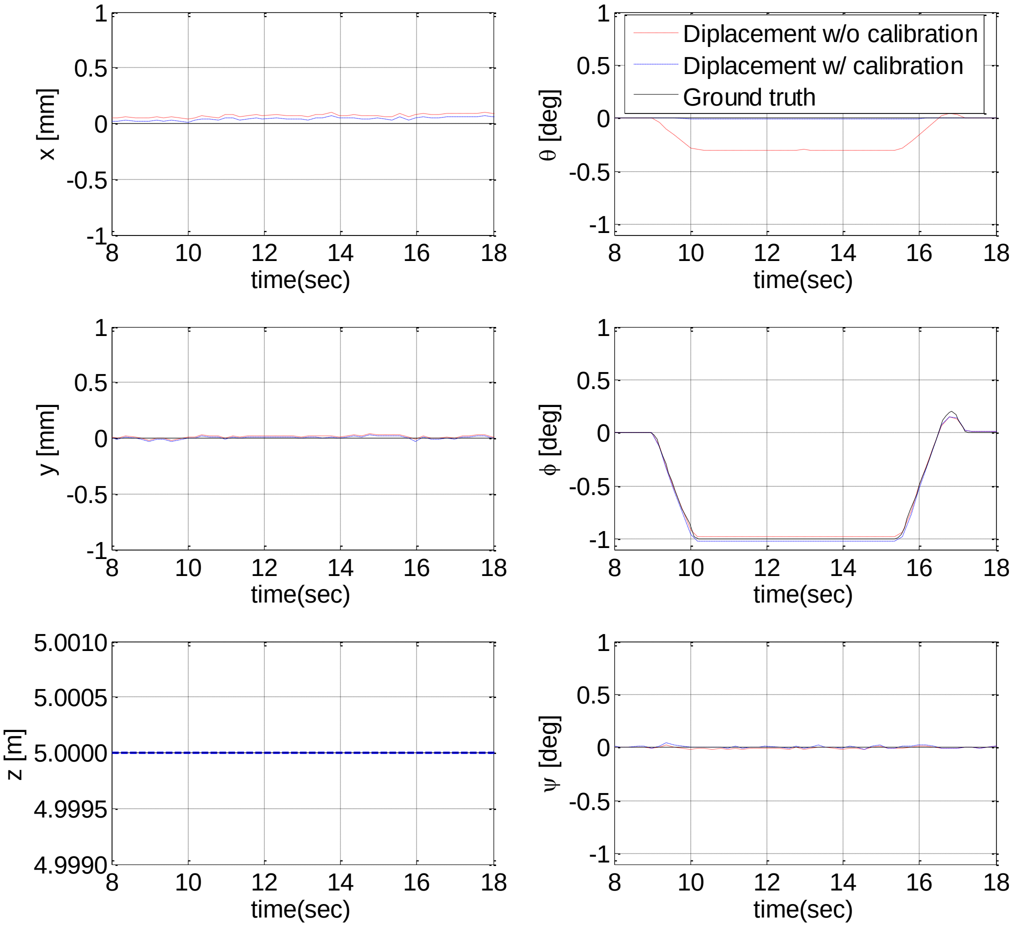


Fig. 11 Experimental result at a distance of 5.00 m. Estimated displacement for dynamic rotation about Y-axis. Solid line: result from the motion stage. Dash-dotted line: estimated displacement by using ViSP without the proposed calibration method. Dashed line: estimated displacement by using ViSP with the proposed calibration method

