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Monocular Vision-based Displacement Measurement System Robust to Angle and Distance Using Homography

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ABSTRACT

Displacement of a civil structure contains important information about structural behavior that helps confirm safety and serviceability. Displacement measurement by conventional devices such as LVDT is still challenging due to issues in the cost-effectiveness and accessibility to measurement locations. This paper presents a monocular vision-based displacement measurement system (VDMS) that is cost-effective and convenient installation. The proposed system is composed of a low-cost aftermarket camera, a specially-designed marker, and a laptop computer. The motion of the marker attached to the structure is captured by the video camera, that is subsequently converted to the time history of a dynamic displacement response using planar homography. Planar homography is a transformation matrix mapping any two planes in the three dimensional space, and it can map an image plane into the real marker's plane which may be at an angle with respect to the camera axis. The system was validated by a lab-scale test using a shaking table. Experimental results show proposed system has a good agreement with LDV regardless of camera positions.

KEYWORDS: *Displacement measurement, vision, camera, marker, planar homography*

1. INTRODUCTION

Structural safety is an important issue to enhance sustainability of civil environment. As displacement responses indicate structural behavior due to exposed dynamic loading, it has been widely used as an index for confirming serviceability and safety of the structures. For that reason, displacement should be measured satisfying several requirements, such as acceptable accuracy to be used as a safety indicator, inexpensive system cost, easy installation, and short measurement time. To satisfy these requirements, various type of displacement measurement system and devices have been developed.

Traditional displacement measurement is conducted by several devices such as linear variable differential transformer (LVDT), laser Doppler vibrometer (LDV), and global positioning system (GPS). The LVDT measures displacement by linearity between cylindrical magnetic core's movement and induced electrical signal. Though LVDT provides acceptable accuracy in inexpensive cost, magnetic core should be contact with structural surface. Hence, additional structures such as jigs and scaffolds are required to be constructed around the measurement location to fix the transducer. These additional structures can generate significant level of noise due to their own movement. Moreover placement of the additional structure near the measurement location is often impossible due to existing water or traffic under the structure. The LDV measures displacement via the Doppler shift effect of a laser. The LDV provides exact displacement measurement up to picometer accuracy and easy installation process by pointing laser to measurement point. Disadvantage of the LDV is expensive cost of the device and no flexible device installation point since measurement is done only along the laser direction. The GPS measures displacement by obtaining the position of receiver from satellite ranging method. Reference point exists in the space, hence attaching GPS receiver at the measuring point is all the requirement for measuring displacement. However, GPS technology is not capable of mm resolution and its price is also very high.

The Camera has been considered as an effective alternative to existing displacement measurement devices for

civil structures as cameras' capability increases with lowering price. Various types of vision-based displacement measurement systems (VDMS) have been developed. Most of the VDMS use a marker whose geometry is known prior, is attached on the structure and movement of the marker is captured by camera [1][2][3][4]. Computer algorithm is then detect position of marker in the video and calculates structural displacement. Various type of VDMS has been developed manly depending on displacement measurement algorithm.

In this study, a VDMS on the basis planar homography is proposed for real time planar displacement measurement. The proposed system requires a single camera that does not need to be calibrated, a planar marker with four white circles on the black background, and a laptop computer running a real-time algorithm that detects markers' positions and calculates structural displacement using planar homography algorithm. The real marker's plane and marker images projected on the image sensor are mapped by planar homography that enables camera to be located arbitrarily. Lab-scale experiment on a shaking table is conducted to verify system's robustness about distance and angle between the camera and the marker.

2. MONOCULAR VISION-BASED DISPLACEMENT MEASUREMENT SYSTEM

Proposed monocular vision-based displacement measurement system measures structural displacement by using single camera and image processing algorithm. This system is composed of hardware that takes video of marker attached on the structural surface and software that calculates structural displacement from the video using Otsu's thresholding method and planar homography mapping algorithm. Hardware and software will be described in detail in the following subsections.

2.1. Hardware

Monocular VDMS used in this study consists of a marker, a camera, a frame grabber, and a laptop computer as shown in Figure 2.1. The marker is attached on the structure to be monitored and moves along with the structure. The marker is designed with the conversion information from pixel unit to metric unit. Since the planar homography is calculated using at least four points on two planes, the marker is designed with four large white circles against black background. The camera is stably located on any spot where the camera can look at marker, and takes a video (i.e., a series of images) of marker's movement. Frame grabber transmits the video to the computer frame by frame so that computer can manipulate the digital video data sequentially. The computer calculates metric displacement from the frame using software described in the following section. The hardware specification used in this study is also tabulated in Table 2.1.

