# MEASUREMENT OF STRUCTURAL DISPLACEMENT USING VISUALLY SERVODED PAIRED STRUCTURED LIGHT SYSTEM

Haemin Jeon[1], Yousuk Bang[2], and Hyun Myung[2]*

[1] *Department of Civil and Environmental Engineering, KAIST, Daejeon, Korea*
[2] *Department of Civil and Environmental Engineering /Robotics Program, KAIST, Daejeon, Korea*
** Corresponding author (hmyung@kaist.ac.kr)*

**ABSTRACT**: Over the past several decades, there has been rapid growth in research on the displacement measurement system for large structures. However, widely used sensors such as accelerometers, strain gauges, PZT, and GPS have disadvantages that they indirectly measure the displacement, are difficult to install, or costly to maintain. To solve the aforementioned problem, a paired structured light (SL) system was introduced in the previous study. Each module is composed of two screens facing with each other each with one or two lasers and a camera. Though the system can successfully estimate 6-DOF displacement, the measurable displacement range is limited due to the limited screen size. In this paper, therefore, a visually servoed paired SL system is proposed. The newly proposed system uses a visually servoed 2-DOF manipulator in order to make the projected laser beams are always on the screen. In other words, the laser pointer is controlled by a manipulator before it gets off. Various experiments were performed to validate the proposed system. The results show that the proposed system estimates 6-DOF displacement with high accuracy and with largely expanded measurement range. By cascading multiple modules, the proposed system can be applied to the massive structures such as long-span bridges or high-rise buildings.

***Keywords***: *SHM, Displacement, Laser, Vision, Manipulator, Visual Servoing*

## 1. INTRODUCTION

As structural health monitoring (SHM) has gained great attention for several decades, various monitoring systems or sensors have been developed. Especially, structural displacement monitoring is considered one of important categories of SHM. To measure the structural displacement, conventional sensors such as accelerometers, GPS, and LVDTs have been widely used. However, aforementioned sensors have problems that a) it indirectly measures the displacement, b) the cost is relatively high, or c) it is hard to install or maintain. To solve the problems, vision-based displacement monitoring system has been researched. Although the vision-based displacement monitoring system directly estimates the displacement and the cost is relatively low, the displacement can be estimated only if the line of sight (LOS) is preserved [1-2]. In detail, most of the vision-based displacement monitoring systems install the targets on the structure and a camera on a fixed point captures the movement of the targets from a far. Because the distance from the camera and the target is long, it is highly affected by the external changes such as weather or illumination. In this paper, therefore, a visually servoed paired structured light (SL) system is designed to directly estimate the displacement, be relatively cheap, and be strong to the external environmental changes. The remainder of this paper is structured as follows. In Section 2, the visually servoed paired SL system and its kinematics are described. In Section 3, the experiments were performed to validate the performance of the proposed system. In section 4, conclusions are discussed.

## 2. VISUALLY SERVOED PAIRED STRUCTURED LIGHT SYSTEM

In the previous study [3], Myung *et al.* proposed the paired SL system as shown in Fig. 1. As the figure shows, each side is composed of one or two lasers, a camera, and a

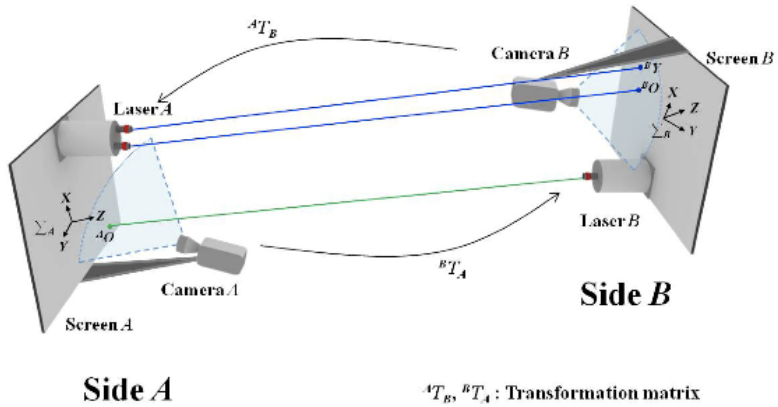


Fig. 1 Paired Structured Light System

screen. The laser on each side projects its parallel beam to the screen on the opposite side and the camera near from the screen captures the image. By calculating the positions of the three projected laser beams, both the translational and the rotational displacement each in 3-DOF between two sides can be estimated since we observe it in 2-DOF screen. In other words, totally 6 unknowns can be calculated from the positions of the three projected laser beams, since each position has $x$ and $y$ information.

