Environmental Engineering and Management Journal January 2018, Vol.17, No. 1, 209-216
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu

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LANDSLIDE SURVEILLANCE USING A WIRELESS MEASUREMENT GRID

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Abstract

This paper presents a wireless landslide measurement grid based on new type of transducers. Magnetic strain gauges are used as sensitive element for the transducer. Measurements regarding landslide displacement and orientation were done using strain gauges based on amorphous magnetic microwires (MAW). In order to identify small changes in the monitoring area, a grid of multiple measurement points is placed. Measurement nodes acquire modulus and direction of displacement vector reporting the data through serial communication to the central unit coordinator. A complex system that collects data from multiple locations is developed. Data is collected wirelessly by a central server. Evaluating the landslide acquired information, we have established a relationship between the system readings and the landslide movement.

Keywords: amorphous magnetic microwires, landslide displacement, strain sensor, wireless sensor network

Received: December, 2013; Revised final: July, 2014; Accepted: July, 2014; Published in final edited form: January 2018

1. Introduction

Some of existing technologies for monitoring landslide phenomenon use: radar satellite interferometry (Antonello et al., 2004; Farina et al., 2007; Singhroy and Molch, 2004; Tarchi et al., 2003; Zhou et al., 2009), laser scanning (Corsini et al., 2007) or high resolution imaging via satellites (Nichol et al., 2006). Another used technique is based on GPS - Global Positioning System (Gili et al., 2000), optical fiber configurations (Higuchi et al., 2005) or theoretical modeling of the terrain (Martinez-Grana et al., 2016). The main disadvantage of the mentioned systems is that most of them use physical connections (cables) between sensors (Rosi et al., 2011).

Usually landslides cover wide surface areas, making the task of their monitoring very difficult (Maftei et al., 2012), in terms of equipment employed and data transmissions. Heavy rainfall can produce landslide reactivation or acceleration in a short period.

Preventing human losses and decreasing the economic impact caused by a natural hazard such as a landslide are two important aspects that reinforce the utility of a real time landslide monitoring and alerting system. Important data sources as rainfall, pore water pressure or landslide displacement can be used to analyze the dinamics of a landslide (Mora et al., 2003), and to identify triggering factors that could produce a landslide (Arghiuș et al., 2011; Lazăr et al., 2012).

Due to some important advantages like the mobility of the devices within the environment, the flexibility to add or to remove a device to/from the system without any disruption, cost saving, etc., the use of wireless communication technologies has become an important tool of modern life (Postolache et al., 2012). Wireless networks are also used because of their enhanced security with role-based access and encrypted transmissions, significant reduction in data retrieval time (Donciu et al., 2015) and efficient network management (Bădescu et al., 2011). If we consider some spatially distributed autonomous

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sensors to monitor physical or environmental conditions and to cooperatively pass their data through a network to a main location, then we discuss about a wireless sensor network (WSN).

This paper presents a landslide measurement grid capable of measuring the displacement vector (modulus and direction) of landslide movements. The system measures displacements using transducers based on strain gauges (Fosalau et al., 2013) mounted on multiple measurement points along a rod placed within a borehole.

2. Landslide triggering mechanisms

The primary causes and triggers that are involved in the initiation process of landslide movements can be explained in terms of variations in stress conditions at a point in the slope and critical changes in failure conditions. In this section we describe the factors that act as triggering mechanisms from the perspective of soil dynamics.

Usually landslides are triggered by a complex combination of influencing factors. The first major triggering factor we discuss about is the rise in groundwater level leading to a critical pore water pressure value. When pore water pressure acting on a sliding surface increases due to various causes, the stress state shifts toward the critical point at the failure envelope, thus enhancing the probability of landslide activation. Among possible causes of increasing pore water pressure one can mention: infiltration from the surface layer, exfiltration from bedrock, preferential water flow and convergent flow. These factors cause local accretion of groundwater levels with a major impact on landslide dynamics.

Another important cause is represented by changes in slope inclination that act as possible triggering mechanisms for landslides. These changes can be initiated by human activities, such as cutting into hill slopes and overloading steep or potentially unstable hillside areas with heavy constructions. The erosion process at the toe of hill slopes through natural or anthropic courses also creates favorable conditions for slope failure. When slope inclination increases due to changes in landforms, the stress state approaches the failure limit and the safety factor decreases. The critical point is met when the stress state reaches the failure envelope, thus causing a landslide to occur.

