The functionality assessment of geodetic monitoring systems for analyzing structural elements

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SUMMARY

Geomonitoring and structural monitoring systems currently play a crucial role in comprehensive facility risk management - both at their implementation and subsequent maintenance. Especially in the dynamic development of BIM (Building Information Modelling/Management) technologies, such systems allow for precise and systemic management of building objects and stand a part of the modern investment process. The knowledge base created during their practical implementation is the core of current systems, ensuring the safety of structures and a proper construction process of the erected buildings. This is of particular importance in construction works, sometimes very technologically advanced structures - high-rise, industrial, or public objects. In addition to assessing newly constructed facilities, it is also possible to research the impact of external conditions on the entire investment process - environmental, geological, or geotechnical. Structural monitoring systems are also a part of a thriving, dynamically developing industry in civil engineering. For many years, we have been observing an intensive increase in the number of available solutions, companies offering similar services, and tailor-made systems supplied by particular manufacturers.
Nevertheless, such solutions are mainly limited to closed environments aimed at specific instrumental solutions and software. In this respect, there are practically no solutions with an open structure or open source. Moreover, the possibilities offered by manufacturers - modules, functions, and procedures are usually not in line with the real challenges posed by a specific facility. These factors create an actual demand for flexible, mobile, and fully scalable systems best adapted to essential needs. The authors have analyzed the geoinformation solutions available in the market and systematized their functionality. The study allowed for developing a prototype solution integrating the work of sensors (mainly land surveying instruments) within the frame of a newly developing geoinformation platform. The general assumption is to ensure the long-term operational stability of reflectorless total stations in terms of complete laser scanning and automatic triggering of measurements and data reception in the open transmission protocol.

1. INTRODUCTION

Manufacturers, geoinformation technology suppliers, and scientific institutions have been developing structural monitoring systems applied to engineering for many years [1-5]. Specific needs inspire many dedicated, tailor-made solutions. For example, the publication [6] describes the assumptions of such a system in the context of monitoring the roof of the Forest Opera in Sopot, Poland. Other similar solutions have been described in numerous publications – for example, [7-10]. Noteworthy is the list of commercial geodetic monitoring systems prepared in 2012 by the Polish geoinformation journal [11]. This period in Poland was characterized by the significant activity of geoinformation technology providers, especially in the context of the implementation of critical projects in the dynamically developing domestic economy. As one of the first successful implementations of such integrated geomotoring systems, we can mention the project of monitoring tailings pond embankments "Żelazny Most" implemented for KGHM Polska Miedź SA [12]. Other examples can be the Brown Coal Mine in Bełchatów [13] or the construction of the Warsaw Metro Line 2 [14]. In highly industrialized countries of the world, the development of geodetic monitoring systems has been observed for several decades. There are many examples of implementations and problems of a technical nature solved on these occasions. Many of them resulted in publications of various nature. It is worth mentioning here, e.g. [15-18], although the list of items that can be cited contains thousands of scientific articles, technical reports, or chapters in monographic studies. Numerous handbooks are published in many languages – mainly in English or German [19-20]. There are also many similar studies in the domestic publishing market, among which we can mention [21-22].

Geomotoring systems are also a thriving, dynamically developing industry in civil engineering. For many years, we have been observing an intensive increase in the number of available solutions, enterprises offering this type of service, as well as the resolutions themselves provided to the market by manufacturers. The systems supplied by well-known manufacturers are noteworthy, sometimes with a dominant market share. Generally, however, such arrangements demonstrate a relatively compact structure focused on specific instrumental and computer solutions. In this respect, there are practically no solutions with an open layout. The possibilities proposed by manufacturers – modules, functions, and procedures often do not correspond to the real challenges posed by a specific object. These factors build an actual demand for flexible, mobile, and fully scalable systems that can be adapted to real needs as much as possible. Observing current trends in the surveying market, one can notice the dominant role of mobile solutions mainly developed at the expense of desktop solutions, sometimes not very effective. The latter is not sufficiently flexible and requires large amounts of equipment to make significant financial outlays. In most cases, manufacturer's solutions also determine utilizing specific brands of the measuring equipment, which ties users with particular technologies for longer, often generating high costs (service, maintenance, technical support).

The current state of knowledge has inspired the authors to carry out analytical and conceptual work aimed at:

- Classification of available solutions in geodetic monitoring and emphasizing their characteristic features.
- Defining potential development opportunities in designing a new, universal system based on the existing state of the art.
- Proposing a new solution considering the needs of contemporary contractors, surveyors, civil engineers, or geotechnicians.