This hardware configuration is simple to install, since no preprocessing like camera calibration is required (The homoraphy matrix contains the information about the camera calibration). In addition, displacement can be calculated from 20m~30m far from structure using optical zoom. Further improvement is possible by using additional optical zoom.
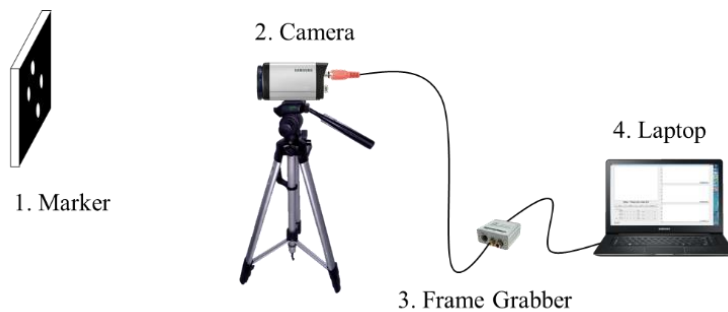

Figure 2.1 Hardware configuration of VDMS

Table 2.1 Hardware details

Parts	Model	Features
Camera	SCZ-2373n	NTSC output interface (640×480 resolution, 29.97 fps), x37 optical zoom
Frame Grabber	myVision-USB DX	NTSC/PAL input interface, USB 2.0 output interface
Laptop	LG A510	1.73 GHz Intel Core i7 CPU, 4GB DDR3 RAM

2.2. Software

Measuring displacement starts from finding centroids of four white circles in the taken images, e.g. extraction of image coordinate. Real-time extraction of image coordinate is achieved by means of image binarization using Otsu's thresholding method, and taking mean value of white pixels in the binarized image. The four centroid points are used to convert the movement of marker in the images to one in real world. Metric displacement calculation is accomplished by mapping image coordinate system into the plane marker plane, e.g. world coordinate system, via planar homography mapping algorithm. Overall process is illustrated in Figure 2.2.
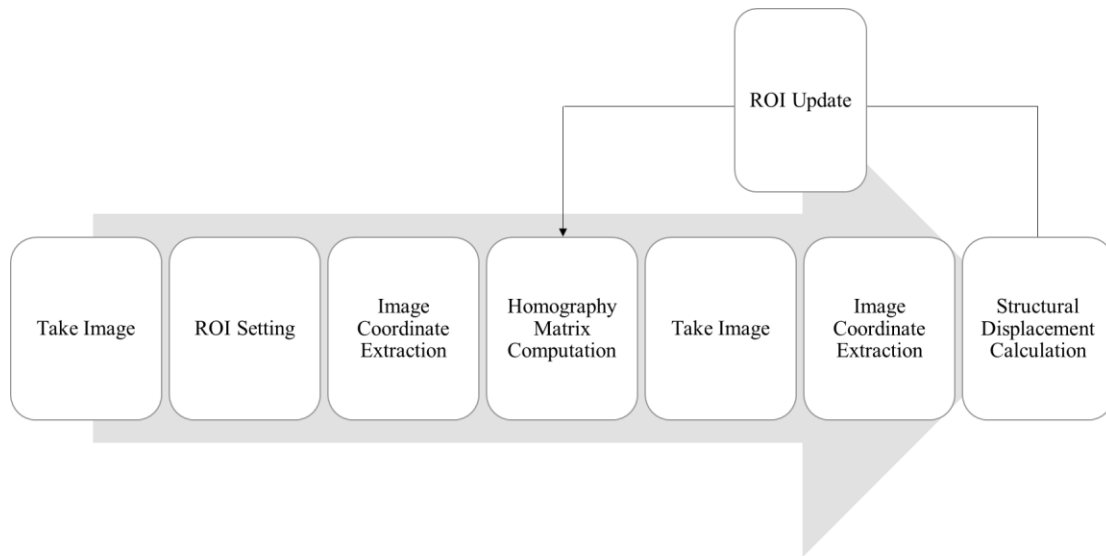
Figure 2.2 Overall software process

