Structural displacement estimation through the fusion of millimeter wave radar and accelerometer

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Abstract. Although displacement measurement is essential for many civil infrastructure applications, the accurate estimation of structural displacement remains a challenge. In this study, a structural displacement estimation technique was developed for civil infrastructures by fusing measurements from collocated accelerometer and millimeter wave radar. An initial calibration is firstly performed using a short time period (less than 1 minute) acceleration and radar measurements to determine unknown parameters required for estimating displacement from radar measurements. Then, with the help of acceleration measurement, displacement is estimated from radar measurement in real-time using the determined parameters. Finally, the estimated radar-based displacement is fused with acceleration measurement by a finite impulse response filter to estimate a displacement with improved accuracy at the cost of a short time delay. The feasibility and effectiveness of the proposed displacement estimation technique were validated by performing a laboratory test on a four-story building model and a field test on a pedestrian steel box girder bridge. In both tests, the proposed technique was able to accurately estimate displacements with root mean square errors of less than 0.3 mm.

Keywords: Displacement estimation, millimeter wave radar, finite impulse response filter, accelerometer, data fusion

1 Introduction

Displacement is essential for monitoring 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 acceleration-based displacement[1]. Though such a drift could be eliminated by high-pass filtering, the improtant low-frequency structural displacement will be eliminated as well [2]. Attempts have been made to fuse accelerometers with other types of sensors that measures or estimates displacement for improved displacement estimation. For example, displacements have been estimated by the fusion of real-time kinematic global navigation satellite system (RTK-GNSS) and accelerometers[3], the fusion of strain sensors and accelerometers[4, 5], the fusion of inclinometers and accelerometers[6], and the fusion of vision camera and accelerometers[7].Note that such fusions allow for both high- and low- frequency displacement estimation with a high sampling rate.

Radar systems have been studied over a decade for structural displacement measurement[8, 9]. Currently, millimeter wave (mmWave) radar has been developed and it is a promising technique for measuring tiny displacements [10]. This study attempts to fuse mmWave radar and accelerometer for displacement estimation. With the help of acceleration measurement, displacement is firstly estimated from radar measurement. After that, the radar-derived displacement is fused with acceleration measurement using a finite impulse response (FIR) filter to further improve displacement estimation accuracy. Note that an automated initial calibration is performed using a short-time period (less than 1 minute) radar and acceleration measurements to determine parameters required for estimating displacement from radar measurements. The remainder of this paper is organized as follows. Section 2 illustrates the working principle of the proposed technique. The experimental validation of the proposed technique on a four-story building model and a pedestrian bridge is presented in Section 3. The concluding remarks are provided in Section 4.

2 Methodology

This study proposes a displacement estimation technique that fuses mmWave radar and accelerometer. As shown in Fig. 1(a), a mmWave radar and an accelerometer are placed at the same location of a structure where displacement to be estimated. The flowchart of the proposed technique is shown in Fig. 1(b). With the help of acceleration measurement, a displacement is firstly estimated from radar measurement in real time. After that, the radar-based displacement is fused with acceleration measurement using a complementary FIR filter to obtain an improved displacement, which has higher accuracy than the radar-based displacement.

2.1 Improved radar-based displacement estimation algorithm

Figure 2 shows the overview of the improved radar-based displacement estimation algorithm. Fourier transform is first applied to real-time radar measurement to obtain raw phase. Note that here phase information, instead of frequency information, is used for high-accuracy displacement estimation. However, phase wrapping can be a serious issue with a large structural displacement, and then phase unwrapping becomes necessary. Unlike the existing phase unwrapping algorithms[12], which require a ad-hoc threshold, an adaptive acceleration-aided phase unwrapping algorithms [11] is applied to recover unwrapped phase. Afterwards, the unwrapped phase is used to estimate a radar-based displacement. The

