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Advancing Infrastructure Health Monitoring with Multi-Sensor Systems and Geospatial Technologies

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ABSTRACT: This paper presents an integrated structural health monitoring (SHM) system combining multi-sensor networks with geospatial GNSS technologies to enhance infrastructure resilience. Developed by the authors, the system unites millimeter-accurate TEXtant® GNSS monitoring with MSS® leak detection and environmental parameter sensing, all synchronized via the TEX-Sky Monitoring Cloud. Validation efforts included comparative field testing against International GNSS Service (IGS) standards at GFZ Potsdam, demonstrating millimeter-level positioning precision. Real-world deployments—including the Aquitaine Bridge (France), slope monitoring for mining operations (Germany), tank basin and catch basin monitoring at a chemical facility (Germany), and the first station of the cross-border Asia Minor GNSS Network—confirmed the system's operational robustness. Time-synchronized multi-sensor datasets enable predictive maintenance, early anomaly detection, and asset life extension. The modular and scalable system architecture adapts flexibly to diverse infrastructure contexts. Future integration with machine learning technologies is anticipated to enhance pattern recognition and anomaly detection. This work highlights the role of synchronized, multi-parameter monitoring as a foundation for next-generation infrastructure management and public safety.

KEY WORDS: Structural Health Monitoring (SHM), GNSS, Multi-Sensor Systems, Autonomous GNSS Monitoring, TEXtant, TEX-Sky Monitoring Cloud, MSS Leak Monitoring, Big Data Analytics, Predictive Maintenance, Tectonic Monitoring

1 INTRODUCTION

The increasing age of global civil infrastructure, combined with escalating environmental stresses and rising usage demands, has highlighted critical vulnerabilities in bridges, tanks, basins, slopes, and other key structures. Traditional inspection practices—largely reliant on manual surveys and infrequent assessments—often fail to detect the early-stage, progressive deformations that precede catastrophic failures. Recent advancements in geospatial positioning, sensor miniaturization, and wireless data technologies offer unprecedented opportunities for real-time, high-precision structural health monitoring (SHM). Among these, Global Navigation Satellite System (GNSS) monitoring, capable of millimeter-level displacement measurements, has emerged as a core technology. When augmented with complementary sensing modalities—such as leakage detection, corrosion monitoring, and environmental parameter tracking—an integrated, multi-sensor SHM network becomes feasible. This paper presents the development, validation, and practical deployment of such an autonomous multi-sensor SHM system, rooted in high-precision GNSS science, geodetic surveying, and real-world engineering applications. Field-tested at critical infrastructure sites—including the Aquitaine Bridge in France, containment structures in the chemical sector in Germany, and a planned tectonic GNSS monitoring network across Asia Minor—the system demonstrates the viability of scalable, time-synchronized, automated infrastructure health management.

The system's foundation lies in two core technologies developed in-house: the TEXtant® GNSS movement monitoring system and the MSS® Leak Monitoring system. Since 2011, the MSS® system has been successfully deployed in landfill and hazardous waste facilities, starting with the first permanent installation at a power plant in Eemshaven, Netherlands. Building upon this experience, the TEXtant® GNSS system introduces fully autonomous, millimeter-accurate displacement monitoring without dependence on local reference networks. Both technologies are unified under the TEX-Sky Monitoring Cloud, a scalable, modular platform enabling synchronized multi-sensor integration, advanced data analysis, and future AI-assisted pattern recognition. The development of this platform addresses urgent needs for resilient, autonomous, and real-time infrastructure monitoring to enhance public safety, optimize maintenance strategies, and support sustainable asset management.

2 SCIENTIFIC BACKGROUND AND MOTIVATION

The urgent need for continuous, high-resolution monitoring of civil infrastructure becomes increasingly apparent as traditional inspection methods often fail to detect subtle but critical early-stage deformations. As Ghaffarian et al. (2023) emphasized, aging structures and increased environmental stress demand real-time monitoring solutions. While several commercially available GNSS systems can achieve millimeter-level precision using base-rover configurations, they depend on local reference infrastructure and often require significant setup and must all be post-processed by experts. These constraints render them impractical for fully autonomous real-time PPP monitoring

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across multiple or remote sites. Motivated by these challenges, the authors developed a new system architecture aiming to bridge the critical gap between high-precision monitoring and full automation.

