Structural Displacement Estimation of Rail Bridges Through Millimeter-Wave Radar, Accelerometers, and Non-Dedicated Multi-Modal Sensing

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ABSTRACT

Rail bridges are essential components of modern transportation networks but often operate beyond their intended service life, leading to growing concerns about structural integrity and public safety. Traditional structural health monitoring (SHM) systems can be prohibitively expensive and complex, limiting their widespread use—especially for smaller rail bridges with constrained budgets. To address these challenges, we present a novel, cost-effective radar–accelerometer fusion sensor designed to provide real-time, high-precision displacement and acceleration measurements. Our approach integrates a millimeter-wave frequency-modulated continuous-wave (FMCW) radar module with a three-axis MEMS accelerometer, enabling accurate detection of even the slightest structural movements. Specifically, our sensor achieves a root-mean-square error for displacement below 0.1 mm, which is suitable for capturing subtle deformations that may indicate underlying structural issues. The hardware leverages off-the-shelf components, including an Infineon 60 GHz radar chipset and a microcontroller equipped with wireless interfaces (2.4/5.0 GHz Wi-Fi, Bluetooth, and Gigabit Ethernet), all housed in a compact ($100 \times 80 \times 50$ mm^3) enclosure. Due to its streamlined design and off-the-shelf parts, mass production costs can be kept under $1,000, making it feasible for large-scale deployments. To enhance measurement fidelity, the sensor employs automatic radar target selection, guided by initial radar and acceleration data, to overcome multiple reflections and phase ambiguity in FMCW signals. This ensures robust performance under a range of field conditions and traffic scenarios. Beyond local displacement and acceleration measurements, our framework incorporates existing fiber-optic cables—originally installed for telecommunications—to form wide-area strain gauges. By using distributed fiber-optic sensing, rail bridge operators gain a broader, continuous view of structural behavior across extensive spans without requiring further dedicated sensor installations. These data sources are synchronized with a common NTP server, enabling advanced analytics that fuse displacement, strain, and vibration information into a unified, real-time rail bridge monitoring platform. Through this multi-modal integration, our radar–accelerometer fusion sensor not only addresses critical cost and scalability concerns but also provides a transformative leap in monitoring accuracy and operational efficiency. By integrating cost-effective hardware and distributed fiber-optic sensing, rail bridge stakeholders can pursue more precise, data-driven maintenance strategies, leveraging highly accurate displacement and acceleration measurements to proactively address structural concerns and extend service life

INTRODUCTION

Accurate displacement measurement of railway bridges is essential for evaluating their structural integrity and ensuring public safety, particularly under dynamic loads induced by high-speed train operations. Reliable monitoring systems provide critical insights into bridge behavior, informing proactive maintenance and helping prevent structural failures. However, current displacement monitoring technologies face challenges, such as sensitivity to environmental variations, operational complexities, and high deployment costs, limiting their widespread implementation.

Millimeter-wave frequency-modulated continuous-wave (FMCW) radar sensors offer a promising solution due to their inherent advantages, including compact size, high accuracy, and resilience to environmental disturbances. Their short-wavelength radar signals enable the detection of subtle structural movements, essential for precise structural assessments. Nonetheless, radar-based measurements face challenges such as phase ambiguity and reliance on optimal reflection targets, which complicate long-term monitoring and accuracy under dynamic conditions. To address these limitations, the integration of radar sensors with complementary measurement technologies is necessary.

This study presents an advanced displacement measurement system primarily leveraging FMCW radar sensors, designed explicitly for rail bridge monitoring. Our approach employs an adaptive algorithm that automatically selects optimal radar reflection targets, effectively addressing phase ambiguity through complementary displacement estimation techniques. These methods significantly enhance accuracy, providing reliable displacement measurements suitable for safety-critical rail infrastructure.

Furthermore, to expand the spatial coverage and enhance the accuracy of distributed displacement assessments, we propose future integration with distributed fiber-optic sensing techniques. By utilizing pre-existing fiber-optic cables initially installed for telecommunications purposes, the bridge's structural deformation across extended spans can be continuously monitored, enabling a comprehensive and detailed evaluation of structural performance. This integrated approach promises not only improved monitoring accuracy but also a scalable, cost-effective solution for widespread deployment on railway bridge networks.

