Video-based Deformation Measurement System for Structural Health Monitoring

Yoon Bong SHIN* Yohan PARK** Gwanwoo PARK** Seung-Hwan SIN*
Young-Min KIM* and Hwi KIM**
*Disaster Prevention Research Team, Daewoo E&C, Korea
E-mail: yoonbong.shin@daewooenc.com
**Department of Electronics and Information Engineering, Korea University, Korea
E-mail: hwikim@korea.ac.kr

Abstract

Studies have shown that structural health monitoring of structures are important for public safety, maintenance cost, and design of future structures. Among these structures, long-span bridges are in high demand of structural health monitoring, because these structures are venerable to wind load due to their flexibility; therefore, dynamic response of the structure must be monitored for safety. Typical laser displacement measurement sensors which are attached to the bridge structure require long cables to transfer data between the sensors to the measurement system, which may cause the measurements to be unreliable. In this paper, a video-based non-contact remote three-dimensional (3D) vibration measurement system is proposed and developed. The system takes disparity images of the structure and analyzes the 3D structural deformation data through direct linear transformation (DLT) algorithm. Thorough testing and evaluation of the video-based measurement system are required in a controlled laboratory environment prior to on-site implementation on real structures. Wind tunnel test of a model bridge is carried out to evaluate the performance of the proposed system. The experimental results of the video-based deformation measurement system are compared with those of conventional laser displacement measurement device.

Key words: Structural Health Monitoring, Direct Linear Transformation, Wind Tunnel Test, Displacement, Vibration, Bridge

1. Introduction

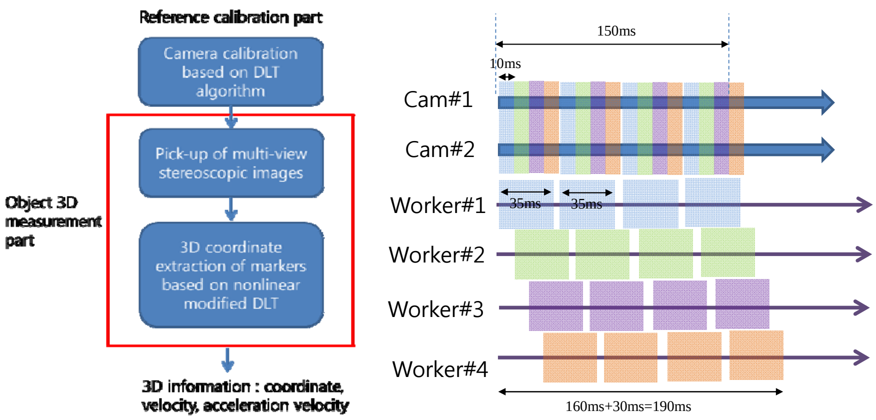
Structural health monitoring of structures are important for safety, maintenance cost, and design of future structures. Long-span bridges are especially in high demand of structural health monitoring due to vulnerability when subjected to wind load; therefore, dynamic response of the structure must be monitored for structural performance. Displacement measurement sensors provide essential information to determine the integrity, durability and safety of a structure. These sensors can be divided into contact sensors and non-contact sensors, and both sensor types have its advantages and disadvantages. Laser deformation sensors based on laser Doppler effect(1) is accurate but limited to 1D deformation measurement, thus uneconomical. Video-based measurement system is able to measure multiple points of interest; therefore, numerous displacement sensors can be replaced with video-based measurement system. Video-based deformation monitoring method is cost-effective and its performance was validated in 2D deformation measurement (2,3).

Considering 3D deformation monitoring, we can see that three displacement contact sensors are required to measure 3D displacement at points of interest on the structure and those contact approaches are not easy to manage and extend cost-effectively. However, video-based non-contact remote 3D displacement measurement system can overcome disadvantages of contact displacement sensors and laser deformation sensors in 3D measurement dramatically and economically. Multiple points of interest on the structure for structural health monitoring will increase the number of sensors effectively.