As Elsaid (2025) demonstrated, low-cost, multi-frequency GNSS receivers can achieve comparable accuracy to high-end systems when calibrated and combined with precise point positioning (PPP) software. PPP enables centimeter- to millimeter-level positioning accuracy by combining precise satellite orbits, clock corrections, and advanced error modeling, without reliance on local differential reference stations (Teunissen & Montenbruck, 2017).

Moreover, a significant gap persists: there is a lack of fully autonomous GNSS-based SHM systems capable of delivering millimeter-level real-time accuracy without requiring expert recalculations. Traditional IGS stations, for example, do not recalibrate continuously, and thus their displacement data may not reflect real-time changes critical to detecting early-stage structural degradation. Millimeter accuracy is essential because slight, continuous movements—caused by temperature, dynamic loads, or tectonic effects—can serve as precursors to catastrophic failures such as bridge collapses, landslides, dam breaches or earthquakes. Monitoring vulnerable and aging infrastructure without such precision carries unacceptable risks. The collapse of the Carolabrücke in Dresden, Germany, in September 2024, illustrates the fatal consequences of undetected structural fatigue (City of Dresden, 2024).

Therefore, the TEXtant® GNSS system was conceived with three key objectives: to provide continuous, unmanned, millimeter-accurate monitoring; to automate data processing and alarm generation without human intervention; and to support early hazard detection across a wide range of critical infrastructure types. It operates autonomously 24/7, with real-time or daily processed datasets accessible through the TEX-Sky Monitoring Cloud.

The importance of rapid deployment and flexibility was highlighted when, just one month after the completion of the TEXtant® system's one-year trial phase, a devastating earthquake struck Turkey and Syria in February 2023. Responding immediately, the first TEXtant® GNSS station for tectonic monitoring was donated to the city of Adana, Turkey, and installed in April 2023 atop the City Hall with support from Mayor Zeydan Karalar. The Adana station now delivers daily millimeter-level movement results to the TEX-Sky Monitoring Cloud, marking the first operational node of the Asia Minor GNSS Network project.

Beyond GNSS-based monitoring, integrated multi-sensor networks further expand system resilience. Cawley (2018) highlighted the necessity of linking strain, acoustic, and environmental data streams to enhance the robustness of predictive analytics. Multi-sensor systems like TEXtant®, when combined with leak detection, corrosion monitoring, and environmental sensing, offer unprecedented opportunities for proactive, data-driven maintenance strategies.

3 TEXTANT® GNSS TECHNOLOGY: DEVELOPMENT AND VALIDATION

3.1 System Design and Autonomy

The TEXtant® GNSS system was developed by the authors as a modular, autonomous monitoring solution designed to meet the millimeter-accuracy requirements of geodetic infrastructure monitoring. The device architecture includes an energy-efficient processing unit, solar power modules, and the capacity to host up to four GNSS antennas per station. The entire system is configured for fully autonomous operation, from data acquisition to daily processing, and network transmission via secure cloud protocols.

3.2 PPP Algorithm and Accuracy Optimization

Building on the scientific foundation presented, the development of the GNSS-based monitoring solution centers on the integration of autonomous, low-cost multi-frequency receivers configured to operate without dependence on local reference networks. The approach leverages precise point positioning (PPP) as its core processing strategy, supported by algorithms specifically refined for structural health monitoring applications.

In Elsaid's doctoral research (Elsaid, 2025), the implementation of improved dynamic modeling within GNSS algorithms was shown to increase both stability and precision in real-world environments. The TEXtant® system developed through this research was subjected to rigorous field testing, including comparative validation with a conventional geodetic reference system. Results revealed a convergence between autonomous GNSS solutions and classical base-rover measurements, confirming the capability for millimeter-accurate displacement tracking over long time periods.

3.3 Field Validation at GFZ Potsdam

A pivotal phase in this validation process was conducted at the IGS station POTS, located at the German Research Centre for Geosciences (GFZ) in Potsdam, Germany. The developed TEXtant® system was connected in parallel to the existing geodetic Javad receiver at the GFZ, sharing the same GNSS antenna. This configuration enabled a direct comparison under identical atmospheric and signal conditions.

