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Advanced Monitoring Systems for Infrastructures: Integrating 6D Sensors and Low-Cost High-Precision GNSS

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ABSTRACT: Structural Health Monitoring (SHM) is vital for ensuring the safety and longevity of infrastructures, utilizing various sensor-based techniques to detect damage, assess performance, and monitor long-term deterioration. Traditional methods, such as visual inspections, lack precision and are prone to human error, whereas more advanced techniques like vibration-based monitoring, acoustic emission, strain gauges, and GNSS offer real-time damage detection and millimeter-level precision but often require complex planning and high costs. The presented 6D sensor, developed for infrastructure monitoring, accurately measures complex displacements and rotations, offering enhanced precision through a combination of machine learning and mathematical algorithms. When paired with low-cost, high-precision GNSS systems, it provides comprehensive real-time data on both localized and large-scale structural movements, improving insights into infrastructure behavior under various environmental conditions and loads.This paper explores the integration of 6D sensors with GNSS technology, discussing the advantages of real-time monitoring for predictive maintenance and presenting insights from ongoing project results.

KEY WORDS: IoT, Sensors, AI, SHM, 6D, GNSS

1 INTRODUCTION

Structural Health Monitoring (SHM) is essential for ensuring the safety and longevity of bridges, employing various techniques to detect damage, assess performance, and monitor deterioration over time. Traditional methods, such as visual inspection [1], are widely used due to their simplicity and cost-effectiveness but often lack precision and are prone to human error. More advanced techniques include vibration-based monitoring [2], which identifies global structural changes through dynamic responses, and acoustic emission [3] methods that detect stress waves from internal cracks. Both offer real-time damage detection but vary in sensitivity and applicability.

Strain gauges and fiber optic sensors (FOS) [4]-[6] provide localized measurements of stress and deformation with high accuracy. FOS excels in long-term durability and precision but comes with higher installation costs. Laser scanning and LiDAR [7] are effective in capturing surface deformations and creating detailed 3D models but can be limited by weather conditions. GNSS [8][11] is used in infrastructure structural health monitoring to provide high-precision, real-time measurements of large-scale displacements and deformations, enabling accurate tracking of structural movements over time for enhanced safety and maintenance planning.

Emerging technologies like wireless sensor networks (WSN) [9],[12] enable real-time data collection of multiple physical measurement parameters reduced costs, but allowing data fusion and better remote data interpretation.

2 TECHNOLOGY OVERVIEW

2.1 Magnetic 6D-Sensor

The continuous monitoring of the structural integrity of transportation infrastructure requires precise and reliable measurement methods.

The 6D sensor from SuessCo is based on a magnetic field sensor array that measures position and rotation relative to a permanent magnet with high accuracy [13]. The system captures movements in all six degrees of freedom (X, Y, Z as well as roll, pitch, and yaw) and achieves a repeatability of ±50 µm in the translational axes and ±0.1° in the rotational axes. This is accomplished through a combination of machine learning and mathematical algorithms that allow precise recalculation of the measured values in real time. The high precision and easy installation make these sensors particularly suitable for monitoring critical infrastructure components such as bridge bearings.

Using an array of magnetic field sensors for position determination offers significa1nt advantages, particularly due to the overdetermined nature of the system, which enhances accuracy and reduces the impact of external influences. With multiple sensors, the system collects redundant data, allowing it to cross-reference measurements and filter out inconsistencies caused by magnetic stray fields, interference from electrical fields (such as those from power lines), and thermal fluctuations. The overdetermined setup enables compensation for temperature-induced changes in the magnetic field, ensuring that the sensors remain accurate even in varying thermal conditions. This redundancy improves robustness, compensates for local anomalies, and results in more precise and stable position determination.

Self-diagnostic feature ensures that the sensor operates reliably by detecting potential faults, calibration drift, or performance degradation in real time. As a result, the system can immediately alert operators to any issues, reducing the risk of inaccurate data or sensor failure.

Therefore, accurate recalculation of the position is performed on a webserver to allow the usage of low performance microprocessors. Transmitting the sensor data is possible via

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Wi-Fi or LTE-M allowing worldwide usage. For the 6D sensor also an external antenna is used to increase RF performance. An external battery pack with cable connection allows long time measurements with measurement frequencies down to 15 minutes and sending intervals of 1h. The Battery pack can be placed where they can be reached easily. The sensor itself has dimensions of 170 mm x 100 mm x 45 mm for a 60 mm x 30mm x 20mm measurement range allowing direct installation inside bridge bearings for example. This design features a physically separated sensor array and reference point. Unlike traditional systems, where precise alignment between components is often required, the 6D sensor allows the sensor array and reference magnet to be installed independently of each other. Traditional systems often require meticulous positioning to ensure accurate data collection, which can be labor-intensive and time-consuming. This flexibility is especially beneficial in challenging environments, such as bridges or large infrastructure, where precise alignment may be difficult to achieve. Additionally, a separated system is more adaptable to various structural configurations, improving scalability and reducing the risk of installation errors.

Additionally, a 3D version of this sensor type is available. It has internal antennas and batteries further reducing the footprint by sacrificing the euler angle values.

