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RESEARCH ON THE DEVELOPMENT OF TOOLS, METHODS AND TECHNOLOGIES INVOLVED IN THE STRUCTURAL MONITORING PROCESS OF BUILDINGS, IN STATIC AND DYNAMIC REGIME.

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ABSTRACT

The purpose of this paper is to present the development of tools, methods and technologies belonging to traditional and alternative methods in the context of their extensive involvement in the vast structural monitoring process defined as SHM, the priorities and perspectives of SHM integrating monitoring manager systems in the thematic area of Terrestrial Measurements Sciences. We have been able to make precision measurements in static regime for the past 200 years, since the advent of theodolites and levels that could ever more accurately determine movements in plane-slippage and on the vertical- absolute and relative subsidence of buildings or parts thereof. The emergence, after 1950, of electro-optical distance measuring devices introduced a new dimension to measurements, at least in plane, no longer based merely on angular measurements. Then, the invention of new devices, tools, methods and technologies allowed the final protocol for obtaining information on the behavior of the structure to change its direction from interpolation. In the case of static monitoring, interim data are obtained by interpolation and are subjet to sequential analysis like in the case of continuous, dynamic monitoring..

Keywords: ***Structural monitoring manager systems, theodolites and levels, static monitoring, dynamic monitoring.***

1. INTRODUCTION

The activity, *“Tracking behavior over time of land and buildings”,* have a history of over 150 years (Chrzanowski 2004), which merges with the advent of optical-mechanical instruments for measuring angles and level differences, theodolites, level, has dealt with quasi-static structural monitoring. In fact, between the observation cycles, at an interval of several months to several years, based on the evolution of the phenomenon of subsidence and landslides, there were deviations of a few millimeters or fractions of a millimeter. In this context monitoring was considered static. This process begins and should be tracked immediately upon completion of foundations and will continue after the commissioning of the buildings until these displacements are completely removed. The known method is the middle precision geometric leveling regularly comparing, through measuring cycles, the position of mobile markings, mounted on the structure, to benchmarks considered fixed, mounted in areas considered stable over time. At the same time, there is a danger-for any reason-of movements in plane of the building or structural parts thereof, phenomenon known as sliding. The tracking method used was, for a long time, angular intersection. Since the appearance of state-of-the-art total stations it can be combined with planimetric raying. By measuring cycles one can see the same variation of the relative positions, but this time in the horizontal plane(Rădulescu Gh.M., 2003). The Figure 1. shows the two movements of tracked constructions, like so: a. the occurance of subsidence phenomenon, tracking subsidence by middle geometric leveling, b. the occurance of slippage phenomenon, tracking slipping through angular intersection.

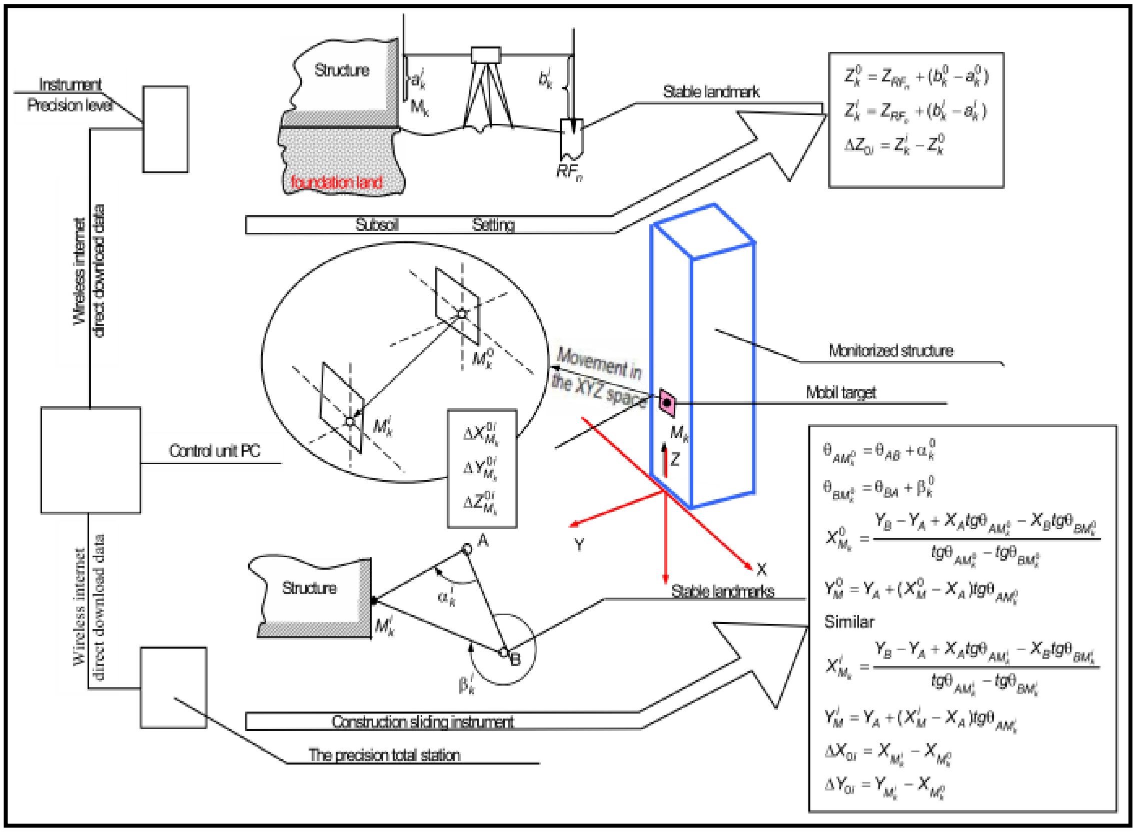

Figure 2. Tracking behavior over time in static regime(TBTSR). Causes and methods (Sourse: Author)