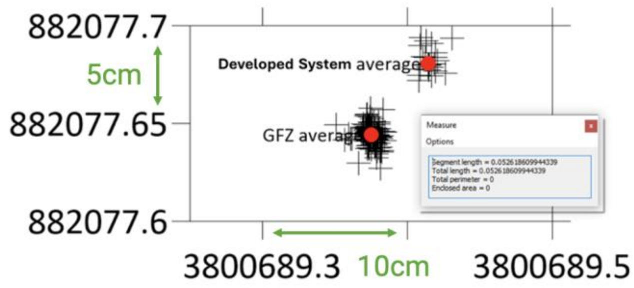

Figure 1. Comparative analysis of the developed TEXtant® GNSS system (23-day dataset) and the GFZ reference system (90-day dataset), demonstrating consistent millimeter-level precision (Elsaid, 2025).

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As detailed in Elsaid's thesis, a 23-day dataset collected from the TEXtant® receiver was compared against a 90-day reference dataset from the GFZ system. The comparative analysis yielded exceptional results: horizontal and vertical deviations remained within millimeter thresholds, and no long-term drift or divergence was observed throughout the monitoring period (Elsaid, 2025).

Elsaid emphasized that despite the economical and compact design of the TEXtant® device, the results demonstrated its capacity to meet professional-grade geodetic standards. The thesis further highlighted the device's resilience under fluctuating atmospheric conditions and its reliable convergence behavior during daily sessions.

Figure 2. TEXtant® GNSS station initiating autonomous operation and data processing upon activation.

3.4 *Cross-Validation with Bernese and NRCan*

Further scientific credibility was added through collaboration with the Canadian Geodetic Survey (NRCan), where raw GNSS datasets from TEXtant® were submitted to the Natural Resources Canada PPP server for validation. The NRCan PPP analysis confirmed the integrity and reliability of the device's positioning performance. Additionally, Bernese GNSS Software, a respected academic processing tool developed at the University of Bern, was used for post-processing, yielding comparable accuracy (Elsaid, 2025).

Hardware-level accuracy was validated by comparison with the co-located IGS reference station at GFZ, equipped with a high-grade Javad GNSS receiver. Despite its simplified electronics and energy-saving design, the TEXtant® system achieved millimeter-accurate results closely matching the IGS benchmark, demonstrating scientific and operational robustness.

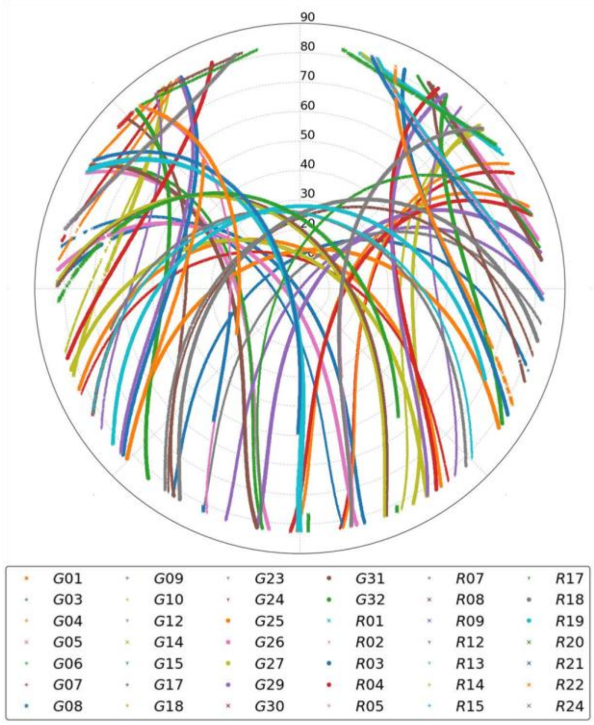

Figure 3. Satellite distribution improvement after antenna calibration and receiver tuning, highlighting enhanced tracking stability and reduced signal loss (Elsaid, 2025).

3.5 *Deployment and Scalability of the TEXtant® System*

A critical innovation of the TEXtant® development is the deployment of solar-powered, autonomous GNSS stations requiring minimal maintenance. As highlighted by Liu et al. (2016), low-power GNSS configurations enable extensive, scalable monitoring across geographically distributed assets without compromising precision.

TEXtant® units operate fully independently, automatically processing data and uploading daily results to the TEX-Sky Monitoring Cloud. Field deployments—including the Aquitaine Bridge and landslide-prone slopes in Germany—validated the system's capability to detect millimeter-level displacement, including thermal expansion effects and gradual settlement trends.