2.2 Low-cost high-precision GNSS

Both commercially available systems and in-house developments have demonstrated reliable measurement performance in various studies [11][12][14]. For comparison, 3D polar measurements from tachymetric monitoring systems were used as a reference. In recent years, a range of GNSS multi-frequency OEM boards with corresponding antennas has become available [15]. Before deploying GNSS technology for automated monitoring, it is crucial to evaluate its performance, particularly its 3D accuracy and long-term stability. Optimal results are generally achieved through the analysis of 24-hour session averages [11][12][14], which can also be evaluated on an hourly basis by incrementally extending the evaluation window. However, this approach introduces latency, which reduces the system's responsiveness.

An alternative method involves RTK-GNSS for direct deformation measurements, with some OEM boards supporting a measurement frequency of up to 100 Hz. Manufacturers have integrated carrier-phase ambiguity resolution algorithms into GNSS boards, and through efficient transmission of RTCM correction data via NTRIP, these receivers can deliver RTK positions in standardized NMEA format. Additionally, affordable antennas are now widely available, and their impact on measurement accuracy has been thoroughly investigated in several studies [8],[10],[15]. On-site data is transferred to a web service where the Wa2 module [15] computes, analyzes, and adjusts each baseline combination. However, this method is not suited for large-scale network extensions due to its inherent limitations.

Further testing with the open-source software RTKLib [16] has shown comparable accuracy, with ambiguity fix rates ranging from 95% to 100%. Using this approach, the GNSS system was implemented and tested in various pilot projects. In one such project, GNSS measurements provided results comparable to those from tachymetric systems. GNSS is particularly effective in tracking absolute deformation trends over extended periods in outdoor environments, offering greater insights than a four-week total station measurement. This capability enhances safety on construction sites. Although GNSS systems can operate independently of other monitoring systems, their high-power consumption remains a limitation for long-term, battery-powered applications. Addressing this issue is a key focus of future developments.

2.3 Installation and mounting

The 6D sensors are mounted directly on or inside the bridge bearings to precisely detect movements and rotations. This type of installation is particularly suitable for monitoring thermally induced displacements caused by temperature changes. The sensors can be configured to detect even the smallest changes in bearing position, which may indicate structural issues.

The 6D sensors are designed to be installed even in hard-to-reach areas, such as bridge bearings or expansion joints. The physical separation between the sensor array and the reference magnet allows flexible installation without requiring precise alignment of components. In many cases, the sensors can be mounted directly in polymer or roller bearings using magnets. However, depending on the complexity of the bearing structure, detailed planning in advance is necessary. For this purpose, creating a digital model of the bearing is recommended to precisely design the mounting structure and ensure optimal sensor placement. This approach minimizes installation errors and allows for perfect integration, especially in bearings with complex geometries.

For monitoring large-scale displacements, particularly of bridge piers and foundations, GNSS systems are used. These systems detect movements in the sub-centimeter range and are especially effective in open, unobstructed environments. When installing GNSS systems, the cable length to the antenna is limited. To bridge longer distances, expensive signal amplifiers are often required. Therefore, it is important to define during the planning phase where the GNSS antenna and the processing unit should be positioned to minimize signal loss.

To simplify the installation of GNSS antennas, we have developed a custom 3D-printed component that allows the antennas to be mounted directly onto standard satellite dish brackets. These mounts are not only stable and widely available but also easy to install, offering a cost-effective solution for most standard applications.

For more complex requirements, it may be beneficial to develop custom mounts specifically tailored to local conditions to ensure the optimal performance of the GNSS systems.

3 SENSOR INTEGRATION AND DATA FUSION

3.1 Combining 6D-Sensors and GNSS

The combination of using high precision 6D sensors to measure bridge bearings, along with advanced GNSS technology, provides a comprehensive solution for monitoring and quantifying the behavior of bridges under various conditions. The 6D sensors, capable of capturing movements in all six degrees of freedom, three translational (X, Y, Z) and three rotational (pitch, yaw, roll)—offer precise insights into the thermal expansion and contraction of bridge structures. Thermal movements, which occur due to temperature fluctuations, can cause significant structural shifts, particularly in bridge bearings. With the 6D sensors, it becomes possible to

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detect and quantify these minute thermal movements, providing engineers with real-time data to assess how the bridge reacts to environmental changes.

In addition to thermal movements, the 6D sensors can also capture the influence of external loads, such as wind pressure or traffic. The dynamic load exerted by vehicles crossing the bridge, combined with the fluctuating forces of wind, can cause stress and movement within the structure. By continuously monitoring these factors, the sensors help assess how well the bridge is handling daily operational stresses. This data is crucial in predicting potential issues and mitigating risks, allowing for proactive maintenance and increased safety.

When paired with a GNSS system, such as a high-precision multi-frequency GNSS module, the monitoring system becomes even more powerful. GNSS technology provides sub-centimeter accuracy in measuring the movement of the bridge's supporting pillars. While the 6D sensors offer detailed data on the local movements at the bearings, the GNSS system can monitor the larger-scale displacements of the bridge's foundations or pillars. This combined approach enables a thorough understanding of whether observed movements are due to thermal expansion of the bridge deck or are indicative of potential structural issues with the bridge's pillars or foundations.

For example, if the sensors detect movement at both the bearings and the pillars, the GNSS system can help differentiate between the natural thermal expansion of the bridge deck and actual shifts in the foundation. This distinction is crucial because movements caused by thermal expansion are usually temporary and reversible, whereas foundation movements could signal more serious issues, such as settlement or structural fatigue.