However, the measurable range of the proposed system is limited due to the limited screen size. In details, the proposed system cannot estimate the displacement if one of the projected laser beams is not on the screen. Therefore, 2-DOF manipulator is introduced as shown in Fig. 2. As the figure shows, the manipulator which holds the laser(s) controls the pose of the lasers to target the screen all the times.

The overall process of the newly proposed system is shown in Fig. 3. As shown in the figure, the camera on each side captures the image of the screen and then the lens distortion is calculated. Afterward, the screen boundary is detected and the homography is calculated. Then, the positions of the projected laser beams are calculated with the known screen size. The rotation angles of the 2-DOF manipulators are calculated to minimize the difference of the desired laser beam positions and the current laser beam positions. Finally, the 6-DOF displacement is estimated from the rotation angles of the manipulators and positions of the projected laser beams. After calculating the 6-DOF displacement, the displacement is calibrated with the initial offset. In detail, the calibration matrix is formed from the first scene and inverse of the calibration matrix is multiplied to the matrix of the estimated displacement for calculating relative displacement from the initial pose.

The kinematics defines the geometric relation between the observed data $m = [{}^AO, {}^BO, {}^BY]^T$, encoder information from the 2-DOF manipulators, and estimated displacement $p = [x, y, z, \theta, \varphi, \psi]^T$. Here ${}^AO$ is the projected laser beam on screen $A$, ${}^BO$ and ${}^BY$ are the projected laser beams on screen $B$. To derive the kinematics, the transformation matrices ${}^AT_B$ and ${}^BT_A$ are used. The ${}^AT_B$ is a transformation matrix that transforms the coordinate $B$ to the coordinate $A$. The ${}^AT_B$ can be obtained as the product of translation and rotation matrices along $X$, $Y$, and $Z$ axes as follows:

$$ {}^AT_B = T(x,y,z)R(x,\theta)R(y,\phi)R(z,\psi). \qquad (1) $$

Using ${}^AT_B$ and ${}^BT_A$, the projected laser beam ${}^AO$ can be obtained as follow:

$$ {}^AO = {}^AT_B \cdot {}^BT_{B'}[0\ L\ Z_{AB}\ 1]^T \qquad (2) $$

where, ${}^BT_{B'}$ is the transformation matrix consists of encoder information of the manipulator on side $B$, ${}^BT_{B'} = R(x,\theta_{enc})R(z,\psi_{enc})$, where $\theta_{\mathrm{enc}}$ and $\psi_{\mathrm{enc}}$ are rotated angles about $X$ and $Z$ axis, respectively, $L$ is the offset of a laser point from the center of a screen in $Y$ direction, and $Z_{BA}$ is the distance from screen $B$ to screen $A$. Similar to ${}^AO$, ${}^BO$ and ${}^BY$ can be obtained as follows:

