Development of a Rainfall-Triggered Landslide System using Wireless Accelerometer Network

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Abstract

Recently, Micro-Electro-Mechanical-Systems (MEMS) based accelerometers become a good candidate for replacing the geophone and inclinometer in landslide monitoring. By integrating different kinds of sensors to each node of a communication system, Wireless sensor network (WSN) is a good facility to measure and remote monitor the environment's parameters. Obviously, the cost of the WSN needs to be reduced in order to set-up the systems in many more wide, unstable slopes. However, for a low-cost solution, there is no Wireless Accelerometer Network (WAN) could provide all information of vibration, inclination, and displacement at once due to essence drawbacks of MEMS based sensors. Therefore, in this paper, we explored the use of low cost, three degrees of freedom (3-DoF) ADXL335 chip based MEMS accelerometers to measure and real-time monitor the inclination, the vibration, and the displacement of the soil slope. Both deterministic and stochastic errors are investigated to maximally reduce the incorrectness from sensors. Several signal processing algorithms are applied to provide the accurate information of the inclination and vibration. For the displacement estimation, a novel procedure is proposed to eliminate the accumulated error.

Keywords: *Accelerometer, Inclination, Displacement, Landslide, Vibration, Wireless Accelerometer Network*

1. Introduction

The landslide is one kind of serious hazards that cause substantial life and financial losses. In order to manage and reduce its damages, many efforts to monitor and alert landslides are studied and developed. Among these technologies, wireless sensor network (WSN) can be used to monitor and alert landslides in specific slopes that belong to the high risk [1].

Previously, geophones, which are buried under the investigating slopes, have been used to detect the motion of the soil for many years due to many advantages such as no requirement of electrical power to operate, and ability to detect extremely small ground displacements [2]. However, in order to measure the soil slope, an inclinometer must be added. Recently, due to the strong grow of MEMS technology, MEMS based sensors offer low cost, small size, and good quality. Moreover, a MEMS based accelerometers can measure the vibration of the soil, the soil slope, and the movement of the soil [3,4].

In [5], the authors detect and measure vibrations caused by landslides by using accelerometers from Micaz. Several hard thresholds are proposed to alert about the possibility of the landslide. However, the information about the inclination of the slope or the precise movements of soil is not mentioned.

In [6], the authors proposed to use a MEMS inclination sensor to acquire the real time data of the slope ground displacement, and transmit to an early warning system by a WSN. The information about vibration or displacement was not observed in this study.

In [7], the authors used a 3-axis MEMS accelerometer ADXL-335 to acquire the vibration data only. Either information about the inclination or displacement is mentioned.

Also in many previous studies such as [8,9], there is no research could provide three parameters: the inclination, the vibration, and the displacement concurrently. Especially, acquiring the displacement from acceleration sensor is a challenge due to the seriously accumulated error.

Therefore, in this research, we explored the use of low cost, 3-DOF (degree of freedom) ADXL335 chip based MEMS accelerometers to measure and real-time monitor the inclination, the displacement and the vibration of the soil slope. Both deterministic and stochastic noises are investigated to maximally reduce the error from sensors [10]. Several algorithms are applied to provide the accurate information of the inclination and the vibration. For the displacement estimation, a novel procedure is proposed to eliminate the accumulated error. The wireless accelerometer network (WAN) is developed based on Zigbee protocol to provide a low-cost, flexible, and reliable solution for the landslide monitoring system.

2. Working principles

2.1. Acceleration sensor

MEMS involve the integration of micro sensors and actuators that sense the environment and react to changes in that environment. Micro-machined inertial sensors that consist of accelerometers and gyroscopes have a significant percentage of silicon based sensors. The accelerometer has got the second largest sales volume after pressure sensor. Accelerometers can be found mainly in the automotive industry, biomedical application, household electronics, robotics, navigation system, landslide monitoring and so on. Various kinds of accelerometer have increased based on different principles such as capacitive, piezoresistive, piezoelectric, and other sensing facilities. The concept of accelerometer is not new but the demand from commerce has motivated continuous researches in this kind of sensor in order to minimize the size and improve its performance [11].

