Advanced Monitoring Systems for Bridge 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 bridges, 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 bridge 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.

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][5][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][9][10][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 following chapter describes the patented high-tech 6D sensor [13] designed for digital long-term monitoring of complex movements. The SuessCo 6D-Sensor precisely captures absolute position changes and rotations between two objects. It measures the three spatial axes (X, Y, Z), the corresponding rotational values (3 Euler angles), and temperature data.

Figure 1: 6D position sensor based on magnetic field measurements showing axis orientation.

The Sensor is based upon a magnetic field sensor array which measures the strayfield of a permanent magnet. In order to enable high-precision determination of the position (Repeatable accuracy: X,Y,Z: ±50 μm, α,β,γ: ± 0,1°) a gradient-based optimization method that iteratively determines the optimum translation and rotation of the sensor array relative to the reference magnet is used.

In order to map the entire phase space accurately and robustly, it is essential that the initial value for the iterative method is as precise as possible. In particular, the initial value for the rotation must be set to the correct octant in order to guarantee the convergence of the iterative method.

We use supervised machine learning to select this starting value. The time-consuming training is performed once with analytically calculated training data and stored for later use.

The prediction for translation and rotation of the sensor array can be calculated with very high efficiency after training has been completed and then serves as a starting value for the gradient method described above. The combination of the two algorithms provides very accurate results and is robust against sensor noise and strong rotation. In addition, this method offers very high speed with moderate resource requirements.

This approach allows for precise quantification of results, ensuring that data outputs are consistent with the underlying model. If the measured values deviate significantly from the expected model behavior, the system flags an error, preventing erroneous outputs. This built-in validation process ensures high reliability, as only valid data is accepted, reducing the risk of incorrect results and enhancing system robustness.

Using an array of magnetic field sensors for position determination offers significant 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. Additionally, the used magnetic field sensors are rated for the usage in the automobile applications. This offers the distinct advantage of built-in self-checking capabilities, allowing them to continuously monitor their own functionality and accuracy. This 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, the accurate recalculation of the position is performed on a webserver in order to allow the usage of low performance microprocessors. Transmitting the sensor data is possible via wifi or LTE-M allowing a worldwide usage. For the 6D sensor also an external antenna is used in order 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.

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

There are basic Dashboards, as shown in Figure 2 and Figure 3, allowing fast and easy data visualization, sensor / project / user / alarm management and reporting. White labeling and custom translations are also included, allowing easy worldwide adaptation.

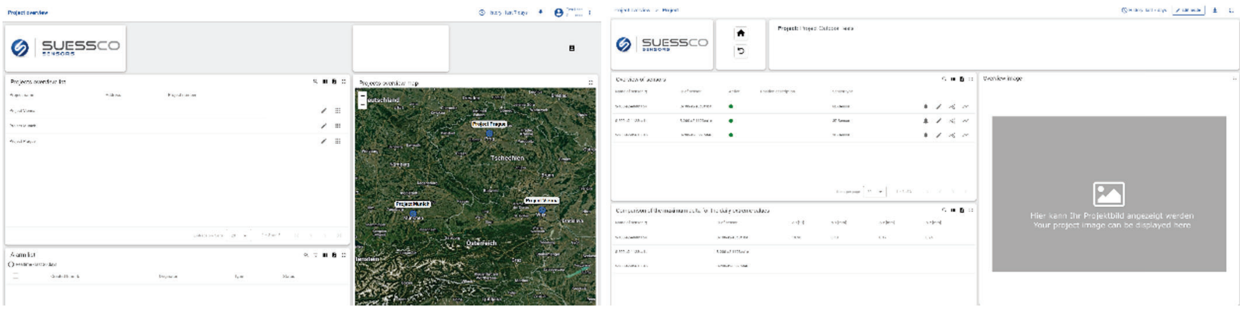

Figure 2: The left image shows the project overview, and the right image shows the project details inside an example dashboard.