Increases in slope inclination can be the single triggering mechanism producing a landslide but are usually accompanied by variations in pore water pressure.

A third important triggering mechanism is represented by the static weight exerted on the slope. Increase in static weight values that exert pressure on slope can be produced mainly by two factors, which are overloading the slope during construction works and heavy rainfall events that add additional weight to an unstable slope area. When the weight of a soil mass increases, the stress state approaches failure limit, resulting in the decline of the safety factor. Similarly to the case of slope inclination, other factors often accompany increases in static weight of soil to trigger hazardous landslides. Increases in soil weight during extended rainfall periods have been mentioned as a cause of landslides activation in areas that contain earth layers with high pore volumes (Chigira and Yokoyama, 2005). Among important factors that have direct consequences over landslide dynamics, the vegetation must be mentioned. Strong vegetation growing in area that presents landslide threat has positive impact by strengthening the resistance of soil layers. Positive effects of vegetation on the strength of soil are typically considered as support provided by root systems of trees, acknowledged as an increase in soil cohesion.

Because slope movement is a phenomenon that occurs in a gravitational field, the steeper the slope, the larger the shear stress and the more susceptible the slope is to failure. The planar geometry of the hill slope is another important factor affecting slope stability. Landslide initiation during rainfall is affected by the three-dimensional concentration and diffusion characteristics of the landform related to subsurface water. Recent scientific investigations regarding slope stability (Chigira and Yokoyama, 2005; Gomi et al., 2004; Roberts et al., 2004) have confirmed the higher susceptibility to failure of concave-shaped slopes that concentrate subsurface water compared to convex slopes that dissipate subsurface water. Another confirmed fact is that convex-shaped slopes placed near abrupt ridges are more disposed to sliding and collapsing movements during intense seismic activity (Keefer, 1984a, 2002). Considering the complex cumulus of these landslides triggering factors a precise, sensitive and permanent monitoring system must be put into action in order to obtain information that could be used to assess in real-time the risk of landslide activation. Such a monitoring solution is represented by our system that is able to precisely measure in real-time with high sensitivity data referring to landslide displacement vector, as we will describe in the following sections.

3. Grid construction

We propose a landslide surveillance system composed of multiple measurement nodes spread across the target area in a grid configuration, as described in Fig. 1a. Due to the numerous influencing factors that act on the dynamics of landslides, the areas prone to activation present a technical challenge in terms of measurement and monitoring technologies. Taking into consideration these facts we have developed our concept as a grid based measurement system that uses multiple measurement nodes to acquire landslide activity data. Each grid node manages a series of measurement points (Fig. 1b) mounted on a sensing pole that measure landslide activity at specific depths for a complete characterization. The measurement points are fixed on the sensing pole at depths determined by geological studies that analyze the structure of earth layers in targeted areas prone to landslide. A measurement node has in its structure a flexible pole on which multiple measurement points are mounted. Landslide displacement causes the deformation of the pole which is sensed by our system as a variation of electric potential.

The measurement nodes that survey landslide movements are managed by a central unit coordinator that sends commands to the measurement grid in order to assess the land movements. Measurement points are composed of a microcontroller, an analog signal processing circuit and a measurement bridge. Measurement nodes activities are coordinated via a wireless link by a central server. The structure of a measurement point is presented in Fig. 2a, while the component connections are shown in Fig. 2b (Fosalau et al., 2013). A measurement point is composed of the following electronic circuits: power supply, signal generator, peak detector, microcontroller and a RS-485 transceiver. Landslide movements are sensed using strain gauges mounted in a bridge configuration. Four strain gauges annotated Z_1, Z_2, Z_3, Z_4 as specified in Fig. 1 are mounted in a bridge configuration to compose the sensing element. The four strain gauges are placed on the sensing rod 90 degrees apart each other.