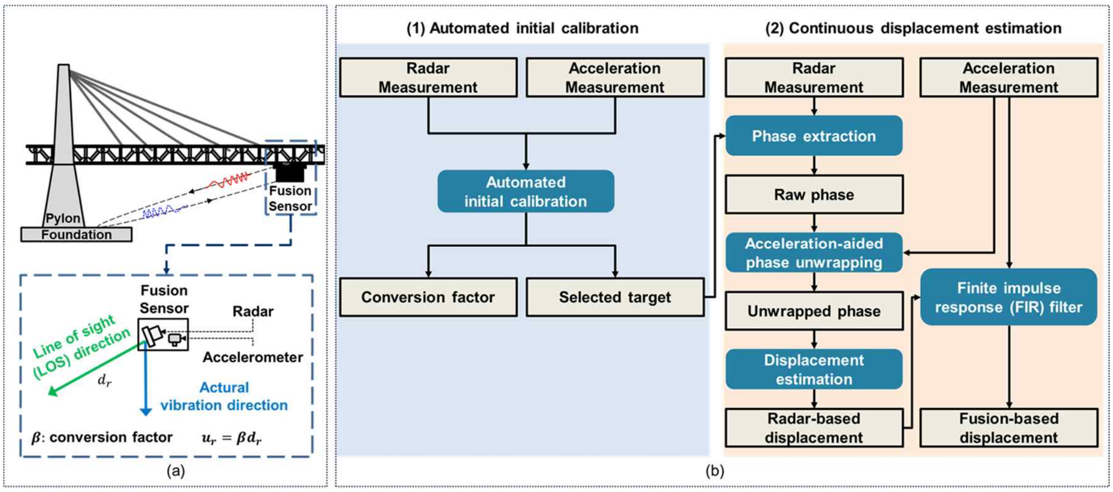


Figure 1. Overview of the proposed displacement estimation approach integrating FMCW radar and accelerometer: (a) schematic illustration of sensor installation on a rail bridge structure, and (b) data fusion workflow highlighting automated calibration, phase-unwrapping, and FIR-based displacement estimation.

METHODOLOGY

The proposed displacement measurement approach integrates a compact millimeter-wave FMCW radar sensor with a high-precision MEMS accelerometer, co-located at strategic positions on rail bridge structures. This integrated sensor arrangement simplifies installation, eliminates the need for external reference targets, and supports reliable, long-term monitoring. The radar component utilizes an Infineon 60 GHz FMCW chipset, selected for its high accuracy, robustness in outdoor environments, and minimal power consumption. A MEMS accelerometer complements the radar by providing stable acceleration measurements, crucial for enhancing displacement measurement reliability and resolving radar ambiguities.

An essential initial step involves automatic calibration to identify optimal radar reflection targets. Initially, synchronized short-duration radar and accelerometer data are collected (typically under one minute). During this calibration, the system automatically selects the optimal radar target by minimizing the root mean square error (RMSE) between high-frequency displacement estimates independently derived from radar and accelerometer measurements. This process generates a precise conversion factor, translating radar-measured line-of-sight displacement into the actual structural displacement direction. This automatic calibration significantly reduces manual setup efforts and ensures consistent performance in varying operational conditions.

A critical limitation of radar-based displacement measurements is phase ambiguity (phase wrapping), particularly under conditions involving substantial structural movements exceeding radar wavelength constraints. To address this challenge, we implement an accelerometer-aided adaptive phase-unwrapping algorithm. The algorithm employs current accelerometer data and previous radar displacement estimations to predict structural displacement at each measurement step. By comparing this predicted displacement against radar's measured wrapped phase, the algorithm accurately determines necessary multiples of 2π corrections, effectively resolving phase ambiguities and ensuring accurate displacement measurements even under large dynamic vibrations.

Once the radar-based displacement is accurately estimated using the accelerometer-aided phase-unwrapping method, further refinement is conducted using advanced sensor data fusion techniques. A finite impulse response (FIR) filter systematically combines radar and accelerometer measurements, significantly reducing measurement noise and drift. The FIR filter leverages radar's precise high-frequency displacement detection and the accelerometer's stable low-frequency characteristics, achieving robust and accurate displacement estimations suitable for real-time structural monitoring under typical dynamic loads induced by high-speed trains.

To enhance spatial resolution and provide comprehensive distributed displacement profiles, future implementations will integrate radar-based point measurements with distributed strain data from existing telecommunication fiber-optic cables. By applying distributed fiber-optic sensing methods, such as Rayleigh-based optical frequency domain reflectometry (OFDR), the bridge's structural deformation can be continuously monitored along extensive spans, significantly augmenting the spatial coverage and resolution of displacement monitoring. This future integration aims to create a robust, cost-effective, and high-resolution multi-modal structural monitoring platform for rail bridge infrastructure.

