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Structural displacement estimation using high-sampling acceleration and temporally-aliased low-sampling vision measurements

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ABSTRACT

Displacement plays a crucial role in structural health monitoring, but the accurate measurement of structural displacement remains a challenging task. Nowadays, some researchers attempt to estimate structural displacement by fusing vision camera and accelerometer measurements. Considering hardware limitations and computational costs, vision measurements are commonly performed at a low sampling rate. Nevertheless, the use of a low sampling rate may cause temporal aliasing in vision measurements, which can cause large displacement errors. In this study, we propose a finite impulse response (FIR) filter-based technique to estimate structural displacement using high-sampling acceleration measurement and low-sampling vision measurement with temporal aliasing. By explicitly eliminating the error induced by temporal aliasing, the displacement estimation accuracy can be significantly improved compared to existing FIR filter-based techniques. The proposed technique was experimentally validated on a single-story building model, and the results show that the displacement estimation performance of the technique was insensitive to the sampling rate of vision measurements. Structural displacement was accurately estimated even when temporal aliasing was present in vision measurements.

Keywords: Displacement estimation, finite impulse response filter, temporal aliasing, vision camera, accelerometer, data fusion

1. INTRODUCTION

To prevent disastrous consequences from civil infrastructure collapse, continuous monitoring of structural health is crucial. This monitoring involves analyzing and identifying various loads and structural responses over the service life of a structure to assess its performance and safety. Among the techniques used in structural health monitoring, displacement response measurement is essential, as it provides insight into the behavior of structures and aids in evaluating their safety. Various structural displacement sensing techniques have been proposed, including the use of accelerometers[1], real-time kinematic global navigation satellite system (RTK-GNSS)[2], strain sensors[3], radar systems[4], and vision cameras[5]. However, each of these sensors has its own advantages and disadvantages. Recently, there has been a trend in combining multiple types of sensors to improve displacement estimation[6-8]. This includes combining accelerometers with strain sensors[9,10], vision cameras[11,12], or millimeter-wave radar[13]. It is worth noting that sensor fusion can improve accuracy and increase the sampling rate of the estimated displacement.

When fusing accelerometers with other sensors, an initial displacement is firstly estimated from these sensors, which is fused with acceleration measurement from accelerometers to obtain an improved displacement. Fusion of acceleration measurement and initial displacement estimation has been widely explored using finite impulse response (FIR) filters[14,15]. Figure 1 illustrates the general process of the existing structural displacement estimation technique through the fusion of high-sampling acceleration and low-sampling displacement measurements. A high-sampling high-frequency displacement is firstly estimated from high-sampling acceleration measurement by double integration and high-pass filtering with a cutoff frequency of f_c. Meanwhile, a low-sampling low-frequency displacement is first extracted from a

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low-sampling displacement measurement using a low-pass filter, which is up-sampled to match the sampling rate of acceleration measurement to obtain a high-sampling low-frequency displacement. The final high-sampling displacement is estimated as the combination of the high-sampling low-frequency and high-frequency displacements.

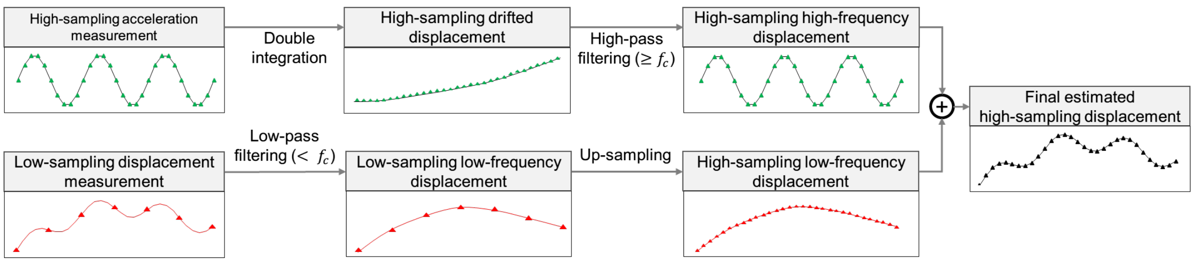

Figure 1. Flowchart of existing FIR-filter-based fusion of high-sampling acceleration and low-sampling displacement measurements for structural displacement estimation.