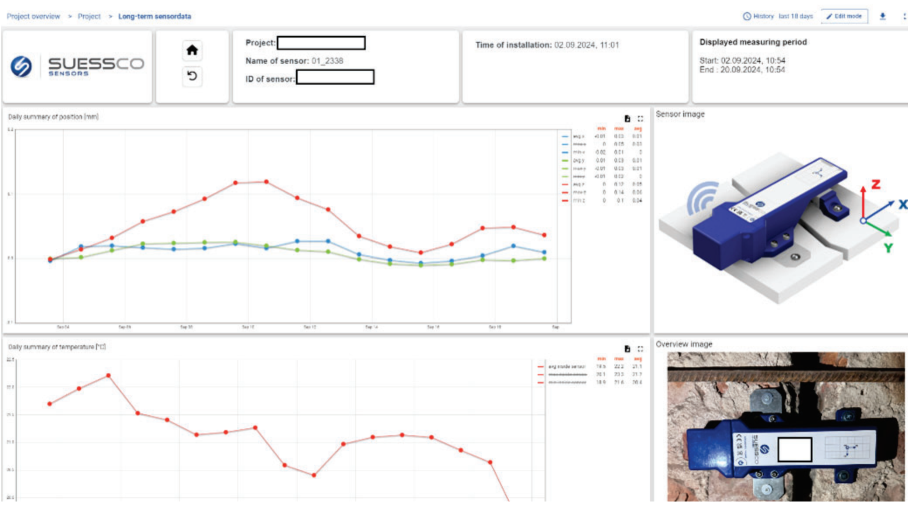

Figure 3: A detailed dashboard view of a single 3D sensor is shown. The values in the top graph represent daily averages and maximums, while the bottom graph displays the corresponding temperature data.

4 Bridge Monitoring Project Overview

The following section presents various applications of 6D sensors in bridge monitoring, demonstrating their effectiveness in capturing complex structural behaviors. It includes a comparison between 6D sensors and traditional vibration wire sensors, showing close correlation in the measurements, which validates the accuracy and reliability of the 6D sensors. A 3D plot illustrates the movement of a bridge bearing, offering a visual representation of displacement across all axes, highlighting the impact of thermal expansion on the structure. Also, a graph representing the thermal expansion behavior is described. One of the case studies focuses on a bearing that exhibited significant lateral (Y-axis) movements, underscoring the sensor's capability to detect critical structural shifts that might otherwise go unnoticed. Additionally, the chapter discusses various possible mounting options for the 6D sensors, emphasizing their versatility and adaptability to different bridge configurations. These examples showcase the value of 6D sensors in providing comprehensive, real-time monitoring data, which is essential for ensuring the long-term safety and performance of bridges.

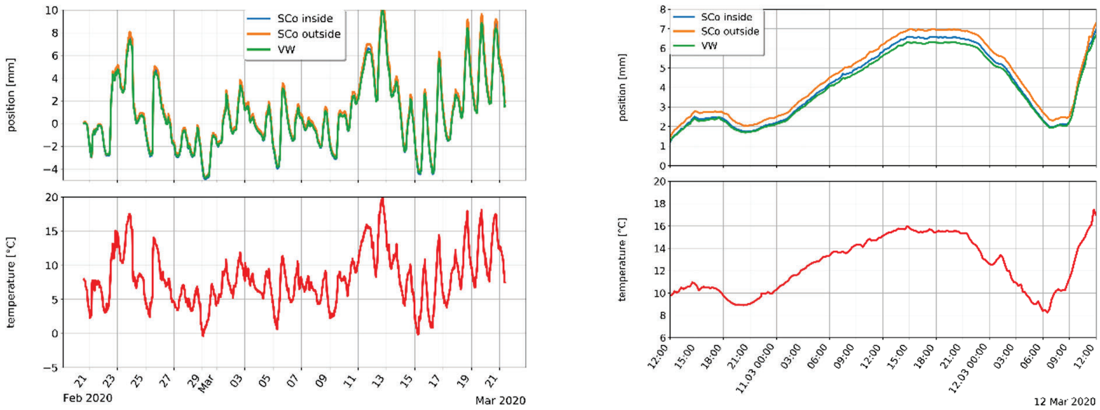

Figure 4: Comparison of two 6D-Sensors (blue and orange) with varied installation directions and a vibrating wire (green) sensor.

Two plots, one coarse (Figure 4 left graph) and one zoomed (Figure 4 right graph), are used to compare the data from two 6D sensors mounted on the same bridge bearing but installed in different orientations, alongside data from a vibrating wire sensor also mounted on the bearing. The coarse plot provides an overview of the measurements over time, showing the overall movement and response of the bearing under various loads and environmental conditions. Despite the different mounting configurations, the two 6D sensors exhibit nearly identical movement patterns, closely matching the data from the vibrating wire sensor. This indicates that the sensors are accurately capturing the same physical behavior of the bearing, with only minor variations.

