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FUSION OF GEODETIC AND MEMS SENSORS FOR INTEGRATED MONITORING AND ANALYSIS OF DEFORMATIONS

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Abstract: Automated shape-measuring arrays of micro-machined sensors based on micro-electromechanical systems (MEMS) technology are capable of determination of deformation components with sub-centimetre accuracy over several hundred metres. The fusion of MEMS sensors with automated geodetic monitoring systems supplies the information needed for the determination of the three-dimensional displacement and strain fields and rigid body movements of the deformable object. All of these systems can take advantage of wireless communication methods integrated with internet delivery. A simple fusion of MEMS shape-measuring arrays (ShapeAccelArray- SAA) with GPS, supported by Precise Position Monitor (PPM) software, and robotic total stations supported by Deformation Detection System (DDS) software is shown for a laboratory setup. Concepts for more complex combinations of field equipment and field data are proposed.

1. INTRODUCTION

Growing concerns regarding public safety, environmental protection, and efficient industrial production have dramatically increased the demand for automated deformation monitoring systems. Bridges, dams, nuclear power stations, and open pit mines are examples of applications that benefit from implementing monitoring systems. Such systems are expected to provide multi-dimensional alarms, visualization of results in near-real time, and sub-centimetre accuracies.

The deformation behaviour of any investigated object is fully determined if the three-dimensional strain field and rigid body movements (translation and rotation) can be derived from the monitoring observations (Chrzanowski et al., 1983). Among the available geodetic and geotechnical/structural technologies, there are very few, if any, sensors that can independently satisfy this monitoring criterion. In most cases, various techniques must be combined into an integrated monitoring system (Chrzanowski, 1993; Chrzanowski et al., 1986).

Presented is the fusion of a new geotechnical technology, ShapeAccelArray (SAA) (Measurand Inc., 2008) with robotic total stations (RTS) and global positioning system (GPS) technology supported by software developed at the Canadian Centre for Geodetic Engineering (CCGE). A brief overview of each of the above technologies is given followed by an example of their integration in a laboratory setup.

2. MEMS SENSORS

2.1 Overview of MEMS Technology

Micromachined electromechanical system (MEMS) sensors are used in large quantities by the automotive industry for airbag deployment. Other high-volume applications include pressure sensing, inkjet printing, and angular rate sensing. Most MEMS are created from pure silicon with tiny dimensions (< 1 mm). Pure silicon demonstrates negligible fatigue and hysteresis, and high yield strength, making it superior to steel for sensor construction (Bryzek, 2005).

MEMS accelerometers are made on single-crystal silicon wafers in a semiconductor process line. There are many MEMS to a wafer, leading to a low cost per sensor. Layers of materials including polysilicon, insulators, and others are deposited on the wafer and selectively etched to create micromechanical structures.

A simplified one-axis accelerometer is shown in Figure 1. A proof mass is supported at its ends by “bow” springs and is free to move left and right, having been freed from its substrate as shown in the inset. The mass has “fingers” that move with it, separated by gaps from fixed electrodes. Variations in the gaps are sensed by the electrodes as a change in capacitance. Typically, a MEMS package measuring 1.5 mm x 4 mm x 4 mm will include two or three orthogonal accelerometers, along with circuitry to produce analog or digital outputs corresponding to accelerations. The tiny dimensions and excellent properties of the silicon are ideal for damage resistance and long-term stability.