However, a temporal aliasing issue occurs in the low-sampling displacement measurement with the existence of displacement above its Nyquist frequency (f_N). As shown in Figure 2, displacement components above f_N will appear as the components with lower frequencies, thereby causing inaccurate displacement estimation. Note that temporal aliasing errors with frequencies above f_c do not affect the final estimated high-sampling displacement, because that low-sampling displacement measurement only contributes to the portion of the final estimated high-sampling displacement with frequencies lower than f_c. An effective remedy for anti-aliasing is to low-pass filter the analog signal prior to sampling, but it is not applicable when the low-sampling displacement is measured using a vision camera.

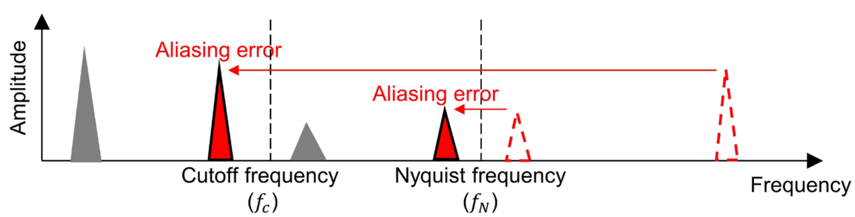

Figure 2. Temporal aliasing issue in the LS displacement measurement with the existence of displacement above its Nyquist frequency.

In this study, a technique for estimating high-sampling displacement is presented by merging high-sampling acceleration with temporally-aliased low-sampling vision-based displacement through FIR filters. By explicitly removing the temporally-aliased error in the vision-based displacement, the accuracy of the displacement estimation is notably enhanced when compared to existing FIR filter-based techniques. The remaining sections of the paper are structured as follows. In Section 2, we briefly discuss the proposed displacement estimation technique, followed by a lab-scale test to validate its performance in Section 3. Finally, in Section 4, we present our concluding remarks.

2. METHODOLOGY

This section outlines the proposed high-sampling displacement estimation technique achieved through FIR-filter-based fusion of high-sampling acceleration and temporally-aliased low-sampling vision-based displacement. An overview of the proposed technique is presented in Figure 3. A vision camera is affixed to a structure to track a natural target from the structure's surroundings using a low sampling rate (F_s), while an accelerometer is installed at the same location as the vision camera to measure the structure's acceleration with a high sampling rate. Assuming that the structure has displacement with a frequency above $F_s/2$, the displacement estimated from vision measurement is affected by a temporally-aliased error. It is worth noting that several computer vision algorithms have been developed and applied for vision-based displacement estimation, and in this study, a template-matching algorithm based on zero-mean normalized cross-correlation[16] is adopted. The proposed technique involves estimating the temporally-aliased error in the low-sampling vision-based displacement using acceleration measurement and then eliminating it to obtain an anti-aliased low-sampling vision-based displacement. The high-frequency component of the acceleration-based displacement and the low-frequency component of the anti-aliased low-sampling vision-based displacement are then combined to estimate a high-sampling displacement. It should be noted that the anti-aliasing vision-based displacement was up-sampled to match the acceleration measurement sampling rate.