WAN that integrates accelerometers can be used to characterize the location of failure planes as well as measure the direction of landslide movement (see Figure 1). The system can acquire subsurface movements automatically at a programmable time intervals and provide a useful tool for geologists and engineers to improve subsurface characterization, and monitor construction activities in real time manner.

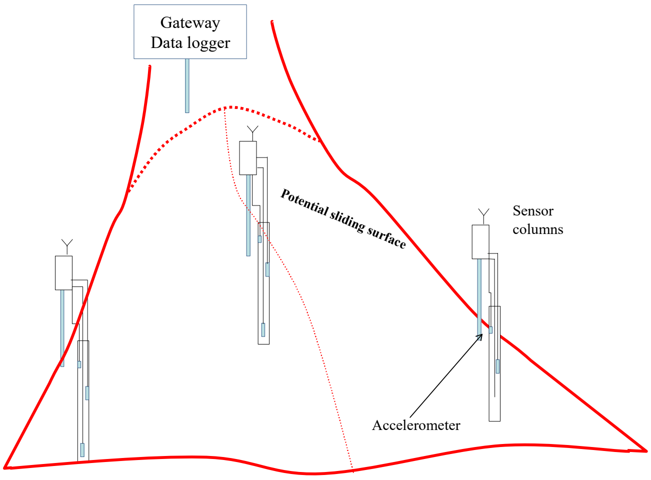


Figure 1. Illustration of setting sensor columns in an unstable slope to form a WAN.

Figure 2 shows the commercially procured breakout board having the dimensions of 18×18×1.63 mm^3 with a light weight of 1.18 *gram*, where the ADXL 335 chip is mounted. The chip is of very small size 4×4×1.45 mm^3. ADXL-335 is small, low power, 3-axis accelerometer with the conditioned voltage output. The ADXL335 has a measurement range of ± 3 g. The ADXL335 belongs to the family of the capacitive sensors, which are based on the principle of the change of capacitance in proportion to the applied acceleration. Depending on the operating principles and external circuits, capacitive sensors can be broadly classified as electrostatic-force-feedback, and differential-capacitance accelerometers. This accelerometer is a poly-silicon surface micro machined sensor which is built on top of a silicon wafer. Poly-silicon springs suspend the structure over the surface of the wafer and provide a resistance against acceleration forces. Deflection of the structure is measured using a differential capacitor that consists of independent fixed plates and plates attached to the moving mass. If an accelerative force is applied, then the capacitance will change. By using some circuitry to convert from capacitance to voltage and we will get an accelerometer. The output signals are analog Voltages that are proportional to acceleration. The advantages of capacitive sensors such as ADXL-335 are high sensitivity, low power consumption and low temperature dependence. Bandwidths of this accelerometer can be configured within a range of 0.5 Hz to 1600 Hz for *X* and *Y* axes, and a range of 0.5 Hz to 550 Hz for the Z axes [6].

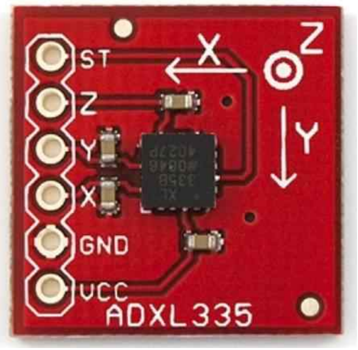


Figure 2. A photo of the accelerometer ADXL-335 mounted on a breakout board.

The formula for calculating accelerator at one axis is

$$A_i = \left[\frac{V_i}{1024} * R_{ADC} - O_i \right] / S_i, \; i=X,\, Y,\, Z \tag{1}$$

where A_i is the value of acceleration in direction $i=X,Y,Z$; V_i is the value after sampling of the i^{th} axis; R_{ADC} is the reference of voltage; O_i is 0 *g* voltage after the calibration of the i^{th} axis; and S_i is the electronic sensitivity of the accelerometer of the i^{th} axis. In this study, the analog-to-digital converter is a built-in component with a resolution of 10 bits can encode an analog input to one in 1024 different levels R_{ADC}.