Tracking behavior over time in dynamic regime, appeared and was formed as a need to monitoring the behavior of structures in dynamic regime (Rădulescu Gh.M., 2003). Buildings with very bold and innovative design features required in situ study of the objectives, both during execution - and post-execution. Basically, this process checks if the actual behavior falls under the project specifications. The opportunity of this new branch of Science of Terrestrial Measurements appeared in the 1970s, but has developed at an accelerated pace in the last 20, primarily due to projects involving the construction of bridges and very tall buildings, where it contributed significantly in the execution by developing new tools and technologies. An effect of those anterior presented was reconsideration of calculus methods, of standards, of concepts regarding mathematical modeling in the projecting process of constructions, but it must be pointed a very important fact: no design method can be validated unless after an analysis regarding the behavior through execution and in time of the construction under the action of disturbing factor's action, wind, earthquake, unequal sunny, at this chapter the geodesic measurements being the ones that give possible answers. In short, these were the factors that led to the shift from "Tracking behavior over time" to "Structural Monitoring", later incorporated in the comprehensive "Structural Health Monitoring". (Rădulescu Gh.M., 2015)Modern continuous methods, appealing to modern techniques (usually sensory), do not exclude but complement methods considered classic, so that the monitoring of the health of constructions now comprises all these methods, from middle precision geometric leveling for static analysis of settlements to the use of fiber optic sensors and to monitoring the oscillations of structures in kinematic regime. Two types of constructions have led to the concept of Structural Monitoring, later extended to Structural Health Monitoring: bridges and very tall constructions. Figure 2. presents the synthesis "Tracking behavior over time of constructions" in dynamic monitoring, methods and tools used(Rădulescu Gh.M., 2015).

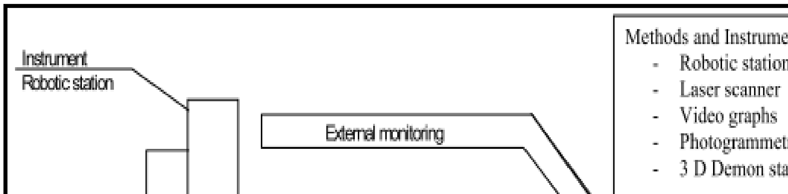

Figure 2. Tracking behavior over time in dynamic regime(TBTDR). Causes and methods. (Sourse: Author)

Since the difference between SM and SHM is derived from non-topographical causes, like the evolution of the state of construction materials (rheology, corosion, etc.), the analysis by the designer of the risk of an object, we will keep the wording SM in the paper to define the new concept of tracking behavior of buildings under different effects of static or kinematic stress factors. The concept was later extended to all categories of SM constructions, incorporating "Tracking behavior over time", meaning that long-term effects are detected by conventional means and those taking place now are detected by the new SM methods. Four common causes of the opportunity of introducing continuous monitoring under kinematic regime in these structures: uneven exposure to sunlight, wind, earthquakes, usage or stand-by mode of the structure. Recreating the optimal design cycle of special reinforced concrete and metal structures in a certain space: in-situ behavior under the action of some stresses variable in time (wind, temperature, exploitation), implies monitoring them in dynamic regime Among the applications of SURVEYING in the field of Structural monitoring (figure 2), the "dynamic" part refers to the study, recording and processing of characteristic parameters of external influences, as well as of the geometry of structures, under the action of some variations of some stresses in a short period of time (at most 24 hours). For special structures, the "behavior at temperature variations" lies within dynamic analysis, implying a diurnal variation of the geometry, therefore measurable parameters using classical means. Also the "behavior under the action of wind" or under load lies within dynamic analysis, generating a variation of the geometry, with optimal data collecting periods between 0.01-1 s. In this case, the classical operating means of SURVEYING are not operable (Rădulescu A.T.G., 2011).,

2. REQUIREMENTS WHEN DEVELOPING NEW MONITORING SYSTEMS

There are currently many monitoring systems, generally cheap as far as instruments go, but expensive in terms of systems. Four directions should be followed in perfecting existing SHM methods:

1. Activity and structure safety

New SHM systems must ensure functionality of monitored structures throughout their expected life. While the best monitoring strategy depends on engineers, the performance of monitoring systems depends on technology(Glisici 2000).

2. Technological aspects

New technologies can use ever more sophisticated - and cheaper - systems, tools and methods. In order to ensure structural safety, a modern monitoring system has to be easy to use, fast to install, durable, reliable, independent from human intervention, fully automatic and insensitive to external influences (temperature, electro-magnetic fields, humidity etc.). (Glisici 2000).

3. Economic aspects

It refers to the ratio between investing in new technologies and the surplus of information. It is possible to invest in expensive technology but with a low maintenance cost that rush a profit. Permanent monitoring offers greater possibilities for timely interventions. Monitoring systems are best employed if they are present on structures from construction to dismantling. Of course, engineers decide the schedule of measurements. Using permanent monitoring, the disadvantages of periodical inspection can be avoided. Using permanent monitoring as a mean of control may decrease the maintenance cost by 10%.

