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Research paper

GEOTECHNICAL AND GEODETIC STRUCTURAL MONITORING FROM THE PERSPECTIVE OF THE INDUSTRY 4.0 CONCEPT AND CHALLENGES TOWARD INDUSTRY 5.0

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Abstract

Contemporary challenges in monitoring and preserving civil and infrastructure structures require the application of intelligent, digitally supported systems. This paper presents the possibilities and benefits of applying Industry 4.0 concepts in the field of geotechnical and geodetic structural monitoring, with a particular focus on sensor networks (IoT), edge computing technologies for integrating various types of data, and cloud platforms for managing and controlling the collected information. Implementation examples are presented in the context of urban construction sites. The second part of the paper analyzes the challenges and perspectives of transitioning toward Industry 5.0, which emphasizes human-centered design, sustainability, and system resilience. The need to balance automation with the human role is highlighted, along with maintaining infrastructure safety and environmental responsibility. It is concluded that the integration of these concepts transforms the way critical structures are monitored and maintained, significantly enhancing the overall safety and efficiency of the system.

Key words: *geotechnical monitoring, geodetic monitoring, IoT, edge computing, structural health monitoring, system resilience*

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1. INTRODUCTION

Structures and infrastructure systems play a significant role in improving the economic, social, and environmental welfare of nations [1]. Faced with challenges affecting both old, traditionally built infrastructure and new structures striving to be instantly constructed and technically sophisticated, humanity, perhaps more than ever before, has the need to establish control over the behavior and maintenance of its environment. The aging of structures, the progressive increase in operational demands, extreme weather events caused by climate change, as well as the pressures of social and economic factors (lack of maintenance funding, urbanization, population growth), create a complex environment in which monitoring the real behavior of structures has become essential.

The service life of structures does not progress evenly or predictably. Even during the construction phase, deviations can occur that cause behaviors different from those anticipated by design and simulations. During operation, structures are exposed to variable conditions, loads and external influences, that often exceed the predicted scenarios, both in type and intensity. The accumulation of these uncertainties throughout the entire life cycle of a structure presents a serious challenge to everyone responsible for its safety, maintenance, and reliable operation.

Although regular inspections provide a certain level of safety, they are time-limited and focused only on visible parts of the structure, while changes occurring between inspections remain undetected. Their safety, functionality, and longevity are directly linked to the ability to continuously monitor their condition and to respond in a timely manner to changes that may threaten their stability. By installing a network of sensors at key locations of the structure and continuously measuring parameters that reflect mechanical behavior and external influences, it is possible to monitor, in real time, changes in stability and structural integrity. This is why the concept of Structural Health Monitoring (SHM) was developed, with the aim of providing reliable and continuously updated information about the actual condition of a structure. Definition of SHM is given at [2], where structural health monitoring is defined as the measurement of the operating and loading environment and the critical responses of a structure to track and evaluate the symptoms of operational incidents, anomalies, and/or deterioration or damage indicators that may affect operation, serviceability, or safety reliability.

Although the implementation of SHM systems represents a significant advancement in infrastructure asset management, realizing their full functionality requires detailed project preparation, careful integration with existing risk assessment methodologies, and the establishment of clear protocols for data analysis, interpretation, and application. The data acquisition portion of the SHM process involves selecting the excitation methods, the sensor types, number and locations, and the data acquisition, storage, transmittal hardware [3]. In line with modern requirements, there is an increasing need for the development and application of intelligent, digitally integrated monitoring systems. In this context, the concept of the Fourth Industrial Revolution (Industry 4.0) introduced a new paradigm, bringing smart sensor networks, the Internet of Things (IoT), big data processing, and artificial intelligence into the field of structural monitoring. However, as the world rapidly moves toward the principles of Industry 5.0 in which a human-centric approach, sustainability, and collaboration between humans and machines will play a key role, new questions and challenges arise: How can SHM systems be designed to ensure technical reliability and promote infrastructure resilience in response to social changes, ethical demands, and ecological imperatives? The concept of Industry 5.0 provides a different focus and highlights the importance of research and innovation to support industry in its long-term service to humanity within planetary boundaries [4]. The aim of this research is to analyze the application of Industry 4.0 technologies in structural monitoring, with a particular focus on geodetic and geotechnical monitoring. Within the research, perspectives of the transition toward Industry 5.0 are also considered, which promises further improvements in the precision, efficiency, and automation of infrastructure monitoring processes.