The electronic sensitivity of the accelerometer is defined as the ratio of its electronic output and its acceleration input slope of the calibration curve relating the output with zero offset voltage:

$$S_i = \frac{V_{out}}{a} \qquad i = X, Y, Z \tag{2}$$

where V_{out} is the voltage output acquired by applying an acceleration *a*. The static sensitivity of the sensor is characterized by rotating the accelerometer's sensitive axes around the earth's gravitational vector from 0^o to 180^o that corresponds to the acceleration range of 2*g* ($g=9.8\ m/s^2$). From the experiment, the sensitivities are estimated as S_X= 0.336 V/*g*, S_Y= 0.337 V/*g*, and S_Z = 0.329 V/*g*, respectively.

The resolution defined as the noise divided by the sensitivity can be expressed as:

$$R_i = \frac{V_i^{noise}}{S_i} \qquad i = X, Y, Z \tag{3}$$

where V_i^{noise} is the voltage output (caused by the noise) acquired by applying an acceleration $a = 0$ (m/s^2). There are several main sources of noises such as the thermal (Johnson), the flicker (1/*f*), and the quantization noises. By using the power spectrum density (PSD) and Allan variance methods [10], the dominant noises existed in this ADXL are close to the white noise, whose densities are 215 $\mu g / \sqrt{Hz}$ (in X and Y axes), and 430 $\mu g / \sqrt{Hz}$ (in Z axis), respectively.

2.2. Wireless Accelerometer Network

2.2.1 Hardware components

Figure 3 shows the diagram of a sensor node in the WAN in which the accelerometer ADXL-335 is integrated. Other sensor such as moisture, pore pressure sensors can also be integrated to the sensor node. In this kind of applications, a sensor node is also called sensor column. The sensor column will be buried underneath the unstable slope site in order to monitor various parameters related to the landslide. The Atmega328 microprocessor from Atmel is programmed to acquire the analogue signal from sensors, convert to digital format, pre-process, and forward to the RF-module. The RF-module is the Zigbee [12], which is based on the IEEE 102.15.4. This standard has attracted researchers to use for WSN due to its advantages such as power saving, reliable, short time delay, large network capacity, safety, and low cost of components [13]. A real sensor column is designed and assembled as shown in Figure 4.

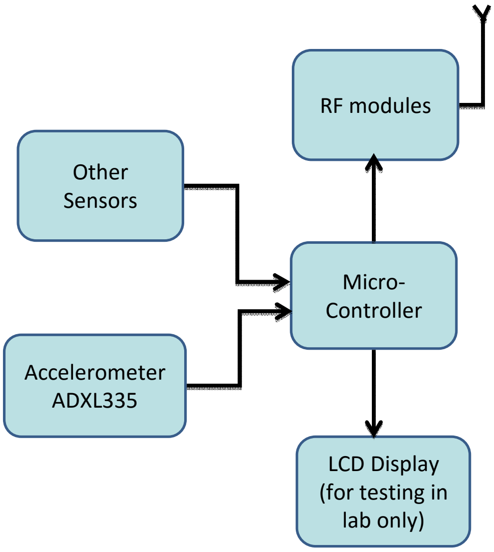


Figure 3. Diagram of a sensor node in the WAN.

Figure 4. A photo of a sensor column in the outdoor communication system test.

The proposed WAN shown in Figure 5 is used to measure parameters of the environment for landslide monitoring. For this kind of application, the topologies of this WAN can be designed as a star [14], a tree [15], etc. The data will be sent to a data logger through a gateway node.

