Journal of Global Positioning Systems
Vol. 22, Issue 1:167-168

Journal of Global Positioning Systems
2026
© CPGPS

ERROR MITIGATION AND QUANTITATIVE ASSESSMENT OF GNSS-BASED STRUCTURAL DEFORMATION MONITORING FOR LONG-SPAN BRIDGES

PhD Candidate: Liangliang Hu

Supervisor: Dr. Xiaolin Meng

Graduate Program: Civil Engineeering

Institution: Beijing University of Technology

Date: June, 2026

Abstract

Long-span bridges are critical components of national transportation systems, and their operational safety is directly related to traffic continuity and socio-economic stability. With the continuous increase in bridge span length and the intensification of external excitations such as wind, temperature variation, and traffic actions, structural dynamic responses and deformation mechanisms exhibit pronounced nonlinearity, multiscale behavior, and multi-source coupling characteristics. Accurate measurement and quantitative analysis of deformation induced by coupled loads across multiple time scales have therefore become key challenges in the long-term reliability assessment of long-span bridges. Owing to its capability for continuous, real-time, and absolute displacement measurement, the Global Navigation Satellite System (GNSS) has become one of the core sensing technologies in structural health monitoring (SHM) systems for long-span bridges.

However, several critical challenges still hinder the engineering application of GNSS-based bridge monitoring: (1) GNSS multipath errors under complex service environments exhibit strong time-varying and environment-coupled characteristics, making accurate modeling and real-time mitigation difficult; (2) GNSS time series are susceptible to outliers, leading to false alarms and reduced reliability of structural warning systems; (3) existing SHM systems primarily focus on state monitoring and lack real-time deformation prediction capability; and (4) GNSS monitoring results are predominantly time-series-based, with limited ability to quantitatively interpret the relationships between multi-source environmental loads and structural responses. These issues restrict the effectiveness of GNSS in bridge condition identification and safety assessment. To address the above challenges, this dissertation establishes an integrated research framework for GNSS-based deformation error suppression and quantitative assessment of long-span bridges, encompassing four aspects: observation-domain error mitigation, coordinate-domain multi-source data fusion, deformation prediction, and state quantification. The main contributions are summarized as follows:

1. A multi-task GNSS multipath mitigation method incorporating environmental perception is proposed. The influence mechanisms of structural location and environmental loads on GNSS multipath errors are revealed, demonstrating that wind speed and temperature affect multipath characteristics by altering the relative geometry between receivers and surrounding reflectors. A LightGBM-based model is developed to predict and suppress multi-frequency pseudorange and carrier-phase multipath errors using satellite geometry, signal quality indicators, and local environmental features. Thirty days of field measurements show that the proposed method achieves multipath reduction exceeding 50% for pseudorange measurements and 30% for carrier phase measurements, while reducing ambiguity re-fixing time to 4 s with a training time of only 1 min, outperforming conventional sidereal filtering, hemispherical models, and mainstream machine learning approaches.

2. A robust multi-rate GNSS/accelerometer

Kalman filtering method based on simplex optimization is developed. To suppress the influence of abnormal GNSS observations, the traditional least-squares state estimation is reformulated as an optimization problem based on the Huber loss function. Unlike conventional robust filters that rely on gradient computation, the proposed method employs the Nelder–Mead direct search algorithm to optimize the non-differentiable loss function. At each epoch, a simplex is constructed around the predicted state and iteratively updated through reflection, expansion, and contraction operations, enabling efficient outlier suppression without gradient information. Experimental results using real bridge data demonstrate that the proposed method improves displacement estimation accuracy by approximately 21% in terms of RMSE and reduces the probability of false alarms under transient disturbances, effectively suppressing warning triggers caused by noise fluctuations within the deformation threshold of ±3σ.

3. An online adaptive artificial neural network–based deformation prediction method is proposed. The macroscopic relationships between environmental loads and structural deformations are first investigated, revealing a significant time-lagged response of vertical deformation to temperature with an average delay of approximately 210 minutes and a correlation coefficient of −0.92. To overcome the limitation of conventional models that cannot be updated online, a parameter update strategy based on "fixed feature layers and fine-tuned output layers" is proposed. By freezing most network parameters and performing online gradient optimization only on the output layer, the model maintains stable load–deformation representations while adaptively adjusting to real-time load variations, thereby achieving stable real-time prediction with reduced computational cost and latency. Validation using nine days of bridge monitoring data shows that the proposed method achieves coefficients of determination (R^2) of 0.98 and 0.87 for lateral and vertical deformation prediction, respectively, with corresponding RMSE values of 1.26 cm and 2.52 cm. Furthermore, SHAP-based interpretability is integrated into the real-time prediction framework to simultaneously quantify the contribution of each environmental load to the predicted deformation.

4. An adaptive OSR-VMD decomposition method constrained by modal sparsity and reconstruction fidelity is proposed for deformation quantification. To address the difficulty of quantitatively attributing structural deformation under coupled multi-source loads, a multi-criteria optimization objective incorporating total bandwidth, modal separation, spectral overlap, and reconstruction energy loss is constructed. A genetic algorithm is employed to automatically optimize VMD parameters, enabling the extraction of deformation modes with clear physical interpretations. Case studies on the Forth Road Bridge establish explicit quantitative relationships: lateral wind speed is identified as the dominant factor governing lateral deformation, with an average increase of approximately 2.5 cm per 1 m/s increase in wind speed; temperature is the primary driver of vertical deformation with a significant delayed response, where a 1°C increase leads to an average reduction of approximately 3.8 cm in vertical deformation. Moreover, the proposed method is capable of stably identifying vertical deflections induced by traffic loads even in the absence of synchronous meteorological data.

Keywords: GNSS, structural health monitoring, error mitigation, real-time deformation prediction, quantitative assessment