4. Aesthetic aspects

Most bridges or tall buildings tracked are important architectural landmarks of the area. SHM cannot interfere with visible, massive instruments that are asynchronous with the environment.

3. THE MAIN TRENDS IN THE DEVELOPMENT OF SHM TECHNOLOGIES

Starting 30 years ago, from the classic stage in the life of any construction with more than two levels (Norm P 130, for Romania), "Tracking the behavior over time of constructions and land," the structural monitoring activity, best known today as Structural Health Monitoring (SHM), has undergone spectacular changes that can be classified in two directions(Rădulescu A.T.G., 2013):

1. Development of ***surveying*** monitor. techniques
2. Development of ***sensory*** monitor. techniques.

The buildings that have spurred the development of SHM tools, methods and technologies are bridges, followed equally by very tall residential buildings and, to a lesser extent, other constructions: dams, tunnels and other underground works, pipelines, seagoing and river vessels and so on.

There are currently about 100 companies in the world known to be related to the SHM activity, including SHM software and tools manufacturers, companies performing monitoring activity and / or research in the field. Over time, different specialists expressed their opinion on the existing technique of structural monitoring. Thus, in the paper Dynamic Monitoring of Deforming Structures: GPS Versus Robotic Tachometry Systems (Radovanovic, 2001), the authors conclude that: “The performance of a robotic tachometric system has been compared to that of GPS under two kinematic operating modes – stop-and-go and true kinematic”.

In general, it is more desirable to be able to monitor a moving point throughout its trajectory.

In conclusion, the authors believe that the solution of the time tagging problem is most crucial in developing an RTS-based monitoring system.

If this level is achieved, then RTS can become a viable option to GPS in many outdoor applications, and will become an indispensable tool in monitoring moving structures indoors.

Note that in this study we used a Leica TCA 2003 total station and a GPS device, Trimble 4700. Given that both systems have evolved a lot in these 12 years since the statements made, it is interesting to carry out such a study at present, and so I plan to make it using Leica technology, for both devices. The peak of SHM technology, unrivaled even now after four years, has been the monitoring of the highest residential building in the world, the Burj Khalifa Tower, completed in 2010 in Dubai. I have synthetically described the technology used in the next chapter dedicated to high-rise buildings. Nevertheless, the final conclusion of the paper "Validating the Structural Behavior and Response of Burj Khalifa: Synopsis of the Full Scale Structural Health Monitoring Programs" (Abdelrazaq 2010) is worth mentioning: ”The survey and SHM programs developed for Burj Khalifa will with no doubt pioneer the use of survey and SHM program concepts as part of the fundamental design concept of building structures and will be benchmarked as a model for future monitoring programs for all critical and essential facilities. However, advancements in computer and IT technologies, innovative advancement in fiber optic sensors, nanotechnologies, dynamic monitoring devices, new GPS system technologies, and wireless monitoring techniques will be used as a base for future survey and SHM programs and it will become an integral part of the building design and Intelligent Building Management System”.

It is interesting to note that the bibliography lists another reference work of recent years, "In-construction vibration monitoring of a super tall structure using a long-range wireless sensing system" (Ni, 2009) with reference to SHM for the 610 m-tall Guangzhou Television and Sightseeing Tower (GTST). The paper concludes: “Besides this preliminary application of wireless sensing technologies on monitoring the in-construction supertall structure, future study will be conducted to simultaneously collect acceleration measurements at different heights along the tower. Using simultaneous acceleration data, vibration mode shapes of the tower can be extracted. In addition, the flexibility of the wireless sensing system can be further illustrated by concentrating a larger number of wireless sensors at one section of the 20 tower during each test. The mode shapes of different sections of the tower can be identified separately and stitched together through overlapping measurement points between neighboring sections. It is expected that with very little reconfiguration effort, the wireless system will be able to provide dense measurements and higher-resolution mode shapes than the twenty “fixed” accelerometers of the current wired system”.

Interesting to note that the technology used, which I summarize in my next chapter, substantially differs from the previous one.

In 2006, the mixed research group China-USA is formed, in the field of SHM, consisting of 45 researchers from the Chinese universities Harbin and Dalian, and American universities: University of California, Berkeley, University of Illinois at Chicago and University of Michigan.

The group publishes a first report in 2007: "Sensor technology innovation for the advancement of structural health monitoring: a strategic program of US-China research for the next decade", that outlines the state (in 2006) of SHM technologies and the main research directions possible.

The paper emphasizes the importance of sensory technology, foreseeing several prospects: "Sensors and their role within the global SHM system must be defined in relation to a particular project; this must be done in tandem with the design process of the structure", but notes the emergence of technologies that we find in the Guangzhou Tower, i.e. "wireless sensors with embedded intelligence" or Motes systems or MEMS -based sensors. The report concludes:

“Generation of SHM data from test-beds will allow engineers to begin to examine collected data to determine if it is supplying the pertinent data needed to support damage models that serve as the basis of the damage assessment process”.