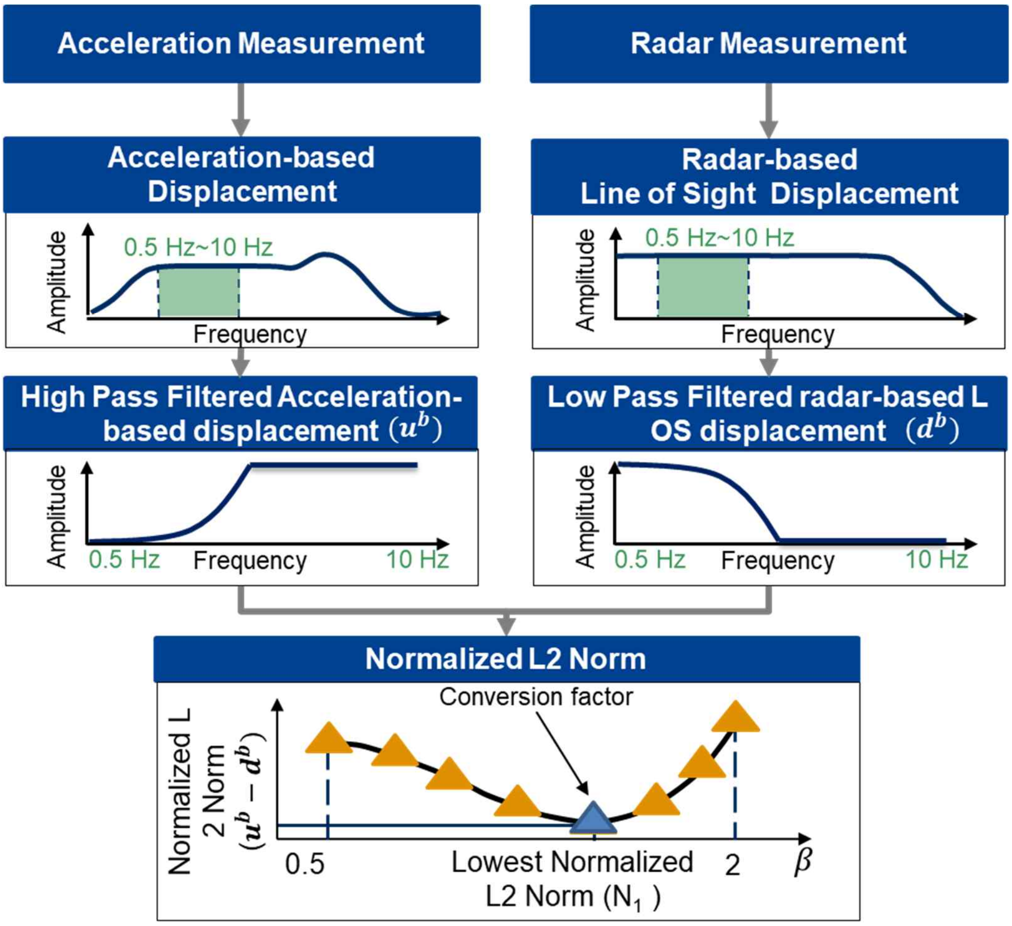


Figure 2. Automated calibration workflow illustrating the selection of optimal radar reflection targets. Radar displacement data undergo low-pass filtering to remove high-frequency noise, while accelerometer displacement data are processed through high-pass filtering to mitigate low-frequency drift. The optimal radar target and conversion factor are automatically determined by minimizing differences between filtered accelerometer and radar displacement signals, ensuring accurate translation of radar line-of-sight measurements into structural displacement.

EXPERIMENTAL VALIDATION

The validation experiment was conducted on a prestressed concrete railway bridge spanning approximately 36 meters, representing typical high-speed railway infrastructure. To evaluate the accuracy and reliability of the proposed radar-based displacement measurement system, integrated sensor units consisting of FMCW radar and MEMS accelerometers were installed at strategic locations beneath the bridge deck. These sensor units were securely fixed directly onto the structure to effectively capture maximum structural displacement induced by passing trains.

For reference measurements, a high-precision Laser Doppler Vibrometer (LDV) was positioned at ground level, directly beneath the midpoint of the bridge span, aligned accurately with the primary sensor unit. The LDV provided reliable reference displacement data against which the performance of the proposed radar-accelerometer system could be evaluated.