These applications demonstrate the robustness and scalability of the TEXtant® concept, enabling broader use in earthquake-prone regions, industrial facilities, and coastal infrastructure. Furthermore, the modular architecture supports integration of supplementary sensors such as accelerometers, leak detectors, and strain gauges, providing a comprehensive and expandable framework for structural health diagnostics.

4 THE TEX-SKY MONITORING CLOUD ARCHITECTURE

The TEX-Sky Monitoring Cloud represents the data infrastructure backbone of the multi-sensor SHM platform. Developed to support continuous, time-synchronized acquisition and correlation of high-frequency monitoring data, the cloud-based system functions as a central interface for real-time infrastructure condition analysis. Its architecture enables

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integration across multiple sensor nodes and locations, transforming raw data into accessible and actionable insights.

Monitoring networks benefit significantly from centralized cloud-based storage and synchronized databases. As noted by Wu et al. (2018), cloud platforms offer scalability and interoperability, two essential features for long-term SHM in complex environments. Within this architecture, each GNSS or auxiliary sensor station independently uploads data via secure protocols, with redundant backups to ensure data integrity. The system maintains strict time-stamping and correlation rules across parameters such as displacement, leakage, temperature, or vibration, thereby enabling consistent multi-variable analysis.

By enabling daily automated reports and long-term pattern visualization, the TEX-Sky Monitoring Cloud supports transition from reactive to preventive maintenance regimes. This shift aligns with Su et al. (2018), who emphasize that cloud-enabled SHM platforms foster predictive analytics through longitudinal data analysis. The TEX-Sky interface provides stakeholders with graphical dashboards, alarm notifications, and exportable analytics, tailored to engineering, operational, or regulatory needs.

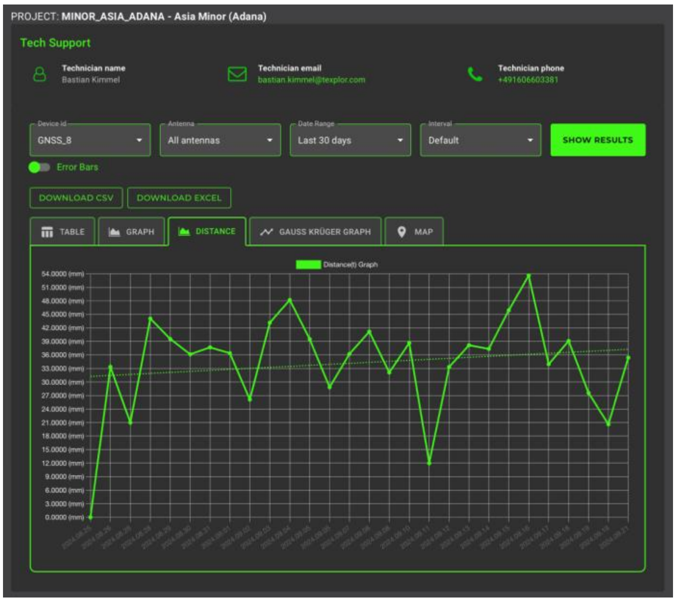

Figure 4. TEX-Sky interface displaying visualized GNSS results, including Gauss-Krüger and UTM coordinates.

The TEX-Sky Monitoring Cloud was developed in-house to support flexible, scalable integration of diverse sensor types. Its modular database structure not only enables real-time SHM across multiple sites but also prepares the platform for future machine learning applications. By continuously expanding the database design, the system already allows seamless transfer of automatically generated monitoring data into AI-based anomaly detection tools, ensuring technological adaptability for evolving SHM needs.

Dang et al. (2022) describe such systems as forming the foundation of Digital Twin implementations, enabling structures to be mirrored in real-time for deeper analysis. While such features remain under development, the system architecture already supports seamless upgrades. Collectively, the TEX-Sky Monitoring Cloud transforms raw sensor data into centralized knowledge—paving the way for more resilient, data-informed infrastructure management.

5 MULTI-SENSOR NETWORK INTEGRATION

An essential component of advanced structural health monitoring (SHM) is the ability to integrate various sensor types into a single, interoperable network architecture. The system developed by the authors merges geospatial GNSS data with time-synchronized readings from multiple environmental and structural sensors, including MSS® leak detection, humidity, temperature, corrosion, inclination, and accelerometers. The integrated network ensures comprehensive infrastructure monitoring across dynamic and static parameters.