2. CONTEMPORARY INDUSTRIAL CONCEPTS IN THE CONTEXT OF GEODETIC AND GEOTECHNICAL MONITORING OF STRUCTURES

Looking back over the past decades, traditional production systems and technologies have often led to serious environmental and social issues, including high resource consumption, global warming, environmental degradation, and increased pollution. These issues prevent the optimization of opportunities for sustainability enhancement, which naturally leads to the question of whether emerging technologies can be used to provide the necessary solutions [5]. These problems pose significant obstacles to sustainable development, prompting an urgent need for a shift in the approach to manufacturing and industry. This has long been a leading topic at global economic forums, United Nations general assemblies, and activist movements raising awareness about the risks present in humanity’s immediate environment.

Industry 4.0 offers a potential solution to many of the ecological and societal challenges that traditional industrial practices and technologies have failed to address. Industry 4.0 addresses and solves some of the challenges facing the world today such as resource and energy efficiency, urban production and demographic change [6]. It not only integrates advanced technologies such as artificial intelligence, big data, blockchain, the Industrial Internet of Things (IIoT), and simulations, but also creates an opportunity for developing more sustainable and efficient production systems. The implementation of Industry 4.0, although complex, has represented a necessary and significant opportunity to overcome the limitations characteristic of traditional industrial practices, enabling the construction of a more sustainable future.

In the context of SHM, Industry 4.0 technologies have shown significant contribution to more efficient monitoring and maintenance of structures such as bridges, tunnels, highways, buildings, and industrial facilities. As data can be measured under varying conditions, the ability to normalize the data becomes very important to the damage identification process. As it applies to SHM, data normalization is the process of separating changes in sensor reading caused by varying operational and environmental conditions [3]. Further, SHM systems rely on the integration of various technologies and sensor platforms stemming from a wide range of engineering disciplines. Geodesy, geotechnics, civil engineering, computer science, and electrical engineering are key fields contributing to the development of these systems.

In the modern approach to preserving the stability and safety of infrastructure, there is a clear recognition of the need to integrate geodetic and geotechnical monitoring into unified, comprehensive surveillance systems. Although each discipline individually provides essential information about the condition of a structure and its surroundings, their combination enables a deeper understanding of deformation mechanisms and the timely detection of potentially critical conditions. In addition to monitoring ground deformations during the design phase, as well as the behavior of constructed objects within the monitored area, these systems also serve to evaluate implemented design solutions. They contribute to the revitalization, automation, and centralization of structural health monitoring, improving the technical surveillance system used for tracking structural behavior and conditions during operation, while simultaneously maximizing ease of use and increasing system accuracy. In the context of increasingly demanding climatic, seismic, and anthropogenic influences on infrastructure, the integration of geodetic and geotechnical monitoring is becoming a standard of good engineering practice, shown int Figure 2.

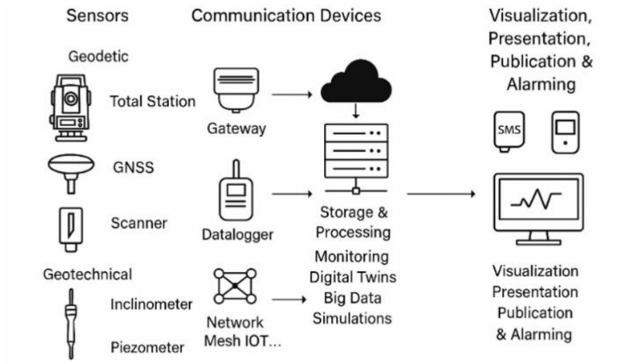

Figure 1. Geotecnical and geodetic SHM architecture

Geodetic engineering plays an irreplaceable role throughout all phases of the life cycle of infrastructure objects, from design and construction to long-term monitoring and maintenance. Geodetic engineering undoubtedly belongs to the group of engineering disciplines without which precise spatial positioning of infrastructure objects would be unimaginable [7]. Within the SHM context, geodetic methods enable quantitative tracking of changes in position, shape, and dimensions of structures with high accuracy and reliability. From the perspective of geodetic acquisition, the primary need lies in the precise measurement of point positions, displacements, and deformations of structures (e.g., bridges, buildings, slopes). These data are usually collected through GNSS systems, total stations, or terrestrial laser scanners.