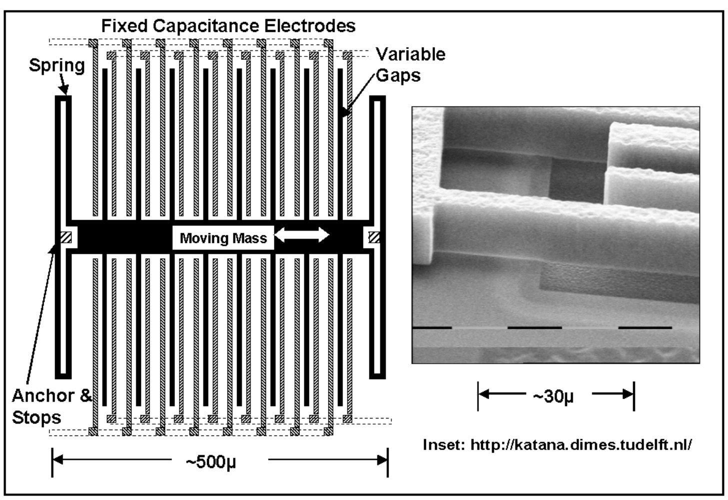

Figure 1 - Left: Simplified plan view of one-axis MEMS accelerometer
Right (DIMES, 2008): Photomicrograph of typical MEMS structure

2.2 Development and Applications of ShapeAccelArray (SAA)

SAA is an array of hundreds of MEMS accelerometers that can be left in a borehole in small (25 mm ID), non-grooved casing, to monitor deformations over long time periods (years) (see Figure 2). Its data are sent wirelessly through the internet (Abdoun et al., 2007). The flexibility of the casing and array enable installations to withstand larger deformations than are possible with conventional grooved casing.

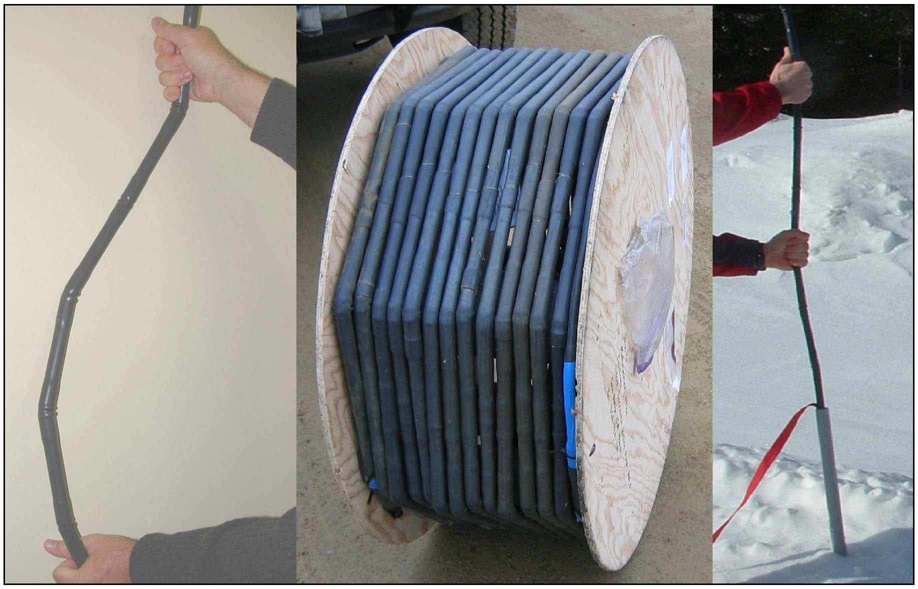

Figure 2 - Left: Flexibility of SAA, Centre: SAA on Reel, Right: SAA Inserted into Conduit

Mechanically, SAA is an array of rigid segments connected by joints that permit bending in any direction, but are stiff in torsion. Standard segment length is 305 mm, which dictates spatial resolution. The hollow segments each contain three orthogonal MEMS accelerometers. Every eighth segment includes a microprocessor. A typical array of 104 segments, 32 m long, can be stored on a reel, ready for insertion. The waterproof coverings have been tested to 980 kPa (equivalent to a 100 m water column).