2. SYSTEM ASSUMPTIONS

Technical details and differences in the functioning of the current structural monitoring systems concern both the type of recommended surveying instruments, the methods of capturing, processing, and analyzing spatial data, as well as the diversity in use. While discussing the appearing challenges, the following criteria inspired our special attention:

- The ability to work remotely with the newly designed system (cloud work) using mobile interfaces.
- The possibility of integrating automatic displacement measurements performed with physical sensors (physical monitoring, also called SHM – *Structural Health Monitoring*).
- Possibility of handling automatic measurements with geodetic instruments (robotic total stations, GNSS receivers).
- The ability to operate instruments from different manufacturers.
- Possibility of using reflectorless measurement technology (in the case of electronic total stations).
- Data adjustment prospects.

Nowadays, each structural monitoring system supplier provides the possibility of integrating surveying instruments with physical sensors. It is currently a standard determined by the need to conduct advanced calculations based on various data sources. The problem of an on-the-fly adjustment, including identifying and eliminating outliers, is quite different. Such functionality is rarely provided in the market. Partially, the ability to adjust observations is possible in the system GeoMoS by Leica Geosystems AG [23-24]. Here, one should mention the problem of an appropriate instrument setup and its configuration regarding adequate and unique projects [25]. However, such a possibility requires purchasing an additional module, which may seem expensive, provided by another collaborating manufacturer. In other cases, the basic functionality of adjusting observations boils down in practice to a preliminary accuracy analysis using basic statistical parameters. However, such an approach does not provide a comprehensive accuracy assessment of surveying works. Another problem encountered in popular structural monitoring systems is their closed structure and the limitation to particular, dedicated measuring instruments.

2.1 Overview of existing solutions

To develop a new approach resulting in designing a new monitoring system considering the current requirements of both science and practice, the authors reviewed the existing solutions in this area. These are both systems used locally – taking into account the conditioning associated with a given type of measured objects and well-known, global complex solutions. The multitude of options available makes the reviewed systems ready to be implemented in different things. However, such extensive and technologically advanced systems are usually designed for monitoring so-called macro-scale objects – such as dams, protective embankments, excavations of open-pit mines, or long suspension bridges. Often, adapting these solutions to the needs of small engineering objects (buildings, masts, chimneys, footbridges, etc.) is a massive challenge for surveyors, geotechnicians, or construction workers. The financial aspect of the ongoing monitoring projects should also be mentioned. In many cases, the budget for this type of solution is significantly limited, promoting the low-cost surveying infrastructure instead.

The following table presents a list of selected geodetic monitoring systems with a description of their functionality. These solutions were divided into domestic – corresponding to local surveying and construction guidelines and global – representing more key manufacturers. Against their background, we present the assumptions of our project performed by the Department of Engineering Geodesy and Measurement Systems, Warsaw University of Technology, and the GEOalpin company located in Warsaw, Poland. This project, developed in the consortium is financed by the National Centre for Research and Development (project "*Intelligent monitoring system for endangered objects based on IMSGeo automatic non-invasive measurements*" - POIR.01.01.01-00-0942/21).

	Project assumptions	Worldwide							Poland		
Solution	**IMSGeo**	**Leica GeoMoS**	**Cyclops & Centaur**	**Delta Link**	**IMG Monitoring**	**GOCA**	**Vista Data Vision**	**GEO-Instruments**	**SmartSense**	**SHM System**	Other local companies performing geodetic and structural monitoring
Manufacturer	**GEOalpin**	Leica Geosystems AG, Switzerland	France, SIXSENSE, grupa VINCI	Topcon, Japan	Italy, IMG ITALY, Img S.r.l	Germany, Hochschule Karlsruhe - Technik und Wirtschaft (University of Applied Sciences)	Iceland, Vista Data Vision	United Kingdom, GEO-Instruments, Keller Group	PolService Co.	SHM System Co., Limited Partnership	
Polish distributor/representative	**GEOalpin Co.**	Leica Geosystems	Soletanche Poland Co.	TPI Co.	Img Monitoring Co.	NO	NO	GEO-Instruments Poland			