The database is complemented through geotechnical approaches, which take into account soil and foundation conditions, including ground displacement, foundation pressures, groundwater level, soil saturation, vibrations, and more. Integrated geotechnical monitoring should include several independent measuring and controlled systems, which should complement each other and ensure structural safety at all stages of construction and operation of the structure [8]. Within SHM systems, geotechnical methods allow for the detection of changes in stress-strain states, stability, and safety of structures in real time. This forms the basis for monitoring the condition of foundation soil and structures that interact with it.

Since all measurements depend on the atmospheric conditions of the surrounding environment, it is important to note that the full potential of monitoring is realized when measurements from temperature, weather, and other environmental sensors are included.

One of the key challenges in managing such systems is interoperability. Different technologies and sensors often use different communication protocols, measurement frequencies, data formats, and measurement units, which can cause difficulties in data alignment. Unstructured data has no concrete data schema for data storage, e.g., a distributed data storage using folder-based storage systems [9]. The main steps to solve that challenge are recognized as standardization, conversion, and validation processes to enable integrated and reliable analysis. Standardization involves harmonizing units, time stamps, and data formats into a unified system that allows seamless interoperability of data from various sources. Data conversion includes transforming data from various technical and physical formats into forms suitable for analysis and further processing. Data validation enables early detection of errors, inconsistencies, and anomalies that could compromise the accuracy of conclusions drawn from the measurements.

Another significant challenge is the synchronization of data in time and space. Measurements from different sensors must be precisely aligned to ensure accurate comparison and integration of data. Inconsistencies in synchronization, such as differences in time stamps or coordinate systems, can lead to incorrect interpretations of the structural condition, which can have serious consequences for infrastructure analysis and management.

System security is also a crucial component in managing complex monitoring systems. These systems must be resilient to data loss, communication interruptions, and potential cyber threats. Traditional sensor-based SHM systems, which rely on IoT-enabled wireless networks, often face cybersecurity vulnerabilities, data tampering risks, and unauthorized access [10]. Ensuring data integrity and availability is essential for maintaining trust in the system, which is critical for making accurate decisions related to infrastructure.

In the following part of this paper, we present an example of a SHM system architecture composed of leading Industry 4.0 technologies, with a proposed application in urban construction sites, and an analysis of the trends to observe in the future.

3. SHM ARCHITECTURE AND APPLICATION IN URBAN ENVIRONMENTS

A complete monitoring system in civil infrastructure is multidisciplinary and requires careful integration of hardware and software components, based on the principles of Industry 4.0, among which IoT, cyber-physical systems (CPS), artificial intelligence (AI), machine learning, digital twins, and simulations are dominant.

The role of CPS in SHM is essential for the development of modern infrastructure maintenance systems, contributing to the real-time monitoring and analysis of physical assets. CPS is defined as transformative technology for managing interconnected systems between its physical assets and computational capabilities [11]. IoT enables the interconnection of various sensors and devices, continuous communication, and data analysis. Furthermore, by analyzing the monitoring needs, defining tolerance thresholds, and enabling predictive thinking, space has been created for the application of AI and machine learning, which play a key role in analyzing data collected from sensors. By using machine learning algorithms, anomalies in structural behavior can be detected and future failures predicted. These systems are capable of learning from historical data and developing models for pattern recognition that indicate potential issues. In this way, AI and machine learning enable a proactive approach to infrastructure maintenance, which can reduce the risk of serious damage and optimize operational costs. In the context of civil engineering, no quantitative methods currently exist that can reliably determine whether buildings are safe for reuse after a strong earthquake. SHM technology could one day enable the reduction of uncertainty associated with existing visual methods for post-earthquake damage assessment. The rapid reuse of buildings, especially those related to production, can significantly mitigate the economic losses caused by major seismic events. Currently, machine learning methods are widely adopted in SHM, yet they are still mostly black boxes. On the other hand, given the significant responsibility associated with SHM, understanding the rationale behind it is critically important [12].

As part of ongoing SHM system maintenance, cloud computing has become essential for centralized storage and processing of data from multiple sources, providing real-time access from any location, particularly valuable in situations requiring rapid response to structural changes [13]. Another important aspect in infrastructure monitoring is the use of simulations and digital twins, which represent a key technologies in structural health monitoring. Digital twins enable the creation of virtual replicas of physical objects which are used to simulate structural behavior under various conditions [14]. These simulations may include factors such as loads, vibrations, and temperature, allowing for a better understanding of the object’s response to external influences. Digital twins can also be used to test different scenarios and predict potential real-world issues, significantly reducing the need for costly physical testing.