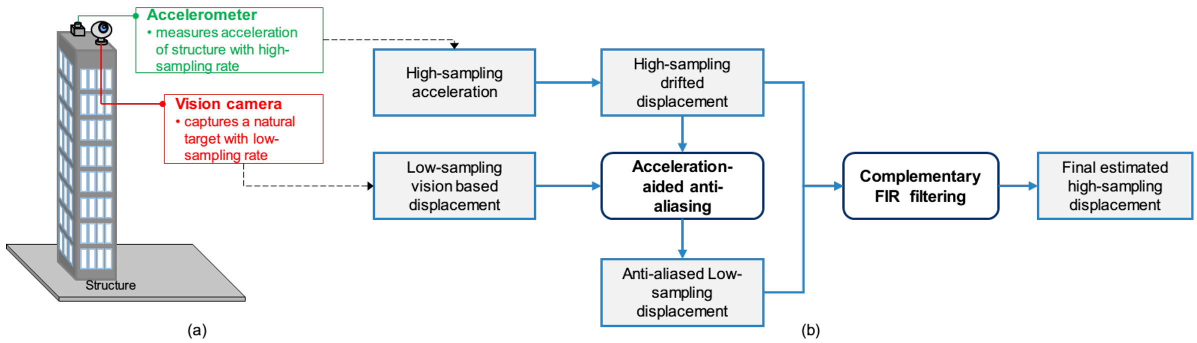

Figure 3. Overview of the proposed FIR-filter-based high-sampling displacement estimation technique through the fusion of high-sampling acceleration and low-sampling vision-based displacement: (a) sensor setup and (b) flowchart.

3. EXPERIMENTAL VALIDATION

3.1 Experimental setup

A lab-scale experiment was conducted to validate the proposed technique, as shown in Figure 4(a). An EpiSensor ES-U2 accelerometer (Figure 4(b)) and a DJI OSMO Action vision camera (Figure 4(c)) were installed at the top of a two-story building structure, and an ELECTRO-SEIS APS-400 shaker moved the structure in a horizontal direction. The ground truth displacement was measured by a Polytech PSV-400 laser Doppler vibrometer (LDV). The vision measurement was recorded at 30 Hz with 4K resolution. Both acceleration and LDV measurements were sampled at 100 Hz. Figure 4(d) shows the field of view (FOV) of the vision camera and the selected region of interest (ROI). The distance between the vision camera and the target, that is, several stones, was approximately 1 m. A mixture of 0.1 Hz and 3.3 Hz sinusoidal signals was input into the shaker to excite the model in this test.

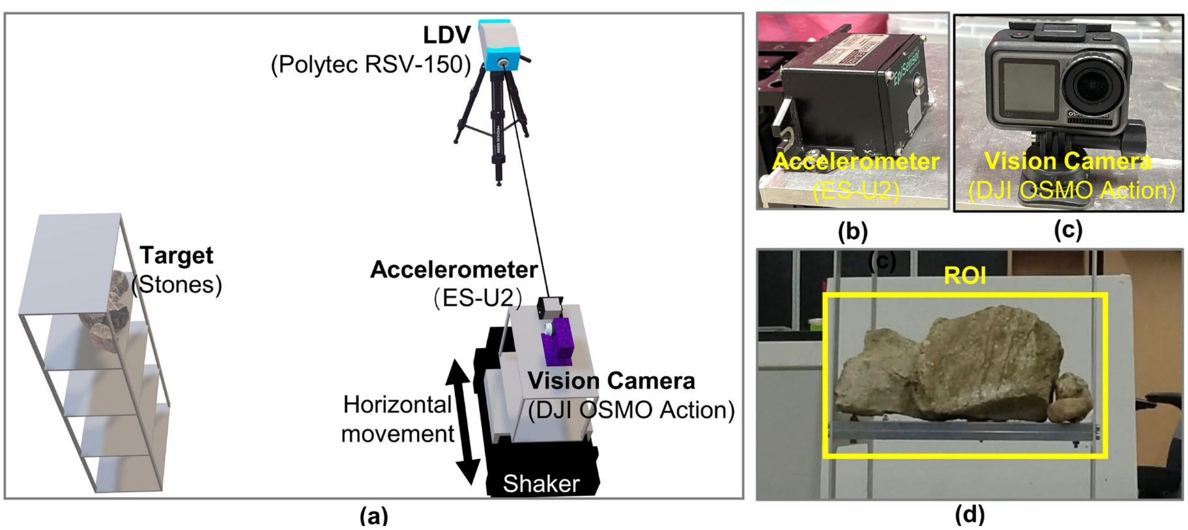

Figure 4. Overall configuration of an indoor single-story building model test: (a) sensor setup, (b) EpiSensor ES-U2 force-balance type accelerometer and (c) DJI OSMO Action vision camera used for displacement estimation, and (d) the field of view (FOV) of the vision camera and the cropped region of interest (ROI).