The zoomed plot (Figure 4 right), offers a more detailed view, highlighting the minute differences between the sensors. These discrepancies are very small and are primarily attributed to installation inaccuracies, such as slight differences in sensor alignment or positioning. Despite these minor deviations, the overall data from the two 6D sensors and the vibrating wire sensor remain highly consistent, reinforcing the reliability and precision of the sensors in capturing the true movement of the bearing. This comparison validates that, with proper calibration and installation, these sensor systems can provide highly accurate and comparable data, even when mounted in different configurations.

Figure 5 shows a 3D plot of sensor data visualizing the movement of a bridge bearing in relation

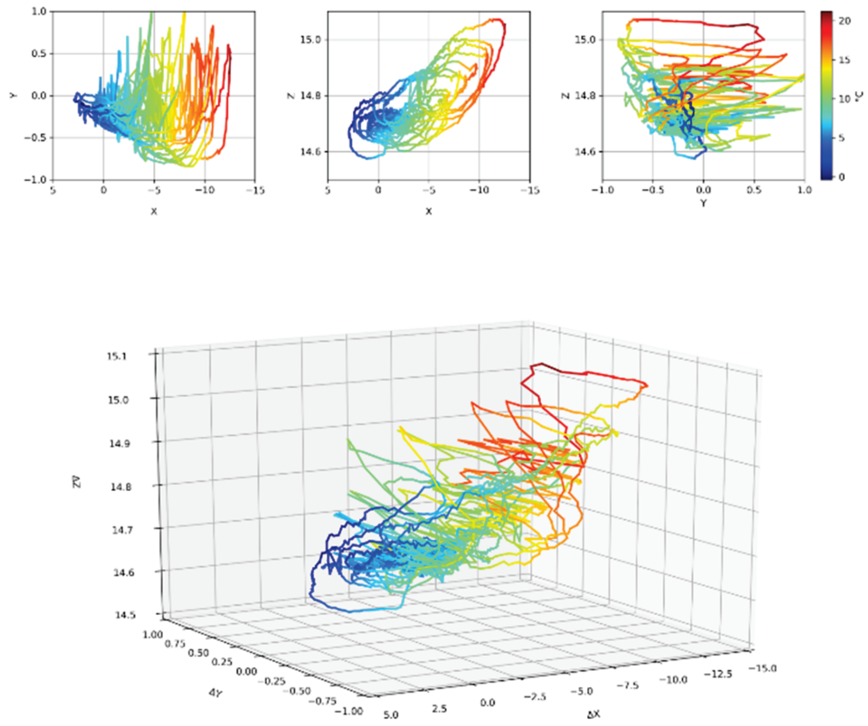

Figure 5: 3D representation of x, y and z axis movements of a 6D-Sensor in mm, colored by temperature.

to temperature provides a powerful tool for understanding the structural dynamics of the bridge. The plot would show the displacement of the bearing along three axes (X, Y, and Z) capturing both horizontal and vertical shifts. As temperature fluctuates, the 3D movement of the bearing becomes apparent, with the plot highlighting the expansion and contraction effects caused by thermal changes. This visualization allows engineers to observe correlations between temperature and structural movement in real-time, helping to quantify the degree of thermal-induced motion and providing critical insights into the long-term behavior and stability of the bridge. By analyzing these patterns, potential issues related to thermal stress can be identified early, leading to more informed maintenance decisions and improved safety.

Figure 6 illustrates the relationship between temperature and the displacement (ΔX_0) measured by the 6D sensor, specifically focusing on the thermal expansion of a steel bridge structure over a measured temperature range. The x-axis shows temperature, while the y-axis represents the displacement of the bridge bearing. The orange line in the plot represents a linear fit with a slope of 0.75 mm/°C, demonstrating a strong correlation between temperature increases and corresponding structural displacement due to thermal expansion. The blue violin plots provide insights into the data distribution and variability, with error bars capturing the range of measurements at each temperature point. Additionally, the number of samples at each temperature is displayed at the bottom, highlighting dense data collection, particularly between 4°C and 18°C, supporting the validity of the linear trend.