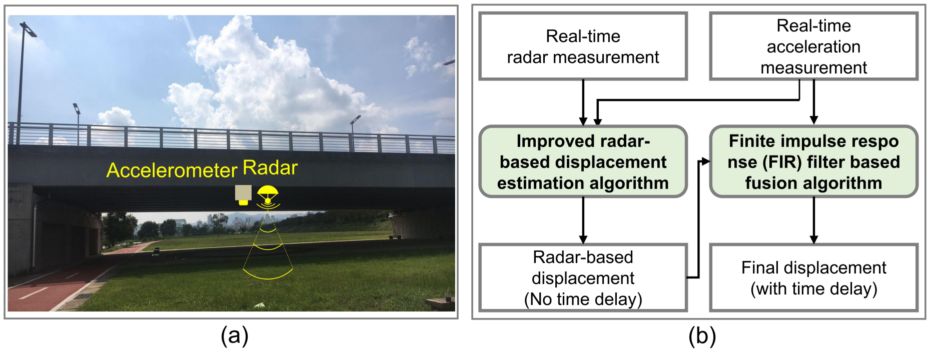

Fig. 1. Overview of the proposed displacement estimation technique using mmWave radar and accelerometer: (a) sensor setup and (b) flowchart.

original displacement estimated from radar measurement is in a light-of-sight direction, which is converted to the structural displacement in an actual vibration direction using a conversion factor estimated by an automated initial calibration[11]. It should be noted that the radar-based displacement is estimated in real-time.

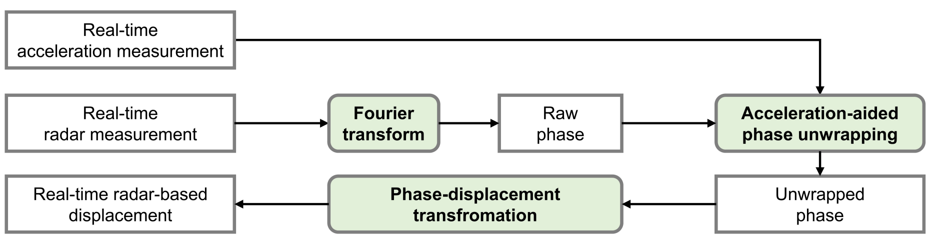

Fig. 2. Overview of the improved radar-based displacement estimation algorithm

2.2 FIR filter based fusion algorithm

To further improve displacement estimation accuracy, an FIR filter-based algorithm [2] was adopted to fuse the radar-based displacement and acceleration measurement as shown in Fig.3. Provided that acceleration measurement and radar-based displacement measurements are available, an error function $\Pi(\mathbf{u}^*)$ is defined within a given time window $[(k-M)\Delta t, (k+M)\Delta t]$ as follows:

$$\Pi(\mathbf{u}^*) = \frac{1}{2}\|\mathbf{L}_a\mathbf{L}_c\mathbf{u}^* - (\Delta t)^2\mathbf{L}_a\mathbf{a})\|_2^2 + \frac{\lambda^2}{2}\|\mathbf{u}^* - \mathbf{u}\|_2^2 \tag{1}$$

and $\mathbf{u}^*$ can be obtained by minimizing $\Pi(\mathbf{u}^*)$ with respect to $\mathbf{u}^*$,

$$\mathbf{u}^{*} = (\Delta t)^{2}\ (\mathbf{L}^{T}\mathbf{L} + \lambda^{2}\mathbf{I})^{-1}\mathbf{L}^{T}\mathbf{L}_{a}\mathbf{a} + \lambda^{2}(\mathbf{L}^{T}\mathbf{L} + \lambda^{2})^{-1}\mathbf{u}; \mathbf{L} = \mathbf{L}_{a}\mathbf{L}_{c} \tag{2}$$

where $\mathbf{u}^{*}$, $\mathbf{u}$,and $\mathbf{a}$ are the final displacement vector $[u^{*}(k-M), u^{*}(k-M+1), , u^{*}(k+M)]^{T}$, vector of the radar-based displacement $[u(k-M), u(k-M+1), , u(k+M)]^{T}$, and measured acceleration vector $[a(k-M+1), a(k-M+2), , a(k+M-1)]^{T}$, respectively. Δt is the time interval of measurements. $\|.\|_{2}$ denotes the two-norm of a vector, $\mathbf{L}_{a}$ is a diagonal weighting matrix of the order $(2M-1)$ with all diagonal entries being 1 except the first and last entries, which are equal to $1/\sqrt{2}$,$\mathbf{L}_{c}$ is the second-order differential operator matrix based on the discretized trapezoidal rule, and λ is the regularization factor.More details can be found in Lee et al[2] and Ma et al[4].