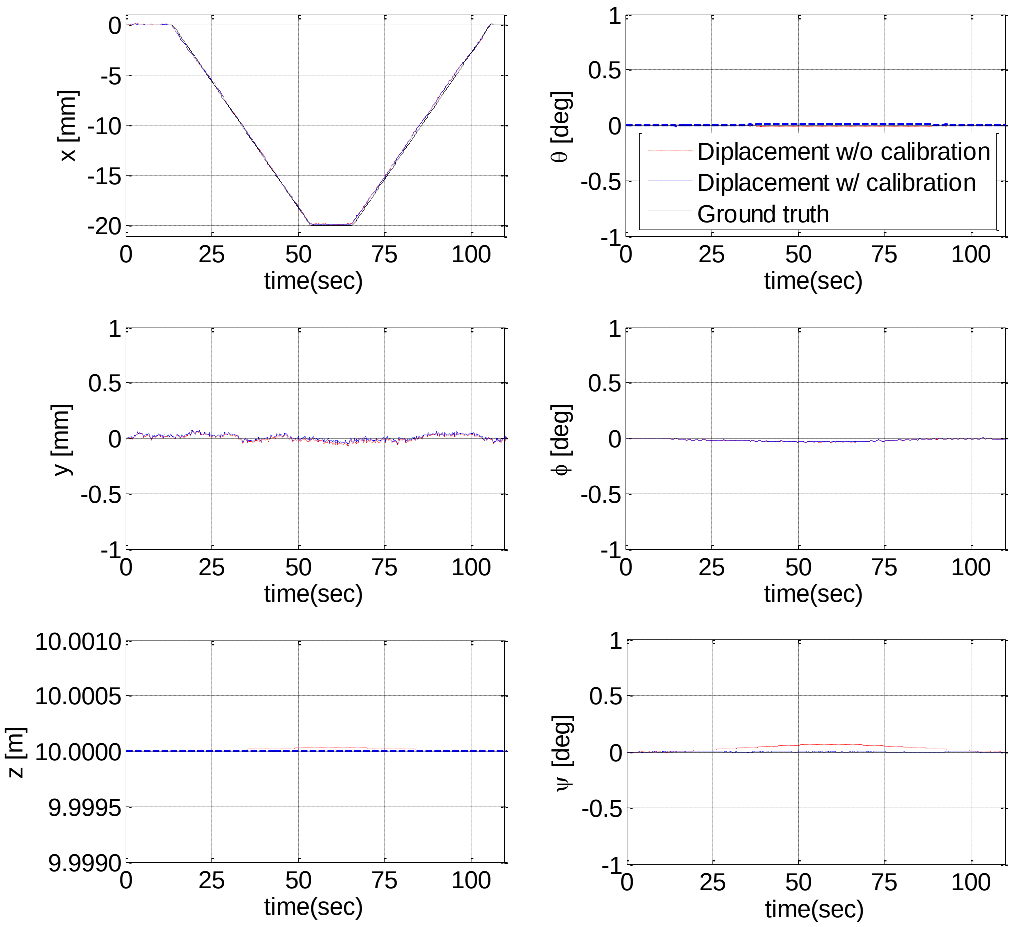


Fig. 12 Experimental result at a distance of 10.00 m. Estimated displacement for dynamic translation along X-axis. Solid line: result from the motion stage. Dash-dotted line: estimated displacement by using ViSP without the proposed calibration method. Dashed line: estimated displacement by using ViSP with the proposed calibration method

