

# Displacement Estimation of Reactor Containment Buildings Using Accelerometer and FMCW Millimeter-Wave Radar

---

HOON SOHN and JIGU LEE

## ABSTRACT

This study presents an advanced fusion-based sensing methodology designed specifically for precise displacement and acceleration monitoring of Reactor Containment Buildings (RCBs). Reliable measurement of structural displacement in RCBs is critical for ensuring structural integrity and operational safety. To address challenges associated with traditional displacement monitoring techniques, this research integrates data from a three-axis MEMS accelerometer and phase-shift measurements obtained from millimeter-wave frequency-modulated continuous-wave (FMCW) radar. By fusing these distinct sensor modalities, we significantly enhance measurement accuracy, achieving displacement estimation resolutions superior to 0.1 mm for both static and dynamic structural responses. The proposed sensor's hardware architecture emphasizes cost-efficiency, compactness, and reliability. The sensor system employs an Infineon 60 GHz radar chipset, combined with a MEMS accelerometer and a microcontroller supporting multiple wireless communication protocols (2.4/5.0 GHz Wi-Fi, Bluetooth, and Gigabit Ethernet). This robust yet economical sensor design results in a compact device ( $100 \times 80 \times 50 \text{ mm}^3$ ) and is projected to cost under \$1,000 per unit when mass-produced, making it highly suitable for wide-scale deployments in nuclear facilities. A key innovation of the developed fusion sensor is its automated best-target selection capability, which utilizes initial short-duration radar and accelerometer readings to efficiently determine the most stable structural reflections and establish accurate conversion factors between line-of-sight displacement and actual structural displacement. Additionally, the accelerometer data aids in addressing the radar phase-wrapping issue through an adaptive phase-unwrapping algorithm, thus significantly enhancing measurement reliability and accuracy. To further improve displacement estimation, radar-derived displacement data is combined with accelerometer measurements using a finite impulse response (FIR) filter, which mitigates noise and drift typically observed in acceleration-based displacement estimations. Through experimental validations conducted on structural models, this sensor fusion method demonstrated improved displacement measurement accuracy with errors consistently below 1 mm. Given its capacity for automatic calibration, effective target selection, and enhanced resilience against occlusions and environmental interferences, the sensor offers a reliable solution for continuous monitoring of RCBs. Ultimately, the proposed sensor fusion approach presents significant potential for adoption in nuclear power facilities, enhancing predictive maintenance, optimizing structural health management strategies, and reinforcing overall operational safety.

## INTRODUCTION

Reliable monitoring of structural integrity in RCBs is critical for ensuring safety and operational continuity within nuclear power plants. Displacement measurements are particularly important as they directly reflect structural stability and performance under various loading conditions, including environmental influences, operational stresses, and extreme events. However, traditional displacement measurement methods, such as Linear Variable Differential Transformers (LVDTs) or optical systems, face significant challenges in nuclear environments. These conventional methods can be prohibitively expensive, difficult to maintain, and sensitive to external factors such as radiation, temperature fluctuations, and humidity, thus limiting their long-term reliability and effectiveness.

Recent technological advancements in sensing provide promising alternatives. In particular, millimeter-wave Frequency-Modulated Continuous-Wave (FMCW) radar sensors offer distinct advantages including high accuracy, robustness against environmental disturbances, compact size, and remote sensing capabilities [1]. Concurrently, Micro-Electro-Mechanical System (MEMS)-based accelerometers have emerged as highly accurate, low-cost sensors capable of capturing dynamic acceleration with minimal drift and high reliability under harsh conditions. Despite their individual strengths, both sensors exhibit inherent limitations: radar sensors can experience phase ambiguity issues due to wavelength constraints, while accelerometers are prone to drift accumulation over time, impacting long-term displacement accuracy [3, 4].

To overcome these challenges, this paper proposes an innovative sensor fusion approach combining the complementary strengths of FMCW radar and MEMS accelerometers to achieve robust, high-resolution displacement monitoring in RCBs. The developed integrated sensor system, which incorporates an Infineon 60 GHz radar chipset, a three-axis MEMS accelerometer, and a multi-communication microcontroller, aims to reliably estimate structural displacement at resolutions better than 0.1 mm under both static and dynamic loading conditions. Moreover, automated calibration and advanced data fusion techniques are employed to enhance measurement precision, simplify sensor installation and maintenance, and ensure continuous real-time structural assessment capability.

