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SHORT COMMUNICATION

USE OF LOW-COST MEMS TECHNOLOGY IN EARLY WARNING SYSTEM AGAINST LANDSLIDE THREATS

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ABSTRACT

Modern methods of monitoring landslides are based on observations of both: direct surveying (GNSS, electronic tachymetry, geometric levelling) and remote sensing (terrestrial and aerial photogrammetry, laser scanning, interferometry), as well as surface and subsurface geotechnical observations (e.g. inclinometers, extensometers, piezometers, etc.). Due to the high cost of installation of these devices and its measurement, the implementations of these methods are usually used on well-defined objects, with established landslide activity and high risk to people's lives.

The main objective of the project was to design, create and do practical tests of simple and inexpensive measurement devices, which detect first symptoms of a potential landslide movements and alert of an existing threat. These devices would be some kind of an early warning system that would register the occurrence of the first movements of the surface layers of soil, which would be a signal to start of geodetic and geotechnical monitoring of potential landslides.

KEYWORDS: monitoring, landslide, accelerometer, early warning system, MEMS

INTRODUCTION

In 2006, the Polish Geological Institute - National Research Institute, under a contract with the Minister of the Environment, started the implementation of a long-term project, Landslide Counteracting System (SOPO). The primary object is to recognize, document and mark on the existing maps in the scale of 1 : 10 000 all landslides and areas potentially affected by mass movements in Poland. The secondary aim is to create a subsurface and surface monitoring system for 100 selected landslides (www.pgi.gov.pl). In Poland in 2010 the estimated number of landslides was about 50000.

A key feature of the proposed surveillance system is monitoring the causal parameters of slope instability (Nescieruk, 2007; http://geoportal.pgi.gov.pl). The implementation of the research task to understand landslides, require:

- obtain data of physical and mechanical parameters of tracks within the landslide; the data should include strength parameters for determining slopes stability,
- determine the exact colluvium thickness,
- locate the course of active slip surface,
- determine the hydrogeological conditions within the landslide,
- determine the level of dynamic surface displacements on the basis of geodetic monitoring of surface,
- determine the level of dynamic deep-seated movements on the basis of subsurface monitoring (Migoń, 2009; Neserciuk et al., 2007).

Monitoring such objects should employ methods for surface and downhole measurements (Toś et al., 2006; Wolski, 2006). Monitoring surface methods include classic and GNSS survey, remote sensing (satellite images, photogrammetric, ground SAR/ InSAR, terrestrial laser scanning, airborne laser scanning), physical methods (extensometers, strain gauges, feelers), and methods of measurement of meteorological conditions (moisture, thermometers, pressure gauges, hygrometers, sensors of snow cover). Methods for monitoring deep-seated movement are: inclinometers, wire TDR sensors, 3Dmems (Abdoun et al., 2005), piezometer, pore pressure sensors, Electrical Resistivity Tomography and Ground Penetrating Radar. Additionally, it is necessary to perform geotechnical drilling to analyse the landslide soil (Bednarczyk, 2007). All these methods examine only a part of the processes occurring in landslide (Ćmielewski, 2012) and are not cheap.

The authors propose the use of low-cost MEMS (Micro Electro-Mechanical Systems) accelerometers to create the early warning systems against threats which allow authorities or the person responsible for crisis management to make a decision at the stage of a possible threat.

CONCEPTION OF AN EARLY WARNING SYSTEM

Objects such as a landslides as a result of the impact of multiple and time-varying physical and environmental processes undergo deformation, the size of which is the main criterion of safety. These objects are monitored in order to obtain information about their conditions and geometric phenomena and processes that affect their safety. An important role for information on sizes, displacements and deformations are datasets in measurement periods. The study of movements can be carried out using various techniques and methods of which the most important are: special geodesic network: photogrammetric measurements, satellite measurement, relative measurements using feeler gauges, extensometer and inclinometer observations.

The present measurement set is, as an alternative to the inclinometer probe consisting of a set of sensors (MEMS), which are connected pivotally and permanently mounted in a tube. This allows the replacement of inclinometer probes and mount, as shown schematically in Figure 1.

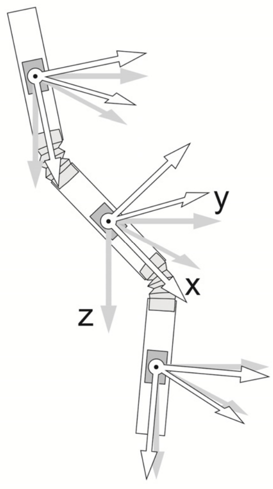

Fig. 1 Distribution of MEMS in the measuring profiles (Ćmielewski et al., 2011).