The 3D shape of SAA in a near-vertical casing is determined from static accelerations of X and Y accelerometers. In near-horizontal mode, the Z accelerometers are used to determine 2D shape in a vertical plane. The accelerometers sense tilt angles according to:

$$Signal = C \times g \times \sin(tilt) \tag{1}$$

where C is a calibration constant and g is the acceleration of gravity. The special joints enable a solution for x, y, and z coordinates at each joint, using rotational transforms relating the orientation of one segment to the next segment (Danisch et al., 2007). The method is an example of 3D shape sensing along paths constrained in degrees of freedom, originally applied using fiber optic curvature sensors (Danisch et al., 1998).

3. ROBOTIC TOTAL STATIONS (RTS)

3.1 Evaluation of RTS Performance

Several models of robotic total stations (surveying instruments with automatic target recognition (ATR) and automated measurements of angles and distances) are available from various manufacturers (e.g., Leica, Trimble, and Topcon). Instrument resolutions of 1 mm in distance and 1 second of arc for angles are available. Robotic total stations use ATR to detect target prisms at distances up to 1500 m. Over distances shorter than a few hundred metres, an RTS can detect displacements with sub-centimetre accuracy at 95% confidence level (Duffy et al., 2002). Over longer distances, the main bias affecting the accuracy of RTS applications is atmospheric refraction. In an analysis of RTS observations made in large open pit mines, Chrzanowski and Wilkins (2005) showed that diurnal cyclic variations due to the refraction of observed directions (both horizontal and vertical) could produce, in extreme conditions, systematic biases of determined displacements of up to 200 mm over distances of 1500 m. Even though averaging 24 hours of observations can decrease refraction errors to a few millimetres, this challenge limits the universality of RTS applications. Since the effects of refraction increase with the square of the distance, it is recommended to place RTSs as close as possible to the observed object. This in turn increases the possibility that the instrument station and reference back sights would be within the deformation zone. To alleviate this problem, GPS can be linked with RTS to provide automated positional corrections (Chrzanowski and Wilkins, 2005).

3.2 Deformation Detection System (DDS) Software Suite

The performance of RTS in deformation monitoring surveys depends, to a large extent, on the quality of the software controlling the automatic data collection and automatic data processing. The software is composed of a series of modules that automate surveying tasks, handle database management, and provide graphical display of results. Processed data are automatically made available in near-real time. There is full support for remote operation via LAN and Internet connections and provider-independent database access. An alarm can be triggered either by individual points or group of points, when their movement reaches a predefined threshold value of either displacement, or velocity, or acceleration. DDS is capable of identifying unstable reference stations using the Iterative Weighted Similarity Transformation (IWST) of displacements (Chen et al. 1990).

4. GLOBAL POSITIONING SYSTEM (GPS)

4.1 GPS for Deformation Monitoring

GPS (and in general, Global Navigation Satellite Systems (GNSS)) offers potential advantages over other geodetic and geotechnical technologies that allows for continuous and high accuracy displacement detection. These include a) line of sight is not required between stations; b) updates can be provided at frequencies of 1 Hz and higher; c) 3 dimensional position information is provided; and d) millimetre level position information is possible for baselines up to about 10 km in length. Certain environments having steep slopes and/or large height differences make it difficult to realize these advantages, by introducing the following challenges (Bond et al., 2007):

a) Mitigation of residual tropospheric delay biases;
b) Providing continuous, high precision updates despite limited satellite visibility; and
c) Connecting to stable reference points.

The major disadvantage of using GPS is the cost of a geodetic grade receiver and antenna. This will ultimately limit the number of units that can be afforded and dictate the spatial resolution of targets that can be monitored using this technology. In most cases it will be more economical to integrate GPS to monitor the stability of other sensors that can provide higher spatial resolution at a lower cost in localized areas (e.g., total stations, laser scanners).