2.2.1. Extraction of image coordinates

Extraction of image coordinate is a process to extract image coordinate of white circles in the image. In the image, there are four white circles to be processed. To extract four image coordinates independently, four region of interest (ROI) are designated by user. Figure 2.3 shows an example of four user-assigned ROIs assigned around the circles on the image. Each ROI includes exactly one white circle on the black background. After ROIs are assigned, image coordinate is extracted for each ROI as Figure 2.4 shows. First image in Figure 2.4 is an example white circle in one ROI. Within the ROI, threshold that can optimally separate white circle from black background is found using Otsu's thresholding method [5]. This threshold is used to form binary image, as middle image of Figure 2.4, by assigning one for pixels that has larger value than the threshold, i.e., white pixels, and zero for the others, i.e., black pixels. Pixels that have value of one are considered as a part of a white circle, thus the average of those pixels' coordinate is equivalent to centroid of the circle as shown in the last image of Figure 2.4. Repeating this process for the other ROIs enables the extraction of four image coordinates for each image. Overall process takes very short time (about 1/300 sec) due to its simple process, hence image coordinates can be extracted in real-time when a regular camera with 29.97 fps or larger is used.
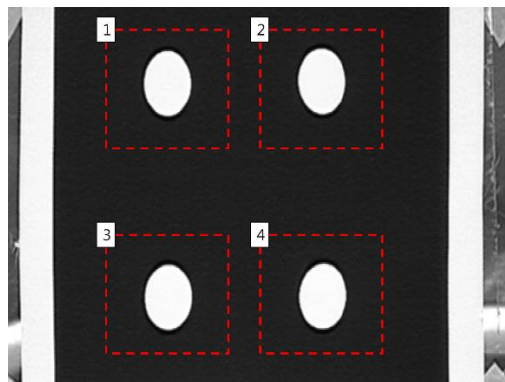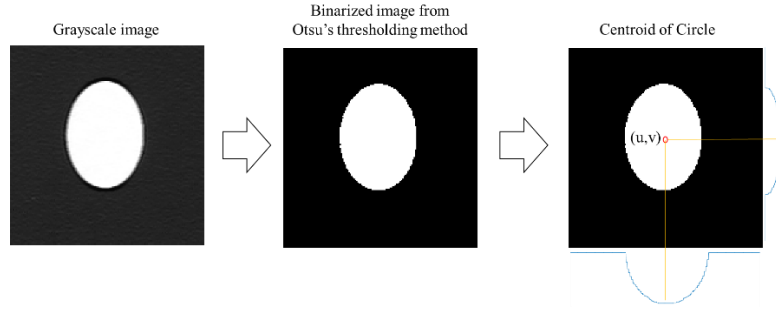

Figure 2.3 Example of ROI setting

Figure 2.4 Extraction process of image coordinate in a ROI

2.2.2. Metric displacement calculation

Metric displacement is calculated from image coordinates using planar homography mapping algorithm. Planar homography is a transformation relationship between two planes in the same projective space [6]. Marker plane, as Figure 5 shows, are projected onto image sensor, e,g, image plane. Thus marker plane and image plane are in the same projective space. Consequently, homography relationship between marker plane and image plane is established.
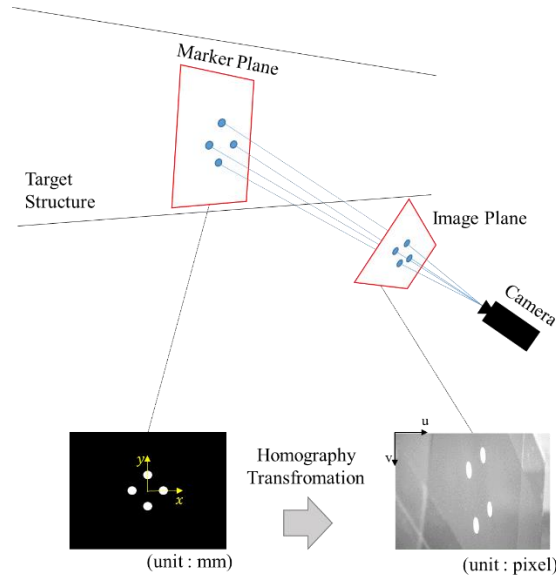
Figure 2.5 Planar homography relationship between image plane and marker plane