The remainder of this paper is structured as follows. Section 2 describes the detailed methodology of the sensor fusion process, emphasizing automated calibration, phase-unwrapping algorithms, and filtering techniques. Section 3 outlines planned experimental validations, highlighting data acquisition, processing workflows, and structural assessment applications. Section 4 presents expected outcomes and implications of this approach, emphasizing its practical benefits and scalability for structural health monitoring in nuclear power facilities. Lastly, Section 5 concludes the paper and outlines directions for future research.

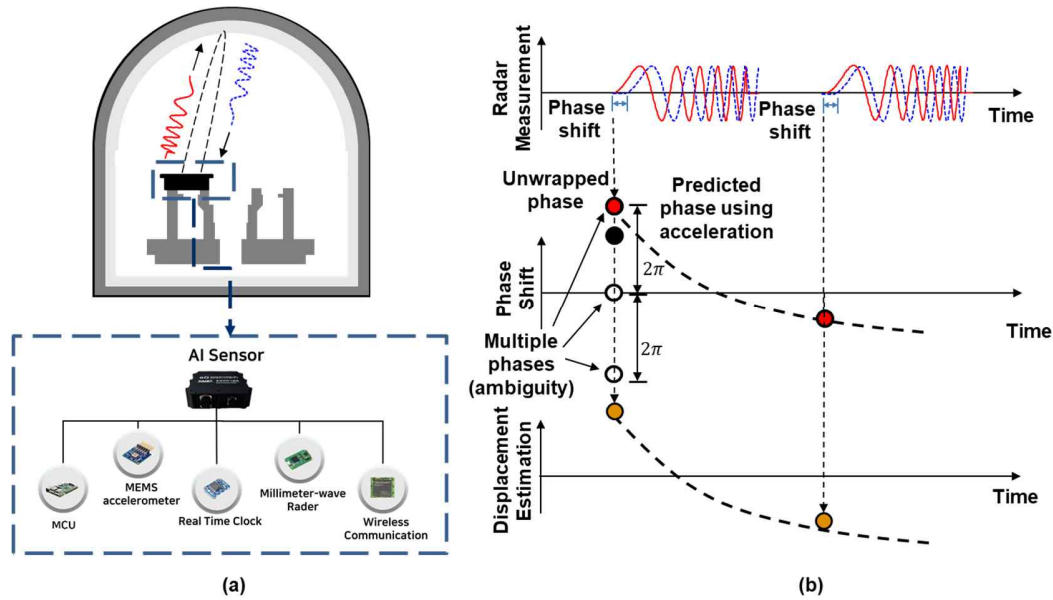


Figure 1. (a) Schematic illustration of the integrated sensor system for monitoring RCBS. (b) Procedure for displacement estimation combining radar and accelerometer data.

## METHODOLOGY

The proposed displacement monitoring system integrates a MEMS accelerometer and FMCW millimeter-wave radar in a compact sensor module, specifically developed for RCBS. Both sensors are collocated and directly mounted on structural measurement points, eliminating the need for external reference targets and significantly simplifying installation. The system consists of an Infineon 60 GHz radar chipset, a high-precision three-axis MEMS accelerometer, and a microcontroller supporting multiple wireless communication protocols, including Wi-Fi (2.4/5.0 GHz), Bluetooth, and Gigabit Ethernet. This integrated design ensures reliability, robustness against harsh nuclear environments, low power consumption, and cost-effectiveness, with projected unit costs below \$1,000 in mass production.

To maximize measurement accuracy, the monitoring system includes an automated calibration procedure executed at the start of sensor deployment. Initially, short-duration (approximately one minute) simultaneous data acquisitions from the radar and accelerometer are performed to determine the most reliable radar reflection target within the detection range. During this calibration phase, the optimal radar target is automatically identified by minimizing the RMSE between radar-derived and accelerometer-derived displacement signals. Subsequently, the system calculates a precise conversion factor between the radar's line-of-sight displacement measurement and the actual structural displacement, ensuring accurate and stable long-term monitoring without continuous manual adjustments.

A key limitation in radar-based displacement estimation is phase ambiguity, known as phase wrapping, especially under large dynamic structural movements. To address this, an accelerometer-aided adaptive phase-unwrapping algorithm is utilized. At each measurement instance, displacement is predicted using recent accelerometer data and prior radar measurements. This predictive displacement estimation helps resolve radar phase ambiguities by identifying and correcting integer multiples of  $2\pi$ .

in the radar-measured phase. Consequently, this method significantly improves the accuracy and reliability of displacement measurements, particularly under dynamic loading scenarios typical of nuclear containment structures.