These four strain gauges are utilized to measure the deformation of the sensing rod caused by landslide activity. We have used strain gauges having as sensitive element an amorphous magnetic micro wire (MAW) of 20 mm in the as-cast form of 101 µm diameter, with composition $(Co_{0.94}Fe_{0.06})_{72.5}Si_{12.5}B_{15}$ (Dias Pereira et al., 2009). The amorphous magnetic micro wires are bonded on pads and stiffened with cyanoacrylate glue on a polyamide substrate to create the strain gauge. Four strain gauges forming a measurement point are bonded onto the surface of the rod whose deformation is to be measured. Landslide displacement causes the deformation of the sensing rod. Exposed to mechanical actions, the strain gauges modify their impedance according to the giant magnetoimpedance effect, unbalancing the measurement bridge (Petrisor et al., 2013). The measurement bridge is supplied with a 5 mA ac current of 1 MHz frequency, provided by a microcontroller digital-to-analog convertor. These parameters assure the maximum operating range of the gauge of ± 200 ppm. The characteristic impedance of the gauge in relaxed state has a value of 21 Ω. The deformations of this transducer, caused by the landslide displacement, are measured along the rod by measurement points. The measurement pole has a length of 3000 mm and a diameter of 32 mm. Three measurement points are mounted on the sensing pole 700mm apart each other. This configuration of the measurement points permits landslide displacement measurements in range of 1 mm to 200 mm with a sensitivity of 1 mm.

Strain gauge impedance variations are sensed by measuring the variation of electric potentials in the points A and B of the bridge, as shown in Fig. 2b. The collected analogue signal is pre-processed first. An amplification block followed by a peak-detector is applied on the signal before the Delta-Sigma Analog to Digital conversion operation (ΔΣ ADC). Improvements of the measurement performance are achieved because this conversion type implements oversampling, decimation filtering and quantization noise shaping for high resolution and excellent antialiasing filtering. Specific computation algorithms are applied on Central Processing Unit (CPU) after which data is send to Universal Asynchronous Receiver/Transmitter (UART) component.

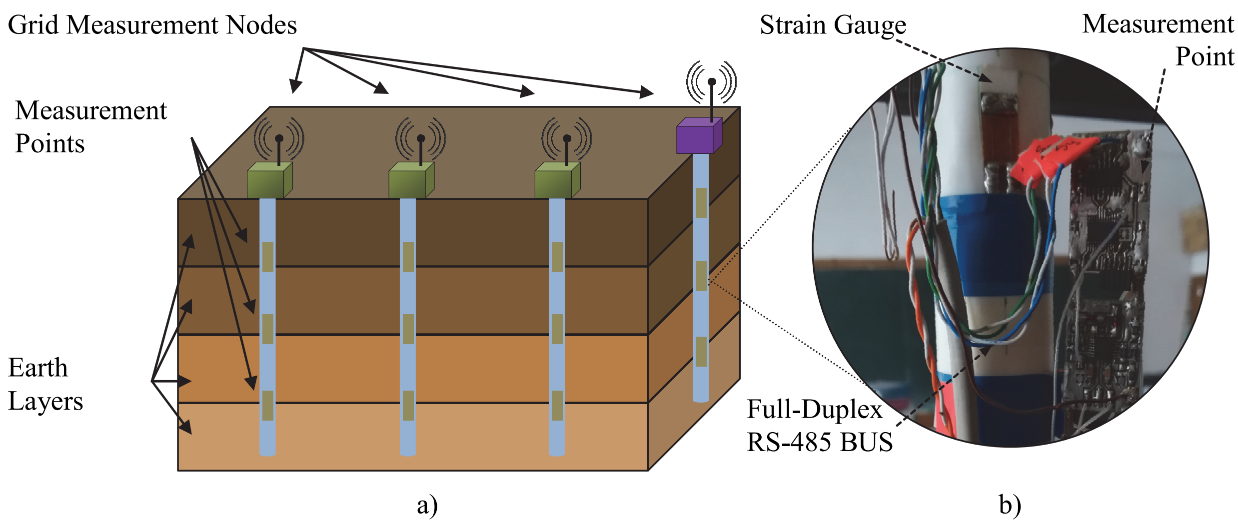
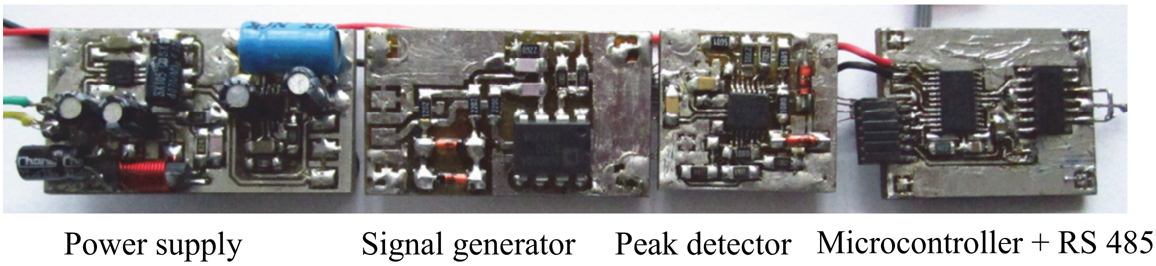
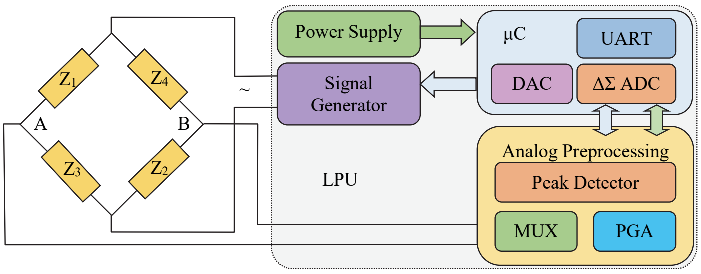