Although the displacement at each time step within the time window can be estimated, the accuracy is highest at the center of the time window. Thus, only the displacement estimated at the center of each time window is retained.

$$\mathbf{u}^{*}(k) = \mathbf{C}_{H}\mathbf{a} + \mathbf{C}_{L}\mathbf{u} \tag{3}$$

where $\mathbf{C}_{H}$ is the $(M+1)^{th}$ row of the matrix $(\Delta t)^{2}\ (\mathbf{L}^{T}\mathbf{L} + \lambda^{2}\mathbf{I})^{-1}\mathbf{L}^{T}\mathbf{L}_{a}$ and is a combination of a double integrator and a high-pass filter. $\mathbf{C}_{L}$ is the $(M+1)^{th}$ row of the matrix $\lambda^{2}(\mathbf{L}^{T}\mathbf{L} + \lambda^{2})^{-1}$, and is a low-pass filter[4].It should be noted that the use of FIR filter introduce a time delay of $(M+1)\Delta t$ in the displacement estimation.

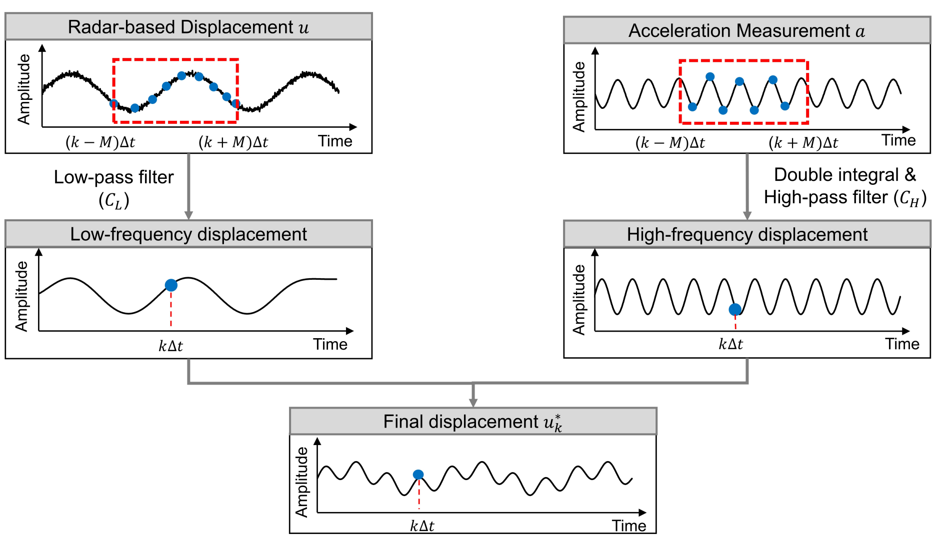

Fig. 3. Final displacement estimation by the FIR filter based fusion of the radar-based displacement and acceleration measurement

3 Experimental validation

The displacement estimation performance of the proposed technique is experimental validated by a laboratory test on a four-story building model and a field test on a pedestrian steel box girder bridge. Fig. 4(a) shows the experimental setup on a four-story building model. A shaker moved the building model in a horizontal direction. The displacement at the top of the building model was estimated using an accelerometer and an mmWae radar installed at same location, and was measured by a laser Doppler vibrometer (LDV). Fig. 4(b) shows the experimental setup on a pedestrian steel box girder bridge. An accelerometer and an mmWae radar were installed at the mid-span of the bridge to estimate bridge displacement at same location. A LDV was installed under the bridge for reference displacmenet measurement. Fig. 4(c) shows the Polytech RSV-150 LDV used in this study which is able to measure displacement with a resolution of less than 1 μm. Fig. 4(d) 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 155 dB dynamic range and a wide frequency response up to 200 Hz. Fig. 4(e) shows the TI IWR1642 mmWave radar used in this study. The radar is an integrated single-chip mmWave sensor based on (frequency modulated continues wave) FMCW radar technology, and is able to operate in the range of 76 to 81GHz band with up to 4 GHz continuous chirp. It has four receive channels and two transmit channels.

