Modern Deformation Monitoring: A Multi Sensor Approach

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Key words: Deformation Monitoring, Total Station, GPS, Geotechnical sensors.

ABSTRACT

Traditionally, deformation monitoring was achieved via labour intensive manual measurements using conventional terrestrial surveying instruments. Continuous automated deformation measurements were first introduced through geotechnical sensors that, once installed, require only infrequent checks of their performance. The advent of motorised terrestrial surveying instruments considerably reduced the labour required to conduct optical deformation monitoring by measuring to a set of prisms at predetermined time intervals. The introduction of GPS technology has provided an additional method to provide continuous measurements for deformation monitoring.

Although many technologies exist to perform deformation measurements, often a combination of these technologies can provide more information to better monitor the deformable object and its surroundings and hence multiple sensor technologies are useful to augment each other. This paper describes a state-of-the-art system that combines multiple sensor types to provide measurements to perform deformation monitoring.

ZUSAMMENFASSUNG

Herkömmliche Beobachtungen von Bodenbewegungen mit terrestrischen Vermessungsinstrumenten erfordern intensive manuelle Arbeit. Kontinuierliche automatische Deformationsmessungen wurden ursprünglich mit geotechnischen Sensoren eingeführt. Nach deren Installation sind nur gelegentliche Überprüfungen ihrer Funktionalität nötig. Der Einsatz motorisierter terrestrischer Vermessungsinstrumente reduzierte die erforderliche Arbeit für Beobachtungen von Bodenbewegungen durch Messen mehrerer Prismen in vorbestimmten Zeitintervallen beeinträchtigend. Die Einführung von GPS Technologien stellt eine zusätzliche Methode dar um kontinuierliche Messungen bei Deformationsmessungen zu ermöglichen.

Obwohl viele Technologien existieren um Deformationsmessungen durchzuführen führt eine Kombination dieser Technologien zu umfangreicheren Informationen um Objekte und deren Umgebung zu beobachten und die einzelnen Technologien mehrfacher Sensoren zu vergleichen. Hier wird ein auf dem neuesten Stand befindliches System beschrieben, welches verschiedene Typen von Sensoren für den Einsatz bei Deformationsmessungen kombiniert.

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1. INTRODUCTION

Deformation monitoring requires the careful collection and analysis of measurements from a number of sources. Not only must the sensors used for data collection be carefully selected, they must also be carefully placed on the object being monitored. The sensors used for deformation monitoring can be grouped into the following categories:

- Surveying
- Geotechnical
- Meteorological

The sensors chosen to complete the data collection component of the deformation studies are based on the characteristics of the object/area being monitored. For example, to monitor a bridge to verify the design parameters and to alert officials in the case of an approaching failure a monitoring scheme which uses the following sensors could be adopted: precise GPS sensors, strain gauges, tilt meters and temperature sensors. Whereas a monitoring application to examine settlement above underground mining activities may utilise the following sensors: a high accuracy total station, magnetic probe extensometers and piezometers. As no deformation monitoring project is the same, each project must be carefully assessed to select the correct combination of sensors to provide optimal results.

This paper describes a state-of-the-art system that combines multiple sensor types to provide measurements to perform deformation monitoring.

2. SENSORS USED FOR DEFORMATION MONITORING

Generally geotechnical and meteorological sensors are capable of providing measurements in 1-dimension. Whereas surveying instruments allow the determination of 3-dimensional movements. The combination of the measurements from these sensors placed at strategic locations provides the basis for deformation monitoring.

2.1 Surveying

The launch of the motorised theodolite introduced the possibility of collecting 3-dimensional positional information for automatic deformation monitoring. Current technology provides total stations that are able to measure angles with an accuracy of ±0.5" (0.15 mgon), and distances with an accuracy of ±1mm + 1ppm to a range of 3,500m (Leica Geosystems, 2002a). Total stations allow the measurement of many points on a surface being monitored within a short period of time. For example, a surface that is being monitored by the placement of 200 prisms would take approximately 17 minutes to measure the 3-dimensional co-ordinates of each point. Using Automatic Target Recognition (ATR) technology (Leica Geosystems, 2002b) each prism can be found and its centre identified to provide precise target pointing. Such technologies are ideal for precise applications where the removal of error sources is desired. The ATR approach used by Leica Geosystems uses non-active prisms and hence does not require a power source at each prism, reducing the cost of each prism installation.

