The 2013 World Congress on
Advances in Structural Engineering and Mechanics (ASEM13)
Jeju, Korea, September 8-12, 2013

DEEP (Displacement Estimation Error Back-Propagation) Method for Cascaded ViSPs (Visually Servoed Paired Structured Light Systems)

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ABSTRACT

In this study, a displacement estimation error back-propagation (DEEP) method for multiple visually servoed paired structured light systems (ViSPs) is proposed. The ViSP is composed of two sides facing each other, each with one or two lasers, a 2-DOF manipulator, a camera, and a screen. By calculating positions of the projected laser beams on the screens and rotation angles of the manipulators, 6-DOF relative displacement between two sides can be estimated. To apply the system to massive civil structures such as long-span bridges or high-rise buildings, entire structure should be partitioned and multiple ViSPs are placed in each partition in a cascaded manner. Entire shape of the structure is monitored by multiplying estimated displacements from ViSP modules. In the multiplication, however, the error residing in estimated displacement is propagated through the partitions. To solve the problem, DEEP method which uses the Newton-Raphson formulation inspired by the error back-propagation algorithm in neural network is proposed. In this method, the estimated displacements are updated in reverse order by minimizing the propagation error. The error at the last module can be obtained by calculating the difference of the 6-DOF relative displacement estimated from ViSP and the positions measured from precise GPS or topographical surveying. The performance of the proposed DEEP method has been verified from various simulations, and the results show that it reduces the propagation error significantly.

1. INTRODUCTION

As structural displacement monitoring is considered one of important categories of structural health monitoring (SHM), various sensors or systems have been developed (Balageas 2006). Especially, vision sensor-based direct displacement measurement

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system have been widely researched due to tremendous development of vision sensor technology. Most of the vision-based displacement measurement system installs targets on a structure and a camera with a zooming capability captures the targets from a far (Lee 2006, Park 2010). Since the distance between the targets and the camera is long, it is sensitive to environmental changes such as illumination or weather condition. Moreover, most of vision-based displacement measurement systems measures 2 or 3-DOF displacement.

To resolve these problems, a visually servoed paired structured light system (ViSP) has been developed (Jeon 2011). The ViSP, which is a later version of a paired structured light system proposed by Myung *et al.* (Myung 2011, Myung 2012), is composed of two sides facing each other, each with one or two lasers, a camera, and a screen. The lasers project their parallel beams to the screen on the opposite side and the camera near the screen captures the image of the screen. To make laser beams appear on the screen all the time, a 2-DOF manipulator holds the laser(s) and controls the pose of laser(s). The relative 6-DOF displacement can be estimated by calculating three positions of the projected laser beams and rotation angles of the manipulators. In comparison with other vision-based displacement monitoring systems, ViSP is robust to the environmental changes due to its unique configuration, the distance between the camera and the screen is short such as 20 cm.

To apply ViSP to real civil structures, multiple modules should be placed in partitions in a cascaded manner and monitor the dynamic movement of the entire structure. In other words, the entire shape of structure can be estimated by multiplying the estimated displacement from multiple modules. However, the multi-module system has a major drawback that the error residing in the estimated displacement is propagated through the multiplication. To solve this problem, a displacement estimation error back-propagation (DEEP) method which uses the Newton-Raphson formulation inspired by the error back-propagation algorithm in multi-layer neural networks is proposed in this paper (Jeon 2013). The remainder of this paper is organized as follows. In Section 2, design and kinematics of ViSP is briefly described. The details of DEEP method is introduced in Section 3. In Section 4, simulations are performed to verify the performance of the proposed method. Conclusions are discussed in Section 5.

2. VISUALLY SERVOED PAIRED STRUCTURED LIGTH SYSTEM (ViSP)

Multiple modules of visually servoed paired structured light system (ViSP) can be applied to civil structures by installing multi-modules in a cascaded manner as shown in Fig. 1. Inside the dashed line box in the figure, details of ViSP are illustrated. As shown in the figure, ViSP is composed of two sides facing each other, each with one or two lasers, a camera, and a screen. The lasers project their parallel beams to the screen on the opposite side and the camera near the screen captures the image of the screen. As the distance between the camera and the screen is short such as less than 20 cm, the system is robust to the environmental changes. To control projected laser beams appear on the screen all the time, a 2-DOF manipulator was added. In other words, the manipulator holds the laser(s) and controls the pose of laser(s). By calculating positions of the projected laser beams on the screens and rotation angles of the manipulators, the relative 6-DOF displacement can be estimated.