Moreover, the integrated system can operate continuously, providing real-time data on the structural health of the bridge. Such monitoring is essential for infrastructure located in areas subject to environmental stresses like fluctuating temperatures, high winds, or heavy traffic. By combining these two advanced technologies, engineers gain a better understanding of the bridge's behavior under various conditions, leading to more informed decision-making regarding maintenance schedules and potential reinforcements. In the long run, this can help extend the lifespan of critical infrastructure while ensuring the safety of its users.

This integration of 6D sensor technology with GNSS monitoring is part of a broader trend toward smart infrastructure, where real-time data is leveraged to optimize performance and prevent catastrophic failures. The ability to continuously monitor both short-term factors, such as thermal expansion, and long-term movements of the bridge's pillars offers a level of detail previously unavailable through traditional surveying methods alone. With further developments, especially in reducing power consumption for GNSS systems, the future of bridge monitoring promises even more efficient, reliable, and autonomous systems.

3.2 Communication and data transmission

The presented sensors use state-of-the-art encryption to protect the data during transmission. When data is sent from the sensors to the webservice, it is encrypted to prevent any unauthorized access or tampering while it's in transit. Data transmission is provided as an integrated service, eliminating the need to manage SIM cards, mobile plans, or network connectivity. This streamlined approach allows for effortless deployment and continuous monitoring with minimal technical oversight. The used LTE-M [17] standard is part of the 4G standard leading to nearly global coverage without any additional checks, only 4G coverage needs to be present. LTE-M normally uses lower frequencies with lower data rate leading to more penetration and coverage than 4G. Most countries offer detailed LTE-M coverage maps, allowing users to accurately check reception in advance and ensure reliable connectivity in the deployment area.

Wi-Fi serves as an additional, efficient method for providing internet connectivity to the sensor, particularly in environments where LTE-M coverage may be unavailable, such as tunnels, mine shafts, or lower basement floors. This alternative communication method is advantageous in settings where the penetration of cellular signals is limited due to physical obstructions or underground conditions. By utilizing existing Wi-Fi networks, the sensor can maintain reliable data transmission in these challenging environments.

High data transfer rates, provided by Wi-Fi connections, are particularly beneficial for transmitting large datasets or high-frequency measurement updates in real time. In industrial or remote monitoring applications, utilizing Wi-Fi ensures continuous sensor operation without the reliance on extensive cellular infrastructure. This capability is especially valuable in areas where stable, high-speed communication is critical for maintaining data integrity and operational efficiency.

The use of Wi-Fi [18] in such scenarios is further supported by modern advances in mesh networking and extended-range Wi-Fi technologies, which improve coverage and signal stability even in hard-to-reach areas. For example, industrial-grade Wi-Fi routers and repeaters can be used to strengthen signals and extend network coverage to areas that would otherwise be unreachable by standard Wi-Fi systems. Wi-Fi's adaptability, combined with robust encryption protocols, ensures secure data transmission and minimizes the risk of loss or interference, making it a suitable solution for reliable infrastructure monitoring in challenging environments.

3.3 Webservice with dashboards

SuessCo developed and provides a web service as an infrastructure solution providing the ability to collect, process, visualize, and manage data from connected devices, such as sensors. It is commonly used for integrating various sensors and IoT devices, enabling real-time data monitoring and control. Web services support data collection through different protocols like MQTT, CoAP, and HTTP, and can process this data using custom logic for actions and alerts. Target applications are remote monitoring and control of IoT devices in sectors like infrastructure monitoring, smart cities, and agriculture.

While this web service provides robust data processing capabilities, it is also possible to configure it for collecting sensor data without relying on any specific platform's native dashboard or visualization tools. In this case, the sensors would send their data via a web service instead of using a predefined interface, allowing them to manage the data independently. This approach offers more flexibility in terms of integrating with alternative visualization platforms or custom-built solutions. Users can access, analyze, and display data from

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their sensors in a more customizable manner, enabling a variety of applications such as advanced data analysis or machine learning.

4 CASE STUDIES

The following chapter presents and analyzes various case studies involving bridges, buildings, and other infrastructure. These projects provide valuable insights into the practical applications of monitoring technologies and the findings related to structural integrity. At the request of the involved clients, the projects have been anonymized to ensure confidentiality.

The values in the following chapter are zeroed by subtracting the initial measurement, allowing for the detection of relative displacements and ensuring comparability.

4.1 Bridge bearings influenced by unintentional manipulation, surface treatment and flood disaster

The first pilot project, which was successfully transitioned into an ongoing monitoring project and has now been running for over four years, involves the monitoring of a steel-element road bridge. Initially, it was unclear whether the end elements at the abutment were impacting, which is why the sensors were first installed there. However, once it was proven that this was not the case, the sensors were subsequently relocated to the bearings of the central pier in the river over the course of the project.

Figure 1. Images of the Monitored Roller Bearing: Left: Condition at installation with corresponding axes; Right: Sensor after maintenance work, displaced and sandblasted

Since July 1, 2022, the sensors have been operating at their new position and have been continuously monitoring the bridge — including during the flood event in 2024, which provided valuable data on structural integrity.