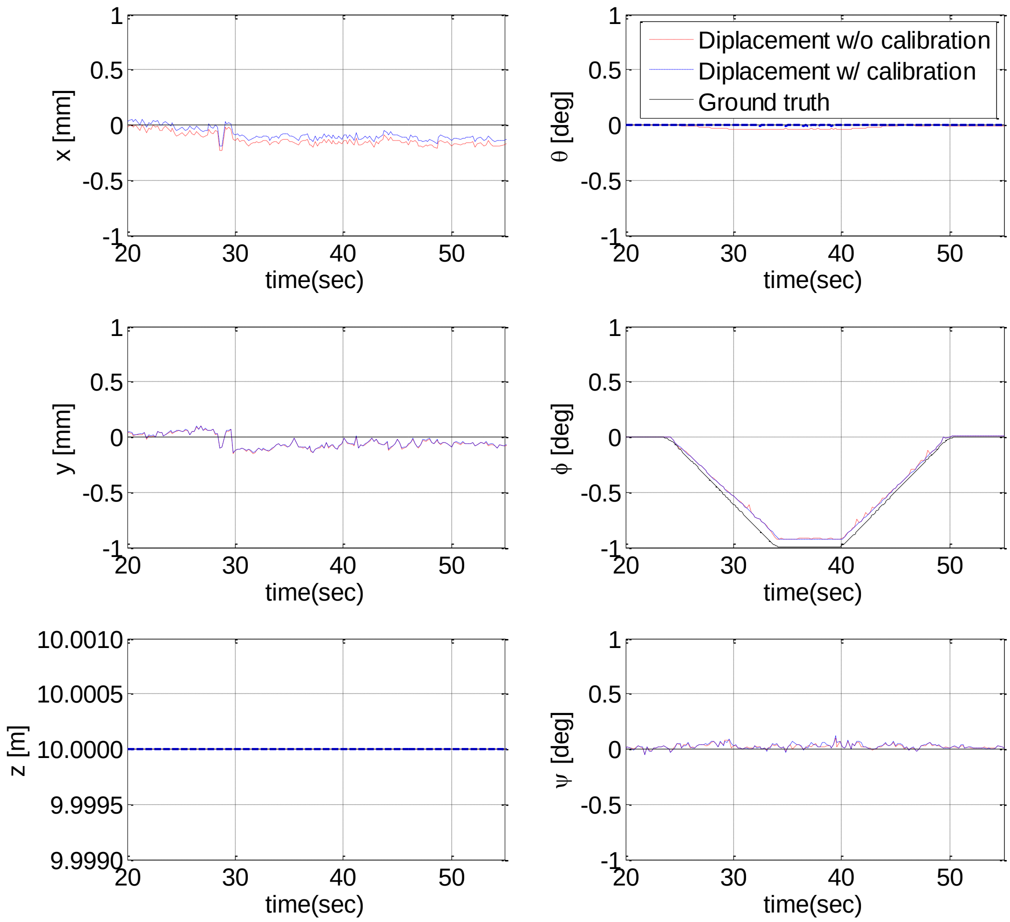


Fig. 13 Experimental result at a distance of 10.00 m. Estimated displacement for dynamic rotation about Y-axis. Solid line: result from the motion stage. Dash-dotted line: estimated displacement by using ViSP without the proposed calibration method. Dashed line: estimated displacement by using ViSP with the proposed calibration method

Table 1 Root mean square errors ($RMSE_T$ and $RMSE_R$) for experimental tests with and without the calibration method. The estimated displacement results with the laser pose calibration method show significantly reduced error

Distance (Z_{AB}) btw two sides	Case	Algorithm	$RMSE_T$ (mm)	$RMSE_R$ (deg)
Z_{AB} = 2.00 m	Translation	ViSP	0.140	0.076
		ViSP + Calibration	0.064 (54%↓)	0.015 (80%↓)
	Rotation	ViSP	0.032	0.586
		ViSP + Calibration	0.022 (31%↓)	0.530 (10%↓)
Z_{AB} = 5.00 m	Translation	ViSP	0.089	0.026
		ViSP + Calibration	0.053 (40%↓)	0.005 (80%↓)
	Rotation	ViSP	0.031	0.227
		ViSP + Calibration	0.020 (35%↓)	0.188 (17%↓)
Z_{AB} = 10.00 m	Translation	ViSP	0.125	0.022
		ViSP + Calibration	0.118 (6%↓)	0.009 (60%↓)
	Rotation	ViSP	0.062	0.324
		ViSP + Calibration	0.05 (19%↓)	0.32 (2%↓)

5. Conclusions

In this paper, an initial laser pose calibration method for a visually servoed paired structured light system (ViSP) is introduced. In application of this system, the accuracy of the displacement estimation depends on the initial pose of the laser pointers. There’s no need to set two screens to be perfectly parallel to each other. The misalignment is considered as the relative displacement of two screens, and it is estimated by the displacement estimation algorithm. The only thing needed for displacement estimation is to make laser beams stay on the screen all the time. To consider the inclinations of the laser pointers, an initial pose calibration method for laser pointers is proposed in this paper. The initial rotation angles of the laser pointers are estimated by using a specially designed jig device. First, each side of the ViSP is fixed on the jig and the inclination angles of laser pointers are estimated. It is then installed on the structure to be measured incorporating the calculated initial poses of the laser pointers. The performance of the method was verified through experimental tests. The results show that 6-DOF displacement can be estimated with higher accuracy by considering the initial pose of the laser pointers. In the future, the ViSP with the initial laser pose calibration method will be applied to various civil structures to assess structural conditions.