The British company TWA launched in 2013 the project entitled "Best Practice Guide for Structural Health Monitoring of Ageing Assets" that will be used in the construction of oil rigs. The project will make a full inventory of all SHM technologies, drafting a code of good practice in the matter. Federal Institute of Materials Research and Testing in Germany made a report in 2006, "F08b Guideline for Structural Health Monitoring" (Rucker, 2006). This paper is a summary of influence factors in SHM, the methodology of diagnosis of analyzed structures and the monitoring methods aiming to guide those who operate in the field to better correlate the three components mentioned. The most important conclusion, by analyzing the entire bibliography, is that experts and the public pay more attention to SHM, which is explained on the one hand by the spectacular growth of the constructive parameters of buildings, on the other hand by the frequent accidents occurring especially in the case of bridges and tall buildings. While I was writing this paper, a 23-storey block of flats in North Korea collapsed. The building was under construction, but over 100 families had already moved in. North Korean authorities did not provide the number of victims. This paper “Dynamic Behavior of Taipei 101 Tower: Field Measurement and Numerical Analysis” (Li 2011) presents selected results measured from a monitoring system with 30 accelerometers installed at six floor levels in 508-m high Taipei 101 Tower located in Taipei City, Taiwan where earthquakes and strong typhoons are common occurrences. Structural monitoring requires recording parameters of the structure, the environment in which the structure exists, and other factors that create stress.

4. MEASUREMENT AND TECHNIQUES FOR MONITORING IN QUASIDYNAMIC AND DYNAMIC CONDITIONS

Security of the civil engineering works requires regular monitoring of the structures. The current methods are often difficult applications, the resulting complexity, dependency from the condition of the atmosphere, and also the costs, limiting the applicability of these measurements. The obtained spatial resolution is generally low, sequential, and only the presence of anomalies in the global behavior relevantly stimulates an accurate assessment. There is therefore, a real need for the instruments that allow a permanent, continuous and automated monitoring of the structure, with high precision and good spatial resolution. In this context, the concept of smart structures has proved effective in other areas, such as monitoring of composite materials or in aerospace applications. These structure types are instrumented with a series of internal sensors, which allow monitoring various critical security parameters, and are useful for the efficient planning of the cost of the maintenance interventions. This includes measurements of deformation, temperature, pressure, wind speed, air humidity and others. The optical fiber sensors have significant advantages compared with the traditional measurement methods, including low cost, versatility in measuring various parameters, insensitivity to electromagnetic influences and corrosion, their small size and high density of information that they can send away. If large number of sensors were installed in different parts of the structure, it would be possible to extrapolate information about the behavior of the whole structure, using these local measurements.

4.1. Laser scanning Techniques

Terrestrial laser scanning enables the measurement and location of a large it takes a laser pulse to travel to it and getting back to the sensor. quantity of 3D points in an automated manner and a very short time. Depending on the type of use, TLS can be operated either from a static position or from a dynamic platform. The operational principle of TLS is similar to that of a robotic total station. However, TLS do not bear an optical sighting assembly, and therefore they do not have the ability to measure on very specific ground features. On the contrary, the measuring head of the instrument is set to carry out distance and angular measurements over a pre-defined angular range and field of view. Most TLS systems used for engineering geodesy applications employ the time-of-flight method. In this case, two operating principles for distance measurement are in use: the pulsed time-of-flight (direct time-of-flight), and the phase difference (indirect time-of-flight) principle. In the first approach, the distance from a TLS sensor to a feature point is determined by measuring the time Subsequently, its 3D polar coordinates are computed using the measured distance together with the horizontal and vertical angles registered in the instrument. In contrast, in the case of phase-based scanners, the ranging principle resides on the phase difference obtained between the transmitted and the received (backscattered) signal from the scanned points. This technique applies to laser systems that emit a continuous string of a laser beam, in a way that, a series of successive range measurements is obtained. The Trimble® GX™ 3D Scanner is an advanced surveying instrument that uses high-speed laser and video to capture vast amounts of coordinate and image data. Trimble® RealWorks Survey™ office software is part of an integrated 3D scanning field and office software suite for surveyors and engineers. Taking advantage of the rich point cloud data provided by the Trimble GX, RealWorks Survey manipulates and manages large scan files to produce dramatic and compelling 2D and 3D deliverables. The software also supports data collected using GPS and total station techniques, so you can coordinate and combine data from a surveying job in one project file for an Integrated Surveying™ solution. Therefore, if benchmarks are assembled on the surveyed structure, these can be monitored in continuous regime, 24/7, recording the displacements of the bridge, under load or under the action of wind or non-uniform sunlight.

Figure 3. Trimble® GX™ 3D Scanner(Sourse: Trimble)

4.2. THE 3DEMON ROBOTIC LASER ROBOVEC SYSTEM,

It is a system created to monitor displacements over time, based on laser technology (251). It also measures distances through laser technology and can act as a robotic laser station in order to monitor multiple points simultaneously. It has a millimeter precision, which means it can be used for monitoring landslides, subsidence phenomenon or any displacement process of a building or land. In order to achieve 3D monitoring of millimeter movements on a technical monitoring scale, the ROBOVEC unit uses on a laser meter and modular biaxial robotics for horizontal and vertical displacements. The instrument is able to measure horizontal and vertical angle variation and the distance between the instrument, assumed to be known and fixed coordinates, and the monitored points. During a measurement campaign, ROBOVEC can perform a self-centered algorithm on selected targets to find the center of the new target, if it moved between two measurements. The measurements are automatically stored on the computer for later analysis. The ROBOVEC system is fully compatible with other SMARTEC products. Measurements can be automatically and dynamically imported into a standard database (SDB) and can be integrated with measurements from other sensors (e.g., static SOFO, Adam, DiTeSt, 3DeMoN-GPS). The main feature is its high accuracy, which can be ± 0.15 mm. The SDB software for analysis of data provided by the 3DeMoN system allows navigation within the SDB measurement database, generated by all SMARTEC monitoring systems: SOFO reading unit, MuST, SOFO optical switches, ADAM modules, oscillating wires, Macro sensors and other data acquisition devices. Main features: compatible with the current SDB software, automatic data export, display of measurements at different points on the image structure, deformation history graph and table showing selected sensors over a previously chosen period, real-time data viewing, fully compatible with all SMARTEC systems and monitoring sensors.