This planar homography relationship is written as,

$$s \cdot \mathbf{i_j} = \mathbf{H} \, \mathbf{w_j} \tag{2.1}$$

Where s is scaling factor, $\mathbf{i_j} = \begin{bmatrix} u_j & v_j & 1 \end{bmatrix}^T$ is image coordinate for j-th circle in the image plane, $\mathbf{w_j} = \begin{bmatrix} x_j & y_j & 1 \end{bmatrix}^T$ is world coordinate for j-th circle in the marker plane, and H is 3 by 3 planar homography matrix. Once H is computed, metric coordinates in the marker plane can be induced by inverse homography transform of image coordinates.

To compute eight degree of freedom of H, eight-point algorithm[7] is used. This algorithm requires at least eight points, thus world coordinates of four circles in the marker plane and the corresponding image coordinates in the firstly taken image are used. From equation (2.1),

$$\mathbf{i_j} \times \mathbf{H} \, \mathbf{w_j} = \mathbf{0} \tag{2.2}$$

Equation (2.2) can be rewritten as,

$$
\begin{bmatrix}
\mathbf{0^T} & \mathbf{-w_j^T} & \mathbf{v_j w_j^T} \\
\mathbf{w_j^T} & \mathbf{0^T} & \mathbf{-u_j w_j^T} \\
\mathbf{-v_j w_j^T} & \mathbf{u_j w_j^T} & \mathbf{0^T}
\end{bmatrix}
\begin{bmatrix}
\mathbf{h^1} \\
\mathbf{h^2} \\
\mathbf{h^3}
\end{bmatrix}
= \mathbf{0}
\tag{2.3}
$$

Where h^{kT} is k-th row of matrix H. Equation (2.3) has rank of 2, thus for simplicity,

$$
\begin{bmatrix}
\mathbf{0^T} & \mathbf{-w_j^T} & \mathbf{v_j w_j^T} \\
\mathbf{w_j^T} & \mathbf{0^T} & \mathbf{-u_j w_j^T}
\end{bmatrix}
\begin{bmatrix}
\mathbf{h^1} \\
\mathbf{h^2} \\
\mathbf{h^3}
\end{bmatrix}
= \mathbf{0}
\tag{2.4}
$$

Equation (2.4) is a homogenous linear equation with the form of $A_j^T h_{9\times 1} = 0$, where $h_{9\times 1}$ is rearranged matrix of H. Using four points,

$$
[\mathbf{A_1\ A_2\ A_3\ A_4}]^\mathbf{T}\mathbf{h} = \mathbf{L^T h} = \mathbf{0}
\tag{2.5}
$$

Thus h is a vector in null space satisfying $L^T h = 0$. In real world, equation (2.1) is not perfectly established due to noise. In this case, h that minimizes the norm of $L^T h$ should be taken. After taking singular value decomposition for LL^T, left singular vector that corresponds to minimum singular value is optimal h. Finally, since s in equation (2.1) has the same value of third entry in Hw_j, j-th circle's world coordinate can be calculated by equation (2.6)

$$
\mathbf{w_j} = \frac{1}{\mathbf{h^{3T}w}}\mathbf{H^{-1}i_j}
\tag{2.6}
$$

No matter where camera is located, homography relationship is established if camera is looking at the marker. Thus, by using planar homography, user can locate camera at any optimal point regardless of angle between marker and camera.