Fig. 1. Landslide measurement system grid structure (updated upon Petrisor et al., 2013)



(a)



(b)

Fig. 2. Measurement point structure: (a) components and (b) basic block interconnectivity (updated upon Petrisor et al., 2013)

3. Wireless sensor network (WSN)

3.1. Protocol selected

Wireless sensor networks are widely applied for area monitoring, environmental/earth monitoring (air quality, forest fire detection, water quality, natural disaster prevention), agriculture, passive localization and tracking, smart houses and industrial monitoring etc. (Ahlawat, 2013; Akyildiz, 2002). Considering the topology, flexibility, low power consumption and long range properties, the ZigBee protocol has been chosen for developing the wireless communication (Dias Pereira et al., 2009; ZigBee Alliance, 2010;).

3.2. Landslide WSN

The sensors described above are arranged within a landslide WSN and represent a node. Every node is constituted by a ZigBee device designed to collect the data from three measurement points. The measurement points are distributed vertically along the landslide transducer and inside a pipe that is positioned on the field in landslide locations of interest. Fig. 3 presents the architecture of a measurement node. In the figure, MBx represents a measurement bridge that provides the analogue information about the pipe distortion, whereas the Local Processing Unit (LPUx) has the configuration presented in Fig. 2b. RS-485 represents a standard industrial serial communication full-duplex transceiver. The Wireless Sensor Node (WSNdx) is a ZigBee device that is the main component of the measuring node. This device is a Jennic DR1048 circuit that includes a JN5148-001-M00 microcontroller. This is a 2.4 GHz IEEE 802.15.4 compliant device with a very low sleep current (2.6 μA – with active sleep timer). Serial communication is established using a RS-485 balanced interconnecting cable. The LPUx tasks include acquiring and processing the information regarding the pipe deformation and receiving, interpreting and transmitting data via UART.

For every measurement point, the temperature and the supply voltage are measured and packaged into the transmitted data. These values are useful for network management tasks. Supply voltage is measured because all the system is powered using photovoltaic panels and, in case of main power failure, other power sources (battery) must be automatically connected to compensate the power drop. The temperature is measured to compensate the variation with temperature of the amorphous wires constant (about 0.11%/°C).

Using a number of WSNdx and a wireless coordinator, a star network topology was developed in order to implement our grid measurement concept. We have chosen this topology because it prevents bouncing data packages through an excessive number of nodes. Each device is inherently isolated by the link that connects it to the coordinator, easily detects faults, removes parts and allows no disruptions to the network when connecting or removing devices.

On the landslide area, the coordinator collects all the data from the wireless sensor nodes. First, all data are compressed in order to allow a fast and efficient transfer. Then, the information is sent from the landslide area to the server via two GPRS (General Packet Radio Service) modems. The server is a computer with database manager software. The software part of the system is used to control the measurement time, to analyze all the incoming data and to report the landslide status via a webpage and an email service. The software continuously monitors the status of all sensor nodes in order to prevent any malfunction situation due to insufficient power supply or other unpredicted events. Data can be accessed anytime, from everywhere, using any device connected to internet (PC or mobile device).