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References

Balageas, D., Fritzen, C.P. and Guemes, A. (eds) (2006), *Structural Health Monitoring*, New Jersey: John Wiley & Sons, Inc.

Jeon, H., Bang, Y. and Myung, H. (2011), "A paired visual servoing system for 6-DOF displacement measurement of structures", *Smart Mater. Struct.*, **20**(4), 045019.

Jeon, H., Shin, J.U. and Myung, H. (2012), "Incremental displacement estimation of structures using paired structured light", *Smart Struct. Syst.*, **9**(3), 273-286.

Jeon, H., Shin, J.U. and Myung, H. (2013), "The displacement estimation error back-propagation (DEEP) method for a multiple structural displacement monitoring system", *Meas. Sci. Tech.*, **24**(4), 045104.

Lee, D., Jeon, H. and Myung, H. (2014), "Pose-graph optimized displacement estimation for structural displacement monitoring", *Smart Mater. Struct*., **14**(5), 943-960.

Jeon, H., Myeong, W., Shin, J.U., Park, J.W., Jung H.J. and Myung, H. (2014), "Experimental validation of viSP (Visually Servoed Paired Structured Light System) for structural displacement monitoring", *IEEE/ASME Trans. Mech.*, **19**(5), 1603-1611.

Ji, Y.F. and Chang, C.C. (2008), "Nontarget stereo vision technique for spatiotemporal response measurement of line-like structures", *J. Eng. Mech. - ASCE*, **134**(6), 466-474.

Kim, S., Pakzad, S., Culler, D., Demmel, J., Fenves, G., Glaser, S. and Turon, M. (2007), "Health monitoring of civil infrastructures using wireless sensor networks", *Proceedings of the 6th Int. Symp. on Sensor Networks*, Cambridge.

Lee, J.J. and Shinozuka, M. (2006), "Real-time displacement measurement of a flexible bridge using digital image processing techniques", *Exp. Mech.*, **46**(1), 105-114.

Leith, J.G., Thompson, A. and Sloan, T.D. (1989), "A novel dynamic deflection measurement system for large structure", *Proceedings of the 4th Int. Conf. on Civil and Structural Engineering Computing*, London.

Marecos, J., Castanheira, M. and Trigo, J. (1969), "Field observation of Tagus river suspension bridge", *J. Struct. Div. - ASCE*, **95**(4), 555-583.

Meng, X., Roberts, G.W., Dodson, A.H., Cosser, E., Barnes, J. and Rizos, C. (2004), "Impact of GPS satellite and pseudolite geometry on structural displacement monitoring: analytical and empirical studies", *J. Geodesy*, **77**(12), 809-822.

Mita, A. and Yokoi I. (2001), "Fiber Bragg grating accelerometer for buildings and civil infrastructures", *Proceedings of the SPIE Smart Structures and Materials: Smart Systems for Bridges, Structures, and Highways*, CA.

Myung, H., Lee, S.M. and Lee, B.J. (2011), "Paired structured light for structural health monitoring robot system", *Struct. Health Monit.*, **10**(1), 49-64.

Nassif, H.H., Gindy, M. and Davis, J. (2005), "Comparison of laser Doppler vibrometer with contact sensors for monitoring bridge deflection and vibration", *NDT & E Int.*, **38**(3), 213-218.

Olaszek, P. (1999), "Investigation of the dynamic characteristic of bridge structures using a computer vision method", *Measurement*, **25**(3), 227-236.

Park, J.W., Lee, J.J., Jung, H.J. and Myung, H. (2010), "Vision-based displacement measurement method for high-rise building structures using partitioning approach", *NDT & E Int.*, **43**(7), 642-647.

Psimoulis, P.A. and Stiros, S.C. (2008), "Experimental assessment of the accuracy of GPS and RTS for Determination of the parameters of oscillation of major structures", *Comput. - Aided Civil Infrastruct. Eng.*, **23**(5), 389-403.
Thorlabs Inc. (2011), *Thorlabs' V21 photonics catalog*, http://www.thorlabs.com
Wahbeh, A.M., Caffrey, J.P. and Masri, S.F. (2003), "A vision-based approach for the direct measurement of displacements in vibrating systems", *Smart Mater. Struct.*, **12**(5), 785-794.

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