The two key pillars of this multi-sensor network are the TEXtant® GNSS system for precise movement tracking and the MSS® Leak Monitoring system for sealing integrity control. Since 2011, the MSS® leak monitoring system has been successfully deployed across a wide range of applications and several continents, including hazardous waste landfills, mining operations, and chemical containment basins, starting with its first major deployment at a power plant project in Eemshaven, Netherlands.

The MSS® leak detection technology is central to monitoring the integrity of sealed systems, particularly for tank farms and containment basins. Its use of conductive cord networks and automated alerting mechanisms has proven effective in early detection of micro-leaks, contributing to environmental safety and regulatory compliance. As demonstrated in deployments such as the tank basins monitored since 2020, this technology reduces inspection effort while ensuring 24/7 leak monitoring capacity.

The interoperability of all sensor modules relies on the synchronized timing and unified data architecture provided by the TEX-Sky Monitoring Cloud. Each sensor type, regardless of its function or installation context, transmits data tagged with precise timestamps, allowing multi-dimensional correlation and anomaly detection. The TEX-Sky Monitoring Cloud itself was independently developed by the authors to serve as a flexible, modular database architecture. It is designed for the long-term storage, processing, and visualization of synchronized SHM data, and it is continuously updated to remain compatible with machine learning (ML) techniques for anomaly detection and predictive analytics.

Kazmierski et al. (2018) note that modular SHM architectures enhance adaptability, enabling sensor types to be added or removed depending on project-specific risks and requirements. This modularity is especially crucial for retrofitting existing infrastructure, where different physical layouts and constraints may exist.

The integration strategy employed supports preventive and predictive maintenance practices by providing a more holistic view of structural conditions. Furthermore, combined datasets improve diagnostic confidence: for example, identifying correlated patterns between displacement, moisture ingress, and thermal expansion.

With ongoing development, future sensor classes—including gas sensors, advanced corrosion probes, and customized client-

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specific sensors—may further extend this multi-sensor network's diagnostic capacity. By consolidating diverse sensing modalities within a unified, scalable system, the platform demonstrates the technical feasibility and operational benefits of fully integrated SHM for modern infrastructure.

6 FIELD DEPLOYMENTS AND CASE STUDIES

This section presents the implementation of the authors' system in diverse real-world environments to evaluate its performance, scalability, and scientific contribution to structural health monitoring (SHM).

6.1 Aquitaine Bridge Monitoring (France)

The Aquitaine Bridge in Bordeaux, completed in 1967, is one of France's major river crossings and represents a landmark of civil engineering from the postwar period. Given its age and strategic importance, it was selected as an ideal candidate to validate the TEXtant® GNSS monitoring system under real-world operational conditions. The bridge's susceptibility to thermal expansion, structural aging, and dynamic traffic loads provides a comprehensive environment to assess long-term monitoring technologies.

Figure 5. GNSS antenna installation on the 90-meter-high pylon of the Aquitaine Bridge in Bordeaux, France.

Since April 2022, an autonomous TEXtant® GNSS station has been continuously operating on one of the 90-meter-high pylons. The system collects millimeter-precise daily displacement data across the X, Y, and Z axes in the ECEF (Earth Center Earth Fixed) coordinate system, processed automatically through precise point positioning (PPP) without the need for local base stations.
The monitoring initiative is carried out in cooperation with Cerema Sud-Ouest. Validation against conventional geodetic measurements confirmed the system's accuracy. As John Dumoulin, MA (Cerema), reported, the TEXtant® system reliably delivers absolute millimeter-accurate displacement values on a daily basis without requiring a fixed reference station (Dumoulin, 2025).
Analysis of the time-synchronized monitoring data has revealed a clear correlation between structural displacement and ambient temperature variations. Specifically, movements along the X-axis exhibit a direct correlation with temperature, while displacements along the Y-axis are inversely correlated. These findings reflect thermal expansion and contraction effects acting asymmetrically on the bridge structure. The observed patterns provide insight into seasonal deformation behavior and demonstrate the utility of high-resolution GNSS data for capturing structural response under environmental loading.
Future plans include the addition of temperature sensors and strain gauges to further enrich the TEX-Sky Monitoring Cloud database with synchronized multi-parameter datasets.

