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GEODESIC MONITORING SYSTEMS: A CRITICAL ANALYSIS OF INSTRUMENTS AND SENSORS USED

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Abstract: *Geodesic monitoring systems are used for the surveillance of several modern constructions. They have evolved very fast over the past years along with several breakthroughs in engineering. The first part of the article presents the main components of such a system: a hardware and a software component. The second part analyzes the different types of sensors used, along with their advantages and disadvantages. As a conclusion we'll present an algorithm for setting up a modern monitoring system. Finally we'll indicate the shortcomings of current implementations and present future developments which will take these systems a step higher.*

Key words: *geodesy, engineering, monitoring system, sensor, tachymeter.*

1. Introduction

A geodesic monitoring system is a system used to observe, to determine and to analyze or assess the geometrical changes that an object goes through in time. The aspects which represent the goal of the study are: the one-, two- or three-dimensional coordinates, the longitudinal or transversal tilts as well as the angles. Sometimes further aspects, like temperature, air pressure or the direction and intensity of the wind have to be taken into consideration. This way it is possible to precisely define the current state of the observed object.

Objects that are observed can be very different, but depending on their characteristics and on the particularities of the monitoring system needed for that specific object, they may be classified as follows:

- Constructions, also called technical objects: buildings, bridges, towers, tunnels, dams etc.
- Surfaces: hills affected by landslides, icebergs, volcanoes etc.
- The level of seas and oceans.

We can define a set of minimum requirements when talking about a monitoring system [1]. These requirements follow two main directions:

- The hardware component which will obtain the data (which will do the measurements).
- The software component which will analyze the data.

In classical geodesic monitoring systems the measurements are done from a static point of view, which means there is a fixed reference frame to which all of the measurements are related [12].

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The goal of this article is to present the general structure of geodesic monitoring systems (hardware and software), insisting on a comparison between the instruments or sensors that may be used in these systems. Finally we will show the current restrictions of monitoring systems and future directions of development.

2. Structure and Components of a Geodesic Monitoring System

The hardware component of a geodesic monitoring system connects a series of elements [4], [6], which are presented in Figure 1. As one can see, such a system is normally controlled remotely; a local station communicates with sensors installed in different points and then sends the data to the remote station. The communication is bidirectional: data is retrieved from the sensors and then sent from the local station to the remote station and commands are sent from the remote station down to the sensors.

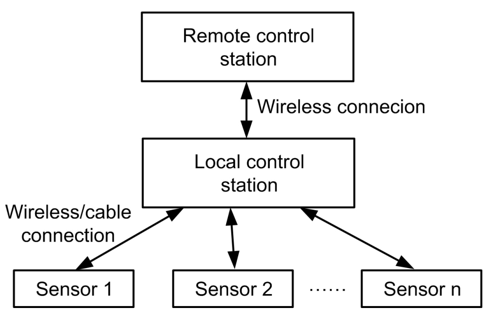

Fig. 1. *The hardware structure of a geodesic monitoring system*

The communication protocol as well as the communication methods may vary substantially. The simplest solution is a serial link used for example to send a command to a sensor, so that the sensor completes a measurement and then sends back its results.

In the specialized literature [7], we've found a description of the commands sent to a Leica total station using the GeoCom protocol. Using these specialized protocols, one can also configure the sensors.

USB ports are another alternative when setting up an interface with the sensors. In case of a permanent installation of the sensors, one can also set up an Ethernet network, but this aspect has been more or less ignored up to date by sensor manufacturers.

The software component is generally more complex than the hardware one and varies more from case to case. Normally one will find a modular approach of the system, which has a series of advantages like the reusability of its components and an easier process of debugging or further development.

The main part of the software component is the one which analyzes the data provided by the sensors and which has to provide the conclusions regarding the structural changes of the objects. This component is located in the center not just because it provides the answer to the main question put to the system but also because it coordinates all of the actions and commands of the other components.

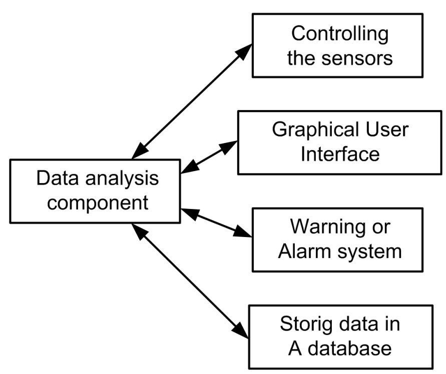

Fig. 2. *The software structure of a geodesic monitoring system*

3. Sensors Used To Collect Data

The term *sensor* must be assessed this time more generally, because the sensor itself might be a complex system, which provides data from certain measurements (the term *instrument* may be more appropriate in this case). These instruments are normally named sensors, because from the point of view of the component which processes data, they just provide the data.