The following section includes both an analysis of the effects of unintended sensor displacement during bridge renovation work (see Figure 4 and Figure 5) and a detailed evaluation of the measurement data collected during the 2024 flood.

The diagram in Figure 2 shows, in the upper part, the sensor's positional displacements along the x-axis (blue), y-axis (green), and z-axis (red). The lower part of the diagram displays the internal temperature of the sensor. The measurements, recorded at 15-minute intervals, are presented here as daily average values.

Figure 2. Measurement data for monitoring a roller bearing: effects of unintended displacements during maintenance work and wildlife damage

As expected, significant fluctuations can be observed along the x-axis due to the thermal expansion of the bridge element. In October 2022, a sharp and abrupt change is visible, which can be attributed to a mechanical shift in the sensor setup (see Figure 1, right). During this period, the sensor was also sandblasted, but this had no relevant impact on the measurement results.

A disruption in sensor data in March 2023 was caused by wildlife damage—specifically, pigeons pecking at the cable. In December 2023, the sensor failed due to a hardware defect, which has already been resolved in the new hardware version of the sensor. Aside from these events, the data shows a very good correlation with the expected thermal expansion and only minor movements along the y- and z-axes.

The diagram in Figure 3 consists of three subplots showing the positional displacements of a sensor along the x-, y-, and z-axes (ΔX_0, ΔY_0, ΔZ_0) as a function of temperature. The measured data points are displayed as blue violin plots with error bars, illustrating the distribution of values at different temperatures. The number of measurements per temperature interval is indicated along the bottom of the x-axis. A different sensor is used in Figure 3 than in Figure 1 and Figure 2. The Sensor in Figure 3 is mounted on a polymer bearing and summarizes historical data from the year 2021.

Top subplot (ΔX_0 position): Shows a strong linear correlation between temperature and displacement along the x-axis. The linear fit (orange line) has a slope of 0.75 mm/°C, indicating thermal expansion of the monitored bridge element, which also aligns well with the expected values. The data spread is relatively small, indicating consistent thermal expansion.

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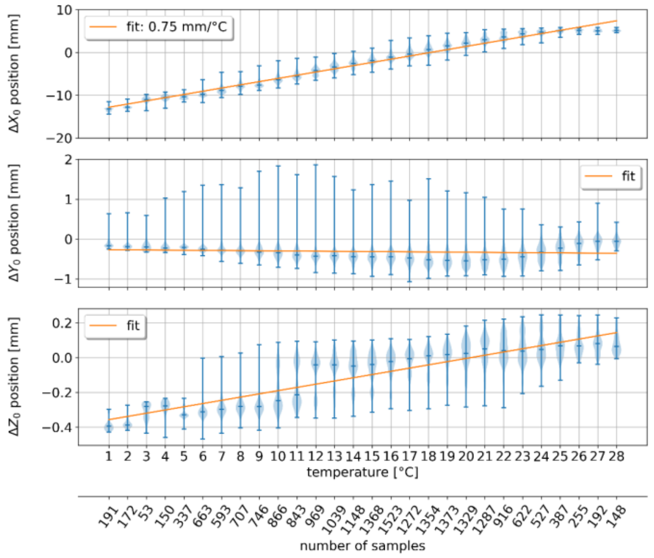

Figure 3. Representation of the Thermal Dependence of Positional Displacement Based on Historical Data.

Middle subplot (ΔY_0 position): No significant correlation is observed between temperature and displacement along the y-axis. The data shows high scatter, indicating non-systematic influences, possibly due to mechanical impacts or disturbances. The fit is nearly flat, suggesting that no temperature-induced movement is expected along this axis.

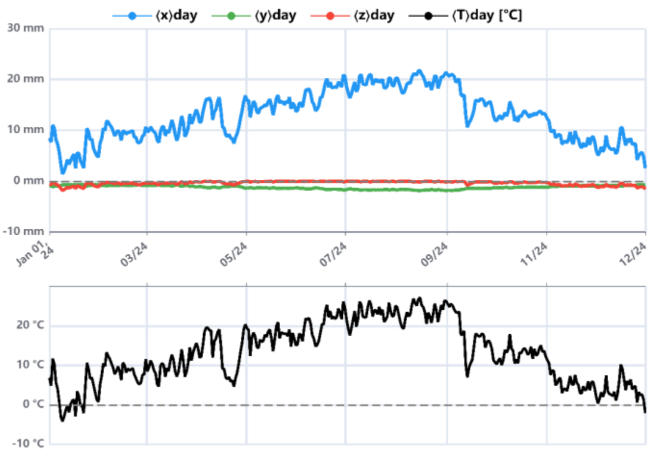

Figure 4. Daily Average Values Independent of the Sensor's Measurement Interval in Figure 1. The data shown is from the year 2024 and includes a flood event in September.

Bottom subplot (ΔZ_0 position): A slight correlation between temperature and displacement along the z-axis is evident; however, the effect is much weaker than along the x-axis. The linear fit shows a small but consistent displacement, indicating minimal thermal movement in the vertical direction. The data scatter is moderate, and the amplitude is significantly smaller compared to the other axes, suggesting lesser influences in this direction.