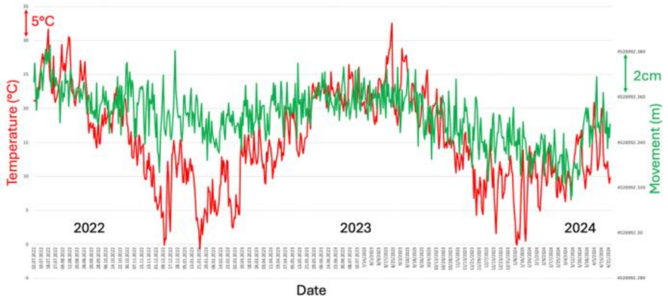

Figure 6. Correlation between X-axis movement (green) and temperature variations (°C, red) from 2022–2024.

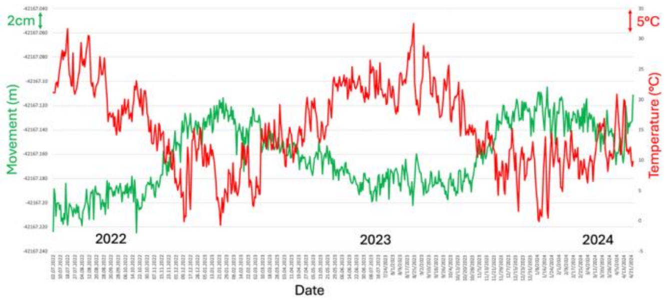

Figure 7. Correlation between Y-axis movement (green) and temperature variations (°C, red) from 2022–2024.

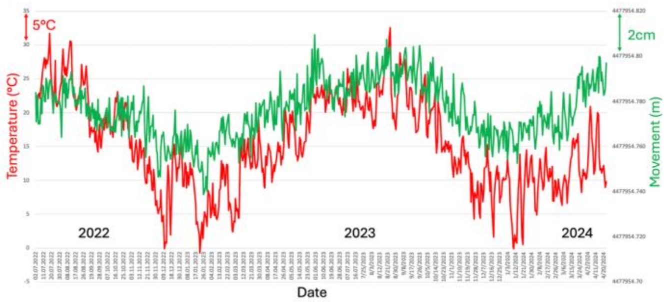

Figure 8. Correlation between Z-axis (height) movement (green) and temperature variations (°C, red) from 2022–2024.

6.2 Asia Minor Cross-Border GNSS Network

The Asia Minor GNSS Network was initiated as a donation-based scientific infrastructure project following the devastating

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Turkey–Syria earthquakes in February 2023. The project aims to establish a cross-border tectonic monitoring and early warning system in one of the most geodynamically active regions worldwide.

Tectonic complexity in the area is driven by the interaction of the African Plate, Arabian Plate, and Anatolian Block. Near the city of Adana, the northward motion of the Arabian Plate compresses the Anatolian Block, forcing it westward along the East Anatolian Fault. This geodynamic regime results in frequent high-magnitude seismic events, making the region a critical focus for real-time geodetic monitoring initiatives.

The first TEXtant® GNSS station was successfully installed atop the City Hall in Adana in April 2023, with the support of the local administration. The GNSS station has been operating autonomously since then, delivering daily millimeter-precision displacement data in X-Y-Z axes. It reliably records both the gradual tectonic drift of the Anatolian Block and abrupt height anomalies associated with seismic events exceeding magnitude 5.

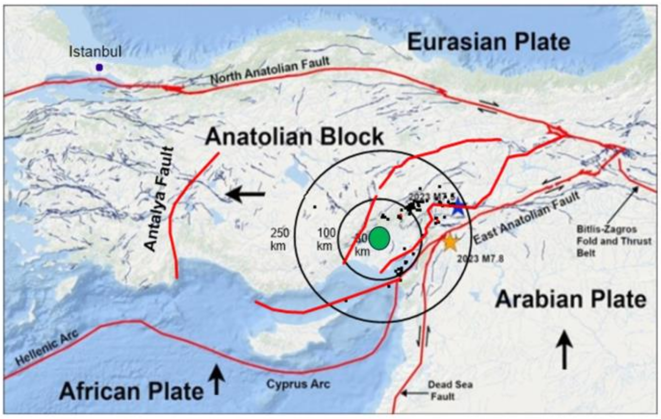

Figure 9. TEXtant® GNSS station in Adana (green), recorded earthquakes (black), and earthquakes >5M magnitude (red).