Next, we'll present the main types of sensors used in geodesic monitoring systems along with their advantages and disadvantages.

3.1. Motorized Tachymeters with Automatic Target Recognition

These are instruments which contain a polar positioning system; they are also called total stations and they can aim an infinity of points in the 3-D space [8-10].

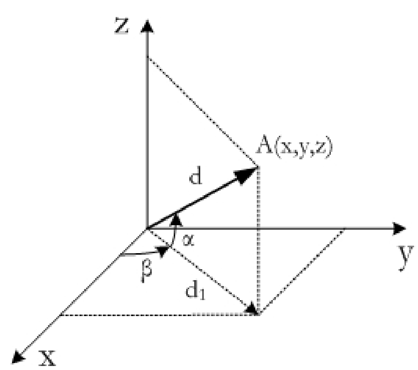

Fig. 3. *Transformation of polar coordinates into cartesian coordinates*

Polar positioning (Figure 3) means that in the horizontal plane there is a rotation by an angle β from a reference direction, here Ox and in the vertical plane there is a rotation by an angle α from the horizontal plane, here xOy. Once the position is reached, and point A is aimed, the measurement of the distance can take place, the result of it being d. The measurement is normally done with the help of a laser device. A first major difficulty of these systems is the fact that any positioning error, even a very small one will lead to an important error for the distance measured. This error will be amplified as the aimed point is further away. Normally the precision requirements of a monitoring system are of a few millimeters.

The second problem is to be able to aim the exactly same point in two consecutive measurements. Thus, if the point moves we'll have to aim it using two different angles (α and β). As a result we'll have to find a way to recognize or to determine the new orientation of the point. There are two solutions for this problem: the usage of a reflecting object or image processing.

The first solution uses a triple prism, which is based on a Lüneburg lens [14]. This lens is practically a sphere, which has a special distribution of the refracting factor, so that all of the incoming beams are concentrated into a single point.

In order to be able to use this technique the tachymeter must have a special feature, namely to be able to measure the intensity of the reflected beam. One can compare the intensity of the reflected beam with the maximum intensity, which is obtained in case the prism is aimed exactly in the center. Now, if the distance to a certain point has to be measured, the tachymeter may scan the area around the supposed position of the point and one can determine the orientation having the maximum intensity for the reflected beam. This way the distance will always be measured to the same pint. This technique is also called automatic target recognition and represents the ability of an algorithm or of a device to recognize targets or objects based on data obtained from sensors.

The second solution is based on digital processing of images [3]. Using a camera, one can take a photo of the desired object, including the set of points which have to be analyzed in terms of displacement. Using digital image-processing one can then determine the new orientation of the points and then with the help of the tachymeter the distance to the desired points can be measured. This technique has two disadvantages compared to the first one: it's more difficult to implement and the precision is coarse.

There are two different technologies used by tachymeter providers to measure distances. They are generally called EDM technologies (Electronic Distance Meter) and may be used with or without a reflecting object: sending a train of impulses to the target and the phase compensation method.

The first method determines the distance by measuring the time needed for the signal to come back to the source. Knowing the light speed through air, the distance to the object can be then determined very easily.

For the second method, the device will send a coaxial beam, modulated in light intensity, which will then be reflected by a prism or another reflecting surface. The distance is then determined using the phase shift between the emitted and the received beam.

The energy used for the first method is greater, which leads to the possibility to measure greater distances (two to three times greater). On the other side, the light beam modulated in intensity leads to greater precisions, especially when using reflecting prisms. Another difference between the two methods is given by the tolerance against interruption of the visual contact to the target. The first technique, using a train of impulses, reacts more robust to such discontinuities compared to the second method, where the phase shifts have to be recalculated. Yet, both of the methods recognize the discontinuities and dismiss the errors, although a time delay is introduced. The measuring time is about 1.5 times higher for the second method (determined mainly by the difference in energy used by the two methods).

One last aspect, which needs to be taken into consideration, is the diameter of the emitted beam. The greater the distance to the desired object is, the more will the beam diverge and the greater the diameter of the beam will be.