After phase-unwrapped radar displacement data are accurately determined, further refinement is achieved through advanced sensor data fusion techniques, specifically employing finite impulse response (FIR) filters. FIR filtering systematically integrates high-frequency radar displacement data with low-frequency accelerometer measurements, effectively mitigating the accelerometer's inherent drift and radar measurement noise as [2]. The fusion process exploits the complementary strengths of both sensors—radar's precise high-frequency response and accelerometer's stable low-frequency characteristics—resulting in highly accurate displacement measurements. Additionally, the sensor system incorporates complementary and Madgwick filters for enhanced accuracy in displacement, acceleration, and structural tilt estimation, ultimately ensuring robust and reliable long-term monitoring suitable for RCB safety management.

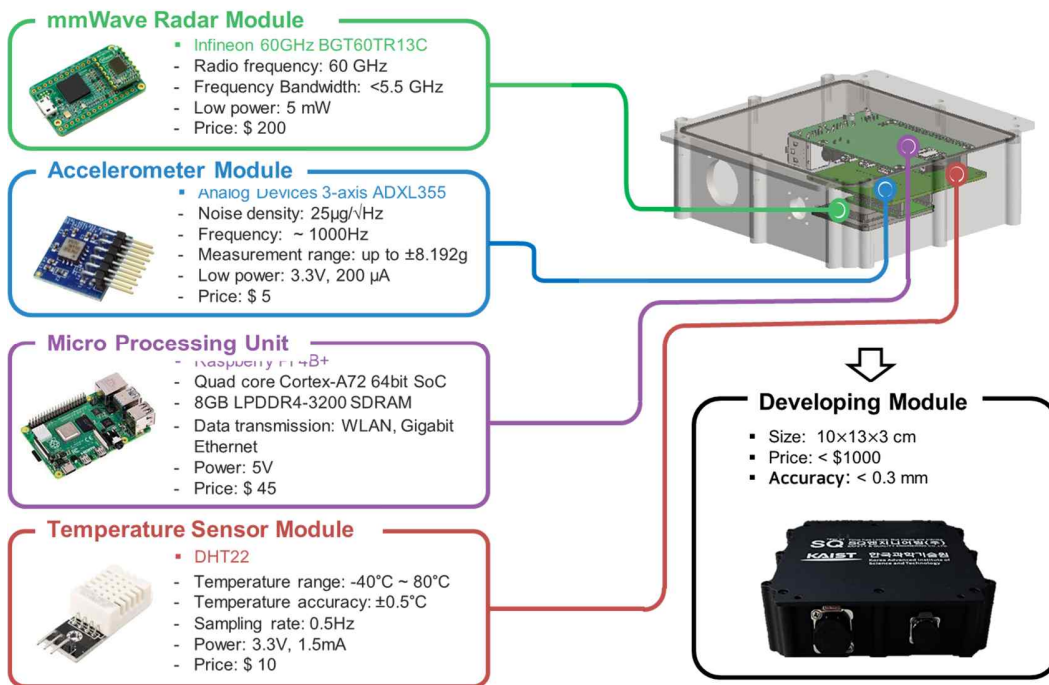


Figure 2. Photograph of the integrated monitoring sensor, illustrating the compact arrangement of the FMCW radar, MEMS accelerometer, microcontroller, and wireless communication interfaces designed for robust structural monitoring in nuclear environments.