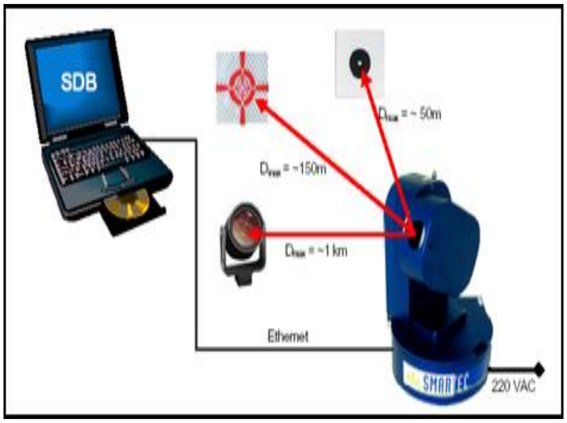

Figure 4. 3DEMON ROBOTIC LASER ROBOVEC system components (Sourse: Rocktest/Smartec)

There have been created classical or laser scanners, video systems, RTK-GPS systems, sensors, stamps, pendulums, laser levels, inclinometers, accelerometers, in general, expert or manager systems for monitoring the structures, in order to punctually, but mostly continuously, record the response of real structures to various stresses, especially wind, earthquake or diverse exploitation conditions. Many are created by companies that produce geo-topographic equipment, especially Leica and Trimble, but there have appeared companies whose main activity area is represented by the monitoring of structures in continuous dynamic regime or which produce instruments for this activity.

4.3. USING THE GPS TECHNOLOGY FOR MONITORING BRIDGES

It should be specified that the first use of GPSs in engineering was for monitoring bridges, in the ‘80, the development of professional GPSs was possible precisely because of these applications. The following applications were for monitoring very high-rise buildings, and the execution and monitoring the time behavior of the Petronas and Taipei 101 buildings was accomplished using this technology.

Figure 5. GPS technology, of geodesic rank can be used for monitoring bridges. (Sourse: Leica)

The Global Positioning System (GPS) is used for many purposes in surveying and geodesy like cadastral surveys, engineering surveys or intercontinental coordinate frames. The main characteristics of the GPS technology of geodesic class are: used signal code and phase in general 2 frequencies, accuracy 0,001 to 0,1 m. Therefore, the GPS antenna is assembled on the monitored structure, recording the position, in continuous regime, through coordinates in the WGS1984 worldwide system, then trans-calculating it in national system and then, for simplification, into a local system. The displacements, oscillations, displacement speed, hence, all the parameters that define the time behavior of the structure under the action of wind or exploitation, are established comparing the coordinates of the axis of the antenna, at various moments.

4.4. SHM THROUGH SURVEYING AND GEODETIC MEANS

The philosophy for developing structural monitoring methods through surveying and geodetic means belong especially to the companies that manufacture and used to manufacture equipment for current measurements of this sort. They have adapted these tools to various SHM activities, meaning that they made the shift from static, sequential measuring methods to dynamic and continuous methods. They also built and developed appropriate software for data processing, display, and transmission. The main competitor is the Swiss company Leica, which, besides the manufacturing of surveying and geodetic SHM equipment, is also involved in effective monitoring and research in this field, to which the Technical University of Cluj Napoca was recently asked to contribute. By analyzing the technology used we will be able to understand the surveying-geodetic operating mode in SHM. Leica has developed the structural monitoring system under the name **Leica GeoMoS** – The Leica Automatic Deformation Monitoring System, the software for automatic data processing, using a technique of combining instruments as a general technique shown in Figure 6.

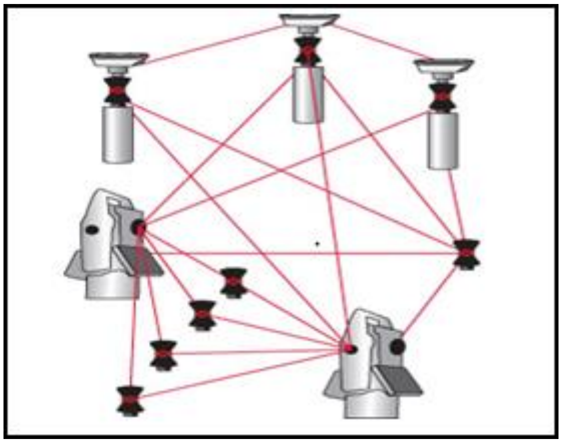

Figure 6. Leica general monitoring technology, using robotic total surveying stations, 360° prisms and GPS receivers (Sourse: Leica)

When designing the Leica GeoMoS software, Leica has provided that each monitoring project has specific measurement and accuracy requirements. The Leica GeoMoS software provides a highly flexible automatic deformation monitoring system that is able to combine geodetic, geotechnical and meteorological sensors to match the needs of your monitoring project, whether it is large or small, temporary or permanent. Leica GeoMoS is a multi-purpose automatic deformation monitoring software that can be used for:

- Structural deformation monitoring (e.g. dams, tunnels, bridges, high-rise buildings, construction)
- Landslide and settlement detection (e.g. mining, rock falls, volcano slopes, subsidence)
- Automated surveys (e.g. continuous, automated measurements) and many more structures.