3.1 Key recommendations for SHM design

Effective design of SHM systems requires careful planning of communication protocols, measurement data validation, format standardization, and ensuring compatibility with analytical software. Based on modern experience and best practices, the following key recommendations are provided:

- Adapting communication technologies to the specific conditions of each location forms the foundation for reliable data transmission.
- For remote, hard-to-access, and energy-constrained environment, such as mountainous areas and tunnel structures, LoRaWAN is recommended.
- Technologies such as LTE-M/NB-IoT are suitable for urban environments with developed mobile infrastructure and stable network coverage.
- Wi-Fi/Ethernet is most appropriate for facilities with existing infrastructure, such as bridges, buildings, and industrial complexes.
- To preserve the integrity of measurement data and enable timely detection of potential errors, it is essential to implement redundant systems by placing at least two different types of sensors at each critical point of the structure.
- Schedule regular field inspections and compare IoT data with manually conducted reference measurements.
- Standardization is of vital importance, both for internal data use and for its use in forensic or legal contexts
- Strict adherence to internationally recognized standards (e.g., ISO, ASTM, DIN) is recommended to ensure the consistency and verifiability of the collected data.
- To enable seamless integration with advanced analytical software solutions, all data should be converted into standardized formats such as CSV, JSON, LAS, or RINEX, and prepared for processing in software tools specialized in structural monitoring.

Table 1 presents sensors, devices, validation methods, data conversion, and standardization approaches used in SHM systems with IoT connectivity for geodetic and geotechnical monitoring.

Table 1. Sensors, devices, validation and conversion, with IoT connectivity and integration in SHM systems for geodetic and geotechnical monitoring

Sensor Type	Description	IoT Prot.	Comm.Dev.	Data Validation	Data Conver
GNSS TS TLS	3D position, displacement angles, distance, 3D coordinates 3D modeling	TCP/IP MQTT, LoRaWAN Ethernet, Wi-Fi, 4G LAN	Modem, RTK base, GNSS Gateway Data logger, Cloud connector Edge device, server	RMS error, PDOP Redundant measurements, control points Point registration, ICP algorithm	NMEA, RINEX CSV, XML E57, LAS, PTS
Inclinom eter Piezome ter Vibratio n Sensor Extenso meter Strain Gauge FBG Tiltmeter	Tilt angle, Pore water pressure, Vibrations and seismic waves, Ground displacements, Structural strain, Distributed strain and temperature, Structural tilt	LoRaWAN LTE-M, RS-485 NB-IoT Wi-Fi, LTE, Fiber Modbus, LoRa TCP/IP Ethernet (DAS) Zigbee	Gateway, Edge computer Data collector, IoT node Seismic station, logger RTU DAQ Optical interrogator IoT Gateway	Reference calibration, drift analysis Comparative manual readings FFT Peak Ground Acceleration Cross-validation with geodetic data Load test, bridge balancing FBG wavelength calibration Linearity test, verification	JSON, CSV SEED, miniSE ED XML HDF5,

3.1.1 Proposed SHM for monitoring construction sites in urban areas

The sensor network must be dense and redundant due to the high risk associated with urban environments, with IoT connectivity enabling real-time monitoring and rapid response. Validation must be conducted regularly, at least on a weekly basis, with an *Alarm Zone* functionality implemented for critical displacement or vibration thresholds. Table 2 presents the main sensor groups along with their typical locations on an urban construction site. Table 3 provides the communication architecture of the system.

Table 2. Key sensors for urban construction site monitoring

Sensor	Function	Location
GNSS receivers (static or dynamic)	Monitoring displacement of adjacent structures and piles	On top of buildings, poles, and at the construction site
Total Station (robotic)	Monitoring relative displacement (prisms on buildings)	On adjacent buildings and monitoring pillars
Terrestrial Laser Scanner (TLS)	3D scanning of construction site deformations	Fixed points around the construction site
Inclinometers (MEMS)	Monitoring tilt of soil masses, piles, foundations	In boreholes, behind retaining walls
Piezometers	Monitoring groundwater level	Boreholes on the construction site
Extensometers	Monitoring displacement of piles and walls	In boreholes and on structures
Vibration sensors	Detecting vibrations from excavation and works	On nearby buildings
Fiber optic sensors (FBG)	Monitoring strain/structural deformations	On critical structural elements
Temperature sensors	Thermal monitoring (important for concrete works)	Embedded in the structure and surrounding environment

Table 3. Communication components for the SHM System on an urban construction site