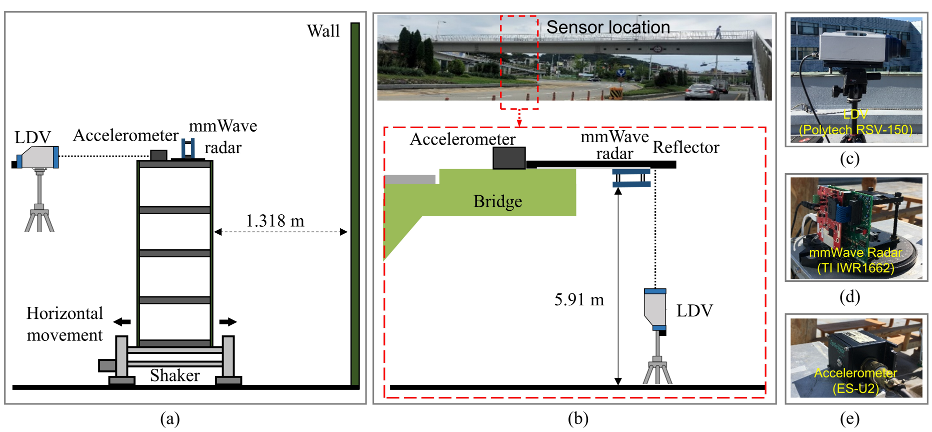

Fig. 4. Overview of experimental validation: (a) sensor setup on a four-story building model, (b)sensor setup on a pedestrian steel box girder bridge, (c) a Polytech RSV-150 laser Doppler vibrometer (LDV) used for reference displacement measurement, (d) a TI IWR1642 mmWave radar and (e) an EpiSensor ES-U2 accelerometer used for displacement estimation.

Displacements estimated by the proposed technique on the four-story building model and the pedestrian steel box girder bridge are presented in Figs. 5 and

6. In both tests, displacements estimated by the proposed technique had good agreement with the reference displacements measured by the LDV. The root mean square errors (RMSEs) were only 0.24 mm and 0.03 mm in the four-story building model and pedestrian steel box girder bridge tests, respectively.

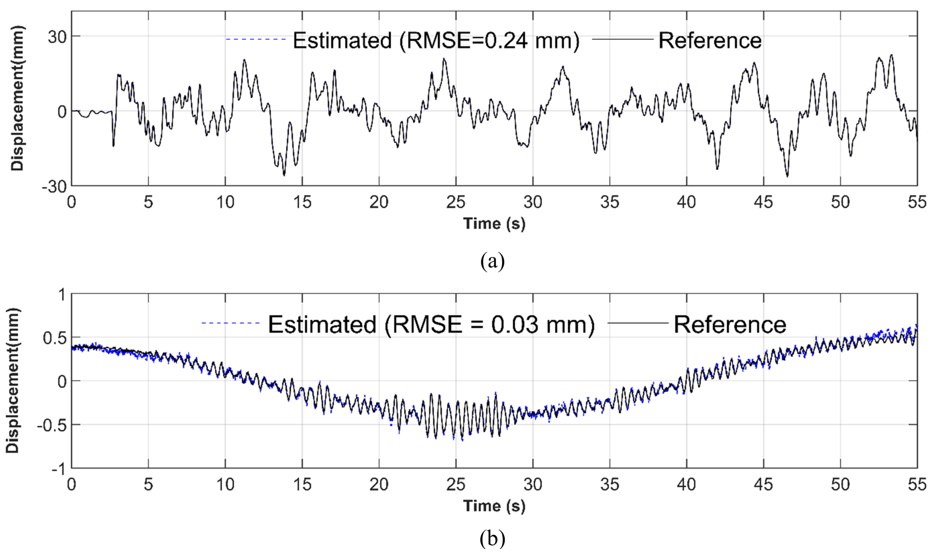

Fig. 5. Displacements estimated by the proposed technique on (a) the four-story building model and (b) the pedestrian steel box girder bridge (whole time period).

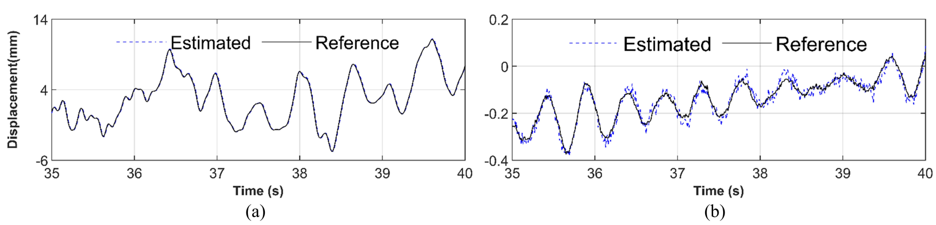

Fig. 6. Displacements estimated by the proposed technique on (a) the four-story building model and (b) the pedestrian steel box girder bridge (zoomed in [35s- 40s]).