The Leica GeoMoS software is comprised of two main applications called Monitor and Analyzer. Leica GeoMoS Adjustment is an add-on software that allows the user to make decisions based on statistically optimized and validated data. The Leica GeoMoS software is highly customizable allowing you to purchase only the functionality you require. The sensor license concept means that the software scales with the number and type of sensors you have connected. Additional functionality can easily be added later should your needs change.

- Monitor is the online application responsible for the sensor control, collection of data, computation and event management.
- Analyzer is the offline application responsible for the analysis, visualization and post-processing of the data.
- Adjustment is the application responsible for the network adjustment, deformation analysis and network simulation.

Leica GeoMoS offers the ability to connect geodetic (total stations, multistations and GNSS sensors) and geotechnical sensors to understand the reasons of any detected movement and to improve the prediction of failure.

- Total Stations: Leica TM50, TS50, TS15, TM30, TS30, TPS1100, TPS1200, TPS1200Plus, TCA1201M, TPS1800 and TCA2003 Series
- Multistations: Leica MS50
- GNSS sensors: Leica GPS System 500, GPS System 1200, GMX900 Series, GM10
- Connection to Leica GNSS Spider for advanced GNSS monitoring
- Levels: Leica DNA and Leica Sprinter
- Tilt sensors: Leica Nivel20 and Nivel200 Series
- Meteorological sensor (e.g. temperature, pressure)
- An interface to Campbell Scientific dataloggers, that can support most commercially available geotechnical sensors to measure environmental effects and

conditions (e.g. extensometers, piezometers, strain gauges, inclinometers, thermometers, barometers, rain gauges, and many more)

The Leica TM30 is designed to meet the highest accuracy standards. High precision measurements, combined with automatic, fast and silent operation ensures that the TM30 detects the smallest movement in all monitoring applications. The structural parameters allow making precise measurements as follows. High accuracy angular measurement of 0,5" or 1"

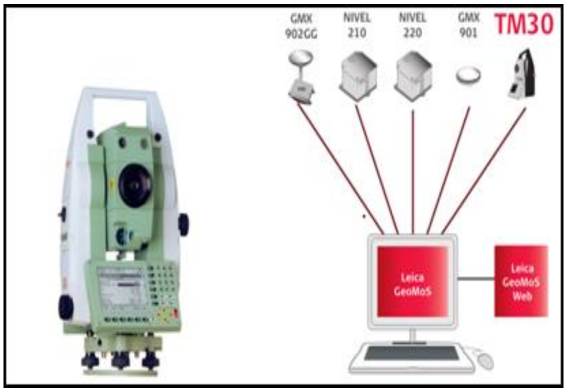

Figure 7. Leica TM30, Monitoring Sensor, Including the station in the Leica integrated structural monitoring system (Sourse: Leica)

The Leica Nivel210/Nivel220 precision inclination sensor for simultaneous measurement of inclination, direction of inclination and temperature based on an optoelectronic concept. For large structure monitoring and engineering constructions such as dams, bridges and high-rise buildings

- The Nivel210 sensor is equipped with an RS232 interface to connect the sensor directly;
- The Nivel220 sensor is equipped with an RS485 interface to use with a bus system.

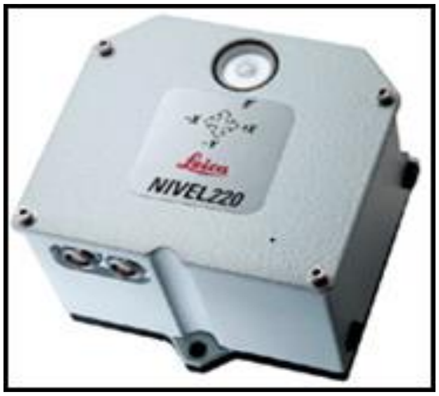

Figure 8. Leica Nivel210/Nivel220, Precision inclination sensor for structural monitoring(Sourse: Leica)

The Leica GMX902 Series is a range of GPS, GLONASS and Galileo receivers, specially developed to monitor sensitive structures such as bridges, mines or high rise buildings and crucial areas such as land slides or volcanoes. The GMX902 Series provides precise dual or triple frequency code and phase data at up to 50Hz as the basis for highly accurate position calculation and motion analysis. There are two models in the GMX902 Series, the GMX902 GG and the GMX902 GNSS.. The GMX902 GNSS integrates seamlessly with the Leica GNSS Spider advanced GNSS processing software for coordinate calculation and raw data storage. The Leica GeoMoS or Leica GNSS QC monitoring software provide advanced data analysis and processing, analysis of movements, data archiving, limit checks, messaging and combination with other.

Figure 9. Leica GMX902 Series, High precision GNSS monitoring receivers (Sourse: Leica)

The Leica GMX901plus is a compact, precise and robust receiver designed specifically for monitoring applications with multiple upgrade options. Sensitive structures such as dams, rock slopes, mine walls and buildings can be monitored around the clock for the smallest of movements.