The tube deflects with the ground. Raw measurements from different levels are stored in a database which is made pre-analysis, signal processing and classification to the object is conducted according to a fixed algorithm on the server (Figure 2).

Processed values are used in a process of monitoring phenomena, in the case of exceeding the alarm thresholds, alerts are sent (SMS, email).

MEASURING DEVICES

The accelerometer can measure linear or angular acceleration. Today's accelerometers are manufactured in MEMS technology, they are closed in single hermetically sealed boxes. Inside box there is a measuring acceleration chamber and often DSP (Digital Signal Processor) too. The most common mounting type is surface (QFN - quad-flat no-leads) and accelerometer dimensions are in the range of 4x4x2 mm. To operate a microcontroller, a transitting module and often ADC (Analog-to-Digital Convverter) are necessary.

The measuring chamber is a structure in which, a semiconductor material (polycrystalline silicon) sets of beams (both fixed and movable) is formed by masking end etching technology. Any movement of the measuring chamber will result in movable beam deflection value which will correspond with acceleration (Figure 3).

The principle of operation of capacitive accelerometers is presented in Figure 4, due to proof mass moving between sensing plates the capacitive is changing.

The change of the capacitive in X, Y, Z axis transducer is converted to voltage, then goes to amplifiers and low pass filters. That signal is changed to digital form by analog-to-digital converter (Figure 5).

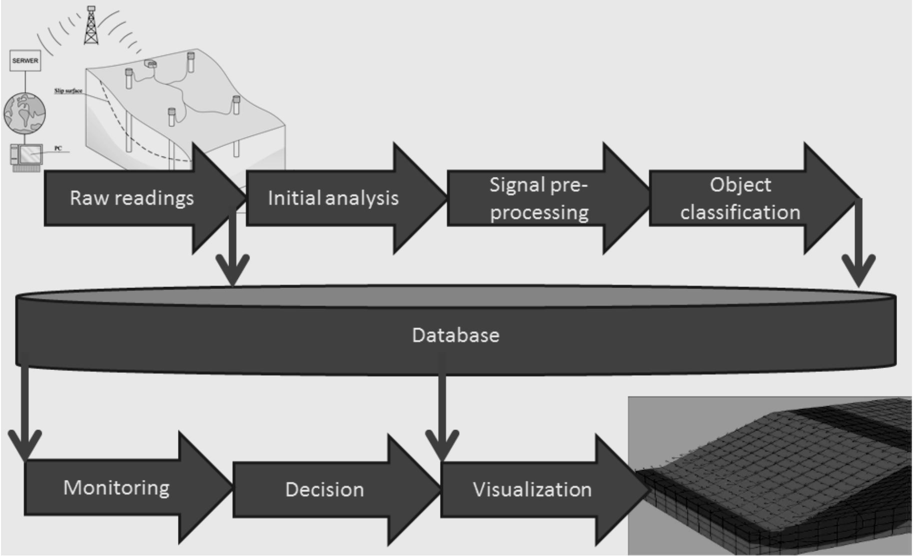

Fig. 2 Simplified scheme of information processing.

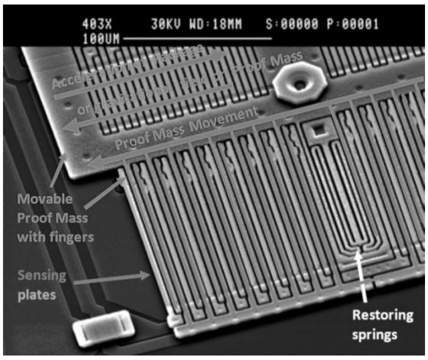

Fig. 3 Electron microscope image of MEMS accelerometer proof mass and principle of operation (Salhuana, 2012).

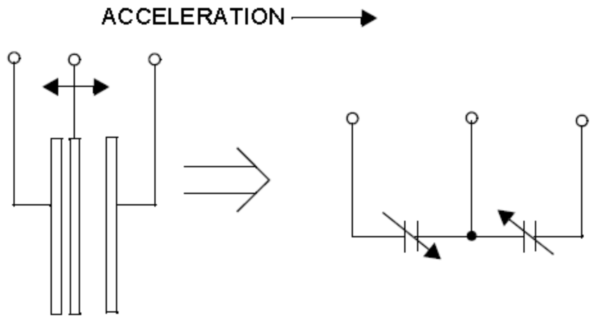

Fig. 4 Principles of a capacitive accelerometer (Freescale Semiconductor, 2009).