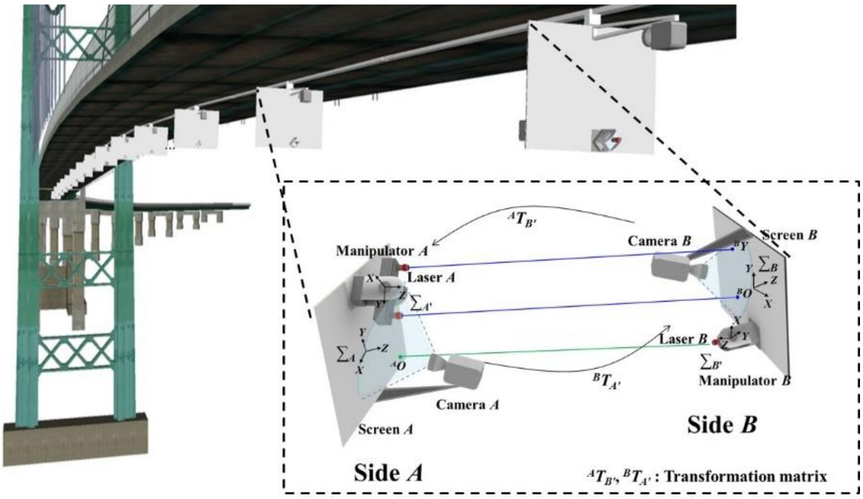


Fig. 1 Application of multiple visually servoed paired structured light system to civil structures. Details of ViSP can be found inside a dashed line box.

The kinematics of ViSP defines a geometric relationship between the observed data, positions of the projected laser beams, $m = [^AO, {}^BO, {}^BY]^T$ and estimated displacement $p = [x, y, z, \theta, \varphi, \psi]^T$ (Jeon 2011). Here ^AO is the projected beam on screen A and ^BO and ^BY are the projected beams on screen B. x, y, and z are the translational displacement along X, Y, and Z axes, respectively, and θ, φ, and ψ are the rotational displacement about X, Y, and Z axes, respectively. By using transformation matrices, ^AT_B and $^BT_{B'}$, and a position of the installed laser on side B, the ^AO can be obtained as follows:

$$^AO = {}^AT_B\,{}^BT_{B'}\begin{bmatrix}0 & 0 & Z_{AB} & 1\end{bmatrix}^T \quad (1)$$

where ^AT_B is the transformation matrix that transforms the coordinate from screen B to screen A, Z_{AB} is the distance from screen A to screen B, $^BT_{B'}$ is the rotation matrix consists of motor encoder information of the manipulator on side B, $^BT_{B'}=R_x(-\theta_{B\text{enc}})\cdot R_z(-\psi_{B\text{enc}})$ where $\theta_{B\text{enc}}$ and $\psi_{B\text{enc}}$ are rotated angles of the manipulator B about X and Z axis, respectively. In the same way, ^BO, and ^BY can be easily obtained by using ^BT_A and $^AT_{A'}$ as follows:

$$^BO = {}^BT_A\,{}^AT_{A'}\begin{bmatrix}-L & 0 & Z_{AB} & 1\end{bmatrix}^T, \quad (2)$$

$$^BY = {}^BT_A\,{}^AT_{A'}\begin{bmatrix}L & 0 & Z_{AB} & 1\end{bmatrix}^T \quad (3)$$

where $^AT_{A'}$ is the rotation matrix consists of encoder information of manipulator A and L is the offset of an installed laser position from a center of a screen in X direction. As $z = 0$ on screens, z component of ^AO, ^BO, and ^BY vectors should be zero. By applying these constraints, the kinematic equation can be derived as follows:

$$M = \begin{bmatrix}^AO_x & ^AO_y & ^BO_x & ^BO_y & ^BY_x & ^BY_y\end{bmatrix}^T \quad (4)$$

where ^AO_x and ^AO_y denote the x and y component of ^AO, respectively.

To estimate the displacement from the kinematic equation *M*, a non-iterative method named incremental displacement estimation (IDE) method was proposed (Jeon 2012). In this method, the displacement is updated from the previously estimated displacement by calculating a difference of the previous and current observed data.

