Chapter 20
Three-Dimensional Structural Displacement Estimation Using a Low-Cost Sensing System Combining a Consumer-Grade Camera and an Accelerometer

Zhanxiong Ma, Jaemook Choi, and Hoon Sohn

Abstract The monitoring of structural displacements is crucial because displacements can reveal critical information about the health of civil structures. Despite this, accurate measurements of structural displacements remain a difficult task. The fusion of a vision camera and an accelerometer has previously been explored to estimate structural displacements, but only in-plane displacements can be estimated. This chapter describes a three-dimensional structural displacement estimation method that fuses measurements from a consumer-grade camera and a triaxial accelerometer mounted on a target structure. An accelerometer-aided computer vision algorithm and an adaptive multirate Kalman filter are integrated to efficiently estimate high-sampling three-dimensional displacements from low-sampling vision measurements and high-sampling acceleration measurements. All parameters associated with the computer vision algorithm are automatically calibrated without any prior knowledge or ad-hoc thresholding. Experimental validation of the proposed method is performed on a four-story building model under varying excitations. Displacements were accurately estimated with a root mean square error of less than 2 mm.

Keywords Structural displacement · Low-cost sensing system · Consumer-grade camera · Accelerometer · Data fusion

20.1 Introduction

Displacement is essential for monitoring the health condition of structures. In practice, displacement is commonly estimated from acceleration measurements by double integration. However, the double integration process could amplify the acceleration measurement noise, thereby causing a huge low-frequency drift in the estimated displacement. Though such a drift could be eliminated by high-pass filtering [1], the important low-frequency structural displacement will be eliminated as well. Attempts have been made to fuse accelerometers with other types of sensors that measure or estimate displacement for improved displacement estimation. For example, displacements have been estimated by fusing an accelerometer with either Global Positioning System (GPS) [2], strain sensors [3], inclinometers [4], or millimeter wave radar [5]. Note that such fusions allow for both high- and low-frequency displacement estimation with a high sampling rate.

Vision cameras have been studied for over a decade for structural displacement measurement, and the authors have also tried to fuse a vision camera with an accelerometer [6, 7]. Such fusion allows for improved displacement estimation accuracy and computational efficiency. However, these studies focus on in-plane displacement estimation only. In this study, we extend our previous method to estimate both in-plane and out-of-plane (i.e., three-dimensional) displacements using a consumer-grade camera and a triaxial accelerometer. An accelerometer-aided computer vision algorithm and an adaptive multi-rate Kalman filter are integrated to efficiently estimate high-sampling displacements from low-sampling vision measurements and high-sampling acceleration measurements. All parameters associated with the accelerometer-aided computer vision algorithm are automatically calibrated without any prior knowledge or ad-hoc thresholding. The remainder of this chapter is organized as follows. Section 20.2 illustrates the overall flowchart of the proposed method. The experimental validation of the proposed method on a four-story building model is presented in Sect. 20.3. The concluding remarks are provided in Sect. 20.4.

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20.2 Methodology

Figure 20.1 shows an overview of the proposed displacement estimation method. A triaxial accelerometer and a vision camera are placed on a target structure where displacement is to be estimated. The accelerometer measures the structural acceleration in three directions with a high-sampling rate, while the vision camera tracks a fixed target from the surrounding of the target structure with a low sampling rate. An accelerometer-aided computer vision algorithm is first used to estimate the three-dimensional structural displacement based on vision measurements. The estimated vision-based displacements are then fused with accelerometer measurements using an adaptive multirate Kalman filter, to obtain final displacements with a higher sampling rate and better accuracy than vision-based displacements. Note that a calibration process is performed automatically to estimate scale factors for unit conversions and to select active pixels with a region of interest (ROI). More details on the automated initial calibration, accelerometer-aided computer vision algorithm, and adaptive multirate Kalman filter could be found in Ma et al. [7].

20.3 Experimental Validation

Figure 20.2a demonstrates the overall configuration of the laboratory test on a four-story shear building structure. The experiment was performed inside the KAIST campus, and a window of an actual building, approximately 20 m apart, was

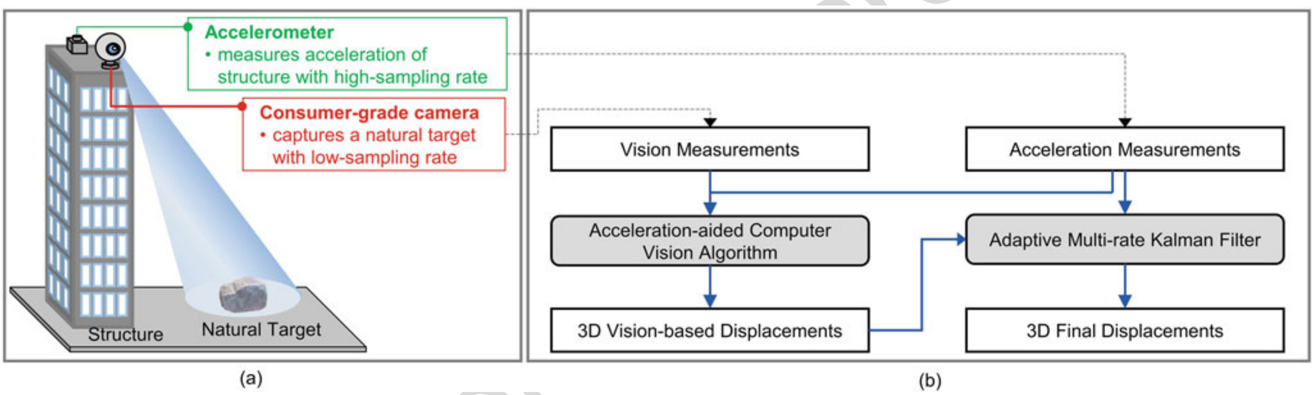

Fig. 20.1 Overview of the proposed displacement estimation method: (**a**) sensor setup and (**b**) overall flowchart