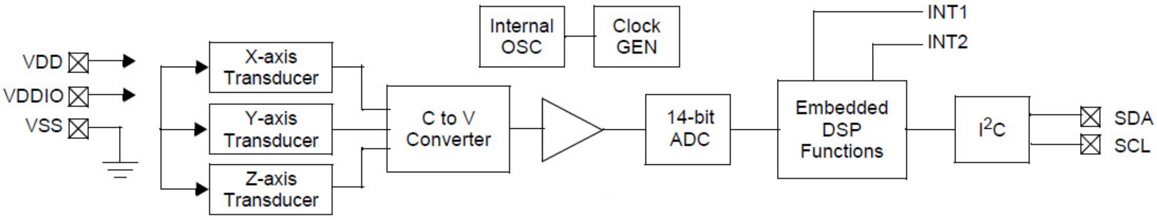

Fig. 5 Operating scheme of digital accelerometer (Freescale Semiconductor, 2012).

The gravitational field vector Gp measured by the device accelerometer is determined by applying roll, pitch and yaw rotation matrices to the downwards pointing gravity vector of magnitude 1 g:

$$G_p\begin{pmatrix} G_{px} \\ G_{py} \\ G_{pz} \end{pmatrix} = R_x(f)R_y(\rho)R_z(Y)\begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} = R\begin{pmatrix} -\sin\rho \\ \cos\rho\sin f \\ \cos\rho\cos f \end{pmatrix} \tag{1}$$

where:

G_p - the measuring unit accelerometer output (measured in the native accelerometer units of g),

R - rotation matrix (shows how the accelerometer output depends on the unit orientation in the earth's gravitational field g).

The accelerometer affects the gravitational field of Earth. Using this assumption, we can calculate the different angles of inclination: ρ - pitch (2), ϕ - roll (3) and θ - deviation from the vertical line (4) (Fig. 6).

The equations to calculate this angels are:

$$\rho = \arctan\left(\frac{-G_{px}}{\sqrt{G_{pz}^{\ 2} + G_{py}^{\ 2}}}\right) \tag{2}$$

$$\phi = \arctan\left(\frac{G_{py}}{\sqrt{G_{pz}^{\ 2} + G_{px}^{\ 2}}}\right) \tag{3}$$

$$\theta = \arctan\left(\frac{\sqrt{G_{px}^{\ 2} + G_{py}^{\ 2}}}{G_{pz}}\right) \tag{4}$$

where:

G_{px}, G_{py}, G_{pz} – raw values from accelerometers.

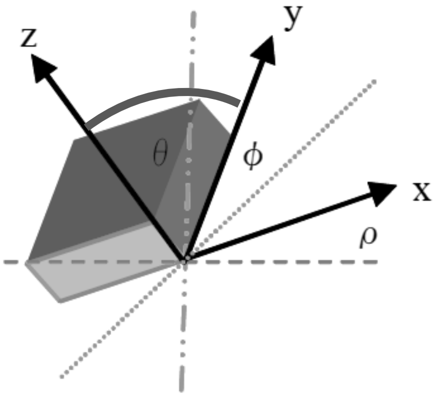

Fig. 6 Graphical visualization of obtained angles.

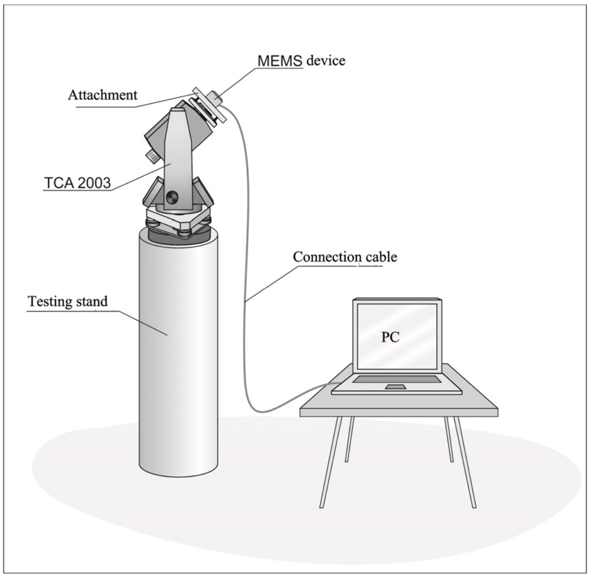

Fig. 7 Experimental stand (Ćmielewski et al., 2011).