3.2 Displacement estimation results

Displacements were firstly estimated by the proposed and existing techniques[14] using 3 Hz vision measurement and 100 Hz acceleration measurement. Considering that the structure had displacement at frequencies of 0.1 Hz and 3.3 Hz, a temporal aliasing error at 0.3 Hz appeared in the 3 Hz vision-based displacement. Then, a low-frequency error is clearly observed in the displacement estimated by the existing technique as shown in Figure 5, and therefore the root mean squares error (RMSE) of the estimated displacement is relatively large (0.606 mm). However, by explicitly eliminating the temporal aliasing error in the 3 Hz vision-based displacement, the displacement estimated by the proposed technique has a good agreement with the reference displacement measured by the LDV and the corresponding RMSE is only 0.187 mm. The frequency spectra of displacements estimated by the proposed and existing techniques are compared in Figure 6. The temporal aliasing error in the 3 Hz vision-based displacement is retained in the displacement estimated by the existing technique but is eliminated in the displacement estimated by the proposed technique, demonstrating the superiority of the proposed technique.

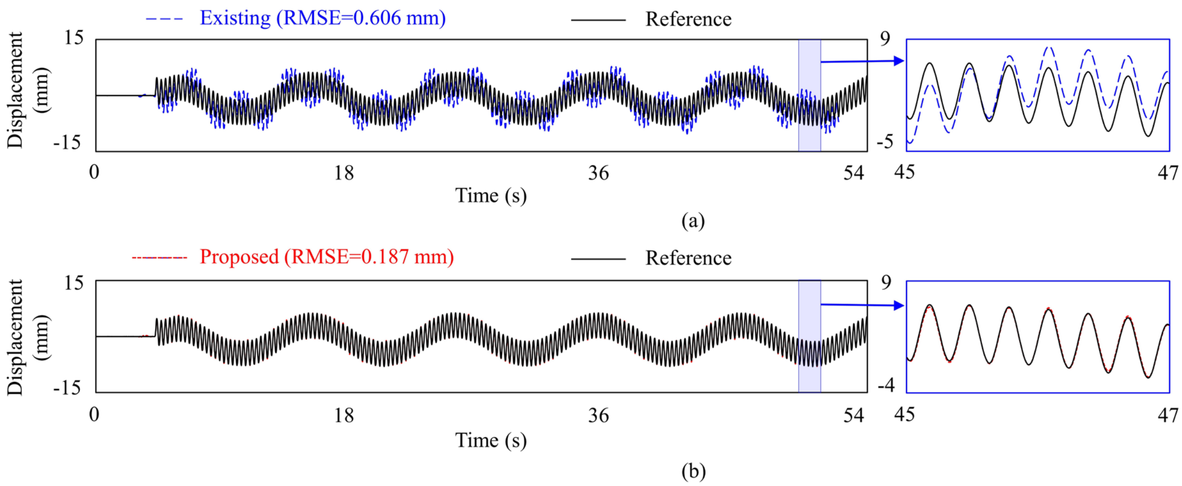

Figure 5. Displacements estimated by the proposed and existing techniques through the fusion of 3 Hz vision-based displacement and 100 Hz acceleration.

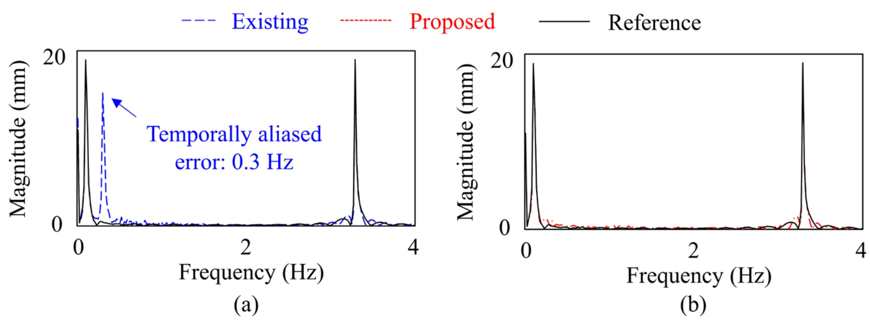

Figure 6. Frequency spectra of displacements estimated by the proposed and existing techniques through the fusion of 3 Hz vision-based displacement and 100 Hz acceleration.