4.2 Precise Position Monitor (PPM)

To address the challenges described previously with implementing GPS in challenging environments, a fully automated, continuous, real-time monitoring system has been developed known as Precise Position Monitor (PPM) software (Bond et al., 2007). The system is capable of providing sub-centimetre precision without having to solve for the integer ambiguity, making it suitable for many deformation monitoring applications. Processing techniques are implemented in PPM to successfully mitigate the effects of residual tropospheric delay biases. PPM also incorporates pseudolite (ground based GPS signal transmitter) technology to provide more frequent solutions in areas of poor satellite visibility.

5. EXPERIMENT DESIGN

5.1 Deformation Monitoring Scenario

To illustrate the benefits of having a multi-sensor, real-time, monitoring system, an application which uses an SAA to monitor vertical displacements is considered. Figure 3 shows a bridge abutment under construction. An SAA (buried) is shown by the red dashed line. The SAA provides mm-level deformation information relative to one of its ends. Since the end may be in the deformation zone, surveying to the end from a stable reference is required. This fusion of line-of-sight geodetic instruments with subsurface instruments is currently done with intermittent manual techniques. This approach would be improved by automated, continuous monitoring, with all data arriving at the same time in the same units and frame of reference. Also illustrated in Figure 3 is an SAA being inserted into 25 mm casing. The same casing and SAA are used in vertical and horizontal installations.

Figure 3 - Left: 2D Deformation Monitoring Near a Bridge Abutment
Right: Installation of an SAA for 3D monitoring

5.2 Fusion of Sensors for Integrated Monitoring

To demonstrate the benefits of fusing geotechnical and geodetic sensors into an integrated monitoring solution, a deformation simulation was carried out as illustrated in Figure 4. The deformation area was instrumented with RTS, GPS and SAA technology. A Measurand SAA (field version), Leica TCRA1100plus total station and 3 NovAtel OEM4 receivers with GPS600 antennas were used for data collection.

The SAA was mounted to a 2”x4”x 5.5” board on top of a concrete pillar. The SAA, operating in horizontal mode, provided vertical displacement information at each of its segments (every 304.8 mm). Three prisms were also mounted to the board to provide horizontal displacement information and to georeference the SAA. The end of the SAA was mounted to a graduated pole which allowed displacements of known vertical magnitude to be introduced. Also connected to the pole were a prism and a GPS antenna.

The RTS was monitored by GPS so that it could be located close to the structure in the deformation zone, minimizing angular and distance measurement errors. The GPS antenna and RTS were attached to a metal plate so that they would move as one entity on top of a translation stage. The translation stage permitted displacements of known horizontal magnitude to be introduced. A reference prism was monitored using GPS, providing a reference orientation for the RTS.