RTK GPS delivers 3-dimensional co-ordinates with an accuracy of ±5mm + 2ppm in real-time with a frequency as high as 0.2Hz (Leica Geosystems, 2002c). Equipment which provides the accuracy achievable with RTK GPS and with the update rates that is possible with modern GPS receivers provide the ideal sensor for monitoring “high” and “low” frequency movements in structures (e.g. bridges and buildings). A number of studies have shown the suitability of using GPS for dynamic monitoring. The interested reader is directed to Ashkenazi et. Al. (1998), Celebi et. Al. (1998) and Duth and Hyzak (1997).

Although GPS provides a valuable tool for monitoring, some environments are not ideal for GPS (Stewart and Tsakiri, 2001). The combination of sensors of various types provides the key to successful monitoring.

2.2 Geotechnical

Geotechnical sensors are used extensively in the monitoring of structures. These sensors are often placed within the structure and out of sight, however they are never out of mind (Encardio Rite, 2002). During construction of the structure geotechnical sensors of the desired type are carefully chosen and placed at strategic locations to ensure that adequate information is provided to verify design parameters, evaluate the performance of new technologies used in construction, verify and control the construction process and for subsequent deformation monitoring (Encardio Rite, 2002).

The main geotechnical sensors used for deformation monitoring include; extensometers, inclinometers, piezometers, strain gauges, pressure cells, tilt sensors and crack meters. Geotechnical sensors can either store the measured data internally awaiting download, or the measurements can be automatically logged to a connected computer. Connection to a computer offers a number of advantages (e.g. data stored at a remote location; ability to change update rate of measurement data, when changes in measured values are detected; no need to visit site to download data) and disadvantages (e.g. transfer media required between sensor and computer, for example cable/radio/GSM; loss of data possible if transfer media is not operating and internal storage is not activated).

Geotechnical sensors provide measurements that are often essential in deformation monitoring. An additional sensor category that completes the portfolio of deformation monitoring sensors, that provide their own analysable measurements or measurements to calibrate additional sensors, is meteorological sensors.

2.3 Meteorological

Meteorological sensors are available in a variety of forms that measure one or more of the required meteorological observables, namely: temperature, relative humidity or dewpoint resp., barometric pressure, wind speed, wind direction, global radiation (solar energy) and precipitation. Sensors that provide such information can be used to calibrate other sensors used in the monitoring program (e.g. calibration of total station distance measurements) or provide valuable information that can be correlated with positional information measured from a total station (e.g. large lateral movements in a bridge can be correlated with significant cross bridge wind gusts, etc.).

2.4 Combining sensors: A case study

Monte Rosa is located in the Piemonte region of Northern Italy. The peak Monte Rosa reaches a height of 4,634m above sea level and represents the second highest peak in Europe. The Comune di Ceppo Morelli initiated a project to monitor a landslide region located at an altitude of 1,200m that is endangering a small road and village. The monitoring required a selection of various sensors, including:

- 1 x TCA 2003 total station;
- 10 x Extensometers;
- 3 x Temperature sensors;
- 3 x Vertical sensors;
- 2 x Three-axis tilt sensors;
- 1 x Rain gauge.

Batteries that are re-charged by a solar panel power the system. All of the measured data is transferred to a central computer via a GSM phone connection. The measurements transferred to the central computer include raw measurements from the total station, geotechnical and meteorological as well as voltage readings from the solar panels and batteries to allow the system to be observed. When movements occur that are larger than expected messages are sent to inform authorities.

The measurements includes five control points located at stable locations and 25 points located on the active landslide area. The measurement station is located on the other side of the valley and hence requires total station measurements to be observed over distance ranging from 1,500 – 2,100m.

Figure 1 indicates movement at point 21 between the 12th July 2000 and the 20th July 2000. This can be best seen through the extensometer readings that are continually collected during this period, and can be confirmed by the slope distance measurements that are obtained intermittently. The intermittent nature of the total station can be attributed to the adverse weather conditions that include long periods of fog, cloud and rain. During this period the total station measurements could not be measured continuously.