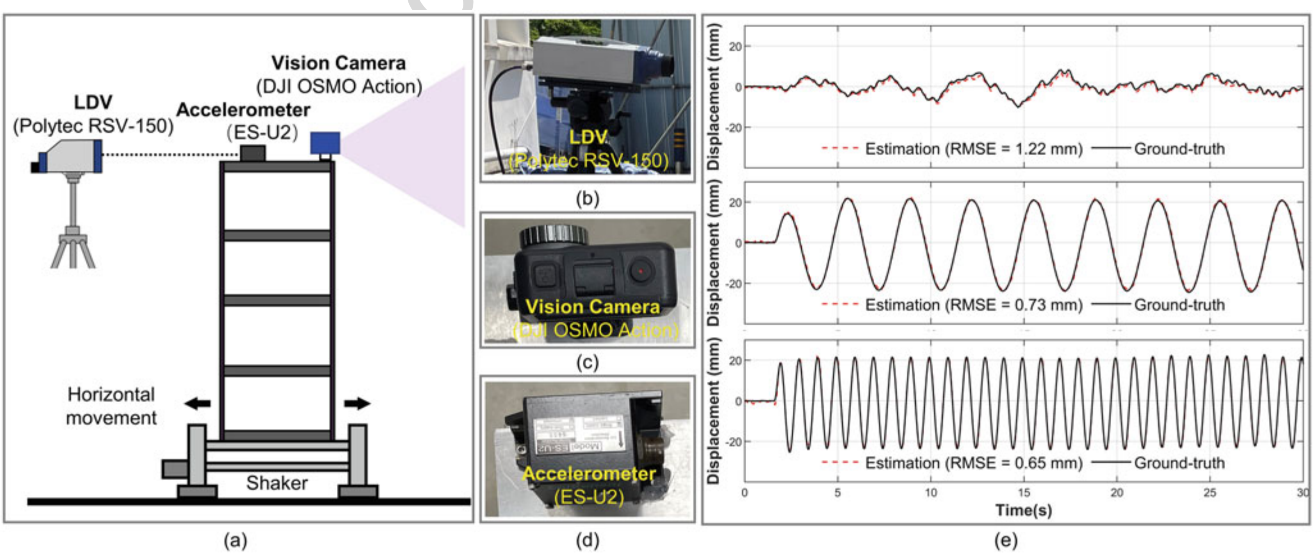

Fig. 20.2 (**a**) overall configuration of the laboratory test on a four-story shear building structure, (**b**)~(**d**) a laser Doppler vibrometer (LDV), vision camera, and accelerometer used in this test, and (**e**) displacement estimated by the proposed method using the vision camera and the accelerometer compared to the ground-true displacements measured by the LDV under three different excitations

used as a natural target. The shaking table moved the shear building structure in a horizontal direction to generate out-of-plane vibration of the structure relative to the natural target. Note that the authors have previously verified in-plane displacement estimation using a vision camera and accelerometer [6, 7], and then this test focuses on out-of-plane displacement estimation only. The displacement at the top of the shear building structure was measured using a laser Doppler vibrometer (LDV) and estimated using an accelerometer and a vision camera installed at the same location. Note that here the LDV was used for ground truth displacement measurement, which is necessary for evaluating the estimation performance of the proposed method. Figure 20.2b shows the Polytech RSV-150 LDV used in this study, and the LDV can measure displacement with a resolution of fewer than 1 μm. Figure 20.2c shows the DJI OSMO Action vision camera used in this study. The camera has a 1/2.3 inch CMOS sensor and an f/2.8 lens with a field of view of 145°. It can be used to record videos with 4K resolution (3840 pixels by 2160 pixels) at a frame per second (FPS) up to 60 Hz. Figure 20.2d shows the EpiSensor ES-U2 accelerometer used in this study, which is a force-balance type uniaxial accelerometer. The accelerometer has an extremely low self-noise with a 155 dB dynamic range and a wide frequency response of up to 200 Hz. In this study, accelerometer and LDV measurements were discretized at 100 Hz using a National Instrument USB-6366 data acquisition device, while the vision measurement was recorded at 4K resolution with an FPS of 10 Hz. Three different excitation signals were inputted to the horizontal shaker in this test. Figure 20.2e compares displacements estimated by the proposed method and measured by the LDV. In all three cases, the estimated displacements have good agreement with the ground-truth displacements measured by the LDV. The root means square error (RMSE) of the estimated displacements were calculated to quantitatively evaluate the estimation performance of the proposed method. Less than 2 mm RMSE indicates that the proposed method can accurately estimate out-of-plane displacement.

20.4 Conclusion

This study proposed a three-dimensional displacement estimation method through the fusion of a collocated vision camera and an accelerometer on a target structure. To validate the performance of the proposed displacement estimation method, a laboratory test was conducted on a four-story building structure, and out-of-plane displacements were estimated under three different excitations. The results indicate that the proposed method was able to estimate displacement accurately with an RMSE of less than 2 mm. However, displacements were estimated only in a single direction, and more experiments are required for validating the proposed method for displacement estimation in all three directions. In addition, efforts are currently being made to develop a structural displacement sensor module by integrating a vision camera, accelerometer, and microcontroller.

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