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STATE OF ART IN STRUCTURAL GEODETIC MONITORING SOLUTIONS

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Abstract: The technical field of structural monitoring has made major progress in the recent years. New developments were driven by the need to keep engineering infrastructures in service beyond their expected lifetime due to limited funds for their replacement (typical case for bridges where the today traffic loads are far above the parameters that have been used to design them) or because the projects are so exceptional and the designers have not yet gained experience on the long term (Burj Dubai eg).

Actually the term “Structural Health Monitoring” is more and more often used and refers to methods witch access the health status and safety of a structure and make estimation of its remaining lifetime.

However, structures can only be kept in service if they do not put the safety of the users at risk. Critical parts of a structure as well as global behaviour have to be monitored in continuous intervals with high precision.

The aim of deformation analysis has shifted and nowadays experts are not even looking if critical points of a structure have moved (and by the way due to thermal loads every structure is moving) but well is some patterns have significantly changed to be alerted and lead more investigations ...

With highest resolution and highest recording rate of today's instruments the small deformations caused by the daily temperature changes, wind loading etc. can be observed.

The paper will review the performances of new geodetic sensors and analysis methods regarding the context of a solution that would address the today interests of the experts. Key successful projects will be used to illustrate that topic.

Keywords: Geodetic Monitoring/Structural Health Monitoring/Deformation Analysis/Total Station/GNSS/Precise Inclinometer/Automatic Target Recognition.

1. FACING NEW CHALLENGES

Engineering companies and contractors are facing challenges never experienced before. They are being charged with – and being held liable for – the health of the structures they create and maintain.

To surmount these challenges, engineers need to be able to measure structural movements to millimetre level accuracy. Accurate and timely information on the status of a structure is highly valuable to engineers. It enables them to compare the real-world behaviour of a structure against the design and theoretical models.

When empowered by such data, engineers can effectively and cost efficiently measure and maintain the health of vital infrastructure. The ability to detect and react to potential problems before they develop helps in the reduction of insurance costs and the prevention of catastrophic failures that may results in injury, death or significant financial loss.

A structural monitoring system will help reduce both the current and long term maintenance cost associated with structural movement and will reduces risks, as data analysis can be used to aid the understanding of current and future implications of structural movements. Safety and structural integrity concerns can be minimized. Contractors can reduce their risk exposure before, during and after a construction project by continuously monitoring the project as it progresses through its lifecycle. Potential problems can be detected and rectified before a critical situation develops.

2. DYNAMIC STRUCTURES IN A MOVING WORLD

Modern cable-supported bridges carry enormous loads across great distances. By design they are dynamic structures that move due to the loads imposed by traffic, wind, heating and cooling, corrosion and other environmental conditions.

Each year landslides cause millions of dollars of damage and loss of revenue to mines, residential and commercial properties, motorways and railway lines.

Cities throughout the world are becoming denser and higher than ever before. The costs of base materials are rising, driving engineers to develop novel construction techniques. They need timely information on any departures from design during the critical stages of construction, such as concrete jetting, deep excavation and support walls. This ensures the integrity of the construction site and the safety of people. They have to provide ongoing verification and documentation of the compliance to construction and design tolerances.

Large earth fill and concrete dams are a critical infrastructure for continuous water supply and power generation. Loading and unloading forces on a dam cause stress on the structure and must be monitored. The stress can be due to fluctuations in the water level, settlement of the structure, nearby landslides or seismic activity. Early detection of a potential problem allows repairs or remedial measures to be taken before a disaster occurs. Even if repair is not possible, with the early warning of a problem action may be taken to mitigate its effects.

New and existing buildings can be affected by daily movements (solar effects, heavy rainfalls), long period movements (settlement) and dynamic movements (resonance, wind and loads). They may also be built in flood or earthquake zones and therefore at risk of being damaged by natural events. Many buildings are aging and their construction materials deteriorating due to time and weathering.

Nothing is static. Buildings and dams settle bridges fl ex and vibrate rock masses shift, mud slides, glaciers flow and volcanoes erupt. Whether by human activity such as mining or by natural processes such as erosion, the world in which we live is continually changing. Management of this change is essential for social and economic advancement. Failure of a bridge can isolate communities and restrict commerce. A landslide can cause financial and human loss, stop mining operations and even impact world mineral prices. Economies and our daily lives are dependent upon the health of bridges, dams, tunnels, elevated road systems, dams, mines and high-rise buildings. Engineers, geologists and other professional are trusted to prevent such disasters.

For the solutions to manage and monitor these structures, they rely more and more on geodetic monitoring solutions.