The first test was to check stability of readings, so the prototype was operating 24h for 120 days. After 4 months, the device was left in more or less invariant environmental conditions. This allowed to calculate stability of readings at the level of ±9 $^{\mathrm{mgon}}$. (Fig. 8)

The second test was to check repeatability. The total station was setup vertical wheel vertically, and for 1000 times, had been tilted from one side to the other at an angle of $\pm25^{\mathrm{gon}}$, paused for readings in the vertical position, and then moved again. The test was performed in X and Y axis. The result are presented in Table 1.

The last test was to check accuracy. In slow motion of total station vertical wheel (duration 2 months, in range $\pm1^{\mathrm{gon}}$, changes $0.0010^{\mathrm{gon}}/1.5\mathrm{h}$), the obtained raw readings are presented in Figure 9.

On charts we can observe an in exactitude which is due to readings without calibration. The manufactures of devices suggest a few ways. One of which is 15 parameter calibration (- model including a cubic nonlinearity).

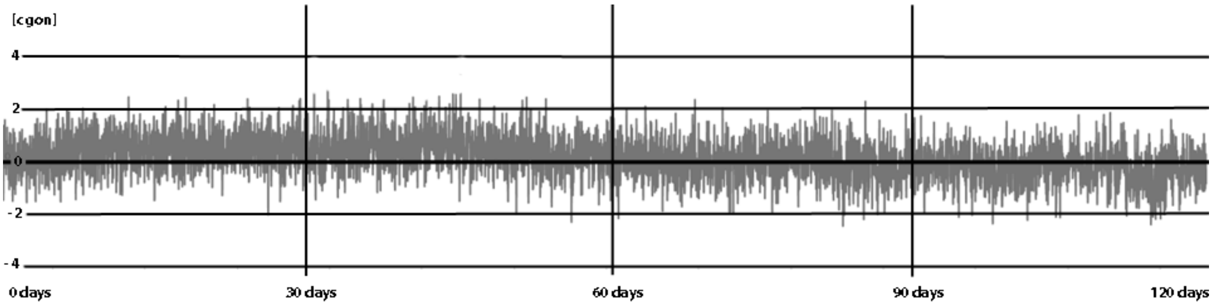

Fig. 8 Stability of readings.

Table 1 Repeatability test readings obtained.

	-25.0000 [$^{\mathrm{gon}}$]		0.0000 [$^{\mathrm{gon}}$]		+25.0000 [$^{\mathrm{gon}}$]	
Series of n = 1000	Angle X axis [$^{\mathrm{gon}}$]	Angle Y axis [$^{\mathrm{gon}}$]	Angle X axis [$^{\mathrm{gon}}$]	Angle Y axis [$^{\mathrm{gon}}$]	Angle X axis [$^{\mathrm{gon}}$]	Angle Y axis [$^{\mathrm{gon}}$]
Minimum	-24.9975	-24.9988	-0.0032	-0.0051	24.9962	24.9941
Maximum	-25.0053	-25.0084	0.0045	0.0017	25.0026	25.0018
Average	-25.0014	-25.0036	0.0007	-0.0017	24.9994	24.9980
(Max-Min)	-0.0078	-0.0096	0.0077	0.0068	0.0064	0.0077
Standard deviation	0.0045	0.0053	0.0038	0.0044	0.0036	0.0041

TEST OBSERVATIONS AND CALIBRATION

An experiment was performed in laboratory conditions on a stand (shown in Figure 7). A computer was connected to a motorized tachymeter and measuring device prototype. To do these tests it was necessary to develop an application to move the tachymeter's vertical wheel. On the test bench a Leica TCA 2003 with horizontal and vertical angle accuracy 0.15 $^{\mathrm{mgon}}$ was used.

There tests were performed, to check: stability, repeatability and accuracy.

$$G_{15} = W\,G_f + V + G\,G_f^{\,2} = \begin{pmatrix} W_{xx} & W_{xy} & W_{xz} \\ W_{yx} & W_{yy} & W_{yz} \\ W_{zx} & W_{zy} & W_{zz} \end{pmatrix} \begin{pmatrix} G_{fx} \\ G_{fy} \\ G_{fz} \end{pmatrix} + \begin{pmatrix} V_x \\ V_y \\ V_z \end{pmatrix} + \begin{pmatrix} G_{xx} & 0 & 0 \\ 0 & G_{yy} & 0 \\ 0 & 0 & G_{zz} \end{pmatrix} \begin{pmatrix} G_{fx}^{\,2} \\ G_{fy}^{\,2} \\ G_{fz}^{\,2} \end{pmatrix} \tag{5}$$