$$ {}^BO = {}^BT_A \cdot {}^AT_{A'}[0\ L\ Z_{AB}\ 1]^T \qquad (3) $$

$$ {}^BY = {}^BT_A \cdot {}^AT_{A'}[0 - L\ Z_{AB}\ 1]^T. \qquad (4) $$

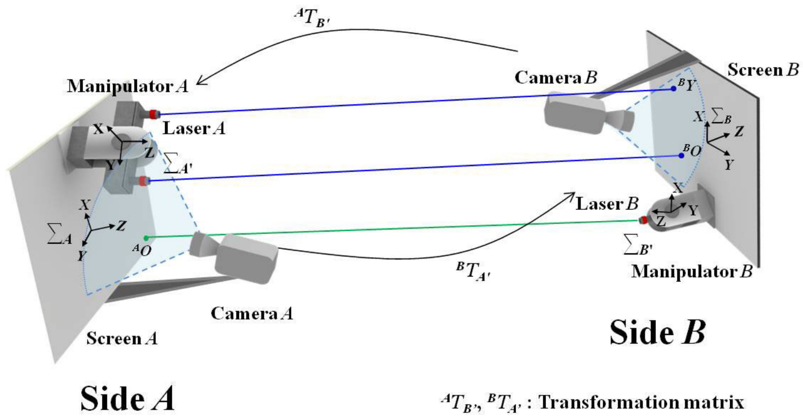


Fig. 2 Visually Servoed Paired Structured Light System

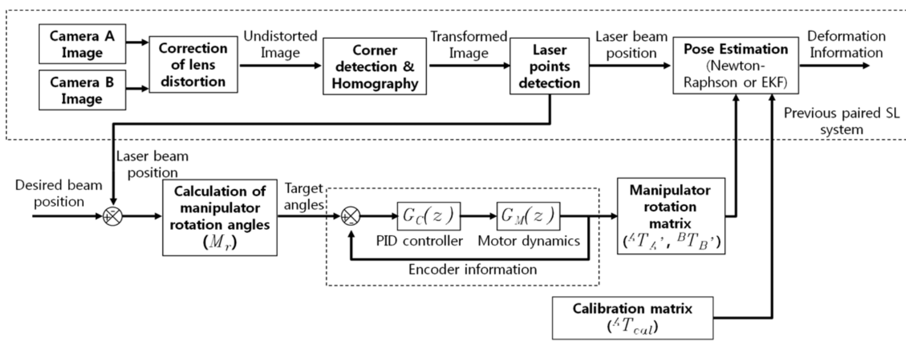


Fig. 3 The estimation process of the visually servoed paired SL system

By putting in the three constraints, the kinematics $M$ containing 6-DOF displacement can be derived.

$$M = [{}^{A}O_x \quad {}^{A}O_y \quad {}^{B}O_x \quad {}^{B}O_y \quad {}^{B}Y_x \quad {}^{B}Y_y]^T \tag{5}$$

By using the Newton-Raphson method, the estimation of $p$ can be obtained as follows:

$$\hat{p}(k+1) = \hat{p}(k) + J_p^{+}(m(k) - \hat{m}(k)). \tag{6}$$

where, $J_p = \partial M / \partial p$ is the Jacobian of the kinematic equation, $J_p^{+}$ is the pseudo-inverse of the Jacobian, and $\hat{m}$ is the estimated observation by $M$.

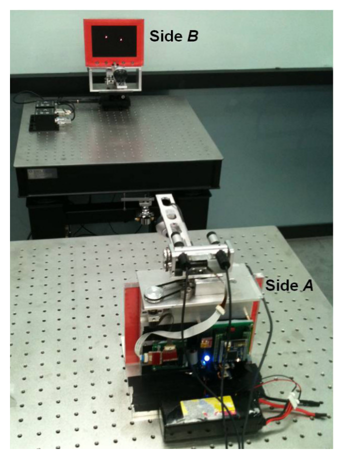


Fig. 5 Experimental setup. On side of the module is laid on the table another on the motorized motion stage which controls the translational and rotational movement.

## 3. EXPERIMENTS

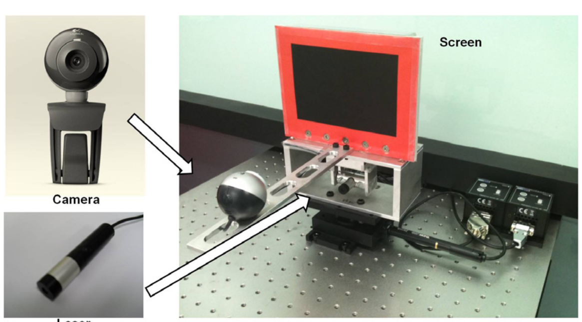


Fig. 4 One side of the proposed visually servoed paired SL system.

To validate the proposed system, various experiments were conducted. One side of the system is composed of one or two lasers, a camera, and a screen (see Fig. 4). Two sides were set to be facing each other as shown in Fig. 5. In the tests, one of the two sides was laid on a ground another on a motion stage which makes the artificial movement between the two sides. The motion stage which is used in the tests is combined of motorized linear translation stage in $X$ direction and motorized linear rotation stage in $Y$ direction. The results of the estimated translational and rotational displacement are shown in the Figs. 6 and 7, respectively. As shown in the figures the proposed system accurately estimates both the translational and rotational displacements.

