Structural Health Monitoring with GNSS and IMU Technology: Precision Solutions for Modern Infrastructure

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Key words

Structural Health Monitoring (SHM), GNSS-based Monitoring, Bridge Displacement Measurement, Multisensor Data Fusion, Real-Time Monitoring, Inclinometers and IMUs, Environmental Sensing, Predictive Maintenance, Early Warning Systems, Infrastructure Safety

SUMMARY

This project aims to develop a high-precision structural health monitoring (SHM) system for bridges by combining GNSS with complementary sensors. The system continuously records structural displacements and environmental influences to enable early anomaly detection and predictive maintenance.

It integrates geodetic dual-frequency GNSS receivers for millimeter-level displacement monitoring, tilt sensors (inclinometers) for angular changes, and inertial measurement units (IMUs) to capture dynamic responses like vibrations. Environmental conditions such as temperature, humidity, and wind are recorded via sensors and an optional weather station to support data interpretation.

The project follows a two-phase approach. In the initial observation phase (6–12 months), the system collects baseline data to characterize the bridge's normal behavior under varying conditions. Based on this, a custom alarm logic is developed, with defined thresholds, alert levels, and automatic notifications.

The system enhances safety, supports efficient maintenance, and enables scalable, transferable monitoring solutions for critical infrastructure.

ZUSAMMENFASSUNG

Im Rahmen dieses Projekts wird ein hochpräzises Monitoring-System zur strukturellen Überwachung einer Brücke entwickelt. Ziel ist die kontinuierliche Erfassung von Bewegungen und Umwelteinflüssen, um potenzielle Schäden frühzeitig zu erkennen und eine vorausschauende Instandhaltung zu ermöglichen.

Zum Einsatz kommt eine Kombination aus geodätischen GNSS-Empfängern (für millimetergenaue Positionsmessung), Neigungssensoren (zur Erfassung von Kippbewegungen) und Inertialsensoren (zur Analyse dynamischer Belastungen). Ergänzend werden Umweltdaten wie Temperatur, Luftfeuchte und Wind integriert, um strukturelle Veränderungen besser interpretieren zu können.

Das Projekt gliedert sich in zwei Phasen: Eine erste Beobachtungsphase dient der Erhebung von Referenzdaten und der Analyse des „normalen" Brückenverhaltens. Anschließend wird ein Alarmsystem mit definierten Schwellenwerten und mehrstufiger Warnlogik implementiert.

Das System ist skalierbar, langfristig einsetzbar und kann auf weitere Bauwerke übertragen werden. Es trägt wesentlich zur Erhöhung der Betriebssicherheit und zur Digitalisierung der Bauwerksüberwachung bei.

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1. Motivations

The safety and longevity of infrastructure such as bridges and buildings are of vital importance to modern society. Many of these structures are exposed to significant stresses over decades – caused by traffic loads, environmental influences, or geological shifts. At the same time, aging processes and material fatigue pose increasing challenges for owners, operators, and engineers.

Continuous monitoring of these structures allows for the early detection of changes, timely risk assessment, and targeted maintenance planning. GNSS-based (Global Navigation Satellite System) technologies offer new possibilities in this context: through precise positioning, even the smallest movements and deformations can be detected – either in real time or over extended periods – including at remote or hard-to-access locations. The aim of this project is to develop or establish a robust and scalable GNSS-based monitoring system that enables permanent, high-precision observation of bridges and buildings. This not only contributes to operational safety and the reduction of long-term maintenance costs, but also enhances public safety and the resilience of our infrastructure.

2. GNSS Measurement Methods and Accuracy

GNSS technology allows for highly accurate position determination by using signals from global satellite constellations such as GPS, GLONASS, Galileo, and BeiDou. The accuracy of GNSS measurements depends on the method and equipment used. Basic single point positioning (SPP), which uses only a single GNSS receiver without corrections, typically achieves an accuracy of 2 to 5 meters and is mainly suitable for navigation and low-precision applications.

Differential GNSS (DGNSS) improves accuracy by applying correction data from a nearby reference station with known coordinates. This method generally achieves sub-meter accuracy and is commonly used in applications like construction surveying or marine navigation.

For high-precision tasks, especially in the context of structural monitoring, carrier-phase-based methods such as Real-Time Kinematic (RTK) and Post-Processed Kinematic (PPK) are most relevant. RTK uses real-time correction data from a base station to achieve horizontal accuracies of 1–2 centimeters and vertical accuracies of about 2–4 centimeters. PPK follows a similar principle, but the correction data is applied after the measurement, which makes it particularly suitable for remote locations or situations where real-time communication is not possible.

Another high-precision method is Precise Point Positioning (PPP), which uses global correction data and advanced models to eliminate errors. Although it does not require a local base station, PPP typically requires a convergence period before reaching its full accuracy of about 5 to 15 centimeters.