3. FROM AUTOMATIC SURVEYING TO PRECISE CONTINUOUS MONITORING

Based on surveying sensors like GNSS receivers and Automatic Total Stations, Geodetic Monitoring solutions are integrating also wireless communication tools, acquisition software's, PC servers, accessories, power supply, solar panels, weather station, warning sensors, web interfaces and analysis to become complex systems. And if the engineers today are considering often the surveying instrumentation just like "sensors" to be plugged and connected to even their real time analysis software's, they shouldn't forget that the key for succeeding in their monitoring projects is first to consider instrumentation and equipments that can deliver high accurate and reliable measurements 24 hours a days and 365 days a year through any communication media under any weather conditions and remotely controlled.

3.1. Advanced Automatic Total Station Designed for Geodetic Monitoring.

Since the beginning of the 19th century, Leica Geosystems has always provided engineers with the latest, revolutionary and most accurate technologies and solutions achieving the highest accuracies possible.

More than 75 years ago, the precision 0.5"-theodolite Wild T3 was introduced. It attracted great interest in the geodetic monitoring community due to its highly precise measurements. In the 1970s, the time arrived where electronics and automation evolved in survey engineering products. At the beginning of the 1980's, Leica

Geosystems released its first total station – the TC2000 – to combine highest precision and highest quality measurements along with automation to survey engineers. The TC2000 was equipped with the first high precision electronic angle measurement system developed by Leica Geosystems. Continuing to provide the best equipment for survey engineers, Leica Geosystems released the total station TCA2003 in the mid 1990s. The TCA2003 was the next generation of 0.5"-total stations to fully integrate electro-optical distance measurements (EDM). In addition, the measurement efficiency was significantly improved by the automation of the measurement process due to automatic target recognition (ATR). The latest generation of highest precision total stations from Leica Geosystems – the TM30 – has reached the pinnacle.

The TM30 allows very quick, highly accurate and precise measurements. It is specifically designed for the highest measurement quality of automated measurement processes.

The newly developed direct drives using piezo technology enable very quick and efficient automated measurements. The rotation speed of the alidade and telescope is up to 200 gons per second. The TM30 is more than four times faster than total stations with conventional drives. Its direct drives alone result in a significant increase of automated measurements possible per hour. One of the key components is the Automatic Target Recognition (ATR) on passive reflector up to a range of 3000 m which means that operations that would never been envisioned before the release of the TM30 can now be realized as well as totally new applications.

The TM30 R1000 Electronic Distance Meter measures to natural targets at ranges of more than 1000m.

The TM30 potential is fully enhanced by Leica Geosystems' GeoMoS Monitoring software.

3.2. GPS L1 single frequency up to GNSS multiple-constellation antennas and receivers.

The Leica GMX901 is a compact, robust and precise single frequency receiver designed specifically for monitoring applications. Sensitive structures such as dams, rock slopes, mine walls and buildings can be monitored around the clock for the smallest of movements. Leica GMX901 streams precise single frequency code and phase data up to 1 Hz, providing the basis for highly accurate position determination and deformation analysis.

Designed with a focus on the essential – low power consumption, high quality measurement, simplicity, durability the Leica GMX901 is an ideal sensor for monitoring. It has a robust housing that is water, heat, cold and vibration resistant and which can be easily mounted on the infrastructure to be monitored.

The Leica GMX902 GG is a high-performance GPS + GLONASS receiver, specially developed to monitor sensitive structures such as bridges, mines or high rise buildings and crucial topographies such as land slides or volcanoes. It provides precise dual frequency code and phase data up to 20 Hz, enabling precise data capture as the basis for highly accurate position calculation and motion analysis.

As with the other receivers in the GMX900 family, the GMX902 GG has been designed and built purely for monitoring applications. The key characteristics of the GMX900 family are low power consumption, high quality measurement, simplicity, durability.

The Leica GMX900 family connects seamlessly to the Leica GNSS Spider advanced GNSS automatic processing software for coordinate calculation and raw data storage. The Leica GeoMoS monitoring software can be used to provide integration with other sensors, analysis of movements and calculation of limit checks. Third party analysis software can also be easily integrated via the standard NMEA interface of Leica GNSS Spider.

3.3. The more precise dual axis inclinometer

The Leica Nivel210/Nivel220 precise inclination sensor for simultaneous measurement of inclination, direction of inclination and temperature is based on an optoelectronic concept. That inclinometer fits well for large structure monitoring and engineering constructions such as dams, bridges and high-rise buildings where high precision information about the inclination and the direction of movements is needed. Two-axis tilt measurements with a resolution of 0.001 mm/m, highly accurate measurements and long-range stability, real-time data on a continuous basis connectable to the Leica GeoMoS monitoring software are certainly the main characteristics of that instrument.