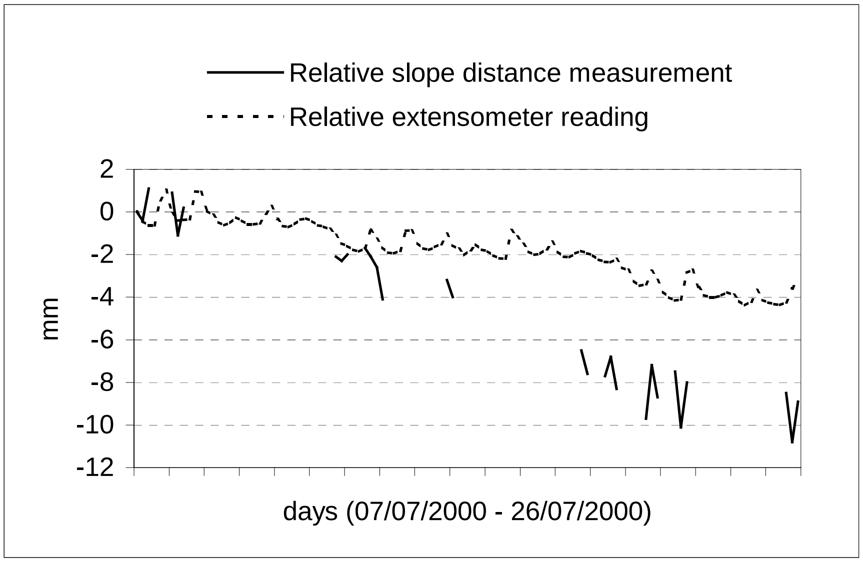

Figure 1 – Relative Extensometer readings and relative Total Station Slope Distance measurements at point 21.

This example demonstrates the benefit of having multiple sensors in the monitoring region that can be used to confirm, or deny, apparent movements.

Sensors alone are not enough to provide a complete monitoring solution. Software provides the essential system component to steer the sensors and log the data they collect.

3. SOFTWARE USED FOR DEFORMATION MONITORING

Monitoring software has significantly increased in functionality and sophistication since the inception of automatic deformation monitoring. Generally, monitoring software systems consists of two components, namely:

- On-line measurement collection; and
- Measurement analysis.

The software components may come from one or more supplier, however, generally suppliers offer a total solution.

3.1 On-line measurement collection

Measurement collection is a complex task that requires careful planning. The sensors used to collect measurement data must be wisely selected. Their locations must be carefully planned and the rate at which they make measurements needs to be selected to match the expected, and possible, changes in the measurable quantities.

On-line measurement collection demands a sophisticated scheduling system to collect the desired data at the required rate. For example, temperature data may be required at a rate of six times per day, whereas RTK GPS positions are required at a rate of 0.2Hz, and TPS measurements to each prism are required once per hour. Managing this scheduling is not trivial, especially when a variety of sensors are used.

On-line measurement collection may also include a level of reduction to convert the measured data into analysable quantities (e.g. a total station slope distance and vertical angle can be reduced to a height difference measurement to enable subsidence values to be ascertained). Upon the completion of on-line measurement collection the data is often stored in a database to allow subsequent measurement analysis.

3.2 Measurement Analysis

Once measurements have been collected they need to be fastidiously analysed to assess if they match their expected values. Such analysis can be realised graphically and statistically or a combination of both techniques.

Often deformation analysis is conducted to allow responses or actions to be taken where the safety of lives and assets are at risk. For this reason, and others, personnel who have specific training and experience in this field should be the only ones to conduct analysis activities. Analysis activities are reliant on the correct selection and placement of sensors in the deformation region. A variety of sensor types are often used to confirm, or deny, detected movements.

Man-made structures are designed to withstand movements of specified magnitudes. Problems can occur when movements exceed the design specifications. Analysis activities need to compare the expected movements and the actual movements under all conditions. Such analysis activities are undertaken not only to monitor movements that may introduce dangerous conditions, but also to assist in designing future structures.