Layer	Component	Description
Sensor Layer	GNSS, Total Station, TLS, Inclinometers, Piezometers, FBG,	Data acquisition from geodetic and geotechnical sensors
IoT Edge Devices	ComBox, Data Logger, IoT Nodes, RTUs	Initial data buffering, basic preprocessing, and transmission preparation
Communication Layer	LoRaWAN, NB-IoT, LTE-M, Wi-Fi, Ethernet	Wireless or wired transmission depending on site conditions
Gateway / Network Layer	IoT Gateway, Cellular Router, Mesh Network	Aggregation and secure routing of data to the central server
Server / Cloud Layer	Local server or cloud storage	Data storage, SHM software processing, digital twin simulation
Processing Tools	AI, ML, Digital Twins, Big Data Analytics	Real-time data analysis, anomaly detection, forecasting
Visualization Layer	SHM Dashboard, Web Access, Mobile App	Real-time visualization, alarms (SMS/email), and reporting tools

Data validation for geodetic monitoring should be performed by comparing RTK measurements with total station readings. Geotechnical monitoring should be validated through manual verification (e.g., dip meter for piezometers), while vibration data should be compared against calculated vibration standards (DIN 4150-3). Alarm thresholds must be defined based on deformation and vibration limits to enable automatic notifications (e.g., SMS/email alerts).

In SHM monitoring of particularly complex and critical structures in urban environments, it is essential to highlight the SHM architecture based on edge computing technology, apart from cloud computing. Edge computing enables data to be processed at the point of collection or in its immediate vicinity, rather than requiring that all data be sent to a central server for analysis. This approach is crucial for applications in geodetic and geotechnical monitoring, where rapid response to changes in structures or ground conditions is required. Data is processed immediately at the source, reducing latency and enabling instant reaction to potential risks or changes. By leveraging edge computing, the latency and consequently the user experience for time-sensitive applications could be improved significantly [15]. For example, if foundation displacement is detected, the system can automatically trigger an alarm or initiate preventive measures. By using edge computing, the need for constant connectivity with central servers is minimized. This is particularly beneficial in areas with poor internet connectivity or where a high level of system autonomy is required. Processing data at the source also reduces the amount of information that must be transmitted to the central system, saving network bandwidth and decreasing server load.

3.2. Case Studies on the Implementation of SHM Systems in Civil Infrastructure

3.2.1 Regent's Park Development Project, London

The Regent's Park Development project in London involved the demolition of a series of buildings, as well as the excavation and construction of new structures. The zone of influence, resulting from unloading during excavation and reloading during construction, extended within a radius of approximately 80 meters. The affected area included protected historical buildings of Grade I and II, London Underground tunnel passages, and electrical infrastructure facilities.

A specialized monitoring system was employed using a combination of optical and sensor equipment to track all changes affecting the objects within the zone of influence. The system configuration enabled continuous automatic monitoring of both aboveground and underground structures, with the objective of generating two types of reports:

- A report analyzing aboveground displacements of buildings and other technical facilities such as power supply stations, and
- A ground movement report, which included monitoring of the Jubilee line tunnel (running north–south) and the Metropolitan line tunnel passing beneath the demolition site.

Two monitoring processes operated continuously as part of the monitoring scheme, which used a combination of multiple geotechnical and optical technologies connected into a unified sensor network:

MultiStations were used for laser monitoring. MultiStations are platforms that combine the features of a total station, laser scanner, GNSS receiver, and a digital optical system for documentation and control. Although still considered high-end systems, their use is becoming increasingly common in projects requiring high reliability and time optimization, especially in the field of engineering geodesy and monitoring.

Wireless tilt sensors were used to track stable deformations, convergence, and longitudinal subsidence in London Underground tunnels.

Automatic monitoring of vibration, noise, and dust was conducted in parallel with the previously mentioned tools.

Alarm functions, based on the GeoMoS monitoring solution, allowed all project stakeholders access to the monitoring database, with different permission levels for viewing, editing reports, and receiving alarm messages. All data were integrated into the GeoMoS software, a commercially available solution that enabled users to have a centralized view of all data through a unified desktop and web interface. Leica GeoMoS is a professional software platform for automated geodetic and geotechnical monitoring of structural and ground displacements in real time. It enables continuous observation of critical infrastructures, such as bridges, tunnels, buildings, dams, and slopes, by integrating data from various sensors (e.g., total stations, GNSS receivers, tilt meters, vibration sensors), performing automated analysis, and providing real-time alerts when predefined safety thresholds are exceeded.