4 Conclusion

This study proposed a displacement estimation technique through the fusion of a collocated mmWave radar and an accelerometer on a structure. In order to validate the performance of the proposed displacement estimation technique, a laboratory test was firstly conducted on a four-story building model. The result shows that the proposed technique was able to estimate displacement accurately with RMSE less than 0.3 mm. In addition, the proposed technique was applied to estimate displacement of a pedestrian steel box girder bridge. Though the bridge has only a tiny displacement (less than 1 mm), the proposed technique was still capable for high-performance displacement estimation. Efforts are currently making to develop a low-cost displacement sensor module by integrating mmWave radar, accelerometer and micro-controller together.

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References

1. Hester, D., Brownjohn, J., Bocian, M., Xu, Y. : Low cost bridge load test: Calculating bridge displacement from acceleration for load assessment calculations. Eng. Struct. 143, 358-374 (2017). doi:10.1016/j.engstruct.2017.04.021
2. Lee, S., Hong, H., Park, H. : Design of an FIR filter for the displacement reconstruction using measured acceleration in low-frequency dominant structures. Int. J. Numer. Methods Eng. 82(4), 403-434 (2010). doi:10.1002/nme.2769
3. Moschas, F., Stiros, s. : Measurement of the dynamic displacements and of the modal frequencies of a short-span pedestrian bridge using GPS and an accelerometer. Eng. Struct. 33(1), 10-17 (2011). 10.1016/j.engstruct.2010.09.013
4. Ma, Z., Chung, J., Liu, P., Sohn, H.: Bridge displacement estimation by fusing accelerometer and strain gauge measurements. Struct Control Health Monit. 28(6), e2733 (2021). doi:10.1002/stc.2733
5. Ma, Z., Sohn, H.:Structural Displacement Estimation by FIR Filter Based Fusion of Strain and Acceleration Measurements. In: The 29th International Ocean and Polar Engineering Conference (2019).
6. Ozdagli, A. I.,Gomez, J. A., Moreu, F.: Real-Time Reference-Free Displacement of Railroad Bridges during Train-Crossing Events. J. Bridge Eng. 22(10), 04017079 (2021). doi:10.1061/(ASCE)BE.1943-5592.0001113
7. Ma, Z., Choi, J., Sohn, H.: Real-time structural displacement estimation by fusing asynchronous acceleration and computer vision measurements. COMPUT-AIDED CIV INF. 37(6), 688-703 (2022). doi:10.1111/mice.12767
8. Zhang, G., Wu, Y., Zhao, W., Zhang, J.: Radar-based multipoint displacement measurements of a 1200-m-long suspension bridge. ISPRS J. Photogramm. Remote Sens. 167, 71-84 (2020). doi:10.1016/j.isprsjprs.2020.06.017
9. Gentile, C.: Deflection measurement on vibrating stay cables by non-contact microwave interferometer. NDT E Int. 43(3), 231-240 (2010). doi:10.1016/j.ndteint.2009.11.007
10. Guo, J., He, Y., Jiang, C., Jin, M., Li, S., Zhang, J., Xi, R., Liu, Y.: Measuring Micrometer-Level Vibrations with mmWave Radar. IEEE Trans Mob Comput. 1-1 (2021). doi:10.1109/TMC.2021.3118349

11. Ma, Z., Choi, J., Sohn, H.: Structural displacement estimation using accelerometer and FMCW millimeter wave radar. Mech Syst Signal Process. Submitted (2022).
12. Wang,G., Munoz-Ferreras,J.-M., Gu, C., Li, C., Gomez-Garcia, R.: Application of linear-frequency-modulated continuous-wave (LFMCW) radars for tracking of vital signs, IEEE Trans. Microw. Theory Tech. 62, 1387–1399 (2014). doi:10.1109/TMTT.2014.2320464