4. GeoMoS

Leica Geosystems has just entered its 3rd generation of monitoring software with the release of GeoMoS (Geodetic Monitoring System). The GeoMoS software supersedes previous Leica Geosystems monitoring software systems, namely: APS (Automatic Polar System) and APSWin (Automatic Polar System for Windows).

4.1 Overview

The creation of the GeoMoS product begun with the creation of a requirements document to define the exact functionality needed to address the demanding requirements. Following the completion of the requirements, user interface prototypes were created and improved through an iterative process of review and updating. In parallel to finalising the user interface prototype, technologies were investigated to address the requirement of wireless data communications for the transferral of data within the system. Database technologies were also examined to determine what would be suitable to store the large amounts of data collected in monitoring applications. Following extensive investigations it was decided to use TCP/IP as the protocol for data transferral within the system and the Microsoft Database Engine (MSDE) to store measurements and computed results from the system.

A fundamental design concept of GeoMoS is that the system is customisable and expandable. This level of flexibility is required as no two monitoring applications are identical; all applications have their intrinsic specialities. GeoMoS is composed primarily of two components:

- GeoMoS Monitor; and
- GeoMoS Analyzer.

The GeoMoS Monitor application is used at the measurement station to connect and collect measurements from the available sensors. Using Extensible Markup Language (i.e. XML scripts) technology, the system can be configured to connect all available sensors. Such sensors include: total stations, GPS receivers, meteorological and geotechnical devices. Within the Monitor application the user configures which points should be measured, using which sensor and at what frequency. Thresholds are then assigned to define what are acceptable levels of movement, and when messages should be sent to notify that a movement greater than acceptable limits has been detected. Upon the availability of an Internet connection at the GeoMoS Monitor location, messages to advise of movements or other system messages can be sent to external locations via e-mail, or as a text message to mobile phones via a provider.

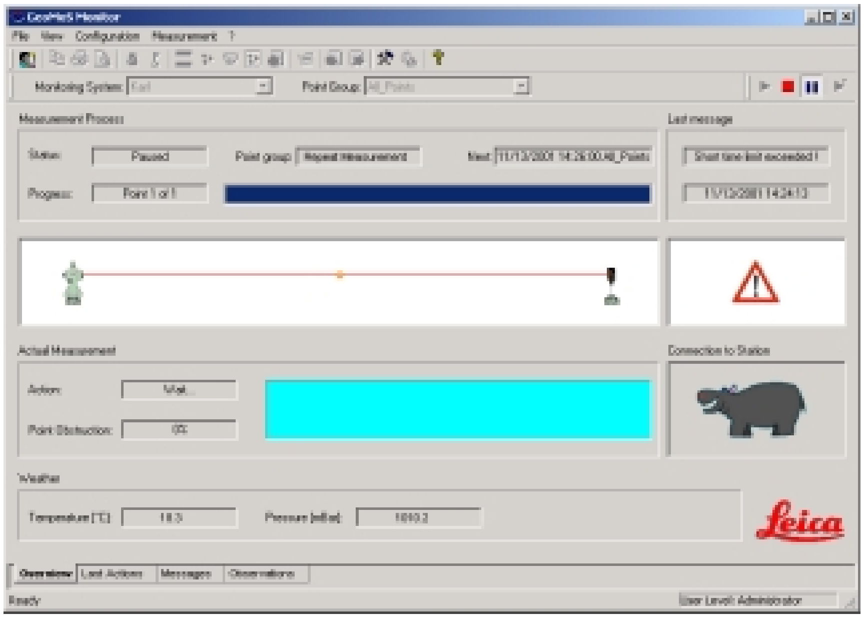

Figure 2 – GeoMoS Monitor

GeoMoS Analyzer provides the functionality to visualise measurements and results in either graphical or tabular form. This tool accesses the same database as the GeoMoS Monitor application uses to write measurements and computation results, and can be executed in parallel to the Monitor application. Flexible graphical displays allow users to show the information in the required form.