In the monitoring of bridges and buildings, where even small deformations can be significant, RTK and PPK methods are preferred. With proper setup and stable antenna installations, they allow for the detection of displacements in the millimeter to sub-centimeter range. This makes GNSS a powerful tool for the long-term, continuous observation of structural behavior and early identification of critical changes.

2.1 Improve accuracy

For the monitoring of bridges and buildings—where even the smallest positional changes of just a few millimeters must be reliably detected—high-precision GNSS measurement methods such as RTK (Real-Time Kinematic) and PPK (Post-Processed Kinematic) are particularly well suited. By using geodetic-grade dual-frequency receivers and high-quality GNSS antennas specifically designed for structural monitoring, measurement accuracy can be significantly improved.

When combined with stable, vibration-free antenna installations—mounted on permanently secured survey-grade reference points—and the use of multi-frequency signals from multiple satellite constellations (GPS, GLONASS, Galileo, BeiDou), it is possible to achieve repeatable positioning accuracies in the range of 1 to 2 millimeters. This level of precision also requires continuous data processing with appropriate tropospheric and ionospheric correction models, as well as successful resolution of carrier-phase ambiguities (integer ambiguity resolution).

The integration of modern GNSS technology, intelligent data processing, and robust, field-proven hardware thus enables millimeter-level, continuous monitoring of structural movements—even in remote or difficult-to-access locations. This makes GNSS-based monitoring a powerful, scalable, and cost-effective tool for the early detection of critical changes in infrastructure over the long term.

3. Enhancing Accuracy and Reliability through Multisensor Data Fusion

To further improve the accuracy, availability, and interpretability of a GNSS-based monitoring system, the integration of additional sensor technologies can play a crucial role. While GNSS provides highly precise information on absolute position and long-term displacements, supplementary sensors enhance the system's ability to detect dynamic processes, environmental effects, and short-term changes.

For example, tilt sensors (inclinometers) and IMUs (Inertial Measurement Units) are capable of detecting minute rotational or tilting movements at high temporal resolution. These sensors respond in real time to structural changes and can identify short-term displacements that may not be immediately apparent in GNSS data due to sampling intervals or atmospheric interference. In combination with GNSS, they allow for cross-validation and increased resilience against signal dropouts or outliers.

Weather stations and environmental sensors provide valuable contextual data such as air pressure, temperature, humidity, wind loads, and precipitation. These parameters can influence both the structural behavior (e.g., thermal expansion) and the quality of GNSS signals. Taking these factors into account not only improves the interpretation of movement data but also enables the application of physical models to better understand correlations.

By applying intelligent data fusion techniques – such as Kalman filters or machine learning algorithms – the system can synthesize coherent, robust, and high-resolution information about the structure's condition and behavior. This results in a monitoring system that is more robust to measurement errors, weather-related disturbances, or GNSS signal obstructions.

Overall, the combination of GNSS, inertial sensors, and environmental data provides a richer situational picture, significantly improved data reliability, and higher operational security – a key step toward predictive maintenance and early risk detection in critical infrastructure monitoring.

4 Measurement concept for structural monitoring of a bridge using multimodal sensors

To ensure the structural health of a bridge, a multimodal sensor system is proposed that can precisely detect both static and dynamic changes in the structure. The objective is to identify early signs of potential damage or critical conditions in order to take timely action. At the core of this concept is a combination of various sensors: high-precision, geodetic GNSS receivers are used to measure absolute movements of the bridge—particularly at critical points such as pier heads or bearings—with millimeter-level accuracy. These are complemented by tilt sensors (inclinometers) that detect minor angular shifts at individual structural elements. To capture dynamic processes such as vibrations or oscillations, accelerometers or inertial measurement units (IMUs) are installed. Environmental conditions are monitored through temperature and humidity sensors, and optionally through a local weather station, allowing for a more accurate interpretation of thermally induced expansion or wind-related forces.

A key component of the monitoring concept is the initial observation phase. Over a period of ideally six to twelve months, all relevant data is collected continuously, without triggering alarms or automated responses. This foundational phase aims to understand the typical displacement and vibration behavior of the bridge under varying environmental and loading conditions. Natural fluctuation ranges, daily and seasonal patterns, and responses to traffic loads are documented. Apparent outliers are assessed to better distinguish between normal behavior and true anomalies in later stages.

Based on the data collected during this initial phase, a tailored monitoring and alarm scenario is developed. For each measured parameter, appropriate threshold values are defined—for example, specific limits for displacements, tilt changes, or accelerations. These thresholds form the basis for a multi-level warning system that differentiates between normal operation (green), observation required (yellow), and critical action required (red). In addition, specific event profiles are established to detect sudden changes such as abrupt movements or atypical vibration patterns. As part of the alarm system, automated notifications are implemented to alert designated personnel in the event of threshold violations—via email, SMS, or integration with central monitoring systems.