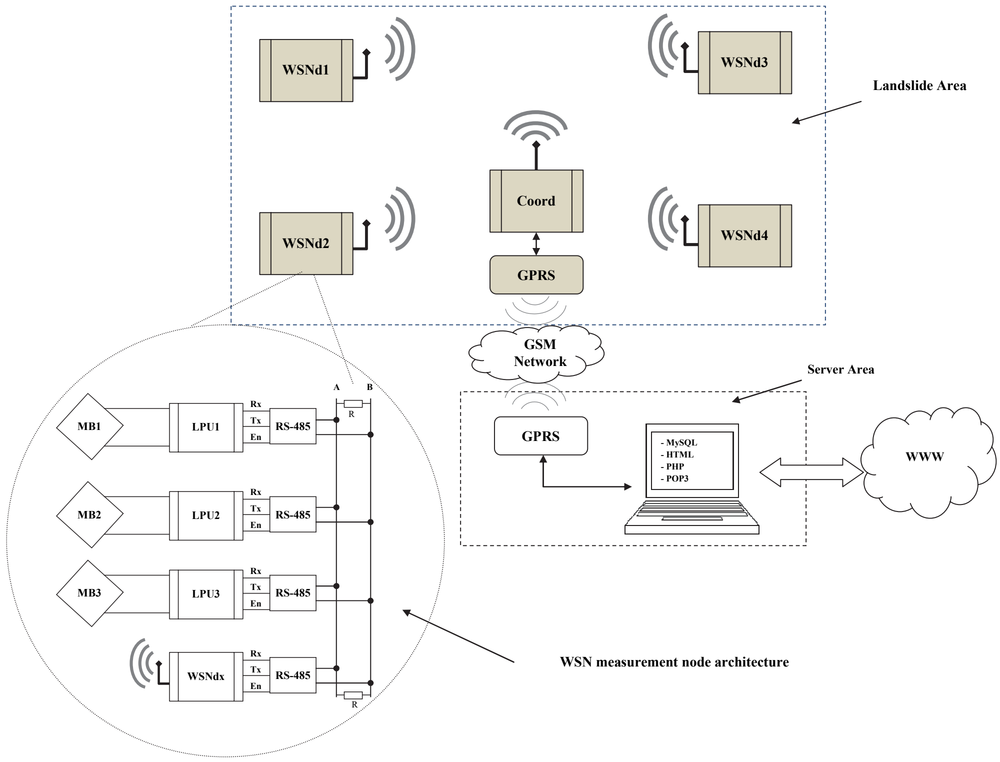


Fig. 3. Landslide Wireless Network architecture, Server Area and WSN measurement node components