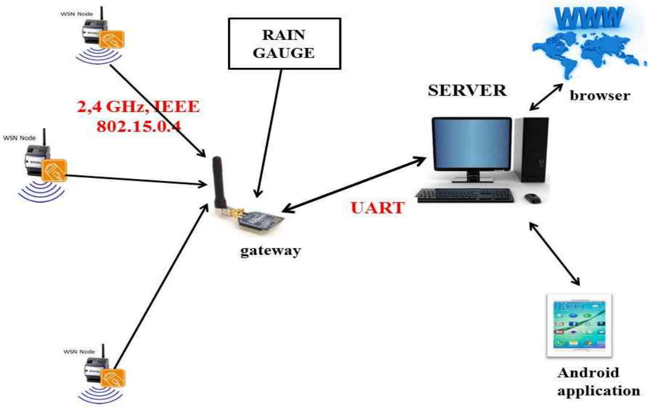


Figure 5. Diagram of the WAN.

2.2.2 Software modules

The microprocessor in each sensor column has three main functions: data acquisition, data processing, and communication. In order to transmit data effectively, the data frame is needed to design carefully. The data frames sent from a sensor column to the gateway or another sensor column would have the following structure:

#	Node ID
#	Time index
#	Battery-time-remaining
#	Data no. 1
#	Data no. 2
#	…

where: node ID is an ID address, the frame index will increase after every packet transmitting, the ith data field is data acquired the ith sensor. Note that one sensor column may consist of more than one accelerometer. Accelerometers can be placed in the different depths of the slope. The information of the battery-time-remaining and the reading time index are also attached into this frame. The gateway receives the data frame after every Ts_1 or Ts_2 (depends on the status of the sensor) and transfers the data to the central computer.

3. Methods and Results

3.1 Vibration measurement

One of the most accelerometer's applications is that using the sensor for vibration analysis. In this section, the accelerometer was utilized to detect an unknown vibration signal from the vibration shaker table. Figure 6 presents the vibration system which uses to test the ADXL-335. This system includes a function generator, a power amplifier, a vibration shaker table, a ADXL-335 sensor, and a data analyze module. The vibration can be monitored in both the time and frequency domains. First, the function generator will create a sinusoidal signal at a certain frequency (F_0). Second, the shaker will vertically vibrate at F_0. Third, ADXL-335 will sense this sinusoidal acceleration and the signal is sent to the analyze module. As shown in Figure 6, the system was established with the "unknown" signal is a F_0=36 Hz. In this test, the "unknown" frequency of 36 Hz is detected successfully.

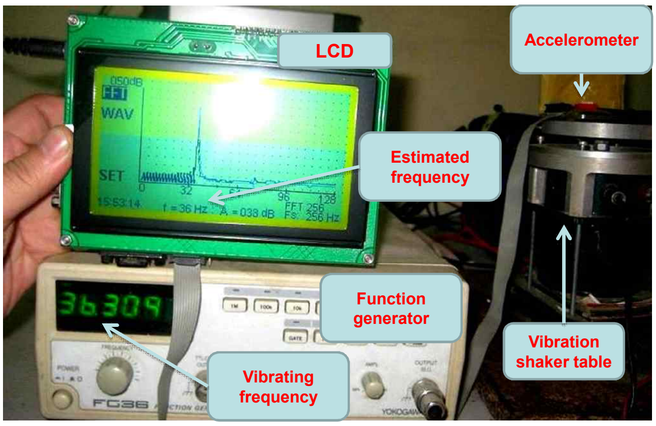


Figure 6. Vibration testing with ADXL-335

3.2 Tilt measurement

To test the acceleration sensor in the tilt measurement, the tilt table is used to change the sensing acceleration from $+g$ to $-g$ (see Figure 7). The static acceleration is acquired by rotating the accelerometer axes around the earth's gravitational vector from 0^o to 360^o that corresponds to the acceleration range of $2g$.