In this paper, a video-based system was developed based on stereo-vision technique known as nonlinear modified direct linear transform (NM-DLT) algorithm(4) to monitor multiple points of interest on structural models simultaneously and in real-time. Video-based measurement system requires to be evaluated prior to on-site implementation onto real structures. Therefore, wind tunnel test of a bridge model was tested to evaluate the performance of the video-based measurement system. Cameras captured the vibration of the bridge model when subjected to wind load, and the captured images were analyzed for model displacement. The displacement obtained from the video-based measurement system was compared with laser displacement measurement sensors for performance evaluation.

2. Principle and algorithm of the proposed real-time 3D monitoring system

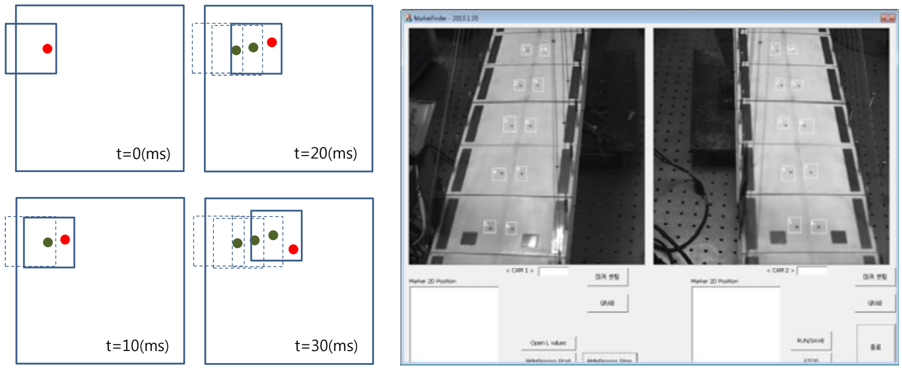
In Fig. 1(a), the work process of the 3D measurement and analysis based on the nonlinear modified direct linear transform (NM-DLT) algorithm is presented. The first step is camera calibration. In this step, structural parameters of the camera such as the three-dimensional position, the direction of the optical axis of the camera, the tilt angle of the camera film, and the effective focal length are analyzed from images of a reference object having plural control points constituting global coordinate standard which are taken by camera to be calibrated. The experimental result of the camera calibration is presented in section 3. The next step is stereo-image pickup by high frame rate synchronized stereo-camera system. In the third step, 2D positions of multiple markers in two corresponding pictures are analyzed and 3D coordinates of the multiple markers are extracted with NM-DLT algorithm. For real-time processing, multi-threads that run independently are created in multi-core workstation (192G RAM, Zeon CPU). Two threads are allocated to control camera#1 and camera#2 taking pictures of 2048X2048 gray images at 150 frames per second. 10 threads collaborate to process the captured stereo-images and analyze the 2D positions of multiple-markers. As conceptually shown in Fig. 1(b), the stereo-images are saved into the image buffer serially in 10ms. In this case, if four image processing workers process their allocated images in time less than 40ms, image processing workers can process the next allocated stereo images in real-time manner without accumulation of pictures.



(a) (b)

Fig. 1 DLT based real-time monitoring algorithm of 3D marker position trace; (a) work flow of 3D measurement and (b) multi-thread based real-time monitoring

For attaining real-time performance and reducing computation burden, adaptive ROI (region-of-interest) tracking algorithm was implemented in the image processing worker thread. In Fig. 2(a), the traces of the rectangular ROI and target maker moving in the image taken by a camera are illustrated conceptually. In Fig. 2(b), snapshot of the user interface of the control software is shown, which shows 10 white-rectangular ROI boxes enclosing target markers on the structural model. Finally, 2D coordinates of the stereo-images are converted to 3D position data by reconstruction algorithm of the MN-DLT module.