Brief system description	**IMS GEO Intelligent monitoring system for endangered objects based on automatic non-invasive measurements**	The world's largest distributor of geodetic equipment. Geodetic Monitoring System software – GeoMOS. The system utilizes automatic measurements and sensors, including total stations.	SIXSENSE, former SOLDATA is a global supplier of monitoring systems based on measuring devices of various brands. Surveying results are presented on the online platform. There is no detailed information on the computational algorithms. System CYCLOPE demonstrated a conservative approach to the calculation of the geodetic network.	Topcon - one of Leica Geosystem's main competitors - geodetic equipment manufacturer. Delta LINK is used to coordinate data and control instruments. Analysis of measurement data takes place in the Delta Watch module.	The company is responsible for monitoring the construction of the Warsaw Metro Line 2. Currently, the dedicated monitoring system uses Leica surveying instruments and other measuring equipment. Projects are governed using a unique web platform.	That rather scientific system was created at the Technical University in Karlsruhe. It works mainly with Leica instruments. Multi-module system for both total stations and GNSS receivers.	Software-based on client-server architecture. Web solution. Comprehensive software enabling displacement monitoring using various sensors. Primary cooperation with the Hexagon group - precisely with GeoMAX.	A system based on structural monitoring using non-geodetic methods. In the case of using geodetic techniques, it uses external solutions, e.g., Leica or Topcon.	System based only on GNSS measurements.	A system based on structural monitoring using non-geodetic methods. In the case of using geodetic techniques, it uses external solutions, e.g., Leica GeoMoS	No use of automatic measurements
Full operation of the system in the WEB environment (CLOUD)	YES	YES	YES	YES	YES – Monitoring Data Dissemination System DDS	NO	YES	No data	YES	No data	NO

Possibility to include in the system automatic displacement measurements with non-geodetic techniques, e.g. inclinometers, slot gauges, strain gauges	YES (developed outside the project, IMSGeo)	YES	YES	YES	YES	YES	YES	YES	NO	YES	NO
Automatic total station measurements	YES	YES	YES	YES	YES	YES	YES	YES	NO	NO	NO
In-house total station control system	YES	YES	YES	YES	YES, although currently, the company uses Leica GeoMoS; it no longer develops its solution, which was used in the past	YES	YES	NO (using external systems)	NO	NO	NO
Robotic total station brands	Leica, Topcon, Sokkia, Trimble	Leica	Leica, Topcon, Sokkia, Trimble	Leica	Leica -	Leica, Topcon, Sokkia	GeoMAX, Leica	NO	NO	NO	NO
Multistation network adjustment	YES	NO	YES	NO	NO	YES	NO	NO	NO	NO	NO
Reference frame stability control	YES	YES (GeoMoS Adjustment)	NO	NO	NO	YES	YES	NO	NO	NO	NO

Reflectorless measurements in monitoring	YES	YES	NO	NO	NO	NO	YES	NO	NO	NO	NO
Rejection of the standpoint stability (possibility to measure within a deformation-affected area)	YES	YES (GeoMoS Adjustment) + GNSS	NO	NO	NO	YES	NO	NO	NO	NO	NO

3. PROJECT WORKS

The first project stage covers the instrumental issues (construction of the recorder) and includes designing, programming, and testing the possibility of using instruments coming from different manufacturers. An essential element of this work package is the using the knowledge and experience of the GEOalpin employees collected in numerous commercial projects performed in the whole country. Completing such a knowledge base should result in a faster selection of optimal solutions, reducing failure.

The second stage (carried out in parallel with the first) includes inventing and selecting appropriate data processing algorithms adequate to the tasks and particular implementations. As part of this work package, multi-variant simulations and adjustments of measured test networks are carried out. What is more, a suitable methodology for integrating measurements using advanced numerical methods is also being developed. The work is carried out in a mathematical and programming environment with the support of computational modules of specialized geodetic software. Advanced computational methods will be used in the field of theory of geodetic observations and displacements and deformations analysis.

The usefulness of various data adjustment methods will be examined as part of the research. In particular, the contractors who plan to verify the suitability of a technique used to calculate displacements by considering only observation differences. The alternative calculation method involves using observations obtained from measurement in individual epochs. The analysis will aim to receive answers to the following questions:

- Does using observation differences significantly reduce the impact of the systematic errors?
- Does the reduction of calculation capacity, and thus - the cost of calculations, compensate for the forced repeatability of the network structure?
- What is the impact of the calculation method on the assessment of the accuracy of the designated displacements?

The Monte Carlo simulation methods will be applied together with matrix algebra in the comparative analyses. Another research problem is setting out rules for processing point clouds.