All those geodetic instruments can be combined in various systems where GNSS antennas collocated with 360° reflector are acting as “Active Control Points” for Automatic Total Stations networked. If multiple total stations are able to make measurements to a common set of prisms, the measurements can be combined in a mathematically optimal way known as network adjustment. By combining the measurements in a network adjustment it is possible to increase the precision of the solution and determine a common reference frame for all total stations even in the case that some of total stations cannot observe stable control points or are themselves unstable.

It has been proved also that the combination of a very precise inclinometer with a GNSS receiver can consist of a stand-alone basic monitoring station for high rise building monitoring and that the performances of the Leica dual-axis inclinometer can fairly compete in the frequency domain with an accelerometer.

Recently the benefit of GNSS Network RTK corrections to provide unbiased positioning information from GPS and GNSS monitoring receivers has been demonstrated for several monitoring projects in Hong Kong.

4. AUTOMATIC NETWORK ADJUSTMENT AND DEFORMATION ANALYSIS

Continuous Geodetic Monitoring systems must also have the capacity to process in timely manner the huge amount of data gathered in a central computing centre to deliver in simple ways (graphically and with clear reports) the reliable warnings and alarms. Leica GeoMoS Adjustment provides an automatic least squares network adjustment, the single epoch automatic deformation analysis based on a rigorous statistical approach and can be used for designing a monitoring project to match the accuracy requirements.

The combination of measurements from multiple geodetic automatic instruments is handled by a robust adjustment ensuring the highest precision and reliability. The detection of outliers is based on multi-level statistical hypothesis tests as well as the detection of unstable fixed points. It is essential for geodetic monitoring applications to have a complete system that can distinguish movement of the structure from problems in the reference frame and can identify which reference points are stable and which are not.

It is also of the prime importance for the engineers managing monitoring projects to have the tool to design the setup of the instruments in such a way that the ensemble will fit with the expected accuracy. Leica GeoMoS Adjustment can simulate the mathematical geometry to optimize the network accuracy and reliability.

5. CASES STUDIES

Several projects will be reviewed to illustrate the state of art of Geodetic Monitoring..

5.1. Permanent Monitoring during Urban Excavation.

During 2007 and 2008 a new residential house was constructed in the middle of a built-up area. The construction project required the excavation of soil sediment layers as well as lowering of the surface groundwater. It was a concern that these actions might endanger the surrounding infrastructure and construction site. Therefore, a permanent monitoring system was required to ensure the safety of surrounding buildings and construction workers. Automatic monitoring, operating 24hrs a day was installed to monitor the adjacent wall. Measurements were taken twice an hour and automatic alert triggers were configured to alert engineers of exceeded thresholds. Based on the long monitoring period immediate corrective measures could be initiated to protect the existing buildings and construction site before serious damage occurred. The effectiveness of the corrective measures was immediately visible due to the continuous monitoring.

5.2. Burj Dubai – Rising High with GPS Network.

Burj Dubai is now the world’s tallest building, nearly twice the size of New York’s Empire State Building and higher than the current title holder, the Taipei Financial Center (Taipei 101) in Taiwan. The final height has been kept secret during the construction stage. Not a secret, on the other hand, was the unique monitoring system the author developed together with Douglas Hayes, Chief Surveyor of Burj Dubai. Reaching top of concrete for the Burj tower at Level 156, at level 585.7 m, Douglas Hayes was impressed: "We have used our Leica GX1200, TPS1201 and Nivel 220 systems all the way - the system has proven to be fantastic. Vertical walls are straight, lift shafts are too - standard deviations of concrete core walls are generally around 7mm. At the very top, I have computed the mean displacement of all core walls: delta Easting = 0mm, delta Northing = 5mm from design position. Of course this quality has come about due to a lot of effort on all sides - not just survey. But for our part I am very pleased with the way things have gone! The system has also allowed me to monitor the structure continuously and remotely, from a dynamic perspective as well as from a long term one, to quite amazing accuracy."

5.3. The Kowloon Southern Link Monitoring Project.

The Kowloon Southern Link project is a 3.8 km extension of KCRC's West Rail Link from Nam Cheong Station connecting to East Tsim Sha Tsui Station of KCRC's East Rail Link. There is about 1.2km of the new extension area located very closely to the existing Airport Express Rail and MTRC Tung Chung Line. In order to ensure the construction works do not have serious structural effect and distributing daily operation and safety of the Airport Express Rail, an Automatic Deformation Monitoring System is deployed mainly to continuously monitor settlement along the affected rail track. The 1.2km track is divided into three different sections (600m,210m and 400m) for continuously monitoring where cover ballasted section, trough section and tunnel section. A pair of mini prisms with tailor-made protection is installed in every 13 m interval along the rail track. TCA2003 Total Station that are driven remotely via a data communication network by Leica GeoMoS software at the Control Centre measure the positional change of each target prism automatically in every 2 hours interval. To get the best line of sight for measurement, those Total Stations are installed at various locations including tunnel wall, roof of rail station and structure along the track.