- Integrated antenna with built-in ground plane;
- Integrated into Leica GNSS Spider and GeoMoS software;
- Simple to set up and configure.

The Leica GMX901plus is a high precision GNSS receiver specially developed for long term monitoring of natural hazards or man-made structures.

Figure 10. Leica GMX901plus, Smart antenna for deformation monitoring (Sourse: Leica)

4.5. SHM THROUGH SENSORY MEANS

Typical New Sensors systems which monitor the geometry and deformations of bridges is: linear variable displacement transducers (LVDT – a distance measuring device), vibrating wire strain gauges, foil strain gauges (set up in quarter, half, or full bridge strain configurations), inclinometers, crack and joint sensors, tilt sensors, piezoresistive accelerometers, piezoelectric accelerometers, capacitive accelerometers borehole accelerometers, servo force balance accelerometers and total stations. The effort focuses on the design and development of a self-displacement measurement device and a wireless data communication system. The diagnosis techniques will include finite-element modeling of the suspension bridge, modeling and measurement of strong wind, earthquakes and traffic loadings, analysis of the ambient vibration data through the use of the technique to eliminate the use of an exciter, a global damage diagnosis technique to identify and characterize the damage, and selection of sensors and techniques to detect localized damage and defects. In principle it is possible to operate bridge-monitoring systems on a periodic or continuous base:

- Periodical testing: measuring the vibration behavior is carried out in specific time intervals. Sensor location should be in accordance with the initial measurement.
- Continuous monitoring: sensors are installed permanently to the bridge, providing a continuous data concerning bridge condition.

A significantly new research challenge is the need to integrate multiple sensor streams to develop local and global health-state indicator variables that need to be queried and monitored by the system. The indicators may be defined as user-specified aggregates (or other functions) over instantaneous values of several data streams, covering one or more sensors. The sensor network may consist of a dense array of heterogeneous sensors (e.g., strain gages, accelerometers, cameras, potentiometers, … etc.). Communicating with sensors has long been limited either to wired connections or to expensive, proprietary wireless communication protocols.

The second direction in the development of SHM technologies was research, inventing, manufacturing, testing and implementing technologies that use different types of sensors. One of the main competitors is the Canadian company Rocktest that, through the acquisition of three additional monitoring equipment manufacturers (Smartec, Telemachus, FISO Technologies), has become the market leader. The analysis of this company’s activity provides all the data on the present state of sensory structural monitoring technologies.

The Roctest Group designs, manufactures and markets sensors and high-precision measuring instruments for the civil and geotechnical engineering market and applications in the energy, healthcare and process control industries. The Roctest Group offers an unparalleled range of solutions combining both traditional vibrating wire technology and state-of-the-art fiber optics. For just a fraction of the total investment cost in new or ageing infrastructure, whether a bridge, tunnel, dam, waterway, high-rise building, an industrial transformer, pipeline or even an oil tanker, the rocktest sensors and measuring instruments reduce the risk of damage to infrastructure and the environment, excessive wear and tear in machinery, and even loss of life.. The products are used in all steps of projects: from the initial planning, construction, and rehabilitation. The company's products can be used for monitoring all types of buildings and facilities, providing integrated monitoring solutions for: bridges, building-type construction, including very tall buildings, dams, tunnels and other underground works, pipelines, geotechnical works, ships, energy and oil constructions and facilities, including offshore drilling, etc. To do this they use a number of 12 lines of product groups comprising 185 sensors, software and other monitoring components, manufactured by the companies themselves, as follows:

1. **SOFO**, Advanced fiber optic system for global monitoring of structures, with 17 categories of sensors, software and other monitoring components,
2. **MuST**, Mutiplexed Strain and Temperature monitoring system based on Fiber Bragg Gratings (FBG), with 20 categories of sensors, software and other monitoring components,

3. **FISO**, Point sensing sensors based on Fabry-Perot Interferometers, with 20 categories of sensors, software and other monitoring components,
4. **DiTeSt/DiTemp,** Distributed Temperature &Strain monitoring (Brillouin/Raman scattering), with 16 categories of sensors, software and other monitoring components,
5. **Vibrating Wire,** Trusted technology for long-term monitoring and geotechnical applications, with21 categories of sensors, software and other monitoring components,
6. **Electrical,** Well proven sensors for easy integration, with 13 categories of sensors, software and other monitoring components,
7. **3DeMoN,** 3-Dimensional Movement Monitoring Network based on Laser technology, with 4 categories of sensors, software and other monitoring components,
8. **SensCore,** Corrosion Monitoring Systems, with 2 categories of sensors, software and other monitoring components,
9. **Mechanical,** Mechanical sensors and components, with 4 categories of sensors, software and other monitoring components,
10. **In-Situ,** Measurement System for assessing mechanical parameters on site, with 14 categories of sensors, software and other monitoring components,
11. **Geomation,** Trusted technology for field data acquisition, transmission and management, with 30 categories of sensors, software and other monitoring components,
12. **Software,** Data Acquisition, Management, Publishing and Analysis, with 5 categories of monitoring software.

The company also has a line comprising 19 general or personalized products for monitoring constructions, equipment or special facilities.