3. DISPLACEMENT ESTIMATION ERROR BACK-PROPAGATION (DEEP)

To apply ViSP to massive civil structures such as long span bridges or high rise buildings, multiple modules should be installed in a cascaded manner. In other words, entire shape of the structure can be monitored by multiplying estimated displacement from each module. In the multiplication, however, the error residing in the estimated displacement is propagated through the multiplication. To solve this problem, a displacement estimation error back-propagation (DEEP) method which uses the Newton-Raphson formulation inspired by the error back-propagation algorithm in multi-layer neural networks is proposed (Jeon 2013). The propagation error is compensated from the last to the first module in reverse order.

The propagation error can be defined as the difference between the absolute position at the last module calculated from other sensors such as precise GPS or topographical surveying ($\bar{p}_n$) and the ViSP (P_n) as follows:

$$E = \bar{P}_n - P_n \tag{5}$$

where P_n can be calculated by multiplication of transformation matrices of estimated displacement D_1 through D_n where n denotes the number of modules. The relative displacement between adjoining i-th module, P_i , can be estimated as follows:

$$P_i = f(g(D_1) \cdot g(D_1) \cdot \cdots \cdot g(D_{i-1}) \cdot g(D_i)) \tag{6}$$

where f is a function that transforms a homogeneous transformation matrix to a vector and g is a function that transforms a vector to a homogeneous matrix.

To update the estimated displacement, the Newton-Raphson formulation with a learning rate, α, is formulated as follows:

$$D_i(k+1) = D_i(k) - \alpha J^{+}{}_{D_i} E \tag{7}$$

where $J_{Di} = \partial E / \partial D_i$ is the Jacobian of the error and $J^{+}{}_{Di}$ is the pseudo-inverse of J_{Di}. The Jacobian matrix can be represented using the chain rule of partial differentiation, yielding Eqs. (8) - (10). As can be seen in Eq. (8), the relative displacement at the n-th module is updated by the Newton-Raphson formulation. By using the chain rule, Eq. (8) can be formulated as Eq. (9). As $\partial E / \partial P_n$ is −1, Eq. (9) can be simplified to Eq. (10).

$$D_n(k+1) = D_n(k) - \alpha J^{+}{}_{D_n} (\bar{P}_n - P_n) \tag{8}$$

$$= D_n(k) - \alpha \left(\frac{\partial E}{\partial P_n} \frac{\partial P_n}{\partial D_n} \right)^{+} (\bar{P}_n - P_n) \tag{9}$$

$$= D_n(k) + \alpha \left(\frac{\partial P_n}{\partial D_n} \right)^+ (\bar{P}_n - P_n) \tag{10}$$

The estimated displacements are updated from the last to the first module in reverse order. Using the updated displacement calculated in the previous step, the error and Jacobian are calculated and then the displacement is updated by minimizing the propagation error. In general, the relative displacement at each module is updated as follows:

$$D_i(k+1) = D_i(k) - \alpha J^+{}_{D_i} (\bar{P}_n - P_n) \tag{11}$$

$$= D_i(k) + \alpha \left(\frac{\partial P_n}{\partial P_{n-1}} \frac{\partial P_{n-1}}{\partial P_{n-2}} \cdots \frac{\partial P_{i+1}}{\partial P_i} \frac{\partial P_i}{\partial D_i} \right)^+ (\bar{P}_n - P_n) \tag{12}$$

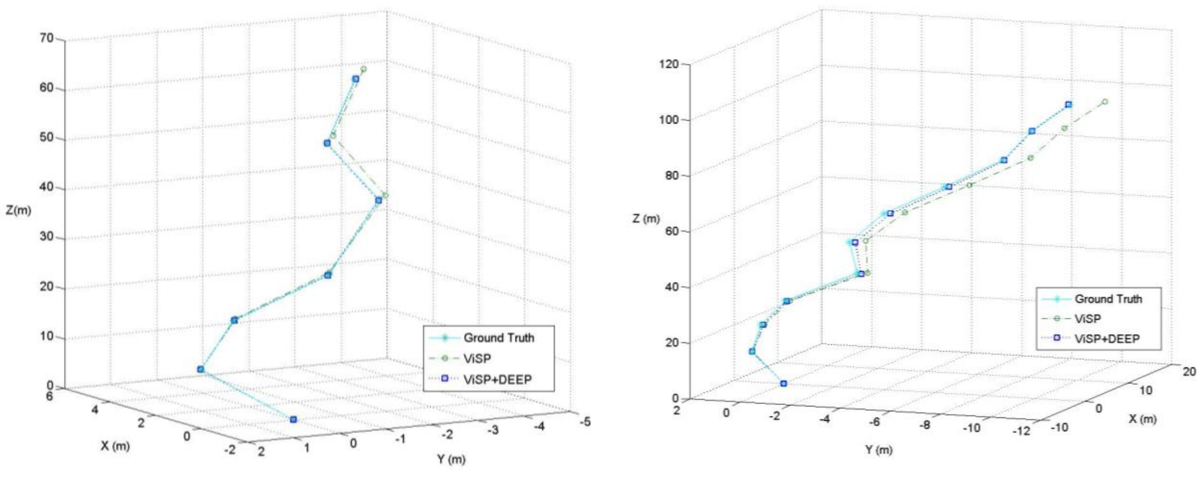
where $i = n, \ldots, 1$.