5.4. Jiangyin Bridge, China – GPS RTK Bridge Monitoring.

The Jiangyin Yangtze River Highway Bridge is the first super-large steel box-girder suspension bridge that spans more than one kilometre in China. It is the longest steel box girder suspension bridge in China, the fourth longest in the whole World. It services a superhighway which is the national key trunk route crossing the Yangtze River. The Jiangyin Yangtze River Highway Bridge is the second suspension bridge that was constructed over the Yangtze River. It lies between Jiangyin and Jingjiang of Jiangsu Province, at the lower reaches of Yangtze River. The upgrade and modification of the superstructure health monitoring system of Jiangyin Yangtze River Highway Bridge was completed using the Leica Geosystems' GPS monitoring system that focused on the monitoring of the girder geometric form and the displacement of the bridge towers. The challenge was to provide a cost effective and innovative solution for delivering 3D positioning information at 20 Hz from several GPS Monitoring stations to advanced analysis application software developed by the engineering company in charge of the whole structural monitoring project.

5.5. Northern Italian Reservoir.

Many of the hydroelectric reservoirs located in the Alps of Northern Italy are built in narrow valleys which are orientated North-West / South-East. Due to the valley's orientation, only one side is exposed to the sun and is subject to significant temperature differences within short periods of time. In many cases this situation has caused a different geological structure in the two sides of the valley. In one of the valleys a double-sweep arc-gravity dam was constructed in the years 1950-1960. In June 1997, a Leica TCA2003 Automated total station was installed near the dam, on the stable right slope, to permanently monitor, with the greatest accuracy, the position of 16 reflectors located on the left slope, with elevations varying from 1730 metres to 2100 metres. The distance from measurement station to target ranges from 170 to 1500 metres. Each of the reflectors is located on a concrete pillar and protected from inclement weather. Two of the 16 targets, located on the left and right side of the basin, are fixed points. The measurement station consists of Leica TCA2003 Automated total station and APS system software. The TCA2003 is located on a very stable pillar enclosed in a building equipped with special glass windows. The application processor is also housed in the shelter. The APS system software controls the measurement procedure based on a point selection made by the operator during a “learn” procedure. The measurement procedure can be easily modified by the operator if necessary. ENEL configured their system so that several measurements cycles would be made every day, starting at selected time intervals. Measurement sequences are defined to begin and end on non-moving control points which have known coordinates.

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References

Brown, N., Kaloustian, S., Roeckle M. (2008). Monitoring of Open Pit Mines using Combined GNSS Satellite Receivers and Robotic Total Stations.

Brown, N., Troyer Lienhart, Zelzer, O., Van Cranenbroeck, J. (2006). Advanced in RTK and Post Processed Monitoring with Single Frequency GPS. Journal of Global Positioning Systems, Vol 5, N°. 1-2:145-151

Van Cranenbroeck, J., Brown N. (2004). Networking Motorized Total Stations and GPS Receivers for Deformation Measurement. FIG Working Week, Athens, Greece.

Zog, H-M., Lienhart, W., Nindl D. (2009). Leica TS30 – The Art of Achieving Highest Accuracy and Performance.

Van Cranenbroeck. J., Aschroft. N. (2007). Single to Multi Frequency GNSS Signal Processing Solutions for Engineering Structure Monitoring Applications. The International Global Navigation Satellites Systems Society Inc. (IGNSS) IGNSS2007 Symposium – The University of New South Wales, Sydney Australia.

Van Cranenbroeck. J., Lui. V., Wu. X. (2007). ICE 5th International Conference Bridge – Beijing, supported by the FIG Commission 6 WG4.

Van Cranenbroeck. J. (2007). Continuous Beam Deflection Monitoring Using Precise Inclinometers. Strategic Integration of Surveying Services FIG Working Week, Hong Kong SAR, China.

Van Cranenbroeck, J. (2007). An Integrated Geodetic Measurement and Analysis System for Large Dams Monitoring. Hydropower & Dams issue 2 : INSTRUMENTATION SYSTEMS FOCUS.

Van Cranenbroeck, J. (2006). Core Wall Survey Control System. Opening paper – 3rd IAG Symposium on Geodesy for Geotechnical and Structural Engineering, 12th FIG Symposium on Deformation Measurement.

Lienhart, W. (2007). Analysis of Inhomogeneous Structural Monitoring Data. Engineering Geodesy – TU Graz, Austria. Shaker Verlag

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