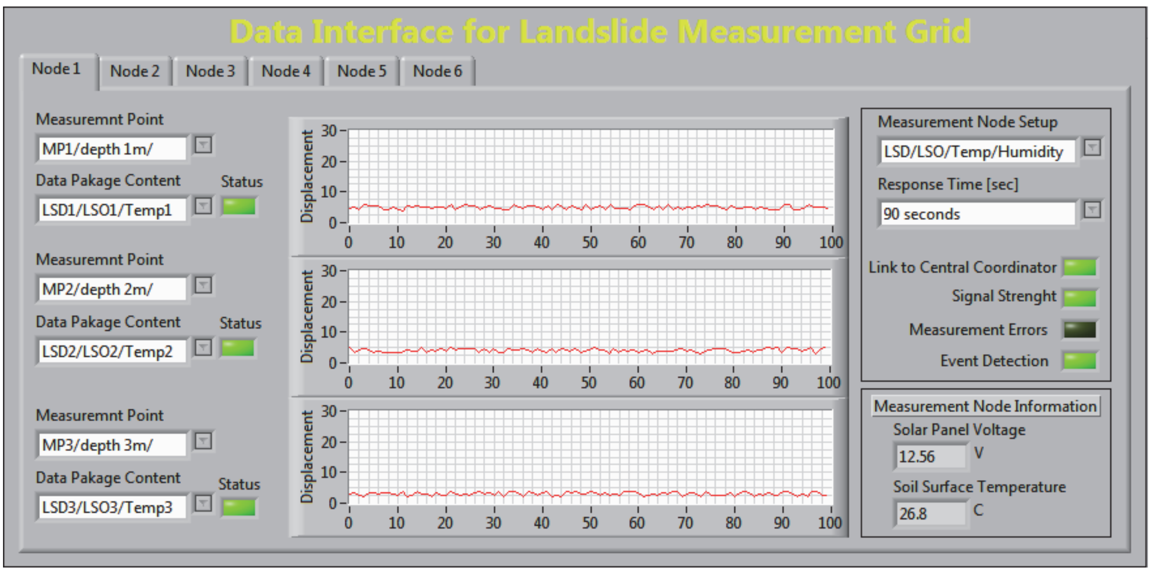


Fig. 4. User interface regarding landslide monitored parameters displaying measurement grid data recorded by the central server

4. Landslide surveillance system software

Continuous measurement data concerning landslide surveyed parameters is received by the central server from GPRS modems. Data packages are handled by our landslide surveillance application running on the server (Fig. 4). It was developed to control the data acquisition process and to display information from grid measurement nodes.

The nodes are identified by unique identification tags compressed in the data package received from every grid measurement node and presented as selectable items designed for displaying measured data. The data packages are uncompressed and the information is stored in a local database containing landslide measurements acquired throughout the surveying period.

The measured parameters displayed by the user interface are: displacement vector, soil temperature in each measurement point, soil surface temperature and solar panel voltage. The measurement nodes send the following status indicators: signal strength, measurement errors, event detection and coordinator link, used to manage the data streams from the grid nodes. Soil surface temperature and solar panel voltage data are suitable to monitor weather conditions; consequently, these parameters are also shown by the user interface. The user interface of monitoring application is able to setup the measured parameters and response time that are specific to each grid measurement node. Parameters like: response time (controls the time interval between two consecutive measurements) and alert threshold range could be configured trough the user interface. Real-time data presentation of valuable information regarding landslide activity makes our implemented application a simple yet effective solution used for monitoring and crisis management. Once all the parameters are configured by means of the user interface, the landslide monitoring systems starts recording landslide activity data. Based on the values of the response time, each measurement node sends measurement commands to all measurement points from its control. Measurement points that receive the data acquisition instruction measure the data regarding landslide activity and transmits the values to the local WSNdx.

Landslide data is gathered from all measurement nodes by the local coordinator that directs this information by GPRS data transfer to our central server for storage and visualization. The specific time for data acquisition and transfer of one measurement point is about 230 ms. The data collection process from all measurement points of one measurement node takes about 700 ms. The data transfer procedure from one measurement node to the local server needs 150 ms to complete. Depending on the number of measurement nodes used for surveying the landslide prone area, the data collection time could have various requirements. For example, if our surveillance grid uses four measurement nodes and we would like to acquire landslide data, our system needs about 1300 ms to complete this process, time measured without the predefined response time. Data flow coming from local coordinator and directed to our central server is managed by a GPRS communication protocol. The local coordinator transfers data packages containing landslide measured data to the central server every 15 minutes. Due to its fast response time, our system provides real-time context related data linked to landslide activation phenomenon activity that specialists could use to mitigate the negative impact that such a natural hazard could have, in the premises that it could occur.

5. Experimental results

Using the above described WSN combined with system software, test measurement data have been collected. We studied the behavior of the measurement parameters by applying a known displacement on the rod. In Fig. 5, the voltages measured on the points A and B of the bridge (Fig. 2b) are presented. The rod was displaced by 32 cm, [-16 cm … +16 cm] along two directions: East-West and North-South. The voltage difference (ΔU) on the measurement points provides useful information about the displacement and the direction of it.

In order to optimize the energy consumption of the entire system, tests regarding the strain gauge bridges supplying voltages have been performed. Fig. 6 presents the bridge measured voltages for three different supply values. One can observe that the measured values directly increase with the supply voltage. This permits lower power consumption if analogue preprocessing stage and acquisition are performed correctly.

6. Conclusions

The presented landslide WSN is based on a ZigBee star network topology. Magnetic amorphous wires strain gauges sensors are used as measurement points. The data is locally processed and then transmitted over the network. The network architecture consists in a coordinator and a certain number of wireless nodes.