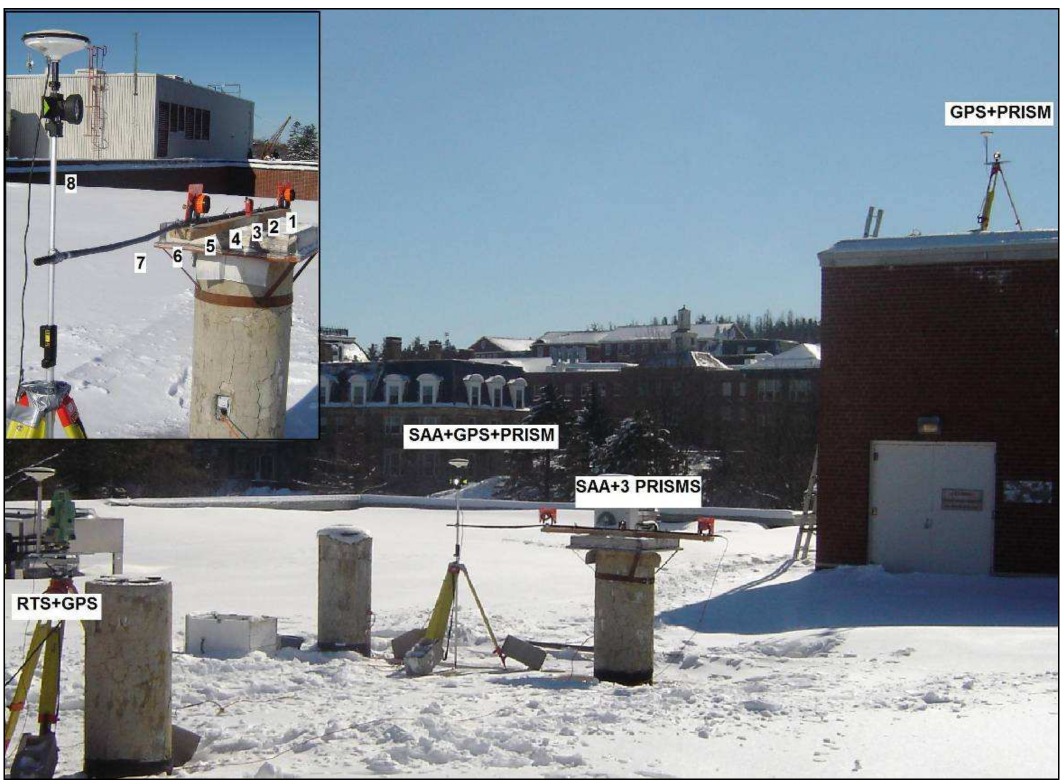

Figure 4 - Integrated Technology Solution for Deformation Monitoring Scenario

Displacements were introduced to illustrate how each technology does not independently capture the entire deformation behaviour, but the integrated system does. Three displacements were introduced:

1. 32 mm horizontal displacement at Point 3 towards Point 4,
2. 6 mm horizontal displacement of the RTS+GPS station, and
3. 20 mm downward displacement of Point 8.

Deformation of eight points of interest and the location of the RTS+GPS station were considered.

6. RESULTS

Table 1 and Table 2 summarize the magnitudes of the respective horizontal and vertical displacements introduced and the magnitudes of the displacements detected by each technology. Comments on the results from each technology are subsequently provided.

Point	1	2	3	4	5	6	7	8	RTS+GPS	RTS+PRISM
SAA	-/0	-/0	-/0	-/0	-/0	-/0	-/0	-/0	-/0	-
RTS	0/0	-/0	32/32	-/0	0/0	-/0	-/0	0/0	8/6	-
GPS	-/0	-/0	-/0	-/0	-/0	-/0	-/0	0/0	6/6	-

Table 1 - Designed Horizontal Displacements and Detected Horizontal Displacements (detected displacement mm / introduced displacement mm, '-' = no information)

Point	1	2	3	4	5	6	7	8	RTS+GPS	RTS+PRISM
SAA	0/0	0/0	0/0	0/0	0/0	5/(5)	12/(12)	19/20	-/0	-
RTS	0/0	-/0	0/0	-/0	0/0	-/0	-/0	20/20	0/0	-
GPS	-/0	-/0	-/0	-/0	-/0	-/0	-/0	19/20	0/0	-

Table 2 - Designed Vertical Displacements and Detected Vertical Displacements (detected displacement mm / introduced displacement mm, '-' no information)

6.1 SAA

Data from the SAA were processed using SAARecorder software. Data were logged for 2 sessions before the 20 mm vertical displacement and for 2 sessions after it. The results are illustrated in Figure 5. It can be seen that SAA performs very well at capturing the deformation behaviour as a continuum. Each of the stable 5 segments shows less than 1 mm of vertical movement. Segments 6, 7 and 8 show progressively more downward displacement. A maximum displacement of -19 mm is illustrated at segment 8. The true values of the displacements at segments 6 and 7 are unknown. The data rate of the SAA was 100 Hz, enabling an alarm latency of 10 seconds from any of the eight segments, based on automated averaging of 1000 samples. Because the SAA is functioning in horizontal mode, it will not detect lateral movements.