However, monitoring is not only carried out by sensors, but it also involves direct or remote visual inspection as well as topographical measuring. The main purpose of instrumentation installed within a dam is to study whether or not the dam is behaving according to design predictions, and to verify design assumptions. Monitoring has for objective to ensure both the longevity and safety of the structure. It must enable timely detection of any behavior that could deteriorate the dam, potentially resulting in its shutdown or failure, in order to implement corrective measures. The SOFO system is a deformation measurement system based on low-coherent interferometry in single- mode optical fibres. It has been successfully tested and applied to different types of civil structures such as bridges, tunnels, dams and piles. Due to its high resolution and precision, long term stability, easy application, and its capability to measure the deformation of very early age concrete, this system has been applied on subterranean structures.

A cut-and-cover tunnel "Champ Baly" on the A1 road, near Yverdon, Switzerland, is cast in high performance concrete and the SOFO system is used to monitor its behaviour. The very early age deformation, cracking localisation and its quantification are presented as well as the evolution of the global spatial behaviour. The SOFO system reveals to be the appropriate monitoring technique for subterranean structures(Glisici 2000). The SOFO measurement system is based on low coherence interferometry in single-mode optical fibres. The three main components of the system are a reading unit, the fibre optic sensors and the appropriate software. Its functional principle is represented in Figure 1.26. The reading unit is composed of a light emitter (light emitting diode - LED), a low-coherence Michelson interferometer with a mobile scanning mirror, optical set up and an internal PC. The sensor consists of two mono-mode optical fibres named the "measurement" and the "reference" fiber. The measurement fibre is in mechanical contact with the host structure and follows its deformation, while the reference fibre, placed close to the measurement fibre, is loose and independent of the behaviour of the structure. Any deformation of the structure will result in a change of the length difference between the two fibres. Infrared light is emitted by the LED, sent through the mono-mode optical fibre to the sensor, split by the coupler and introduced into the two arms of the sensor.

Then, the light reflects off the chemical mirrors deposed on the ends of each of the fibres and returns through the coupler to the reading unit, i.e. to the mobile Michelson interferometer. The interfered light containsthe information of the length difference between the measurement and the reference fibre. This difference is retrieved using the mobile mirror and transmitted to the external PC. By successively repeating the measurements, it is possible to determinate the evolution of the deformation of the auscultated structure. The standard SOFO sensor is composed of two zones, the active zone that is used for the measurement of deformation, and the passive zone that serves as guide of information. The sensor is schematically represented in Figure 11.

The implementation of the SOFO system for the monitoring of structural deformations in the concrete of the Champ Baly cut-and-cover tunnel leads to the following Remarks:

1) The installation of the SOFO system was relatively rapid and did not affect, nor slow down, the construction process;
2) Only one sensor was broken during the installation, which confirms the resistance and reliability of the system. The construction workers were not requires to give particular care to the sensors;
3) The complete history of behavior of each part of the monitored sections, the foundations as well as the vaults was registered. The very early age and early age are included too;
4) The very early age and the early age deformation were measured automatically during the first seven days without any human intervention. Measurements were taken every 30 minutes;
5) Using the SOFO system, it is possible to calculate the evolution of the average strain in different parts of the monitored sections as well as the curvature of the sections. If additional sections of the tunnel had been equipped with sensors, it would be possible to retrieve the spatial deformation of the tunnel using the double integration of the curvature;
6) The SOFO system was able to record the time of opening of cracks as well as to measure their width.

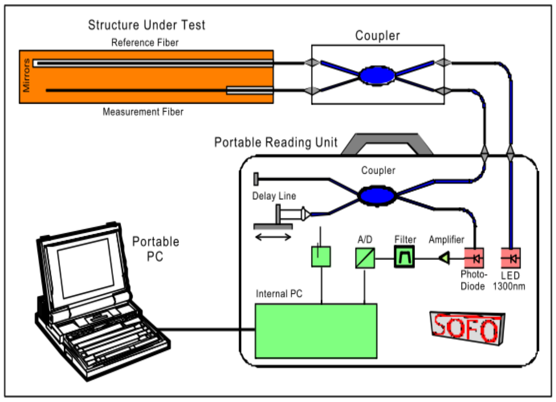

Figure 11. The SOFO system (Sourse: Rocktest)

5. CONCLUSIONS

The emergence of new methods and technologies for structural monitoring has occurred slowly, until two decades ago, while developing new methods, tools and also conventional techniques, nowadays the information explode, appearing practically endless combinations in shaping the time behavior monitoring of an objective. The Initial Structure Evaluation process is the first level of risk assessment for the established inventory of structures. The major aspects of the instrumentation planning process are data management, engineering analysis, and formal reporting. The selection of a measurement technique to be developed in the framework of a research project like **Structural Monitoring** must pursue two main objectives: a new system has to respond to a real need of the end-users, it should constitute an innovative approach in the domain of metrology and present some originality compared to the work of other research laboratories active in the same field. This paper presents the general aspects of Structural Monitoring, which is extremely useful in terms of achieving increasingly challenging constructive performance, both for designers and for operators, builders or geodesists as the basis for future paper: ’’Structural Monitoring Handbook (SMH)’’ covering all details of the behavior in time of construction. Structural monitoring is defined as such type of monitoring that allows conclusions concerning global, structural behavior of the structure and not local, material behaviour. Good monitoring strategy can provide excellent results with relatively limited budget. The systems for monitoring structural health allow the fast evaluation of a building’s state and such a deviation must be made known as an adequate means of increasing safety and of optimizing operational and maintenance activities for complex buildings. Knowledge provided by structural monitoring helped understanding the real behavior of the structures.

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