3.2. GNSS (Global Navigation Satellite Systems)

GNSS is a generic term used to refer to satellite navigation systems (GPS is the best known such system).

Any type of GNSS sensor may be connected to monitoring systems and with the help of the standardized real time protocol NMEA (developed by the National Marine Electronics Association), the communication can be set up very easily. NMEA is a serial communication protocol based on ASCII characters, which defines how data is transmitted from an emitter to more receivers simultaneously.

GPS (Global Positioning System) is a satellite system used for global navigation. It provides reliable data regarding position, direction and synchronization for all of the users, regardless of weather, time of day and position on or near the earth surface. The GPS is made up of three parts: 24 to 32 satellites which rotate around the earth, four monitoring and control stations on the earth and the GPS receivers of the users.

A GPS receiver calculates its position by precisely determining the moment in time when messages from the satellites are received. Every satellite transmits messages periodically, which contain the following pieces of information:

- Exact time of the moment the message was sent;
- Exact information about its position on the orbit;
- General information regarding the state of the system and rough positions of the other satellites.

Knowing the moment when the message was sent and the moment when the message was received, the time interval needed for the message to reach the receiver can be determined. Hence, the distance to the satellite can be calculated by multiplying the time interval with the speed of light.

Using messages from three satellites and the trilateration method [15], the exact position of the receiver can be determined. We won't insist on the presentation of the method, as it is known by the specialists. We'll just remember that in order to determine the coordinates of a point, which is located at the intersection of three spheres, one has to solve a system of three equations with three unknown variables.

Apparently, it would be enough to use the information from three satellites, but only a small mistake in the time measured, multiplied with the speed of light, would lead to a great error when estimating the position. That's why receivers use messages of four or even more satellites.

The most frequent source of errors for the GPS is the receiver clock. The estimated distances between the receiver and the satellites may be a source of relatively big errors, as we've previously seen. Hence, every receiver would need a very precise clock and as a result a very expensive one. On the other side, receiver providers prefer to produce relatively cheap receivers so that many can afford them. The solution for this dilemma is provided by the way the spheres intersect.

Because of the fact that up to 32 satellites rotate around the earth, there is always visual contact to eight to ten satellites. Now the software may use only four satellites (the best positioned four) or a higher number of satellites. In the second case, there will be more equations than unknown values and there won't be a unique solution for this system of equations. In this case the least squares method or a similar method has to be used. This way, if all of the available satellites are used, the solution obtained is at least as good as the one obtained by using only the four best satellites.

When using GNSS sensors some further aspects regarding disturbances [11] have to be examined (offset of the antenna, signal reflection, signal quality etc.).

The main advantage of this solution is that there is no need of visual contact to the desired point. The disadvantage is that there has to be a different GNSS sensor for every point to be monitored. Another disadvantage of these sensors, when used in geodesic monitoring systems, is the fact that they don't provide the high precisions needed for such systems in order to determine displacements of a few centimeters or even millimeters.

3.3. Tilt Sensors

These are mechanical or electrical devices, which determine the exact tilt against the vertical direction (the direction of the force of gravity). Depending on the properties or aspects of the applications, such sensors may be used in order to determine the changes in angle or even angular speeds [2].

The principles used to build these sensors may be very different: the use of a pendulum, the reflecting or refracting surface of a fluid or electrical sensors in special fluids (capacitive fluids or electrolytes). Mostly, they are used for monitoring and safety issues, especially for industrial robots or other machines, canes etc.

3.4. Distance Measuring Systems

One of the dedicated techniques used in monitoring system is to determine the changes of the dimensions of buildings by using special wires, normally called Invar-wires, which have some remarkable properties. These properties are: the very light variation in length of the wire when the temperature rises (the wire can even contract for some intervals of temperature). Normally these wires are made up of nickel (35-36%) and iron (64-65%).

These Invar-wires are mostly used to monitor tunnels. It is an old-fashioned technique, which can't be used in a fully automated monitoring system, because a human operator will have to manage the measurement. Another disadvantage is the fact that an Invar-wire can only determine relative changes in length, for example the distance between the two walls of a tunnel. On the other side, a tachymeter provides absolute changes of the coordinates and it can be placed in a way that doesn't cause inconveniences for the workers (something that is not possible for an Invar-wire).

3.5. Laser Scanning

Looking through monitoring applications of tunnels, we can find systems which are able to automatically determine the deformations by using data obtained through laser scanning. Such a system is used at the Gotthard tunnel in Switzerland (which has been developed by Fa. Amberg Technologie). Laser scanning is very useful when monitoring objects with very wide surfaces.