An example of the optimal least squares solution vectors for one axis:

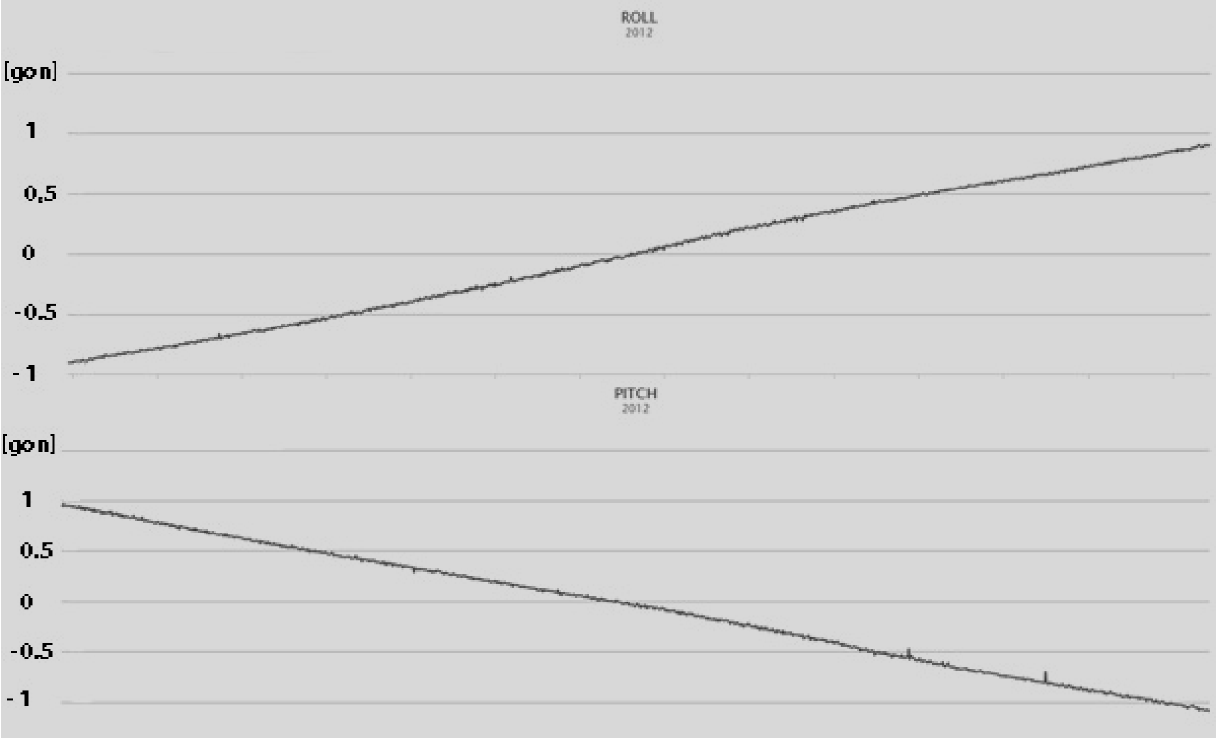

Fig. 9 Graphical interpretation of calculated angles: roll and pitch from raw readings.

Table 2 Suggested angles to calibration devices.

Orientation position	ρ [gon]	ϕ [gon]
1	-39	-50
2	-81	179
3	6	19
4	-18	93
5	18	-107
6	-6	-181
7	81	-20
8	39	150

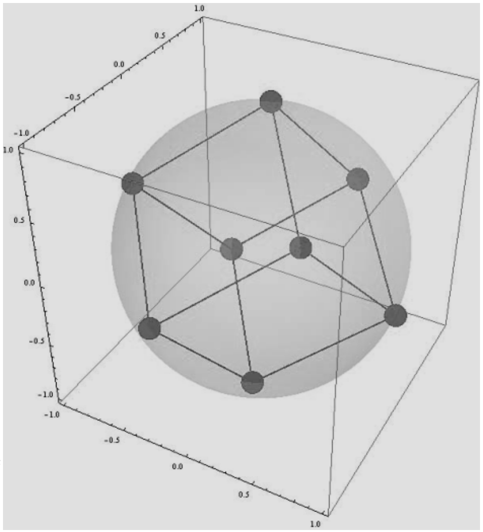

Fig. 10 Graphical representation of distribution on sphere a calibration angles (Pedley, 2013).

$$\beta_x = \begin{pmatrix} W_{xx} \\ W_{xy} \\ W_{xz} \\ V_x \\ G_{xx} \end{pmatrix} = \left(X_x{}^T X_x \right)^{-1} \left(X_x{}^T Y_x \right) \qquad (6)$$

To perform this calibration it is necessity to set devices in 8 positions. In Table 2 there are suggested angles of pitch and roll of the device to use in the calibration procedure.