The standard thermal expansion coefficient for steel is approximately 11 to 13 x 10^{-6} /°C, meaning

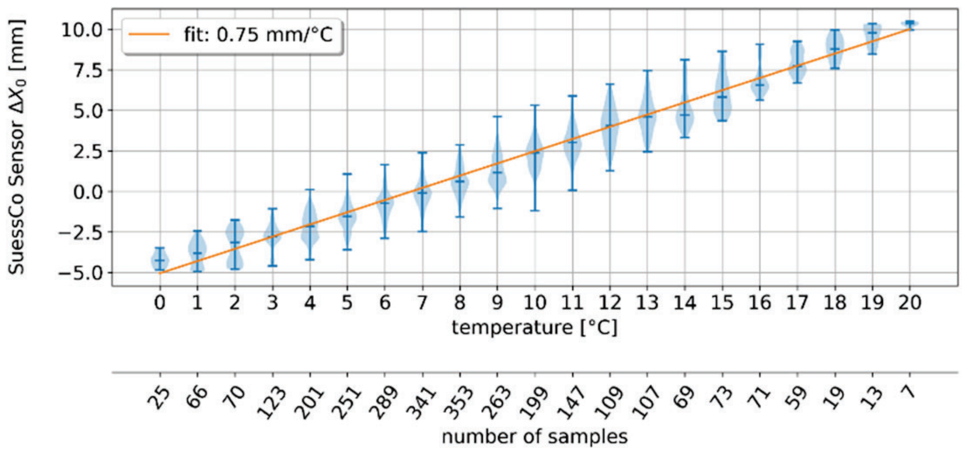

Figure 6: The linear fit of 0.75mm/°C represents the best approximation of mean thermal expansion within the measured values.

that for every degree Celsius of temperature change. For this 80-meter-long steel bridge deck, this would result in an expansion of 0.88 to 1.04 millimeters for every 1°C increase. The fitted displacement rate of 0.75 mm/°C observed in the plot aligns with this expected thermal expansion behavior, confirming that the 6D-sensor accurately captures these structural responses. While the primary axis of displacement exhibits a clear linear relationship with temperature, the other axes do not follow a similarly predictable pattern. This makes it highly effective for monitoring temperature-induced movements, ensuring that any expansions are detected early and accommodated in structural safety assessments.

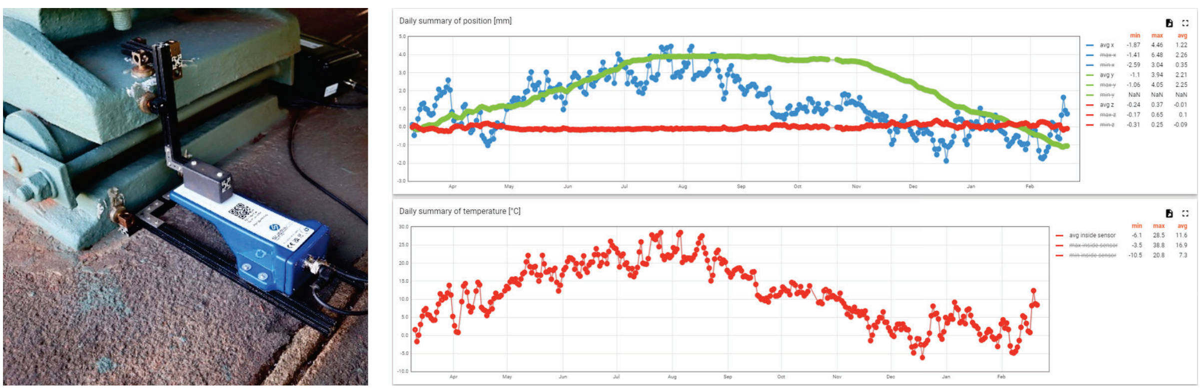

Figure 7: The left side shows a 6D sensor installed on a roller bearing of a railroad bridge. The right top plot shows x (longitudinal movement, blue), y (lateral movement, green) and z (hight, red) axis movements. The right bottom plot represents the temperature. An unpredicted lateral movement in y (green) is clearly visible.

In Figure 7 on the right, the blue line represents the longitudinal movement, which is highly dependent on thermal expansion and, therefore, predicted. However, the lateral movement (green) is unpredicted and occurs at the apex of the curved bridge. These lateral movements were not detected by standard railroad or tachymetric measurements, highlighting the advantages of in-bearing measurements for capturing complex structural behaviors.

Figure 8: The image illustrates several different mounting possibilities: the top left shows a sensor mounted along a thermal expansion joint, the top right depicts installation on a bearing with a slope, the bottom left demonstrates placement inside a bearing, and the bottom right shows a sensor mounted at the bridge's abutment.