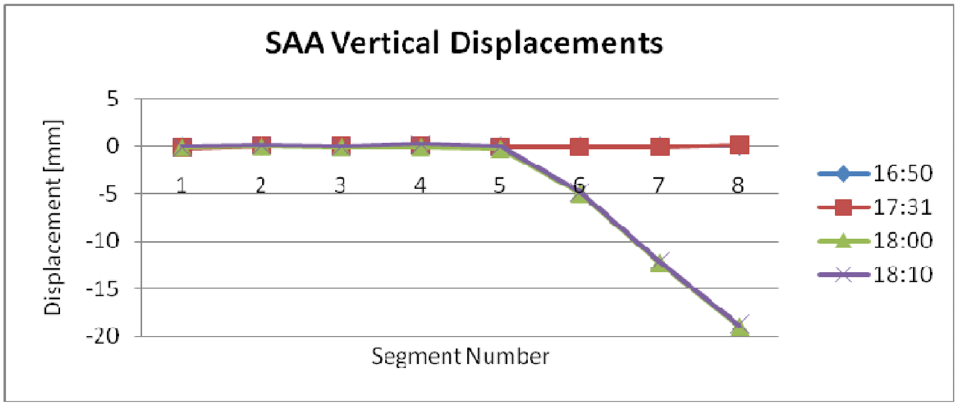

Figure 5 - SAA Vertical Displacements

6.2 RTS

Positions of the target prisms were calculated from the RTS observations using DDS. All displacements of target prisms were detected at mm level in the experiment. The power of the IWST implemented in the DDS is illustrated by the software's ability to detect the movement of the RTS. Displacements of -7.5 mm, 3.4 mm, 0.7 mm were calculated in east, north and up components respectively (8.2 mm horizontal length), which agrees within 2 mm with the known value. The accuracy of the IWST would further improve if more stable reference points were used. Had the software not implemented the IWST, all coordinate calculations would be biased by the full displacement value, unless the position of the RTS would be updated by GPS. The RTS was not able to capture the displacement of points 6 and 7 and the stability of points 2 and 4 since prisms were not located in this area.

6.3 GPS

Baselines from the reference GPS+PRISM station to the RTS+GPS and SAA+GPS+PRISM (Point 8) stations were processed using PPM. Spatial resolution was limited (by available hardware) to these two stations. Displacements of the RTS+GPS station and of Point 8 were detected at mm level. Figure 6 illustrates the 'up' component solutions for Point 8. Several hours are required to detect the full displacement.