The integration of such devices in systems with an automated evaluation of data has been only partially realized.

3.6. Radar-Interferometry

Lately, a new, expensive and very difficult to implement technique has appeared: terrestrial radar-interferometry [13] and sustained by satellites. This technique is based on the overlapping of signals from two or more radio-telescopes. The overlapping may occur electrically, if there is a direct link between the telescopes, or it may occur later on a computer. The overlapped signal is then analyzed with the help of the Fourier transformation and the result is a map of the sighted area. The solution is currently tested by some departments of the ETH Zürich [17] in a common project with different producers. The goal of the study is to determine whether this solution may be used for geodesic monitoring.

3.7. Other Monitoring Principles

There are also different systems of cameras which may be used to determine high-frequency oscillations. As an example, the geodesic institute in Zürich has developed a low-cost system in order to determine the oscillation of bridges. They have used a series of digital cameras or even web-cams and on the bridge there have been mounted a series of LEDs. The movements of the light generated by these LEDs are then analyzed through image processing. This technology has a limited possibility of implementation because of the short distances that may be reached.

4. Conclusions

Using all of the sensors or instruments presented earlier, a multi-sensor monitor-ring system [5], [16] can be set up. In case of every instrument real time corrections have to be implemented, this means there has to be a continuous or persistent calibration of the instruments in order to obtain error-free data from measurements.

Having gathered all of the information needed, we may now formulate the following algorithm used to set up a geodesic monitoring system:

- Detailed analysis of the advantages and disadvantages of instruments used in geodesic monitoring;
- Detailed analysis of the characteristics of the object or of the area which needs to be monitored. The most important criterions which need to be taken into consideration are: the needed precision, measurement frequency (the time interval between two

measurements to the same point), accessibility and visibility of points. The measurement frequency has to become higher, the more devastating the consequences of the exceeding of the tolerance limits would be. These tolerance limits are specified for each point which is monitored;

- Taking the decision about what instruments to use for the monitoring system;
- Realizing the hardware configuration of the system in a laboratory;
- Developing the monitoring software;
- Verifying the static and kinematic precision of the measurements in the laboratory. The most important aspects are the resolution of the measurements and their repeatability;
- Determining the orientation stability of the sensor (especially for tachymeters);
- Determining the stability of the whole hardware and software system (colleting, sending and analyzing data);
- Minimizing the influence of external factors like variations of the supply voltage;
- Installing the monitoring system near to the object or the area which has to be monitored. Starting the monitoring system and observing the results of the realized analyses.

In case of critical applications, where the structural changes of the monitored objects may have disastrous consequences, the monitoring system has to be verified periodically.

When setting up a monitoring system, a stable reference frame needs to be put up, which has to contain one or more stable points situated outside the area where displacements may occur. This reference frame may contain GNSS sensors or just some points aimed by a tachymeter. Further, sometimes one has to mount temperature sensors in order to determine the displacements caused by temperature variations between night and day or even between winter and summer if the monitoring interval is long enough. In case of a long-term project, the temperature sensors may be mounted only in the testing phase and then if there is no correlation between temperature and displacements they may be dismissed.

Geodesic monitoring systems have occupied a central position in the field of geodesic engineering. Using modern measurement methods, the movement of objects can be determined with great precision and in real-time. The systems and structures used may differ substantially from case to case, but the differences are mainly determined by the monitored area or object. Considering these aspects, the right instruments from the list presented above have to be chosen.

Throughout this article we have analyzed the main instruments, we have compared them and shown their advantages and disadvantages.

The degree of automation for these systems is continuously growing, but it hasn’t yet reached its maturity. That’s why for many such systems the evaluation and analysis of the data is still done by experts. The quality of the results depends on two main aspects:

- Type of sensors used and the distance measuring techniques;
- Data evaluation procedure (manual, partially or fully automated).

The greatest challenge for these systems though, is to work through the data obtained and to analyze them. These aspects have to go through an extended process of automation in near future.

Along with this integrated automation, there has to be a continuous developing and improving of the instruments and sensors used, so as to obtain greater precisions for the measurements and consequently for the final results.

Finally, we can conclude that engineering has occupied a central position in geodesic monitoring systems, because the progress in this area is mainly determined by the progress in technology. The only possibility though to make further progress in this area is to try to perform an automatic deformation analysis based on the data obtained through measurements.

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