Once implemented, the monitoring system continues to operate continuously. It is regularly validated and the threshold values are adjusted as needed—for example, in response to construction activities, changes in load conditions, or evolving environmental factors. This concept provides a flexible, scalable, and precise approach to the monitoring of bridge structures and forms the foundation for a modern, data-driven maintenance strategy.

5. Conclusion

The objective of this project is to design and implement a comprehensive, sensor-based monitoring system for the structural health of a bridge. The focus lies on the continuous observation of the bridge under real-world environmental and load conditions in order to detect early signs of damage, material fatigue, or unusual movement patterns. The primary motivation is to significantly enhance the safety and availability of critical infrastructure through data-driven decision-making and proactive maintenance strategies.

The technical concept is based on the principle of multimodal data acquisition. At the core of the system are high-precision GNSS (Global Navigation Satellite System) receivers installed permanently at key structural points of the bridge. These geodetic-grade sensors enable millimeter-level tracking of slow or long-term displacements—such as those occurring at pier heads, deck segments, or support bearings. The GNSS units are complemented by tilt sensors (inclinometers), which detect minor angular changes and settlement movements, as well as by accelerometers or inertial measurement units (IMUs), which capture vibrations and oscillations caused by traffic or wind loads with high temporal resolution.

To better interpret the structural responses and differentiate between normal and critical behaviors,

meteorological and environmental data are also integrated into the monitoring system. Temperature, humidity, and air pressure sensors, along with an optional full weather station, provide essential contextual information. This helps distinguish thermal or weather-related effects from potential structural damage. The combination of all sensor types enables a comprehensive and reliable assessment of the bridge's condition.
A key feature of the project is its structured, two-phase approach. In the first phase, the bridge is monitored continuously over several months without the activation of alarms or intervention mechanisms. The goal of this foundational phase is to build a detailed understanding of the bridge's "normal" behavior under varying loads and environmental influences, including daily and seasonal patterns. This baseline data serves as the foundation for phase two: the development and implementation of a tailored alert and response system.
The alarm system is defined based on the measured data and includes site-specific and structure-specific threshold values for each monitored parameter. A tiered early warning concept—comprising normal operation, observation required, and intervention necessary—ensures that deviations from expected behavior trigger timely notifications to the responsible personnel. Data processing is handled centrally by an analysis unit that may also incorporate sensor fusion techniques (e.g., Kalman filtering) and machine learning algorithms for anomaly detection.
The project is designed to be scalable and transferable to other bridges or structural assets. Through permanent data collection, intelligent data interpretation, and automated alerting, it contributes significantly to the digital transformation of infrastructure monitoring. It enhances operational safety, supports predictive maintenance, and reduces long-term maintenance costs.

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BIOGRAPHICAL NOTES

I received my Dipl.-Ing. in Geodesy from TFH Berlin in April 1991. My career began with a strong focus on CAD software, total stations from Zeiss and Topcon, and GNSS technology, working with industry leaders such as Trimble, Ashtech, and Topcon. For the first ten years, I worked for various companies as a specialist in these fields, gaining extensive experience in geospatial technology, surveying instruments, and high-precision positioning systems.

In March 2001, I decided to start my own business and founded Geo.IT Systeme GmbH. This step allowed me to apply my expertise in GNSS technology to develop innovative solutions. A major milestone in my career was the foundation of navXperience together with Franz-Hubert Schmitz. In early 2010, we began developing the 3G+C GNSS antenna technology, a significant advancement in high-precision GNSS applications. By the end of 2010, we successfully launched the product, establishing navXperience as a key player in the GNSS industry.

Between 2009 and 2011, I worked together with Frank Heinen on the MoDeSh research project, where we developed a six degrees of freedom (6DoF) software to measure movements and deformations on vessels. This project helped advance geodetic monitoring applications and contributed to new measurement techniques. In 2013, the concept of the OSR receiver was born, aiming to enhance GNSS correction services. Since 2015, I have been working with navXperience, Gutec, and Datagrid on this project, pushing the boundaries of high-accuracy GNSS technology.

Since 2012, I have been an active member of the working group AK 3 “Measurement Methods and Systems” within DVW Germany, where I contribute to discussions on geodetic measurement technologies, industry standards, and innovation in positioning systems. Throughout my career, I have been passionate about developing high-precision GNSS solutions that support applications in surveying, precision agriculture, autonomous navigation, infrastructure monitoring, and other demanding positioning tasks. My focus has always been on bridging the gap between research and practical applications, ensuring that new technologies meet real-world needs.

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