

Structural Health Monitoring Based on Integration of GNSS and In-situ Sensors

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ABSTRACT

Structural health monitoring (SHM) is essential in ensuring the safety of large civil engineering structures. Global Navigation Satellite Systems (GNSS) based technology has been commonly used in SHM systems due to its unique ability to obtain real-time three-dimensional (3D) displacement information. GNSS equipment with data sampling rate of up to about 20 Hz has been widely used for this purpose. High-rate GNSS systems (typically up to about 100 Hz) offer additional advantages in structural health monitoring as some highly dynamic civil structures such as some bridges require high-rate monitoring data to capture the dynamic behaviors. The performance of high-rate GNSS positioning in the context of structural health monitoring is however not

entirely known as studies on structural monitoring with high-rate GNSS positioning are very limited, especially considering that some of the satellite systems just reached their full constellations very recently. In addition, GNSS measurements are often integrated with other sensors to enhance the performance of the systems. However, measurement outliers including biases and systematic errors that can significantly reduce the accuracy of SHM results have rarely been considered in the integration processes. In addition, a comprehensive deformation mechanism analysis facilitates structural health assessment and maintenance. Numerous studies have explored the relationship between displacements and single loading, whereas analyzing the interactions of individual

factors with deformation in a multi-loading scenario has not been commonly studied. Therefore, understanding displacement mechanisms of structures accurately is still an urgent issue to be addressed. Some integration approaches are developed in this thesis to fill these gaps. The main innovations of this study include,

First, a series of experiments were carried out with a shaking table to assess the SHM performance of a set of 100 Hz GNSS equipment and three commonly used GNSS positioning techniques, PPP (precise point positioning), PPP-AR (precise point positioning with ambiguity resolution) and RTK (real-time kinematic). It was found that the standard deviations of the 100 Hz GNSS displacement solutions derived from the PPP, PPP-AR and RTK techniques were 5.5 mm, 3.6 and 0.8 mm, respectively, when the antenna was in quasi-static motion, and were about 9.2, 6.2 and 3.5 mm, respectively, when the antenna was in vibration (up to about 0.7 Hz), under typical urban observational conditions in Hong Kong. The results also showed that the higher a sampling rate was, the lower the accuracy of a measured displacement series was. On average, the 10 Hz and 100 Hz results were 5.5% and 10.3%, respectively noisier than the 1 Hz results.

Second, a new robust multi-rate Kalman filter (robust MRKF) was proposed to integrate more

robustly GNSS observations and data from other sensors so that outliers in the GNSS observations could be mitigated in real-time. Experimental results with simulated data from a shaking table and SHM data from Stonecutters Bridge, demonstrated that the proposed method could reduce the effects of outliers effectively and improve the overall accuracy of the integrated monitoring system by up to about 60% compared with using GNSS data alone, and by up to about 50% compared to using conventional MRKF.

Third, we propose a method for integrating multi-antenna (MA) GNSS and accelerometer data based on unscented multi-rate Kalman filter (UMRKF-MA) to mitigate the misalignment errors between GNSS and accelerometer coordinate systems, as well as handle the non-linear systematic errors in the real-time SHM system. For method validation, a shaking table with four GNSS antennas and one accelerometer was used to simulate the motions. The experimental results demonstrated that the proposed method could effectively mitigate the effects of accelerometer baseline shifts and improve the overall accuracy by up to about 40% compared with using GNSS data alone, and by up to about 65% compared to using conventional MRKF.

Finally, we proposed a data-driven deformation mechanism analysis approach by combining a random forest model and

variational mode decomposition (VMD) algorithm. The method aims to assess the effects of different loading factors on the displacement of long-span bridges. We validated the method based on multiple frequency data collected on Tsing Ma Bridge (TMB), a large suspension bridge in Hong Kong. The results revealed that the lateral displacement was controlled by the horizontal wind perpendicular to the centerline of the bridge. The temperature and wind along the direction of the centerline of the bridge were the dominant factors for the longitudinal displacement. The influencing factors for the vertical displacements were complicated,

including a combination of wind along the bridge centerline, temperature, and traffic flows. Specific displacement time series of TMB that responds to the changes in each loading factor can also be derived. The proposed method provides new insights into the impacts of loadings on the displacements of long-span bridges.

This thesis presents several technological advances to derive real-time high-accuracy displacements for monitoring structure health conditions, and new insights into structural deformation mechanisms.