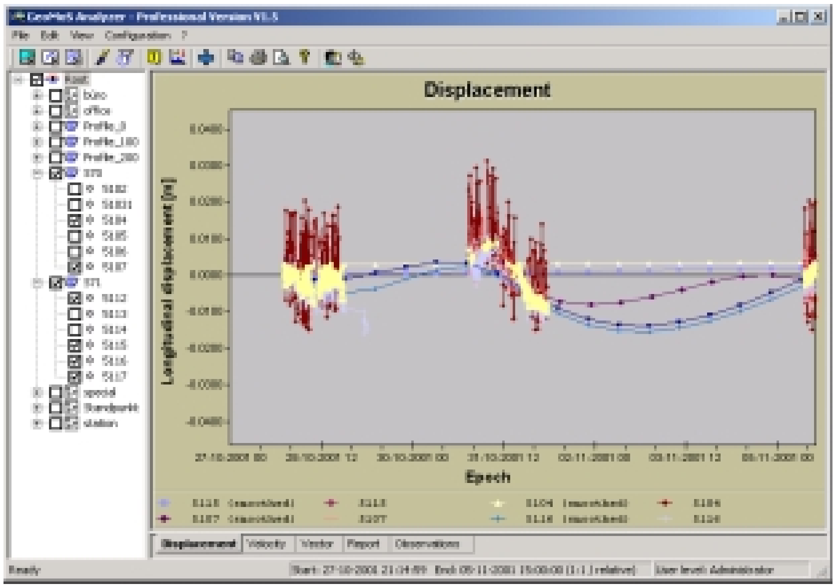

Figure 3 – GeoMoS Analyser

4.2 Sensor Manager

One of the strengths of the GeoMoS is the new Leica Sensor Manager component. This component handles the connections to various types of sensors. Monitoring projects today require the software to connect to many different types of electronic sensors and equipment. The goal of the Leica Sensor Manager is to enable virtually any type of sensor to be connected to the application. The Leica Sensor Manager is a stand-alone component that is one of the core features of the GeoMoS product. The Sensor Manager takes the intelligence of sensor management out of the application itself. The application communicates with Sensor Manager to find out what sensors are connected. The application can send and receive data to and from the sensor without having to know how to communicate directly with the sensor itself. The communication is done through a generic Microsoft standard COM interface between the Sensor Manager and the application.

Sensors are defined in Sensor Manager via an XML Script that is also a defined Microsoft standard. The XML file is a text file that defines the protocol, commands, properties and configuration of the sensor. The schematic design can be seen in Figure 4. Every sensor has its own XML file and is registered with the Sensor Manager.

- Protocol - A sensor can be connected via an input/output port (e.g. serial). The default protocol information for the connection can be defined in the XML file (e.g. baud rate, parity, stop bits etc).

- Commands - The commands that the sensor understands are defined in the XML file.
- Properties - The properties of a sensor are the values that are returned when a command is sent. The properties can be described in detail in the XML file. The Sensor Manager re-organizes this data ready to send back to the application as a generic format.
- Sensor Configuration - The settings and configuration of the sensor is also described in the XML file. Depending on the sensor description it is possible to remotely configure parameters of the sensor via a sensor properties dialog in the Sensor Manager.

It is very easy to integrate additional sensors by defining the sensor description in an XML file. This normally requires the definition of the sensor in a text format file, and in some cases a small driver component, to integrate new sensors. It is possible to integrate a new sensor into the system within a few days. Once the XML file exists and is registered with the Sensor Manager it can also work with the application. Data from the sensor is retrieved through Sensor Manager and stored in the Database. The data from the Database can then be retrieved from the Database and displayed or used in the analysis. This concept allows various TPS Sensors, GPS Sensors, digital levels, meteorological sensors, extensometers, tilt meters and other types of digital sensors to be integrated into the system (Sippel, 2000).