The diagram in Figure 4 illustrates how the bridge responds to seasonal temperature fluctuations and simultaneously shows the impact of exceptional events such as the flood disaster in September 2024. Monitoring data is essential for assessing the structural integrity of the bridge during such extreme situations. The diagram presents the positional displacements of the sensor along the x-axis (blue), y-axis (green), and z-axis (red) throughout the year. The x-axis shows significant variation, with displacements increasing up to 30 mm, indicating thermal expansion of the monitored bridge element. In contrast, the y- and z-axes show only minimal movement, suggesting that the bridge remains largely stable in those directions.

The lower subplot shows the temperature trend over the course of the year. A clear seasonal pattern is visible, with temperatures falling below 0°C in winter and rising above 20°C in summer.

From September 13 to 20, 2024, the bridge was affected by a flood disaster, yet no significant anomaly is visible in the measurement data. The diagram clearly shows that while the displacements along the x-axis temporarily dropped during the flood event, the behavior was consistent with previous temperature fluctuations. Even after the flood, no significant changes in the measurement values were observed. This indicates that the bridge did not suffer any lasting damage from the flood and that its structural integrity remained intact.

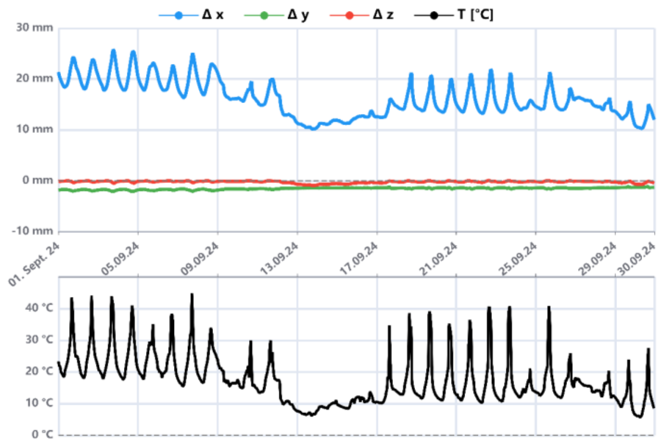

Figure 5. Same Bearing as in Figure 4, but with Detailed Data at 1-Hour Intervals for the Month of September.

This example highlights the importance of continuous monitoring at bridge bearings: On one hand, continuously collected data allows for immediate response to unexpected deviations; on the other hand, it enables the assessment of changes before and after exceptional events such as flooding. This makes it possible to detect potential damage early—during and after such events—and to take targeted action, significantly improving the long-term safety of the infrastructure.

In Figure 5, the data for September is shown at the actual measurement interval of one hour. Even at this higher temporal resolution, no unexpected movements are visible. Even during the flood disaster from September 13 to 20, 2024, the measurements display stable behavior consistent with the typical pattern of thermal expansion. Furthermore, the peak temperature recorded here is significantly higher than the air temperature, as the sensor housing is exposed to direct sunlight.

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4.2 Bridge bearing with transverse displacement

In another bridge project, measurements were conducted at multiple points along a curved bridge located on a creeping slope. The results (Figure 6 and Figure 7) showed that individual bearings exhibited consistent but slow displacement along the y-axis—that is, transverse to the roller bearing's intended direction of movement.

Figure 6. A 6D sensor installed on a roller bearing of a railroad bridge

This motion leads to wear on the bearing's retaining plates. It has not yet been conclusively determined whether the bearings reach a point at which they can no longer compensate for the movements, which could result in unanticipated stresses within the bridge structure.

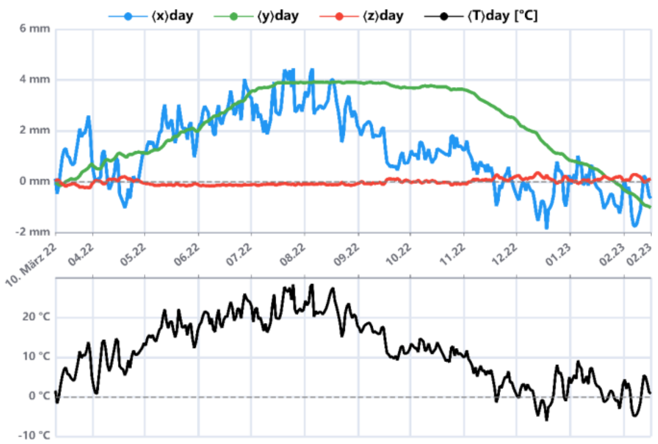

Figure 7. Measurement Results of the Roller Bearing on a Curved Bridge Showing Increased Y-Axis Movement Leading to Wear of the Bearing's Retaining Plates.

Notably, these displacements could not be detected using conventional measurement systems such as total stations or rail surveying; only the wear itself had previously been observed. The precise and multi-axis sensors enabled more detailed detection that was not possible with other methods and thus provided valuable insights into the maintenance strategy.

4.3 Measurement of crack formation on a natural stone railway viaduct

In this project, several sensors were installed on different cracks of a natural stone railway viaduct. The cracks either ran directly through the stones or along the joints between them. The sensors were strategically placed to monitor both types of cracks and to analyze potential differences in deformation behavior.