Graphical representation of distributions on sphere is shown in Figure 10.

Up to this point, it has been assumed that the accelerometer will be used at the same temperature. However, the recalibration should be performed at the two or more different temperatures. In probable operating temperature, extreme minus and plus e.g. -20 °C and 35 °C. One way for the interpolation to an arbitrary temperature T is to use a quadratic curve fitted in to calibration points.

As an example the single parameter Wxx, its temperature dependence would be modelled by values α, β and γ as (Pedley, 2013):

$$W_{xx}(T_i) = \alpha + \beta T_i + \gamma T_i^2 \qquad (7)$$

The previously observed inaccuracies are eliminated as a result of the performed calibration. The achieved accuracy is presented in Table 3.

Table 3 Accuracy after calibration.

TCA2003 [gon]	Roll [gon]	Roll - TCA2003 [gon]	Pitch [gon]	Pitch - TCA2003 [gon]
1.0000	1.0071	0.0071	1.0121	0.0121
0.9000	0.8949	-0.0051	0.9022	0.0022
0.8000	0.7895	-0.0105	0.7964	-0.0036
0.7000	0.6749	-0.0251	0.6805	-0.0195
0.6000	0.5727	-0.0273	0.5795	-0.0205
0.5000	0.4734	-0.0266	0.4794	-0.0206
0.4000	0.3846	-0.0154	0.3897	-0.0103
0.3000	0.2819	-0.0181	0.2875	-0.0125
0.2000	0.1859	-0.0141	0.1933	-0.0067
0.1000	0.0971	-0.0029	0.1018	0.0018
0.0800	0.0710	-0.0090	0.0755	-0.0045
0.0600	0.0566	-0.0034	0.0639	0.0039
0.0400	0.0383	-0.0017	0.0456	0.0056
0.0300	0.0303	0.0003	0.0353	0.0053
0.0200	0.0187	-0.0013	0.0225	0.0025
0.0100	0.0106	0.0006	0.0156	0.0056
0.0000	-0.0001	-0.0001	0.0043	0.0043
-0.0100	-0.0091	0.0009	-0.0022	0.0078
-0.0200	-0.0185	0.0015	-0.0125	0.0075
-0.0300	-0.0280	0.0020	-0.0228	0.0072
-0.0400	-0.0374	0.0026	-0.0303	0.0097
-0.0600	-0.0468	0.0132	-0.0432	0.0168
-0.0800	-0.0676	0.0124	-0.0668	0.0132
-0.1000	-0.0877	0.0123	-0.0875	0.0125
-0.2000	-0.1939	0.0061	-0.1945	0.0055
-0.3000	-0.2937	0.0063	-0.3129	-0.0129
-0.4000	-0.4094	-0.0094	-0.4078	-0.0078
-0.5000	-0.4980	0.0020	-0.4989	0.0011
-0.6000	-0.6122	-0.0122	-0.6133	-0.0133
-0.7000	-0.7122	-0.0122	-0.7091	-0.0091
-0.8000	-0.8108	-0.0108	-0.7993	0.0007
-0.9000	-0.9053	-0.0053	-0.8943	0.0057
-1.0000	-1.0078	-0.0078	-0.9759	0.0241
	STD. DEV	0.0106	STD. DEV	0.0110

DISCUSSION AND CONCLUSION

After the accelerometer is soldered onto its circuit board as a result of thermal stresses during the soldering process, it is necessary to make a new calibration. Fifteen parameters calibration allows satisfactory results. It should also take into account the changes caused by temperature. Therefore it is recommended to make the entire calibration process at different temperatures.

Components used in the prototype obtain the following results:

- - stability of readings 9 ^{mgon},
- - repeatability of readings better then 10^{mgon},
- - accuracy 0.3 mm/m.
- - operating temperature -40 °C to 85 °C
- - cost of device is less than 20€/m and most depend of a cost of communication module (CAN, RS485 or similar) and electrical protection.

This device in the authors opinion should be an additional technique supporting the monitoring of classic observation. Low cost should allow use on a higher number of areas with landslide.

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