3. LAB-SCALE EXPERIMENT

To verify the performance of the proposed VDMS, a lab-scale dynamic experiment is conducted using a shaking table. As Figure 3.1 describes, a marker is fixed on top of the shaking table and camera is positioned by changing distance and angle from marker. Camera's optical zoom is set to make the image as large as possible. Real-time displacement measurement software is implemented using MATLAB 2015a. To compare experimental result, sub-µm resolution of LDV (RSV-150) is also installed to measure the reference displacement of the marker. In the experiment, shaking table is excited in harmonic way with 1Hz frequency and camera is positioned by changing distance from 4m to 20m in 4m interval and by changing angle from $0°$ to $60°$ in $15°$ interval as shown in Figure 3.2.
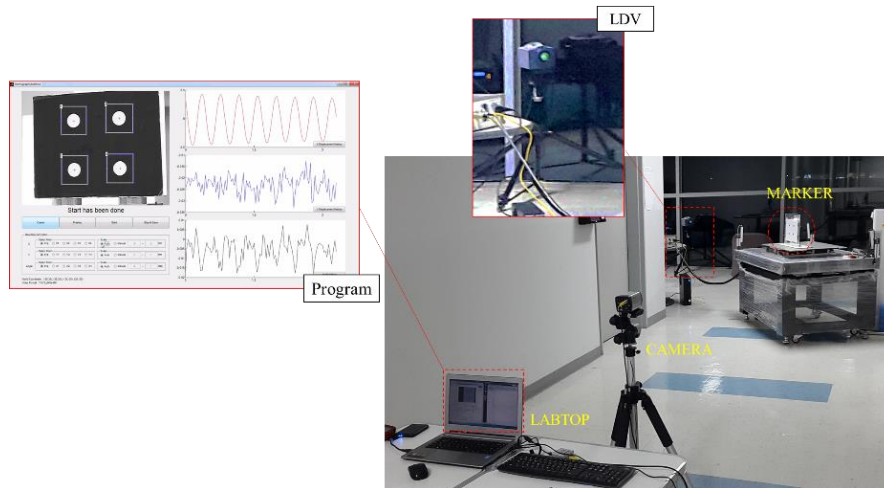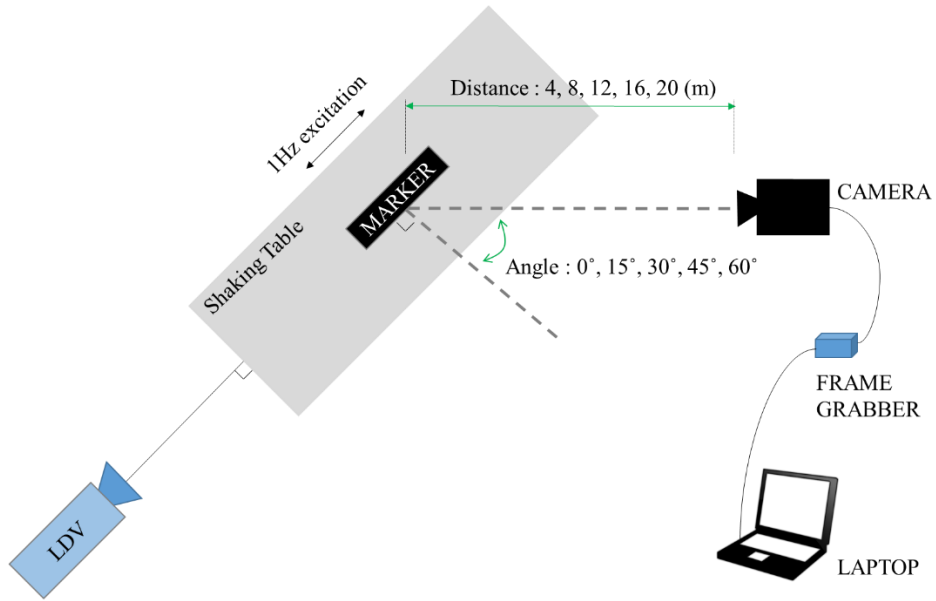