For the monitoring of multiple buildings in this central London project, three MS60 MultiStation devices were used, geometrically linked via common control points connected to a ComBox5 unit. ComBox is a modern ruggedized communication and power management device that allows for easy and fast setup of any monitoring sensor and can adjust power consumption. The latest ComBox devices support communication over EdgeConnect and within LAN. This configuration allows data transmission via internet connection to the GeoMoS server.

The twin-track Metropolitan line tunnel, built of brick, was monitored using an automatically controlled MS60 station that reads rail reflectors and laser scanning data. The two Jubilee line tunnels were equipped with 250 wireless tilt sensors connected via fiber optic cable, enabling data transfer to the internet and further into the GeoMoS system. GeoMoS supports connection with any monitoring sensor or software. Flexible communication options ensure seamless connectivity, sensor management, and instant data storage and analysis. Through the GeoMoS API, GeoMoS data can be integrated into a user's own system. Automated data flows use numerous open interface standards that enable simple but powerful sensor fusion. The GeoMoS Monitor application allows 24/7 measurements with scheduled sensor operation cycles, while all key data are stored in a single SQL database.

This system architecture enabled the observation and recording of building and ground displacement parameters, as well as deformation of railway tracks and segments of London underground tunnels. The centralized software tool recorded all monitoring data collected from various sensor sources, including: 3D reflector data, manual leveling measurements, values from electronic tilt sensors, data from wireless tilt sensors, and results from laser scanning.

Within the London project, the implemented monitoring system enabled the recording of displacements in three dimensions (X, Y, Z coordinates), allowing the determination of characteristics and total 3D deformation values on buildings and the ground. Based on total station measurements, in addition to absolute deformation magnitudes (longitudinal, lateral, and vertical), it was possible to calculate movement velocity and identify types of movement such as regressive, progressive, transitional, or stick-slip models.

Using the system in combination with advanced project management, data processing, and visualization software, real-time information was obtained on longitudinal displacements, lateral displacements, vertical displacements, as well as horizontal and vertical movement vectors across the entire monitored area.

Based on this data, the monitoring team could perform risk assessments and take preventive and corrective actions within the zone of influence. It was also possible to observe changes in movement intensity depending on seasonal conditions, geotechnical factors, and construction activities in the immediate environment. In addition to geometric monitoring, the system also collected data from various environmental sensors on-site, such as dust, vibration, and noise sensors, which operated within their own alarm routines but accumulated their results in a weekly data report within the GeoMoS web interface. The use of GeoMoS Now enabled an integrated data interface for the client's engineers. The software streamlines real-time data flow from thousands of sensor channels into a simple and clear report. The new algorithm automatically processes monitoring surfaces and compares them to reference epochs. Changes exceeding predefined parameters automatically trigger additional laser scan monitoring. This continuous, live communication and data exchange between the field and office—enabled by reliable equipment—eliminates delays, prevents collapses and failures, and removes the need for costly corrective measures.

3.2.2 Crossrail Paddington Station – SHM System for Complex Urban Construction

The following section analyzes a complex infrastructure project in London — *Crossrail Paddington Station* — where structural health monitoring (SHM) systems were implemented. The primary objective was to ensure safe construction and the preservation of existing infrastructure through the deployment of advanced monitoring systems.

The main goal of the *Crossrail Paddington Station* project was to construct a new underground station beneath an existing historic building, without interrupting traffic or introducing safety risks.

The technological monitoring system included 52 Leica TM30 robotic total stations as part of the automated optical system, over 1,800 monitoring prisms, functioning as smart sensors with continuous feedback, IoT architecture enabling the connection of all measuring devices and sensors via optical and wireless communication networks, three central servers for real-time data processing, and software platform Leica GeoMoS. GeoMoS Adjustment and Leica GeoOffice, enabling data processing, analysis, and visualization in real time.

Internet of Things (IoT) enabled constant connectivity between all sensors and devices, allowing the system to operate 24/7 without manual intervention. Smart sensors (robotic stations and prisms) generated large volumes of high-precision data, essential for predictive analysis. Intelligence and automated algorithms, integrated into the GeoMoS software ecosystem, identified displacement patterns, anomalies, and potentially critical deformations at early stages, enabling decision-making without human error. Edge computing architecture allowed preliminary filtering and analysis of data locally before transmission to the central system, reducing latency and improving response time. Digital infrastructure management was achieved through a centralized platform for visualization and alerting, aligned with digital twin concepts for smart cities.