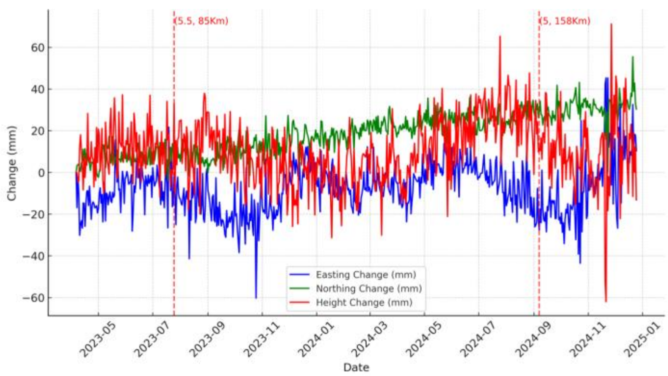

Figure 10. Displacement tracking at the TEXtant® GNSS station in Adana: Easting (blue), Northing (green), and Height (red) changes.

In collaboration with the CNRS National Center for Geophysics in Lebanon and the University of Jordan, preparations are underway for the installation of two additional TEXtant® GNSS stations. Discussions regarding station placement are ongoing, and the delivery and commissioning are scheduled for 2025. These installations mark the next steps in expanding the Asia Minor Network.

The broader objective is to establish a cross-border GNSS infrastructure covering six countries—Turkey, Syria, Lebanon, Jordan, Egypt, and Saudi Arabia. All recorded data are automatically processed via PPP algorithms and archived within the TEX-Sky Monitoring Cloud, facilitating scientific collaboration, seismic risk research, and the future development of regional early warning systems.

This initiative represents the first operational cross-border PPP-based GNSS tectonic monitoring network in the Asia Minor region.

6.3 Landslide Risk Monitoring (Germany)

In a geologically sensitive mining region in Germany, an autonomous TEXtant® GNSS monitoring network was deployed to monitor slope stability. The project area was characterized by historic mining activities, creating a heightened risk of slope destabilization and landslides over time.

Two solar-powered TEXtant® GNSS stations, equipped with a total of six antennas, were installed on the potentially unstable slope. These stations operate autonomously and transmit daily displacement results in X, Y, and Z axes to the TEX-Sky Monitoring Cloud, where the time-synchronized datasets are automatically processed and archived.

Previously, the slope was inspected at intervals by land surveyors, with weeks-long delays between measurements and data interpretation. The introduction of daily, continuous GNSS monitoring significantly enhanced the ability to detect subtle deformations at an early stage. Regular automated reports now document absolute movements in local coordinate systems, offering actionable insights into both spatial displacement and temporal trends. These visualized datasets are used to create detailed deformation maps, illustrating where and by how much the terrain is shifting.

This deployment demonstrates how continuous GNSS-based monitoring provides superior resolution, frequency, and responsiveness compared to traditional manual surveying, contributing to improved risk mitigation strategies for landslide-prone areas.

Figure 11. GNSS antenna connected to an autonomous TEXtant® station powered by a solar energy system.

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6.4 Industrial Multi-Sensor SHM (Germany)

At an industrial site in Germany, a multi-sensor SHM system was implemented to monitor the structural integrity of critical containment infrastructure exposed to heavy operational loads, fluctuating groundwater conditions, and tidal forces from the nearby Elbe River. The aim was to reliably assess structural status, extend service life, and minimize costly manual inspections that disrupt operations.

Since 2020, MSS® leak monitoring has been deployed across three containment structures: a storage tank, a concrete catch basin, and a reinforced concrete basin with a liquid liner. In total, 32 leak sensors were installed—eight around the tank, sixteen around the catch basin, and eight within the basin floor—embedded into both new and existing structures. Early-stage leak detection during commissioning enabled targeted repairs, demonstrating the system's preventive maintenance value.

Figure 12. Leak monitoring system with eight sensors embedded around the perimeter of the monitored tank using mounting sleeves.

In 2024, TEXtant® GNSS movement monitoring stations were added to the network, providing autonomous daily X-Y-Z displacement data with millimeter precision. This data is essential for detecting differential settlements and deformations linked to seasonal groundwater variations and river-induced soil dynamics.