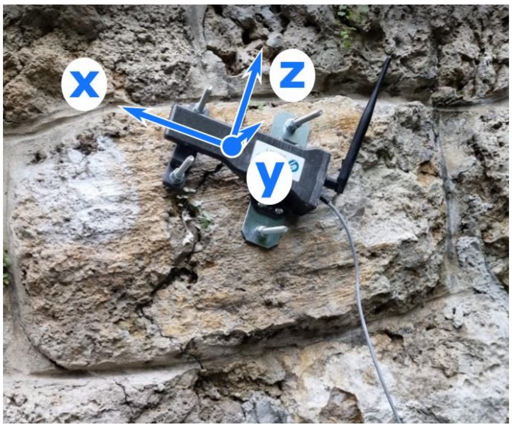

Figure 8. Mounting of the Sensor Above a Crack in the Natural Stone of a Railway Viaduct.

The goal was to monitor the behavior of the cracks: Are they stable, or do they show dependencies on temperature and humidity fluctuations? presents the results from one of these sensors, whose position is shown in Figure 8. In this project, the sensors and reference points could be mounted directly using stone screws or bonded threaded rods, without the need for additional mounting materials. This method enabled a secure and stable attachment directly to the natural stone, allowing for efficient and durable installation.

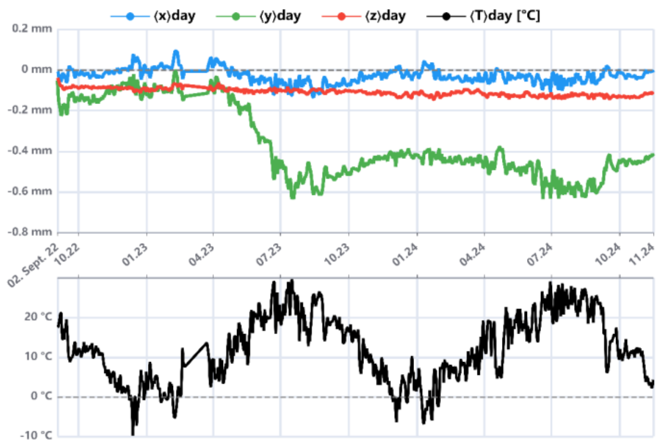

Figure 9. A significant and irreversible change is visible along the y-axis (green). However, the amplitude of this displacement is only about 0.4 mm, indicating a very small but still measurable change.

In Figure 9, only very small changes can be observed overall, as the total amplitude range on the y-axis is just about 1 mm. Nevertheless, a significant and irreversible displacement is evident starting in April 2023. Compared to the measurement

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data from the bridge bearings, the values recorded here differ considerably, confirming the thermal stability of the sensor. This crack exhibits the most active movement among all measured points; however, it was determined that most cracks are generally stable. Therefore, it was decided to reduce the measurement interval to one hour in order to maximize battery life. If necessary, the interval can be remotely adjusted again.

4.4 Crack measurement in a building with supplementary GNSS measuring points

As part of the subway construction works in Vienna, the groundwater level had to be lowered, which led to significant cracking in surrounding buildings even before the actual tunneling began. For this project, several 3D and 6D sensors () as well as GNSS measurement points were installed on the exterior walls of the affected buildings. The GNSS system [11],[12] used in this project (Figure 10) was developed in collaboration with Werner Stempfhuber. The 3D and 6D sensors were easily mounted using conventional screws, while the installation of the GNSS brackets on the building facade had to be carried out by specialized personnel.

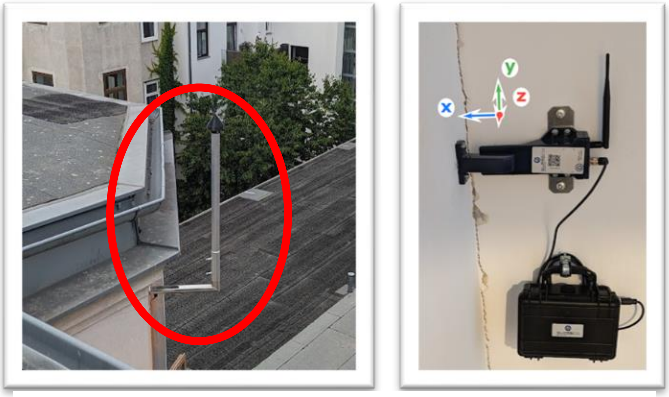

Figure 10. Left: Mounted GNSS antenna on the exterior wall of the residential building. Right: 6D sensor mounted in a building corner near the GNSS antenna.

By combining these two measurement systems, it was possible to precisely monitor the relationship between the cracks and the surrounding walls, while the absolute GNSS system additionally allowed for the detection of potential subsidence of the entire building or individual sections. This approach increases the significance of the measurements and provides the private property owner with reliable data to demonstrate to the construction client any potential effects of the construction work on their property. At the same time, monitoring enables early warning in the event of sudden significant movements, allowing the developer to intervene in time to prevent further structural damage.

Positive feedback also came from the residents of the building, who now feel somewhat safer due to the continuous monitoring of the visible cracks in the structure.

In Figure 10, the sensor is located inside the building, as indicated by the significantly more stable temperature profile compared to previous case studies. Notably, a jump along the z-axis (red) is visible in September (high amount of rain). Although the initial change in September measured only 0.6 mm over a period of about two weeks, it marked the beginning of a continuous increase in movement. By February 2025, the sensor recorded a total displacement of up to 2.3 mm. This deviates significantly from the crack's previous behavior and indicates a structural issue.