The essence of the third and fourth stages is the development of the WEB platform, which is a critical element in managing the operation of the designed system. The work packages also encompass the verification of instruments and algorithms used and invented in the previous stages. Newly developed procedures and algorithms will be implemented using IT tools and programming environments.

As a result, a coherent system will be created, ready for use in any field conditions, regardless of the monitored facility. The data processing and archiving results will feed the newly created knowledge base about the object. In the fifth stage, it is planned to continue the developed system's tests and expand its software with methods of graphical presentation of results (surface approximation methods). The adjusted point clouds will be interpolated and visualized using various geostatistical algorithms. The subject of separate, in-depth analyses will be studying the impact of weather conditions on the monitoring results. While the influence of temperature and atmospheric pressure on distance measurement is well-known and the relevant models are somewhat easy to implement, the impact of the parameters like air humidity on laser scanning results is far more complex. This is particularly important in the analysis of spectral parameters of the reflected beam - sometimes used to determine the non-geometric features of the measured object.

Moreover, our system will automatically detect and identify aspects conditioning the selection of an appropriate mathematical model, such as, e.g., displacement of the reference network, measuring station, or the influence of a so-called noise caused by mechanical interference or meteorological disturbances. Noteworthy is also the system versatility reflected in the possibility of using total stations from all leading manufacturers. Fig. 1 presents a view of the test measuring stations, where the results of the first conceptual work as part of the IMSGeo project were verified.

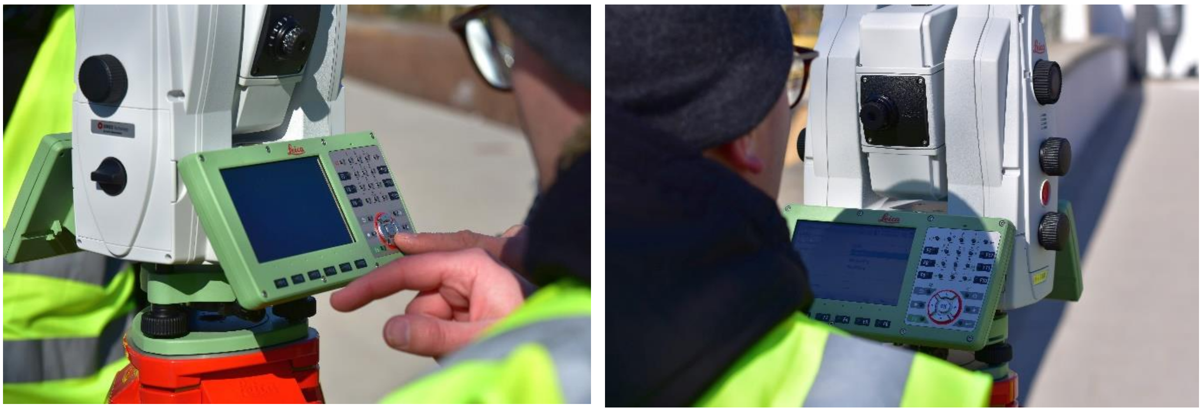

Fig. 1 View of IMSgeo measuring test stations (photo by Oskar Graszka)

4. CONCLUSIONS

Modern geodetic monitoring systems include both instrumental, IT, and database solutions. Designing such scenarios is a comprehensive process that considers many elements from the borderline of various fields of knowledge. What is more, before starting the study work, it is necessary to conduct an in-depth analysis of the current state of the art and define the areas that need to be developed. The article's authors made a functional assessment of most of the available commercial and dedicated solutions, characterized by different architecture or operating philosophies. Concerning the study work carried out, a systemic concept was developed, which has currently been implemented in the form of a project financed by the National Centre for Research and Development. Our system allows for quick and automatic surveying, without human participation, along with the intelligent interpretation of the results.

In our assumption, the newly designed system will be able to constantly monitor the condition of different facilities and study the real impact of construction works on the surrounding buildings. Detected alarm situations (exceeding the permissible displacement ranges) will be immediately reported. The effects of the project in the field of technical solutions will constitute an innovation on a national scale and in the field of applied computing solutions - on a global scale.

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BIOGRAPHICAL NOTES

Krzysztof Karsznia graduated from Wrocław University of Environmental and Life Sciences, with MSc and Ph.D. in geodesy and cartography. He demonstrates over 20 years of working experience in the industry and research. Specializes in structural monitoring and deformation measurements. He is currently employed as an assistant professor at the Department of Engineering Geodesy and Measurement Systems, Warsaw University of Technology.

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