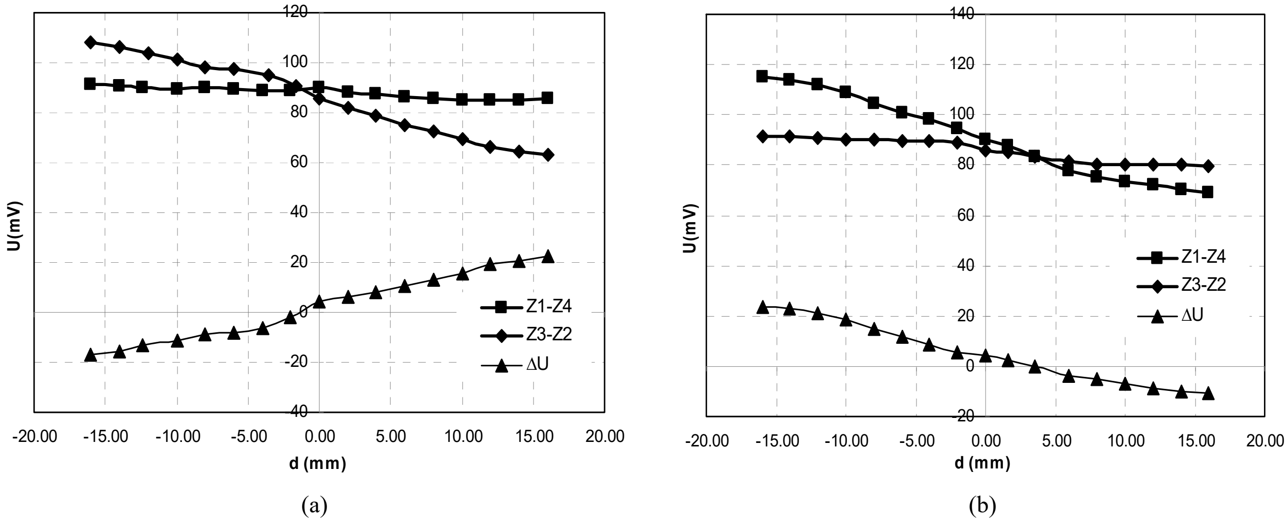


Fig. 5. Voltage variations on two strain gauges (Z1 and Z4) for different displacements and two directions: a) N-S direction and b) E-W direction

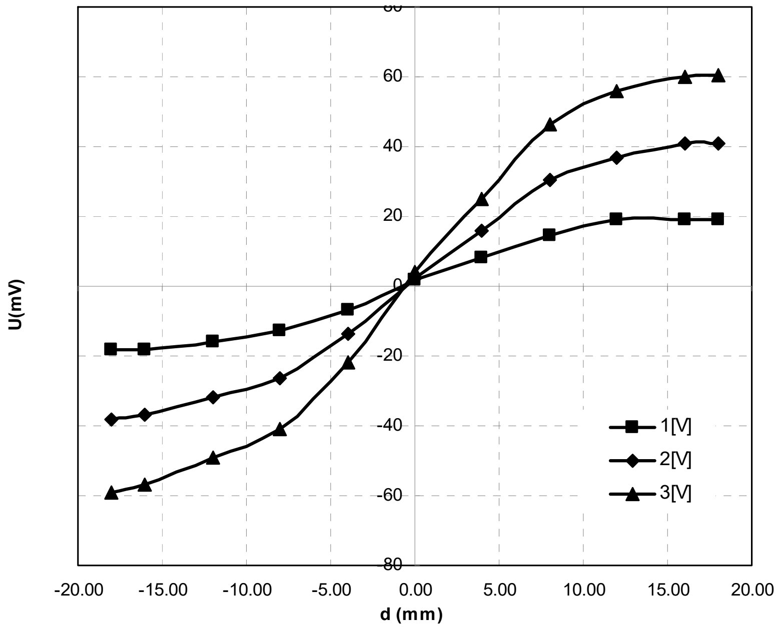


Fig. 6. Measured values for different supply values

Every node is used to collect data from three different measurement points displaced along the rod. The main advantages of the system are: long distance data transmission (up to 1km), power supply monitoring in order to prevent errors because of insufficient supply power and the connectivity with internet space via a multi-protocol (MySQL, PHP, HTML) server. Some functionality tests have been accomplished and the measured values are presented.

Acknowledgment
The results presented in this paper have been financially supported by the Romanian Ministry of Education and Research through the project PN-II-PT-PCCA-2011-3.2-0975, contract no. 63/2012.

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