5 Benefits of Sensor Integration for Infrastructure Monitoring

The integration of advanced sensor technologies, such as 6D sensors and high-precision GNSS systems, significantly improves the ability to monitor and assess the structural integrity of infrastructure, particularly bridges. These sensors offer continuous, real-time data that enhance structural insights, enable early detection of potential issues, support predictive maintenance strategies, and ultimately increase long-term cost efficiency.

6D sensors, capable of measuring displacements and rotations across all six degrees of freedom, deliver precise information on how bridge bearings and other critical components respond to loads, environmental factors [19], and operational stresses. This capability allows a better understanding of complex interactions between temperature changes [20], wind forces, traffic loads, and structural responses. Additionally, GNSS systems, when combined with 6D sensors, enable monitoring of larger-scale movements, such as shifts in bridge pillars or foundation settlements. This dual approach offers a multi-scale perspective, yielding enhanced structural insights that would be difficult to obtain with traditional monitoring techniques alone.

The real-time monitoring enabled by sensor technology allows for early detection of anomalies or deviations from expected bearing behavior [21], such as thermal expansion of bridge decks and abnormal deformations due to traffic or environmental loads. This early detection is crucial for preventing minor issues from escalating into critical failures, thus improving overall safety and reducing the risk of catastrophic structural failure.

The data generated by sensor systems supports predictive maintenance strategies, optimizing maintenance schedules based on actual structural conditions. Trends in the movement of bridge bearings, combined with environmental and traffic data, help forecast when maintenance or replacements will be necessary, reducing unexpected failures and extending the service life of critical infrastructure. This proactive approach lowers overall lifecycle costs by reducing the need for unplanned repairs and minimizing disruptions.

6 Future Developments

Our future sensor developments are focused on significantly reducing power consumption while improving overall accuracy. As sensors become more integral to infrastructure monitoring, particularly in remote or challenging environments, power efficiency is critical. We are working on optimizing the energy usage of our sensors without sacrificing precision, ensuring longer operational lifespans and more sustainable deployments. Additionally, we are expanding our sensor portfolio by incorporating new types of sensors to measure a wider range of physical parameters, further enhancing the depth and versatility of the data collected.

In parallel, we are integrating AI-based anomaly detection algorithms into our systems. These advanced algorithms will enable real-time detection of irregular patterns in sensor data, allowing for proactive identification of potential issues before they escalate. To complement this, we are also implementing dynamic alarming and interval steering capabilities. These features will automatically adjust the measurement frequency based on detected anomalies, ensuring that critical events are captured with higher granularity while maintaining power efficiency during normal operation. This combination of improvements will enhance the reliability, responsiveness, and overall performance of our sensor systems.

7 Conclusions

The integration of SuessCo's advanced 6D-sensor technology with high-precision GNSS systems presents a transformative advancement in the field of Structural Health Monitoring (SHM), particularly for bridge infrastructure. By capturing displacements and rotations across all six degrees of freedom with unprecedented accuracy, 6D sensors provide detailed insights into the behavior of bridge bearings—a critical component often overlooked in traditional monitoring systems. This capability allows for the detection of thermal expansion, contraction, and load-induced stresses, offering new possibilities in the precise quantification of bearing movements.

These sensors, combined with GNSS technology, extend monitoring capabilities beyond localized measurements to include large-scale displacements of bridge pillars and foundations. The ability to differentiate between thermal expansions of the bridge deck and foundation movements is a crucial innovation, providing early indicators of potential structural issues that traditional methods may not detect. This combined approach enables real-time, high-resolution monitoring that enhances the understanding of complex structural interactions under varying environmental and operational

conditions.
Moreover, the integration of machine learning algorithms for data validation and error flagging, along with self-diagnostic features of the sensor array, ensures high reliability and robustness in long-term monitoring applications. The built-in redundancy of the magnetic field sensor array offers superior noise filtering and compensation for external influences, further improving measurement precision.

This new generation of sensor technologies enables continuous, real-time monitoring and supports predictive maintenance strategies by providing detailed, actionable data. The ability to capture fine-scale variations in bearing behavior allows for more targeted interventions, preventing minor issues from escalating into significant structural failures. Future advancements in power efficiency, AI-based anomaly detection, and dynamic measurement interval steering will further enhance the autonomous operation of these systems, paving the way for smarter, more reliable infrastructure monitoring. The innovations in bearing measurements open new frontiers in ensuring the long-term safety and durability of bridges, contributing to a significant reduction in lifecycle maintenance costs and enhancing overall structural integrity.

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