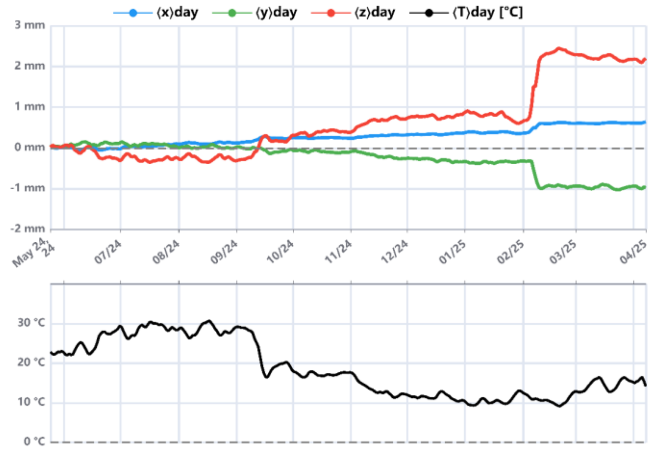

Figure 11. The change in z-axis behavior (red), of the Sensor shown in Figure 10, observed in September 2024, was triggered by heavy rainfall and led to a structural damage event in February 2025.

A different 3D sensor shows even greater displacements (see Figure 12), starting in September 2024 and peaking at up to 10 mm along the x-axis in February 2025. This increased movement is likely due to the sensor's alternative mounting configuration.

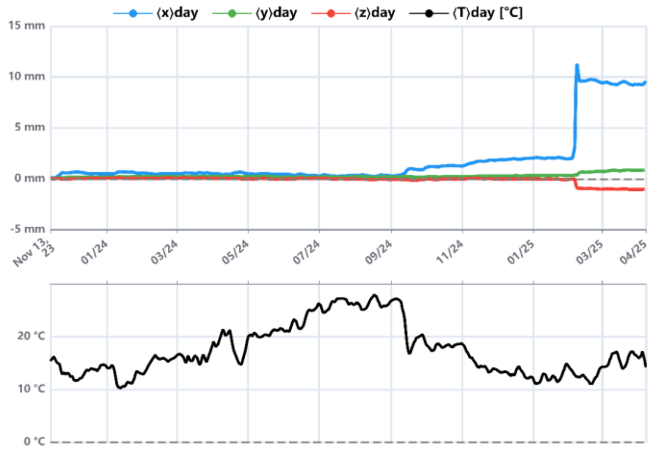

Figure 12. Even higher x-axis peak in February of 2025.

Similar behavior has also been observed in other 3D sensors throughout the building, suggesting that the structural movement is not limited to a single location but affects the entire structure. This indicates a widespread response of the building to external influences, likely requiring a comprehensive structural assessment.

However, these observations were not limited to the 3D sensors inside the building—four GNSS sensors installed at each corner of the structure also exhibited similar behavior. The GNSS points are numbered clockwise, starting from the southeast corner of the building.

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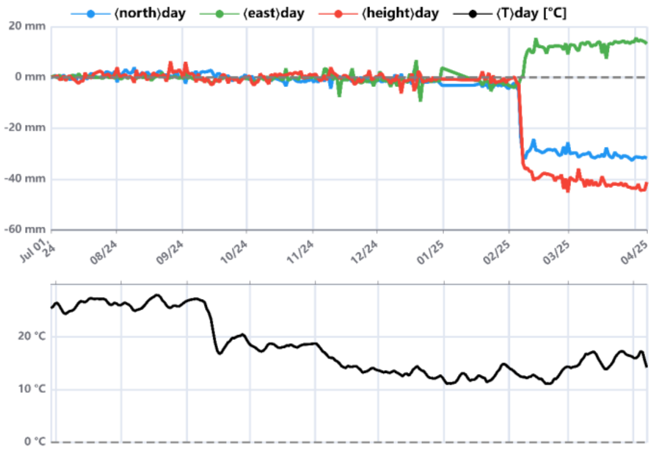

Figure 13. GNSS Point 1 in the south east corner of the building.

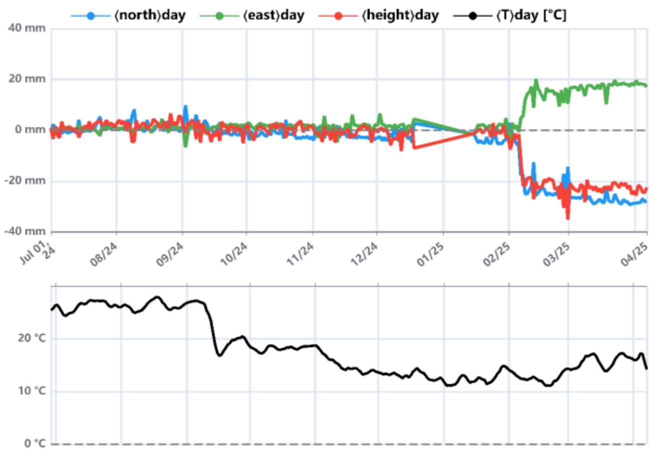

Figure 14. GNSS Point 2 in the south west corner of the building.