(a) (b)

Fig. 2 Adaptive ROI algorithm; (a) traces of ROI and markers (b) snapshot of the user interface of the developed system

3. Wind Tunnel Test

A scaled rigid bridge deck model was test in the wind tunnel lab at Daewoo Institute of Construction Technology to evaluate the video-based measurement system, as shown in Fig. 3(a); furthermore, a cable-stay bridge model will be tested in the future, as shown in Fig. 3(b). The rigid bridge deck model was connected to a spring support system to replicate wind-induced vibration of real bridge deck; the spring support system enables the model to vibrate when subjected to wind loads.

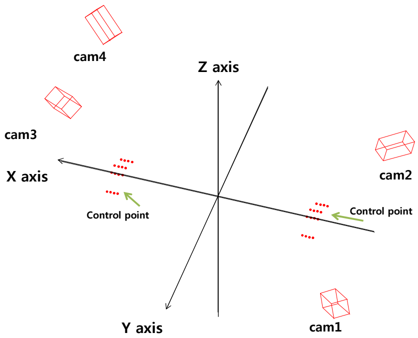
(a) (b)

Fig. 3 Wind tunnel test setup: (a) bridge deck model connected to the spring support system (b) cable-stay bridge model

Four laser displacement measurement devices were installed at the ends of the model to measure the vertical displacement and rotation, and each set of cameras (two cameras) were pointed toward ends of the model, as shown in Fig. 4. The laser displacement measurement device and the cameras recorded data at 100 samples per second, and both systems were synchronized. The model had a natural vibration frequency within 5Hz; therefore, 100 samples per second of data were sufficient enough to capture the dynamic response of the model.

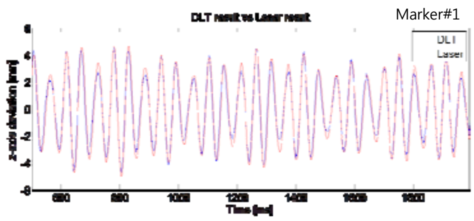
Fig. 5 shows the test results comparison of displacement based on video-based measurement system and laser displacement sensors. Each figure plots the time history displacement of the model from each laser displacement sensors and the displacement obtained from video-based displacement system where the marker is the laser dot from the laser sensor. Test results showed close agreement.

(a)

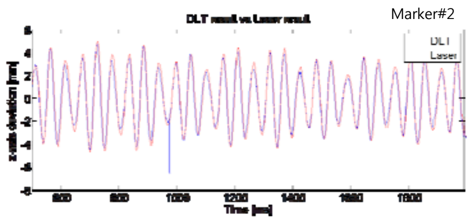


(b)

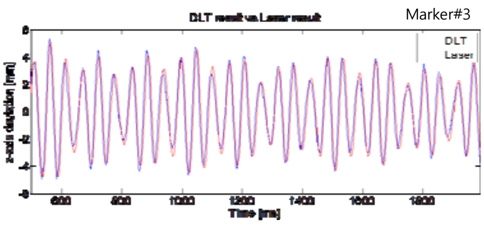
Fig. 4 Video-based measurement system: (a) camera position (b) camera calibration results



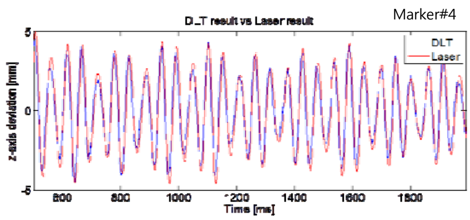
(a)



(b)



(c)



(d)

Fig. 5 Comparison of video-based measurement and laser measurement data: (a) maker#1, (b) marker#2, (c) marker#3, (d) marker#4

4. Conclusion

Video-based measurement system has been proposed and developed to replace displacement measurement sensors used in structural health monitoring. The developed system was tested for performance prior to adaptation in real structures through a scaled model of a bridge deck. The developed system was compared with laser displacement sensors, and the results showed close agreement. Further testing will be conducted for a cable-stay bridge model with various modes of vibration along the length of the bridge.

References

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