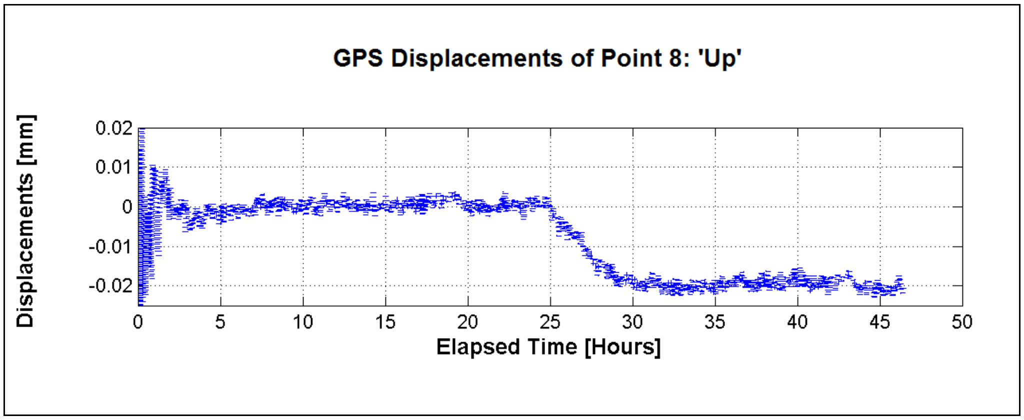

Figure 6 - Up Component Displacement of Point 8 from PPM

7. CONCLUSION

One technology can rarely provide all of the information necessary to fully understand the behaviour of a deformable body. In the bridge abutment scenario considered, one technology could not detect all of the deformation behaviour introduced. By strategically using each sensor, the global deformation behaviour was captured. SAA was able to provide real-time, mm level resolution of the vertical displacements of its segments along a continuum. RTS observations were added to provide absolute referencing of the SAA and to provide lateral displacement information as well. The stability of the RTS was monitored using GPS (this becomes even more important in projects of larger scale). GPS provided high precision, position information of critical deformation areas. SAA and RTS provided cost effective means for densifying the GPS monitoring stations and for providing quick displacement detection. The experiment was simple, but suggests the advantages of sensor fusion, particularly if all the sensors were to produce an integrated data stream. This data integration will be the subject of future work.

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References

Abdoun, T., V. Bennett, L. Danisch, T. Shantz and D. Jang, (2007). "Field installation details of a wireless shape-acceleration array system for geotechnical applications." Proceedings of *SPIE*, San Diego, CA, March 19-22, Volume 6529.

Bond, J., D. Kim and A. Chrzanowski (2007). " Development of a Fully Automatd, GPS Based Monitoring System for Emergency Preparedness and Disaster Prevention: PPMS+RT" *Sensors* 2007, *7*, 1028-1046, 28 June. http://www.mdpi.org/sensors/papers/s7071028.pdf

Bryzek, J. (2005). "Principles of MEMS." Chapter 162 in *Handbook of Measuring System Design*, John Wiley & Sons, Ltd. Available at: http://eu.wiley.com/legacy/wileychi/hbmsd/pdfs/mm573.pdf, Published: 15 July. DOI: 10.1002/0471497398.mm573.

Chen, Y.Q., A. Chrzanowski, and J.M. Secord (1990). "A strategy for the analysis of the stability of reference points in deformation surveys". *CISM Journal*, Vol.44, No.2, Summer, pp.39-46.

Chrzanowski, A. and R. Wilkins (2005) "Continuous monitoring of deformations in open pit mines- problems and solutions" *Schriftenreihe des Institutes für Markscheidewesen*, T.U. of Mining, Freiberg, Heft 2005-1, pp. 17-31.

Chrzanowski,A. (1993):"Modern Surveying Techniques for Mining and Civil Engineering" Chapter 33 in: *Comprehensive Rock Engineering,* Pergamon Press,Vol.3.Chapter 33, pp.773-809.

Chrzanowski, A., Y.Q. Chen, P. Romero, J.M. Secord (1986). "Integration of geodetic and geotechnical deformation surveys in the geosciences." *Tectonophysics* 130 (1986), pp. 369-383.

Chrzanowski, A., Y.Q. Chen and J. Secord (1983). "On the strain analysis of tectonic movements using fault crossing geodetic surveys." *Tectonophysics,* Vol. 97, pp. 297-315.

Danisch, L.A., T. Abdoun, and M. Lowery-Simpson, (2007). *Shape-Acceleration Measurement Device and Method,* US Patent 7,296,363.

Danisch, L.A., Englehart, K., and Trivett, T. (1998). "Spatially continuous six degree of freedom position and orientation sensor", Fiber Optic and Laser Sensors and Applications, SPIE Conf. 3541A, Boston, MA.

DIMES, 2008. "DIMES". *Delft University of Technology, Delft Institute of Microelectronics and Submicrontechnology*, http://katana.dimes.tudelft.nl/, accessed on: 11 March.

Duffy, M., C. Whitaker, A. Chrzanowski, J. Lutes (2002). Interpretation of first results from the automated and integrated monirtoring scheme at Diamond Valley Lake in California. *Proceedings* of the 22nd FIG Congress, Washington, D.C., 19-26, April. CD-ROM.

Measurand Inc., 2008. *Geotechnical Products*: http://www.MeasurandGeotechnical.com, accessed on: 12 March.

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