Construction of the underground station directly beneath a historic building was achieved without damaging the above-ground infrastructure. The system reduced the need for manual inspections, significantly increasing operational efficiency. Data processing speed increased by up to 90%, enabling faster decision-making. Continuous real-time monitoring allowed early-stage response to potential ground movement. Precise risk control led to lower insurance costs and greater confidence among project stakeholders. Most importantly, the system minimized safety risks for both construction workers and station users by automatically detecting potentially hazardous deformations in their early stages.

3.3 Critical Review of SHM System Implementation

The implementation of SHM systems based on Industry 4.0 principles brings promising innovations in automation, predictive analytics, and real-time infrastructure management. However, these advancements also introduce new technical, ethical, and economic challenges that require critical assessment.

SHM systems depend heavily on digital infrastructure: stable electricity supply, continuous internet access, and secure server communication. In events such as power outages, telecommunication failures, or cyberattacks, these systems may completely lose functionality.

As SHM systems connect hundreds of devices via wired and wireless networks, they become potential targets for cyber threats. Risks include data breaches, sensor manipulation, ransomware, and entry points to other critical systems.

Economic Viability Despite claims of cost-saving through preventive maintenance, SHM implementation entails, high capital and operating costs and need for skilled personnel In developing countries or deteriorating infrastructure, such investments may be hard to justify. Sustainable adoption requires scaling system complexity to real risk levels, and ROI-based decision-making and cost-benefit analysis, modular implementation at critical points, use of commercial/open-source tools and standardized protocols, public-private partnerships and alternative funding models and integration with existing asset management and BIM systems.

SHM systems using drones, 3D scanners, or cameras may capture private data (faces, license plates, property details). Even anonymized data sharing could breach GDPR or local laws. Transparency is needed on what data is collected and why, who can access it and under what conditions, how long it is stored and whether it is shared.

While enhancing public safety, SHM systems may pose surveillance risks if not governed ethically. High-resolution sensors and continuous monitoring could intrude into private life. I4.0-based SHM systems must be technically resilient, economically justified, cybersecure, and transparent and ethically aligned. This balance is central to the evolution toward Industry 5.0, where technology coexists with human-centric values, inclusivity, and sustainability.

3.4 Future trends toward the concept of Industry 5.0

Industry 5.0 represents a shift from machine-based automation (Industry 4.0) towards a deeper synergy between humans and technology, integrating advanced tools such as Artificial Intelligence (AI), the Internet of Things (IoT), robotics, and automation [16]. This approach introduces numerous challenges and opportunities, including in sectors such as geodetic and geotechnical structural monitoring.

Industry 5.0 recognizes the potential of industry to drive social transformation, moving beyond the boundaries of digital transformation towards a paradigm that also embraces human and environmental needs. This concept is complementary to the advancements already achieved through Industry 4.0, but adds a new dimension — the dimension of values.

The concepts of Society 5.0 and Industry 5.0 are closely connected, as both refer to a fundamental shift in society and economy towards a new paradigm [16].

Society 5.0 envisions a society where advanced information technologies, the Internet of Things, robots, artificial intelligence, and augmented reality are actively integrated into everyday life, industry, healthcare, and other sectors — not primarily for economic gain, but for the well-being and comfort of every citizen.

A purely profit-driven approach is becoming increasingly unsustainable. In a globalized world, a narrow focus on profit fails to adequately account for environmental and social costs and benefits. For industry to become a genuine source of prosperity, its core purpose must include social, environmental, and societal dimensions. This requires responsible innovation, not aimed solely or primarily at increasing cost efficiency or maximizing profit, but rather at enhancing prosperity for all stakeholders — including investors, workers, consumers, society, and the natural environment.

In the contemporary context of rapid technological advancement, the transition from Industry 4.0 to Industry 5.0 marks a significant shift in how the roles of technology and humans are understood—particularly in fields such as geodetic and geotechnical infrastructure monitoring. Industry 4.0 brought intensive automation, the integration of sensor networks, IoT systems, artificial intelligence, and big data analytics into the processes of monitoring infrastructure assets. These systems enabled continuous real-time data acquisition and analysis, leading to improvements in efficiency, accuracy, and response speed. In this environment, the role of engineers and technicians was largely focused on supervising and managing automated processes. Industry 5.0, however, introduces a new paradigm centered on synergy between humans and technology. The key difference lies in bringing the human back to the core of the process—not as a passive operator, but as an active creator and decision-maker. In geodetic and geotechnical monitoring, this means that advanced tools such as AI and digital twins are not only used for data processing but also to enhance engineering understanding, support complex decision-making, and develop customized solutions tailored to the unique characteristics of each infrastructure asset.