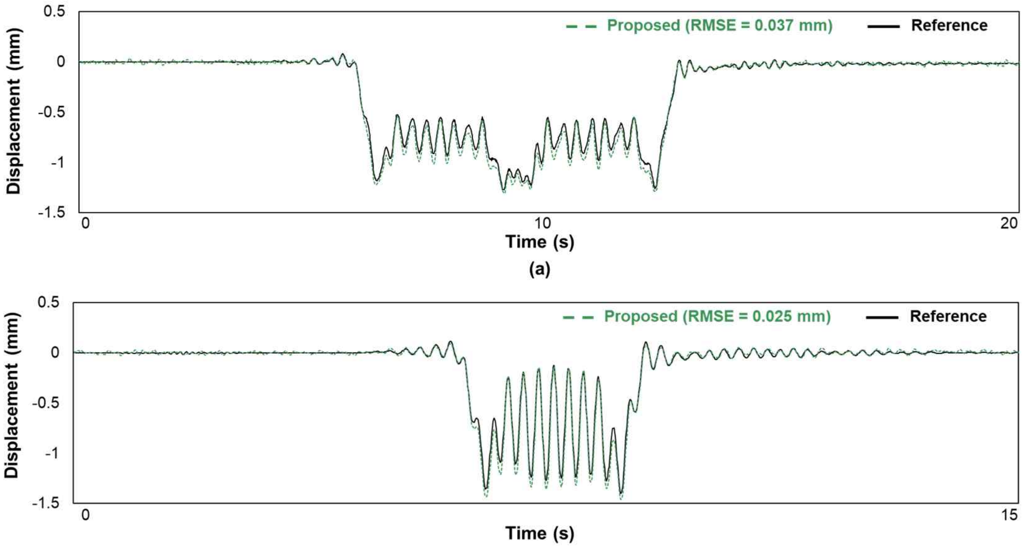
(a) (b)

Figure 3. Experimental setup on the Gongju-Osong High-Speed Rail Bridge: (a) Elevation view indicating sensor positions and the Laser Doppler Vibrometer (LDV) reference measurement location, along with relevant distances. (b) Detailed illustration showing precise sensor installation and alignment beneath the bridge structure.

The displacement monitoring setup included an Infineon XENSIV™ BGT60TR13C 60 GHz FMCW radar chipset, chosen for its superior precision and robustness in outdoor environments, and an Analog Devices ADXL355 MEMS accelerometer, noted for its low noise and high stability. These sensors were connected to an integrated Microprocessor Unit (MPU), enabling synchronized real-time data acquisition. Edge computing capabilities allowed initial displacement data processing directly at the sensor nodes, significantly reducing the amount of data transmitted wirelessly to the centralized monitoring system, thus improving overall system efficiency.

To assess sensor accuracy under realistic operational conditions, the bridge underwent dynamic load testing with passing high-speed trains, including the Korea Train eXpress (KTX) and Super Rapid Train (SRT). Tests were systematically conducted at varying train speeds and frequencies, ensuring comprehensive evaluation across diverse operational scenarios. Throughout testing, displacement measurements obtained from the radar-accelerometer system were continuously compared against LDV reference measurements to quantify accuracy and reliability.

The experimental results consistently demonstrated high agreement between the proposed radar-based displacement measurements and LDV reference data. Figure 4 illustrates representative displacement responses induced by passing KTX and SRT trains, clearly showing the close correspondence between radar-accelerometer fusion measurements and the LDV reference. Quantitative evaluations confirmed excellent system performance, with RMSE values below 0.05 mm, validating the system’s precision and reliability under typical dynamic loads of high-speed rail traffic.



(a)

(b)

Figure 4. Comparison of displacement measurements from dynamic load tests: (a) bridge response induced by a passing Korea Train eXpress (KTX), and (b) response induced by a Super Rapid Train (SRT). The proposed radar-accelerometer fusion sensor results (green dashed lines) closely match LDV reference data (black solid lines). Root mean square error (RMSE) values indicate the accuracy and reliability of the proposed monitoring system.

Future integration of distributed fiber-optic sensing techniques is planned. Leveraging existing telecommunication fiber-optic cables installed along rail bridges can provide continuous distributed strain data across extensive spans. By combining localized radar-accelerometer measurements with spatially continuous fiber-optic data, bridge operators could achieve a more comprehensive and detailed assessment of structural performance, significantly enhancing monitoring coverage and resolution.

CONCLUSIONS

This study presented an advanced radar-based displacement monitoring method for railway bridges using integrated millimeter-wave FMCW radar and MEMS accelerometer sensors. The proposed method effectively addressed traditional measurement limitations by employing automatic calibration, accelerometer-assisted adaptive phase-unwrapping, and FIR filtering techniques. Field validation conducted on the Gongju-Osong High-Speed Rail Bridge demonstrated the system’s excellent accuracy, achieving displacement measurement errors below 0.05 mm when compared to LDV reference data. Future studies will expand the proposed methodology by integrating distributed fiber-optic sensing, leveraging existing telecommunication cables for spatially continuous strain measurements. This multi-modal sensing approach is expected to significantly enhance structural health monitoring capabilities, providing comprehensive, high-resolution assessments of railway bridge infrastructure.

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