Figure 3.1 Lab-scale dynamic test

Figure 3.2 Top view of the experiment

Figure 3.3 is two experimental results in different angle and distance. Two results graph show high agreement of proposed system to LDV results, although two experiments are conducted with changing the camera location. Thus robustness of the angle and distance between camera and marker is obtained by means of using planar homography and optical zoom of the camera.
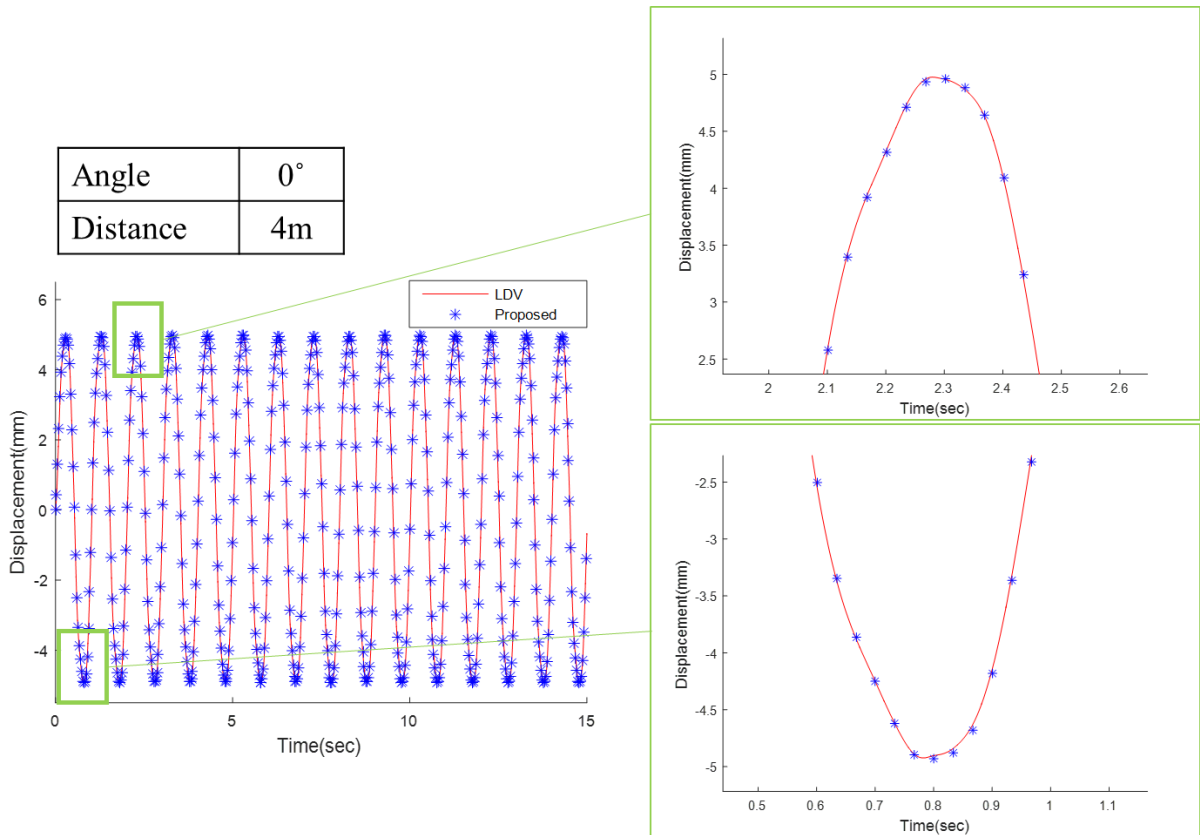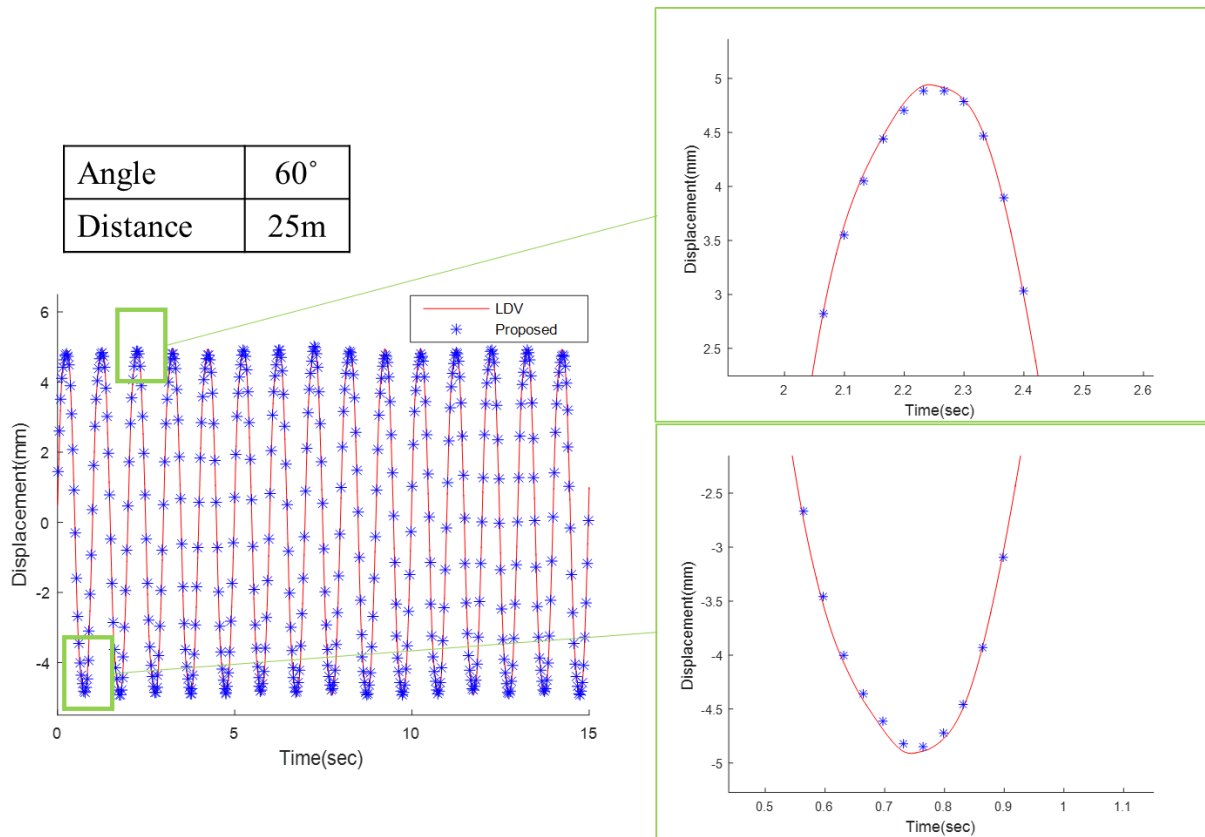
Figure 3.3 Two experimental result