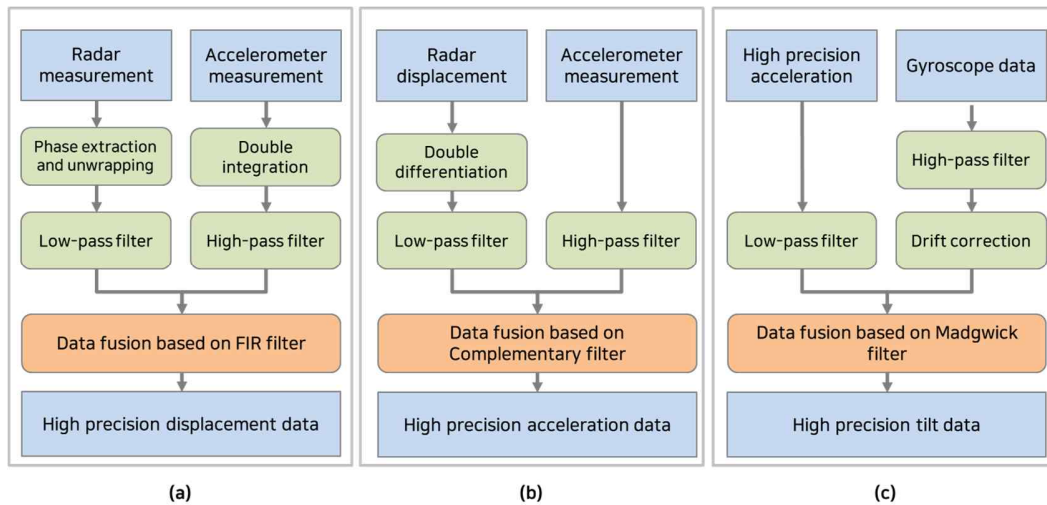


Figure 3. Data fusion workflow diagrams for (a) displacement estimation, (b) acceleration measurement, and (c) structural tilt evaluation, illustrating the integration of radar, accelerometer, and gyroscope data through FIR, complementary, and Madgwick filtering techniques.

## PLANNED VALIDATION

The proposed sensor fusion approach will undergo comprehensive validation through laboratory and field experiments simulating realistic Reactor RCB conditions. The validation procedure begins with synchronized acquisition of displacement and acceleration data from the collocated FMCW radar and MEMS accelerometer sensors. Radar signals will first undergo phase extraction and adaptive phase-unwrapping to address inherent ambiguities. Radar-derived displacement data will then be processed through low-pass filtering to remove high-frequency noise, whereas accelerometer data will be double-integrated and high-pass filtered to reduce drift effects. Subsequently, these processed datasets will be fused using FIR filters, providing precise and reliable displacement estimations essential for structural integrity assessments.

For comprehensive structural monitoring, further processing will extract acceleration from displacement measurements via double differentiation and filtering. Additionally, structural tilt will be evaluated using integrated gyroscope and accelerometer data processed through complementary and Madgwick filters, enhancing overall reliability and accuracy of structural health evaluations.

An essential component of RCB structural integrity is maintaining appropriate tension levels in Post-Tensioning (PT) tendons. The proposed system aims to estimate PT tendon tension indirectly by correlating structural displacement and acceleration data with structural characteristics obtained from finite element models. Continuous monitoring of vertical and horizontal displacements, accelerations, and structural tilt will provide valuable insights into changes in tendon tension over time, facilitating early detection of structural deterioration and enabling proactive maintenance strategies.

The sensor system incorporates on-board TinyAI technology to enable continuous real-time structural safety assessment. By analyzing incoming sensor data streams in real-time, the system can swiftly detect abnormal structural events such as excessive deformation or sudden anomalies, immediately triggering safety alerts. This approach provides operators with rapid identification of potential risks, significantly improving response time and mitigating safety hazards within nuclear facilities.

Extensive field validation tests are planned in collaboration with nuclear facility operators. These tests will evaluate the sensor system’s accuracy, reliability, and robustness under diverse operational scenarios within actual RCB environments. Field-collected sensor data will be rigorously compared against benchmark measurements from validated structural analysis models and existing conventional monitoring techniques. These validations will confirm the practical applicability, accuracy, and reliability of the proposed sensor fusion methodology, facilitating confident implementation in real-world nuclear safety management applications.