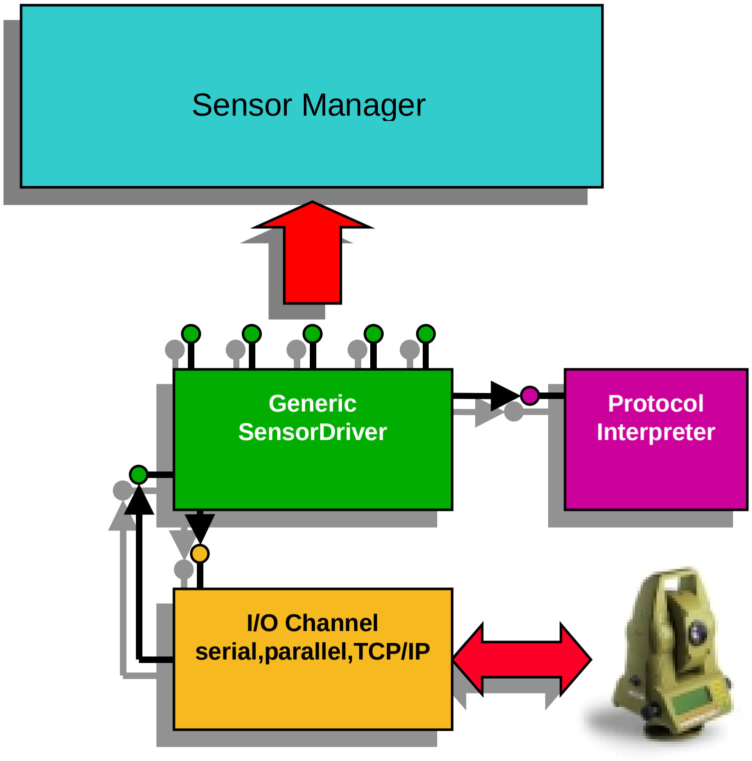

Figure 4 – Leica Sensor Manager

Figure 4 shows the Sensor Manager design, including the interaction of the generic components. The sensor information required for the communication is defined for each sensor in an XML file. The interaction between the sensor and the application is always done via the Sensor Manager providing a generic layer for integrating different types of sensors into an application.

4.3 External tools

The Microsoft Database Engine was chosen to store data within GeoMoS for its flexible and open structure. Within the software industry it is increasingly acknowledged that “openness” is one key to success. Customer requirements are often so diverse that one manufacture cannot satisfy all customers. A technique to overcome this problem is for manufactures to build open platforms that can be localised through custom extensions. GeoMoS is such an open system that allows partners to build on the platform using external tools. Using a programming environment such as Visual Basic, external tools can be developed to perform customised functionality. Standard SQL queries can be executed to access data in the open database, the data can be manipulated and then written back to the database. GeoMoS provides functionality that can execute external tools at given events. For example, after measuring a group of control (fixed) points, an external program can be executed to extract the measured data from the database and perform a unique transformation that computes a scale factor and orientation to be used to subsequent measurements, or to extract the data from the database and format it for customised daily reports. An open system that includes the infrastructure to execute external tools enables the system to be customised for the variety of monitoring projects.

5. SUMMARY

Deformation monitoring is an activity that requires special attention to be paid to the sensors used and their location within the monitoring area. This paper has described the importance of using multiple sensor types to collect data for monitoring purposes, as multiple sensor types can provide a level of confirmation. An example of a landslide monitoring project in Italy was used to demonstrate the benefit of multiple sensor types.

A new state-of-the-art monitoring system was described. The new system, GeoMoS, was described as comprising of two components: GeoMoS Monitor (for on-line data collection and messaging) and GeoMoS Analyzer (for the analysis of collected data). The openness of GeoMoS was highlighted through the Sensor Manager (the ability to connect any sensor to the system via XML scripts) and the ability to execute external tools (e.g. Visual Basic applications) that can access the open database and perform specific functionality.

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BIOGRAPHICAL NOTES

Craig D. Hill, Ph.D., M.App.Sc., B.App.Sc. is currently working for Leica Geosystems AG in Heerbrugg Switzerland. Prior to recommencing employment at Leica, Craig completed a Ph.D. at RMIT University with a research focus on developing field procedures and data processing methods for a combined surveying system using satellite positioning and terrestrial surveying technologies. As Director of Survey Applications Craig is responsible for the marketing and financial management of surveying application software.

Karl Sippel has been working at Leica Geosystems AG for the last 7 years. He is a surveying honours graduate from the University of New South Wales in Sydney, Australia, where he later worked for over 4 years involved in research and teaching of industrial measurements, monitoring measurements using automatic robotic systems and adjustment techniques. He has worked in private survey practice and in commercial software firms and has over 10 years experience developing commercial software.