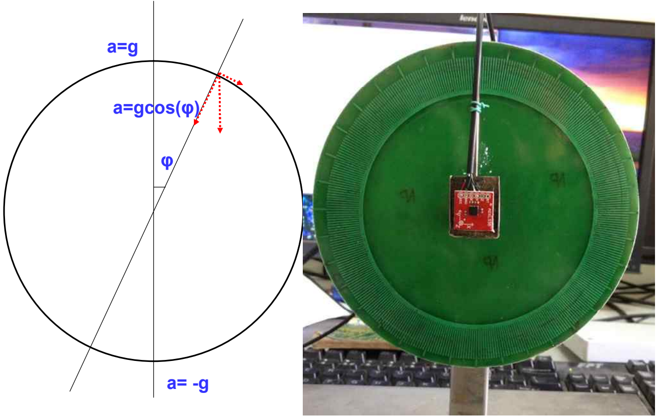


Figure 7. Schematic and real tilt-tables for inclination testing

Figure 8 shows the simultaneous measurements of the accelerations in X and Y axes by changing the angle of rotation. It can be seen that the phase difference between these curves is 90^o because X-axis and Y-axis are perpendicular. In order to estimate the tilt in two dimensional (2D) application, the acceleration in X and Y axes should be integrated.

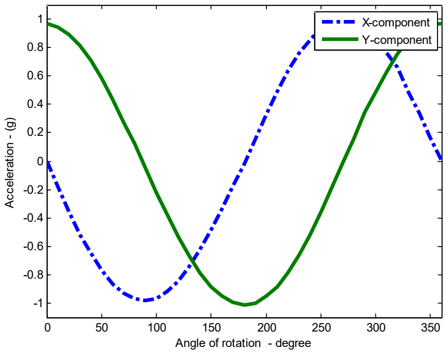


Figure 8. Acceleration measurements in X and Y axes by changing the angle of rotation.

Figure 9 presents the tilt measurement in 2D scenario. In this figure, the estimated tilt is compared to the true one. The measurement error is also computed and shown. Similarly, the tilt estimation in 3D applications can be performed by integration of all three axes of ADXL-335.

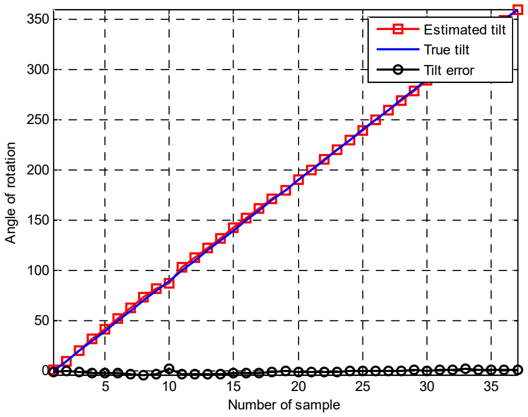


Figure 9. The tilt measurements in 2D obtained by the combination of X and Y acceleration components.

3.3 Displacement measurement

By measuring the instantaneous acceleration from sensors committed to the slope, we can directly estimate the vibration and the tilt of slopes. However, the displacement, which is calculated by the double integration, is strongly affected by the accumulated errors. The accumulated error caused by the offset (see Equation 1) can be assumed to fix by the careful calibration. However, the accumulated error caused by the double integration of random noise (always exist at the sensor's output) cannot be ignored. Figure 10 shows the estimations of the displacement, velocity, and acceleration obtained from an unmoving accelerometer. Despite small values of the acceleration which is close to the Gaussian white noise, the fluctuation of the velocity and the displacement are not ignored. For the purpose of the landslide monitoring, these results, of course, lead to an immediate alert to the responsible people.

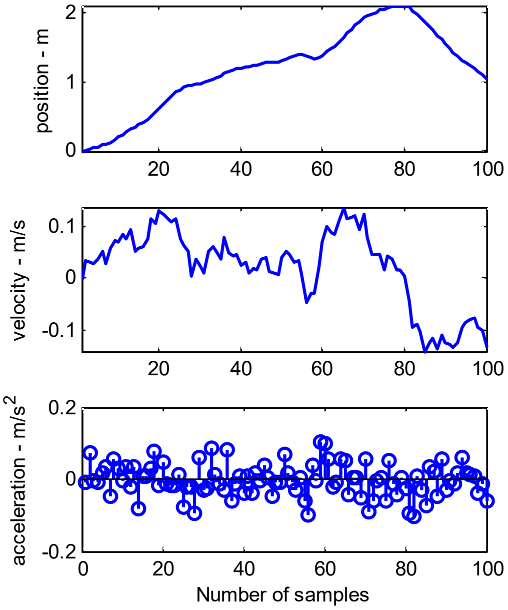


Figure 10. The DVA (Displacement, Velocity, and Acceleration) estimation when the sensor is completely motionless.