A corrosion monitoring system, featuring 64 embedded sensors across both original and newly built concrete walls, enables comparative degradation analysis. Additionally, moisture sensors were installed between double-wall structures to monitor water ingress risks via resistance measurements.

All sensor modules are integrated into the TEX-Sky Monitoring Cloud, allowing centralized, time-synchronized data correlation and automated reporting. The system has been approved by TÜV-Nord, supporting regulatory compliance while optimizing inspection intervals. By reducing the need for frequent manual interventions, the multi-sensor SHM deployment contributes to enhanced operational reliability, environmental safety, and lifecycle cost savings.

Figure 13. The monitoring computer sends all multi-sensory results (movement, leakage, corrosion) to the TEX-Sky Monitoring Cloud.

These case studies demonstrate the adaptability, precision, and value of the authors' multi-sensor SHM system in diverse structural contexts, from heritage bridges to critical industrial assets and geohazard zones.

7 DISCUSSION: PREDICTIVE MAINTENANCE AND AI OPPORTUNITIES

The integration of time-synchronized data streams from geospatial and structural sensors provides a foundation for advanced data-driven maintenance strategies. As infrastructure systems age and face intensifying environmental pressures, the transition from reactive to predictive maintenance becomes increasingly necessary. Long-term datasets derived from autonomous monitoring technologies enable trend analysis, anomaly detection, and system-wide diagnostics—laying the groundwork for intelligent decision support systems.

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A core advantage of synchronized SHM networks lies in their ability to generate longitudinal datasets that capture subtle structural changes over time. As Razali et al. (2020) note, big data analytics applied to sensor data can enhance preventive maintenance by identifying hidden correlations and early-warning indicators. The TEX-Sky Monitoring Cloud facilitates such analyses through automated reporting tools and correlation matrices spanning parameters like displacement, leak detection, inclination, and corrosion.

Furthermore, the platform supports early-stage integration with machine learning frameworks. According to Wu et al. (2018), AI-enhanced SHM platforms can extract latent patterns from high-volume sensor streams, offering insights unattainable through manual evaluation. The cloud's architecture, which time-aligns and stores multi-dimensional data across geographically distributed sites, enables the application of supervised learning algorithms for condition classification and anomaly detection.

The evolution toward data-driven maintenance is also aligned with Digital Twin paradigms. Dang et al. (2022) describe Digital Twins as dynamic virtual replicas of physical infrastructure, continuously updated through real-time sensor inputs. In our framework, the combination of daily GNSS-derived position data and environmental sensor feedback enables a similar mirroring of structural states, especially in applications like slope monitoring and tank basin surveillance.

The benefits of such an approach are multifold: improved lifecycle predictions, optimized inspection intervals, targeted intervention planning, and enhanced safety margins. Ultimately, by embedding intelligence into SHM workflows, engineers can ensure that infrastructure resilience evolves in tandem with societal needs and technological capability.

8 CONCLUSION AND FUTURE PERSPECTIVES

This paper has presented the development, scientific rationale, and field validation of a modular, autonomous monitoring system that integrates multi-sensor technologies with advanced geospatial GNSS capabilities. Designed to achieve millimeter-level accuracy in displacement, leakage detection, and environmental monitoring, the system represents a fundamental shift toward data-driven, real-time structural health monitoring (SHM).

Central to this approach are two core technologies developed by the authors: the TEXtant® GNSS movement monitoring system and the MSS® Leak Monitoring technology. Their integration through the TEX-Sky Monitoring Cloud enables scalable, synchronized monitoring across diverse infrastructure types—from heritage bridges and industrial containment systems to tectonic plate boundaries and geotechnically unstable slopes.

Field deployments in France, Germany, and Turkey have demonstrated the system's scientific robustness, operational reliability, and its capacity to support predictive maintenance strategies. The introduction of fully autonomous, daily-updating monitoring solutions fills a critical technological gap, particularly where traditional inspection cycles or manual GNSS data post-processing fall short.

Continuous, unmanned monitoring systems capable of high-precision results offer new opportunities to prevent disasters such as bridge collapses, dam breaches, and infrastructure failures due to undetected degradation.

Future work will focus on expanding cross-border SHM networks, contributing to the development of international standards for autonomous infrastructure monitoring, and strengthening global collaboration to enhance structural resilience.

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