Beyond technological advancements, Industry 5.0 emphasizes ethical values, sustainability, and social responsibility. In the context of monitoring, this translates into the development of solutions that not only observe and predict the condition of structures but also contribute to long-term safety, resource conservation, and environmental impact reduction. While Industry 4.0 is characterized by standardization and mass deployment of technology, Industry 5.0 promotes flexibility, interdisciplinarity, and a high degree of personalization—an especially important feature in monitoring projects that increasingly rely on the integration of geodetic, civil engineering, and IT systems.

This transformation opens up new opportunities for engineers and researchers in the infrastructure domain, encouraging them to merge technical expertise with creativity and broader societal values in order to develop smarter, more sustainable, and more human-centered monitoring systems.

Table 4 illustrates Industry 4.0 transition to Industry 5.0 in the context of geodetic and geotechnical SHM.

Table 4. Transition of the industrial concept in the context of geodetic and geotechnical SHM

Aspect	Industry 4.0	Industry 5.0
Focus	Automation and optimization of measurement and monitoring processes	Collaboration among surveyors, engineers, and geologists to create innovative solutions
Technology	Remote sensors, IoT devices, robotics, drones, AI for data analysis	Integration of artificial intelligence, robotics, and human skills for accuracy and innovation
Role of Professionals	Supervising automated systems for measurement and data analysis	Human creativity in data interpretation, decision-making, and implementation of tech solutions
Approach to Services & Output	Automated processes in geodetic and geotechnical monitoring, mass data handling	Flexible solutions for precise measurements and personalized monitoring at specific sites
Objectives	Efficiency in data acquisition and processing, error reduction in measurements	Sustainable solutions, data accuracy, increased safety, and ethical application of results
Data & Intelligence Approach	Automated field data analysis, real-time monitoring with minimal human input	Combined machine learning and human interpretation for accurate decision-making in SHM
Ethics & Sustainability	Standardized processes focused on efficiency, with limited attention to social aspects	Active consideration of social and environmental factors in implementing geodetic/geotechnical solutions
Interaction with Technology	Technology automates measurement and data analysis without human involvement	Technology enables informed human decisions and creative field solutions
Personalization	Standardized geodetic networks and measurements with limited adaptability	Customized technologies and methods tailored to client needs and complex geodetic/geotechnical projects

4. CONCLUSION

The implementation of SHM systems has proven essential in urban environments where space is limited and the infrastructure is older and more vulnerable. The integration of geodetic, geotechnical, and environmental sensors into a unified system enables a comprehensive assessment of structural conditions.

Projects such as Crossrail demonstrate that automated monitoring enhances stability during construction, allows for timely response in critical situations, and reduces dependence on the subjective assessment of field engineers. The use of monitorig platforms provides continuous information flow to all project stakeholders through a web interface, accelerating decision-making and improving coordination between design, construction, and maintenance phases. Beyond technical advantages, SHM systems also influence public perception of safety, as they enhance trust in high-risk infrastructure projects.

In the case of Harvard Stadium, the project illustrates how historic structures can be modernized to comply with contemporary safety standards without compromising their authenticity.The project has set a benchmark for monitoring in mega-infrastructure projects that are executed in phases and under operational loads.

The experience at Istanbul Airport demonstrated that seismic monitoring can be integrated into standard geodetic networks without the need for additional seismographs, while simultaneously contributing to the digital transformation of airport operations.

The implementation of Industry 4.0 technologies in the Regent's Park Development project brought significant advancements in the field of structural monitoring. The integration of sensor networks, automated data acquisition, real-time analytics, and cloud-based platforms enabled continuous, high-precision monitoring of complex urban infrastructure, including historical buildings and underground tunnels, during all construction phases. Automated alarms and data fusion from various geodetic, geotechnical, and environmental sensors allowed for timely risk assessments and proactive decision-making, significantly improving safety and operational efficiency.

For the transition toward Industry 5.0, future SHM implementations tend to focus on greater human-technology synergy, ensuring that monitoring systems do not only automate processes but also enhance human decision-making through intuitive visualization, context-aware intelligence, and ethical data governance. In moving toward Industry 5.0, it is essential to adopt human-centric design principles that prioritize ethical safeguards, such as purpose limitation, anonymization of datasets, user rights to data transparency, and independent oversight of SHM data management — to ensure that technological progress respects individual rights and aligns with broader societal values.

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