Figure 3.4 is standard deviation error of overall experimental results using Eq. (3.1)

$$\text{Error} = \frac{\text{std}(x_{\text{LDV}} - x_{\text{proposed}})}{\text{std}(x_{\text{LDV}})} \tag{3.1}$$

To compensate sampling rate difference between LDV and camera whose sampling rate are 6kHz and 29.97Hz, two time series data is synchronized by uniting of two time vector and interpolating displacement vector linearly for the missing points. The graph shows the error is not related to the change of angle and distance. In other words, the proposed system is robust to angle and distance between marker and camera.
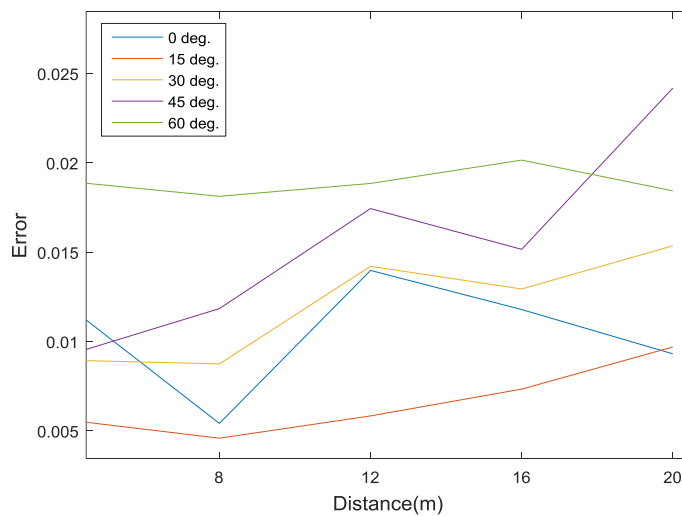

Figure 3.4 Overall standard deviation result

4. CONCLUDING REMARKS

This study proposes a real-time monocular vision-based displacement measurement system offering unconstrained camera installation point. Fast extraction of exact image coordinate is facilitated by introducing Otsu's thresholding method. Unconstrained camera installation point is attributed to planar homography that maps two planes in the 3D space. To verify proposed system's capability of unconstrained camera positioning, lab-scale experiment is conducted using a shaking table. The displacement of the shaking table was measured by the proposed system, and it is compared to sub-μm resolution of LDV. The result can be summarized as:

(1) Angle and distance between marker and camera doesn't have severe relation with error. Thus, the proposed system can be utilized to measure accurate displacement of civil structures in real-time with easy installation step.
(2) Camera used in this study is commercial grade camera with capability of 640×480 resolution and 29.97 fps. By using high performance camera, enhanced displacement measurement can be achieved.
(3) This system is to be verified from various field tests to show its practical performance.

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