In order to reduce the fluctuation of the velocity and the displacement, two following methods can be applied to the acceleration signal: 1) the moving average window, 2) Kalman filter (KF) [16]. The reason is that the acceleration signal from the unmoving sensor is close to the Gaussian white noise. The information of the noise densities in Sec. 2.1 is used to formulate the covariance matrix in the system model. Figure 11 presents the noisy acceleration signal, the signal filtered by KF, the signal treated by the moving average window, and the true acceleration (i.e. 0 m/s^2).

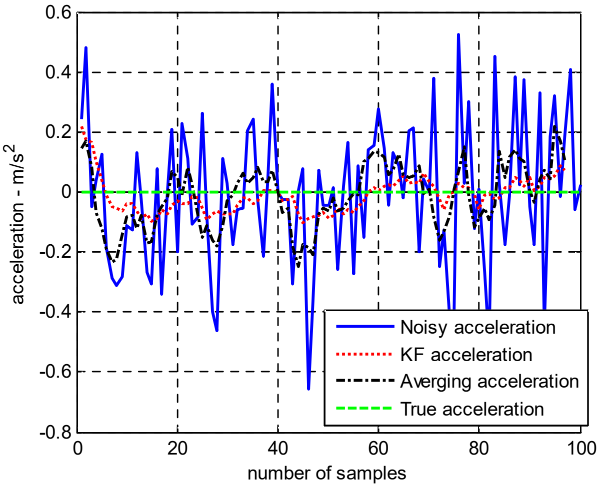


Figure 11. The acceleration signal obtained by a) direct sampling from the sensor, b) filtering by KF, c) filtering by the moving average window, and d) true value (i.e. 0 m/s^2 due to the complete unmovement).

It can be seen that utilizing the KF or the moving average window can reduce effectively the variation of the acceleration. However, due to the accumulation, the fluctuation of the velocity and the displacement still exist. Thus, in the landslide monitoring applications, acceleration needs to combine with a geophone and/or a strain gauge or an extensometer in order to monitor the DVA. It would lead to: 1) the higher cost for each sensor column and the whole system, 2) the higher power consumption for due to the sampling and processing data in each sensor column.

In this study, we introduce a simple and effective procedure to overcome this disadvantage of MEMS based accelerometers. This procedure is summarized in Figure 12.