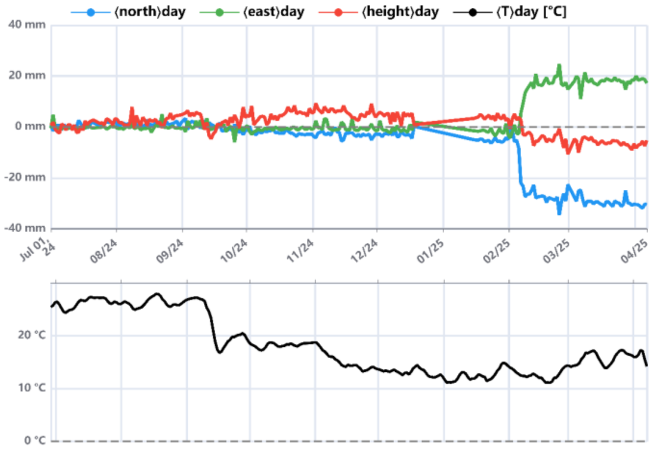

Figure 15. GNSS Point 3 in the north west corner of the building.

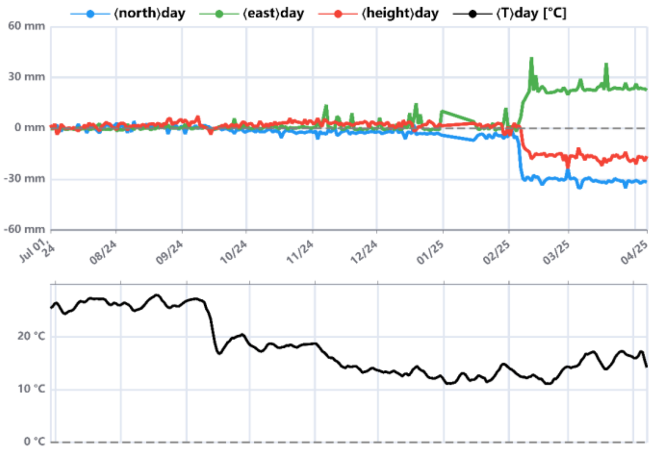

Figure 16. GNSS Point 4 in the north east corner of the building.

For the initial monitoring period (July 2024 to early February 2025), all sensors exhibited only minor fluctuations within a ±5 mm range across all axes. This behavior is consistent with expected seasonal thermal expansion and contraction, as confirmed by the relatively stable and slowly varying temperature profile. Unfortunately due to a power fault there is missing data from beginning to mid-January.

However, a significant and abrupt shift in the displacement data was observed across all GNSS sensors starting in early February 2025. This event was not associated with any comparable temperature anomaly and is thus interpreted as a non-thermal structural movement. The magnitude and direction of the displacements varied by sensor location:

GNSS 1 (Southeast Corner, Figure 13): Displacements of approximately −30 mm in the north direction and −20 mm in height were recorded, accompanied by an increase of +25 mm in the east direction.

GNSS 2 (Northeast Corner, Figure 14): This sensor registered the largest displacements, with −40 mm in the north, and the vertical direction, and +20 mm in the east. The scale of movement suggests significant subsidence and lateral displacement.

GNSS 3 (Northwest Corner, Figure 15): Moderate movement was recorded, particularly to the north with −30 mm and east +20 mm directions. But height stays very stable compared to all other sensors.

GNSS 4 (Southwest Corner, Figure 16): Displacements at this location were also substantial, with movements of approximately −20 mm in the vertical axis and +20 mm in the east direction.

The synchronized onset and consistent directional trends of the displacements across all sensors strongly suggest a global response of the building structure, likely triggered by high rain period in September of 2024 and leading to a massive structural movement in February 2025. Given the known construction activities related to subway excavation in the vicinity, it is plausible that the observed displacements are a direct consequence of these works.

The GNSS and 3D position data thus provides reliable and high-resolution evidence of structural movement, which is essential for assessing building integrity and potential damage progression. This type of sensor-based monitoring offers a valuable basis for initiating countermeasures, engaging with

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responsible parties, and supporting claims for damage compensation.

5 CONCLUSIONS

The multi-year investigations clearly demonstrate the advantages of combining 6D sensors with GNSS measurement systems for monitoring the structural integrity of infrastructure and buildings. This integrated approach offers a significantly enhanced perspective on structural motion detection: while 6D sensors enable detailed analysis of local displacements across all degrees of freedom, GNSS systems provide highly accurate measurements of absolute positional changes. The synergy between these two technologies not only increases the informative value of the measurements but also improves the monitoring of structures under variable environmental conditions, such as temperature fluctuations or groundwater drawdowns—factors that present particular challenges in urban settings.

The deployment of these systems in the presented projects has resulted in a robust data foundation, allowing stakeholders to produce well-founded evidence of potential structural impacts caused by construction activities or environmental influences. Continuous data acquisition supports the early detection of damage risks and contributes significantly to the safety and longevity of the monitored structures. Particularly noteworthy is the real-time monitoring capability enabled by the integrated system, which allows for immediate response to unexpected structural movements and thereby minimizes the risk of significant damage.

Looking ahead, the focus will be on further optimizing the energy efficiency of the deployed sensors and expanding the integration of AI-assisted anomaly detection. These developments will further enhance the precision and operational efficiency of monitoring systems while reducing maintenance costs. The insights and experiences gained from the current projects provide a solid basis for future advancements aimed at improving the reliability and sustainability of monitoring solutions in demanding infrastructure environments.

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