## EXPECTED OUTCOMES AND IMPLICATIONS

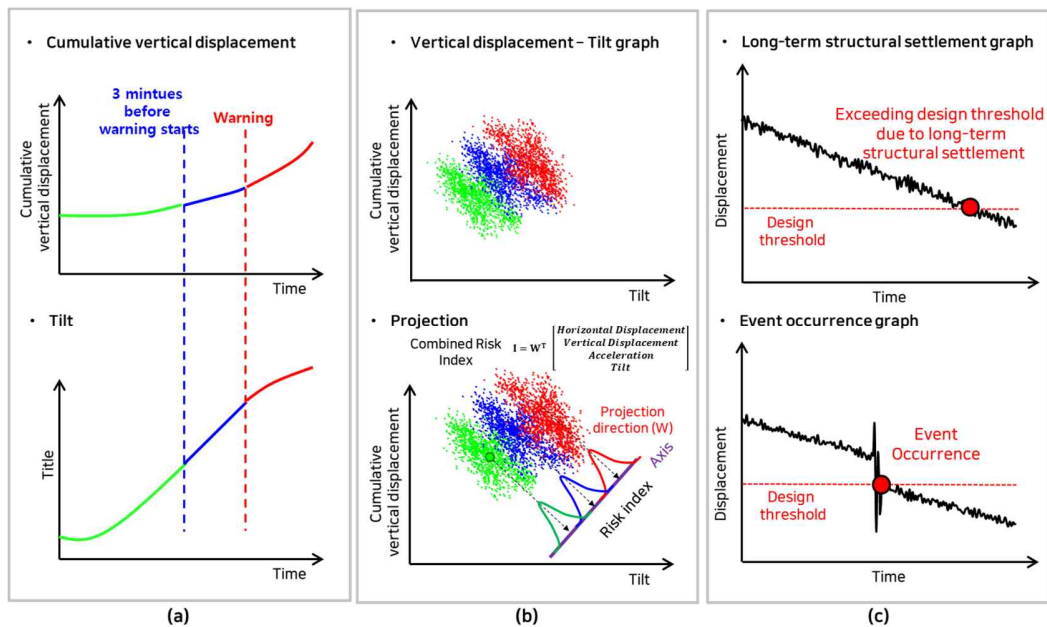


Figure 4. Structural safety evaluation approach for RCBs, showing (a) extraction of risk indicator features, (b) feature-level data fusion, and (c) scenario-based safety assessment using real-time sensor data.

The primary expected outcome of the proposed sensor fusion approach is significantly enhanced accuracy in structural displacement and acceleration measurements within RCBs. By effectively integrating FMCW radar and MEMS accelerometer data through advanced filtering and adaptive phase-unwrapping algorithms, the system aims to consistently achieve displacement estimation resolutions finer than 0.1 mm. This increased accuracy enables early and reliable detection of subtle structural changes, greatly enhancing the capability to prevent severe structural failures.

Integrating radar, accelerometer, and gyroscope measurements with advanced data processing algorithms provides a comprehensive structural health assessment framework. This integrated approach will facilitate not only precise displacement and acceleration monitoring but also accurate structural tilt estimations. Additionally, correlating these structural responses with PT tendon tension through structural analysis models further strengthens predictive maintenance capabilities, supporting proactive decision-making and extending the operational lifespan of critical nuclear infrastructure.

By incorporating TinyAI-based real-time analytics directly within the sensor system, the proposed method significantly enhances the capability for immediate risk detection and rapid response. Real-time structural anomaly detection, facilitated by continuous data evaluation against established safety thresholds, will enable prompt alerts and timely interventions, substantially reducing safety hazards and improving overall operational safety within nuclear facilities.

The proposed sensor system's compact, integrated design ensures cost-effectiveness, ease of installation, and minimal maintenance requirements, facilitating widespread deployment within nuclear power plants. With a projected mass-production cost of under \$1,000 per unit, this affordable solution can feasibly support extensive monitoring networks. Consequently, broader adoption can significantly increase monitoring coverage, enhancing structural safety and operational efficiency across nuclear facilities.

The successful validation and practical implementation of the developed sensor fusion methodology hold potential implications far beyond nuclear power applications. This adaptable monitoring technology can be similarly implemented in other critical infrastructure sectors, such as bridges, dams, tunnels, and large industrial facilities. Thus, the proposed approach demonstrates significant promise in advancing structural health monitoring practices industry-wide, promoting enhanced safety, reliability, and operational performance on a broader scale.

## **CONCLUSIONS**

This paper introduced a novel sensor fusion methodology combining FMCW millimeter-wave radar and MEMS accelerometers for precise displacement and structural health monitoring of Reactor Containment Buildings (RCBs). The proposed integrated sensor system effectively addresses common limitations in traditional monitoring approaches, such as environmental sensitivity, high costs, and measurement ambiguity. Key advancements include automated radar target selection, adaptive accelerometer-aided phase unwrapping, and advanced filtering techniques to achieve displacement resolutions better than 0.1 mm under diverse operational conditions.

## REFERENCES

1. Guo, J., He, Y., Jiang, C., Jin, M., Li, S., Zhang, J., Xi, R., & Liu, Y. (2023). Measuring micrometer-level vibrations with mmWave radar. *IEEE Transactions on Mobile Computing*, 22(4), 2248-2259.
2. Lee, H. S., Hong, Y. H., & Park, H. W. (2010). Design of an FIR filter for the displacement reconstruction using measured acceleration in low-frequency dominant structures. *International Journal for Numerical Methods in Engineering*, 82(4), 403-434.
3. Ma, Z., Choi, J., Yang, L., & Sohn, H. (2023). Structural displacement estimation using accelerometer and FMCW millimeter wave radar. *Mechanical Systems and Signal Processing*, 182, 109582.
4. Ma, Z., Han, K., Choi, J., Lee, J., Kwon, O., Sohn, H., Liu, J., Hwang, D., Aggarwal, J., Noh, H., Cai, E., & Zhang, Y. (2024). Development and field deployment validation of a low-cost and high-precision displacement sensing system by fusing millimeter-wave radar and accelerometer. *Engineering Structures*, 321, 118926.