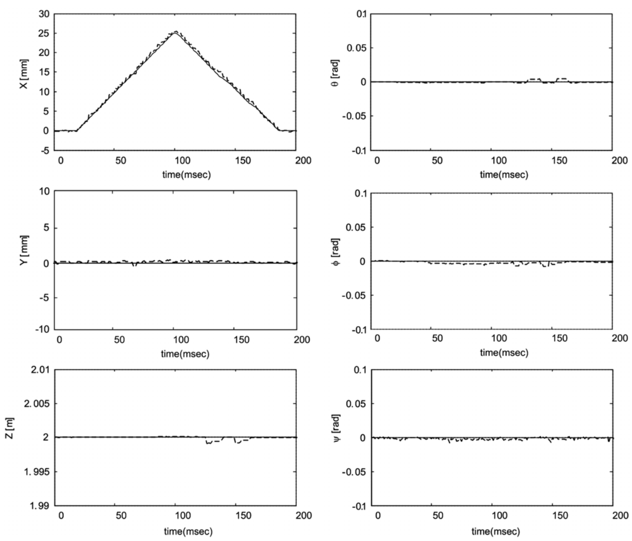


Fig. 6 Experimental result of the dynamic translational displacement about the *Y* axis. The solid line represents the ground truth. The dashed line represents the estimated displacement by the proposed visually servoed paired SL system.

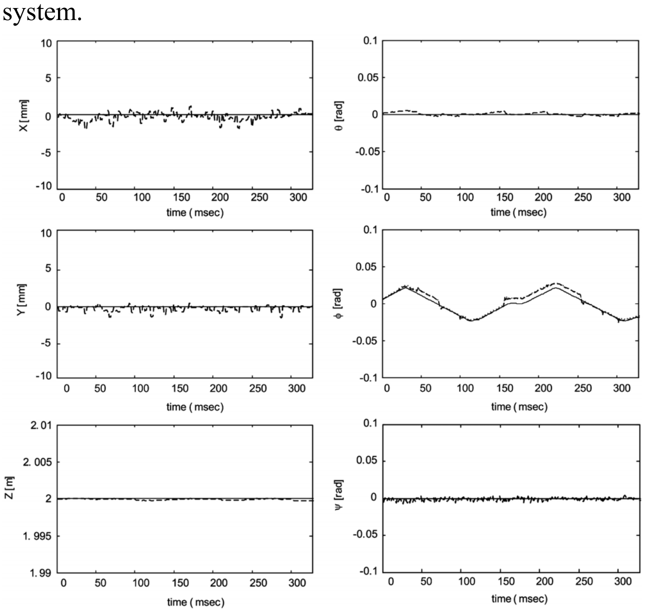


Fig. 7 Experimental result of the dynamic rotational displacement about the *Y* axis. The solid line represents the ground truth. The dashed line represents the estimated displacement by the proposed visually servoed paired SL system.

## 4. CONCLUSIONS

This paper proposes the visually servoed paired structured light system to measure 6-DOF displacement regardless of the screen size or the magnitude of the displacement. To expand the measurement range, a 2-DOF manipulator is introduced and it makes the projected laser beams remain on the screens. The prototype was built and various experimental tests were performed to validate the performance of the system. The results showed that the proposed system can estimate 6-DOF displacement with high accuracy with largely expanded measurement range. By cascading multiple modules, the proposed system can be applied to the massive structures such as bridges or high-rise buildings.

In the future, multiple modules will be built and applicability of the proposed system to real large structures such as long span bridges or high rise buildings will be tested.

## ACKNOWLEDGEMENT

This study was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (No. 2009-0075397).

## REFERENCES

[1] Wahbeh, A. M., Caffrey, J. P., and Masri, S. F. “A Vision-based Approach for the Direct Measurement of Displacements in Vibrating System”, *Smart Materials and Structures*, Vol. 12(5), pp. 785-794, 2003.

[2] Lee, J. J. and Shinozuka, M. “Real-Time Displacement Measurement of a Flexible Bridges Using Digital Image Processing Techniques”, *Experimental Mechanics*, Vol. 46(1), pp. 105-114, 2006.

[3] Myung, H., Lee, S. M., Lee, B. J., “Paired Structure Light for Structural Health Monitoring Robot system”, *Struct. Health Monit.*, Vol. 10(1), pp. 49-64, 2011.