Since the number of displacement variables is more than the number of constraints $\bar{p}_n$, there can be numerous solutions that minimize the propagation error. Therefore, we assume that the updated range of the estimated displacement, ΔD_i, is limited by two constraint values. The constraint values are determined by considering physical limitations of the motors or error covariance of the ViSP. This idea was partially from the control strategy used for redundant manipulators.

Instead of using the Newton-Raphson formulation, the gradient descent formulation can be used. Details of DEEP method with the gradient descent formulation can be found in Jeon (2013).

4. SIMULATIONS

To verify the performance of the proposed DEEP method, simulation with six, and ten modules have been performed as follows. The predefined absolute positions, $\bar{p}_n, \cdots, \bar{p}_n$, are set at first. Then, the 6-DOF displacement between two adjoining modules is estimated by using ViSP with IDE method. Afterwards, the propagation error is calculated by multiplying the estimated displacements. The DEEP method is applied



(a) (b)

Fig. 2 Simulation results with six and ten modules. Solid line with asterisk: ground truth. Dot dashed line with circle: estimated displacement from ViSP. Dotted line with rectangle: updated displacement by using DEEP method and the estimated displacements are updated in reverse order. The updated displacement is set to boundaries if it exceeds the upper and lower limits. The calculation of the propagation error and the displacement update step are repeated until L_2 norm of the propagation error at the last module becomes smaller than the error threshold. In this paper, the learning rate, limits, and error threshold are set to 0.1, [±0.01m, ±0.01m, ±0.15m, ±1°, ±1°, ±1°], and 1.0×10^{-4}, respectively. The limits are determined based on the error covariance of ViSP from previous experimental tests. The distance between each module is set to be 10 m.

The simulation results with six and ten modules are shown in Fig. 2(a) and 2(b), respectively. In the figure, the solid line with asterisk indicates the ground truth, the dot-dashed line with circle is the estimated displacement using ViSP, and the dotted line with rectangle is the updated displacement by using DEEP method. As shown in the figure, the proposed DEEP method reduces the propagation error.

5. CONCLUSIONS

To apply ViSP to massive civil structure, multiple modules should be installed in a cascaded manner and entire shape of structure can be estimated by multiplying estimated displacement from ViSP. In the multiplication, however, displacement estimation error can be propagated. In this paper, therefore, a displacement estimation error back-propagation (DEEP) method, which uses the Newton-Raphson formulation inspired by the error back-propagation algorithm of the multi-layer neural networks, for multiple ViSPs is proposed. In this method, a propagation error at the last module is calculated at first, and then the estimated displacement from ViSP at each partition is updated in reverse order by using the proposed DEEP that minimizes the propagation error. To verify the performance of the proposed method, various simulations have been performed. The results show that the propagation error is significantly reduced after applying DEEP method.

ACKNOWELDGEMENT

This study was supported by the National Research Foundation of Korea (NRF) and funded by the Korea government (Grant No. 2009-0075397). Mr. Myeong is supported by Korea Minister of Ministry of Land, Transport and Maritime Affairs (MLTM) as „U-City Master and Doctor Course Grant Program'.

REFERENCES

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

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.

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.

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.

Myung, H., Jung, J.D. and Jeon, H. (2012), "Robotic SHM and Model-based Positioning System for Monitoring and Construction Automation," *Adv. Struct. Eng.*, **15**(6), 943-954.

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), 45019.

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. Technol.*, **24**(4), 045104.