Displacement was then estimated by the proposed and existing techniques using 100 Hz acceleration measurement and vision-based displacement at varying sampling rates, and RMSEs of the estimated displacements were compared in Figure 7. When 30 Hz, 20 Hz, and 15 Hz vision-based displacements were used, both the proposed and existing techniques estimated displacement accurately because there is no temporal aliasing issue in vision-based displacements. When 6 Hz and 5 Hz vision-based displacements were used, temporal aliasing occurs and the vision-based displacements have temporal aliasing errors at 2.7 Hz and 1.7 Hz, respectively. However, the vision-based displacement only contributes to low-frequency components of the estimated displacement. Therefore, the temporal aliasing errors do not affect the final estimated displacement, and both the proposed and existing techniques still estimated displacement accurately. When 3 Hz vision-based displacements were used, temporal aliasing occurs and the vision-based displacement has a temporal aliasing error at 0.3 Hz, the proposed technique still estimate displacement accurately, but a huge error was observed from the displacement estimated by the existing technique. Note that almost identical displacement estimation performance was achieved by the proposed technique using vision-based displacements at varying sampling rates.

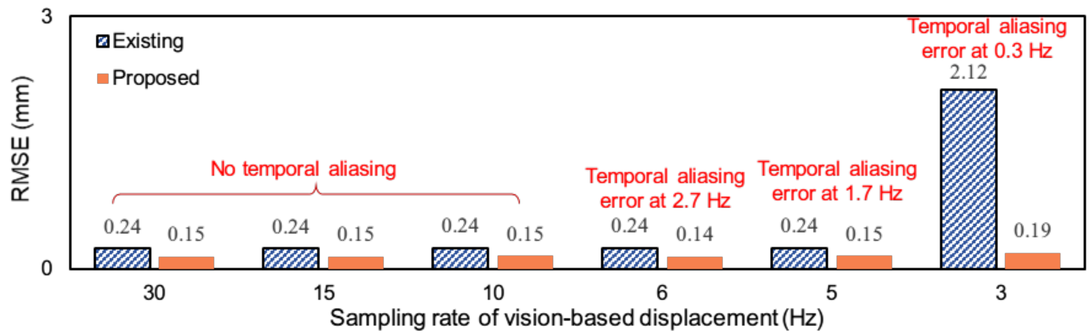

Figure 7. Comparison of displacement estimation accuracy of the proposed and existing techniques using 100 Hz acceleration and vision-based displacement at varying sampling rates.

4. CONCLUSION

In this study, we introduce a novel FIR filter-based technique for accurately estimating high-sampling structural displacements by combining high-sampling acceleration with temporally-aliased low-sampling vision-based displacements. By explicitly eliminating the temporally-aliased error in the vision-based displacement prior to fusion with the high-sampling acceleration, our technique achieves highly accurate displacement estimation. To demonstrate its effectiveness, we apply our proposed technique to estimate the displacement of a single-story building model using 3 Hz vision measurements and 100 Hz acceleration measurements. Despite the low sampling rate causing a temporally-aliased error in the vision-based displacement at 0.3 Hz, our technique still produces accurate displacement estimates at a sampling rate of 100 Hz. Our proposed technique shows great promise for continuous displacement monitoring in wireless sensor platforms, as it does not require high-rate vision-based measurements. We are currently developing a low-cost displacement sensor module that integrates a photodetector for vision imaging, an accelerometer, and a microcontroller to enable the widespread implementation of our technique.

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