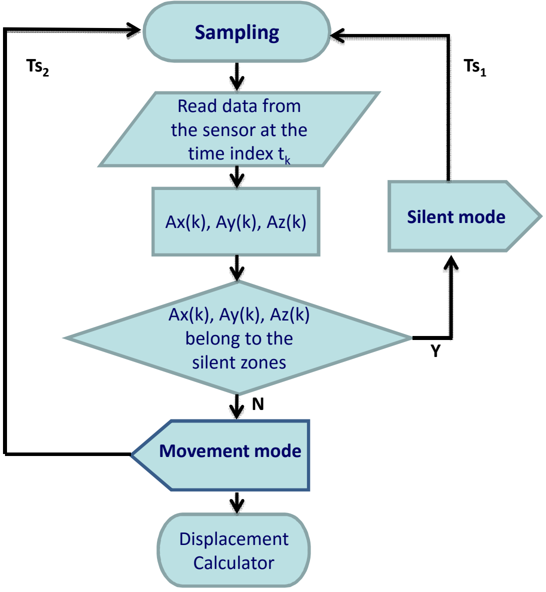


Figure 12. The process flowchart for displacement estimation

In this process flowchart, we have defined concepts of the silent zone as the range of values may acquire when the accelerometer is completely motionless. By a careful calibration, we can simply determine there silent zones correspond to the acceleration components after placing underground. ADXL-335 can sense the acceleration in three directions; hence, there are three silent zones for each acceleration component. If all acceleration components fall into their silent zone, this sensor would follow the silent mode. In the silent mode, the sampling cycle for the next instance is Ts_1. The value of Ts_1 is set at ten minutes; hence, it is long enough to reduce the power consumption due to the processing action of the microcontroller. Note that, the power consumption of a sensor column is the sum of activities such as the processing, transmitting, and receiving data, respectively. If the acceleration is determined to be in the silent zone, we do not need to transmit any data to the higher-level node. Consequently, not only the processing energy is small, but also the transmitting and receiving energies are zeros. Table 1 summarizes the power consumption of each component in a sensor column in order to highlight the advantage of our proposed solution.

Table 1. Power consumption of a sensor column

Components	**Current** (mA)	**Voltage** (V)	**Power** (mW)
Microprocessor	15 (Active) 0.055 (Silent)	3.3	49.5 (Active) 0.18 (Silent)
RF module (Xbee-ZB-PRO)	3	3.3	10 mW (estimated with distance around 400 m) in the fractions of time taken
Acceleration sensor (ADXL345)	0.35	3.3	1.155 mW in the fractions of time taken

In contrast, in the movement mode, the microcontroller will increase the sampling rate of the data (i.e. reduce the sampling time to Ts_2 = 0.5 s) in order to timely track the movement of the slope (see Figure 13). In order to firmly determine if the sensor is in movement mode, we propose a technique to eliminate the abnormal value. In detail, after the first acceleration value falls out of the silent zone, two consecutive samples are also checked. If these samples fall out of the silent zone, they are all brought to the displacement calculator. If the consecutive sample is in the silent mode, the first sample is assumed to be an abnormal value and assigned to 0. Figure 14 shows the corresponding results by applying this technique. In this scenario, the sensor is completely motionless, and eleven abnormal values are eliminated. Obviously, if we increase the range of the silent mode, the number of abnormal values would reduce. However, it may ignore the real movement of the soil.

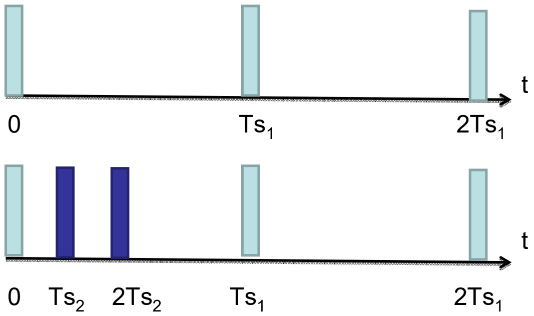


Figure 13. Illustration of changing the sampling cycle in the proposed scheme: Ts_1=10 minutes, Ts_2=0.5 second. If a sample falls out of the silent zone, the next sample would be acquired with a higher rate (i.e $1/Ts_2$).

In the movement mode, the sensor column needs to send the acquired data to the data logger. It searches and sends the request to join any available networks. Obviously, the sensor columns and the gateway node would set up a WSN. The data acquired in the movement mode will transmit wirelessly from the sensor node to the gateway, and then to the data logger. Consequently, the data is automatically uploaded to a MySQL database on a web server. Finally, the web application for remote monitoring is built using web services (see Figure 15). The users can monitor the vibration, the tilt, and the displacement estimated using acceleration data. These values are automatically compared with the determined thresholds in order to make an alert or not. Depend on the kind of landslide (e.g. in rock or soil), the angle of the slope, the thresholds are set differently. For example, with the landslide in soil, changes of the accelerations ranging from 0.2 *g* to 0.49 *g* (in both X and Y axes) indicate the soil movement but not significantly. If the value larger than 0.5 *g*, it indicates a significant change of landslide. If the value larger 1 *g*, it has a very strong signal activity and should be alarmed [5]. In case of alerts, the message is both notified in the website and sends to the mobile phones of the responsive people (see Figure 4).

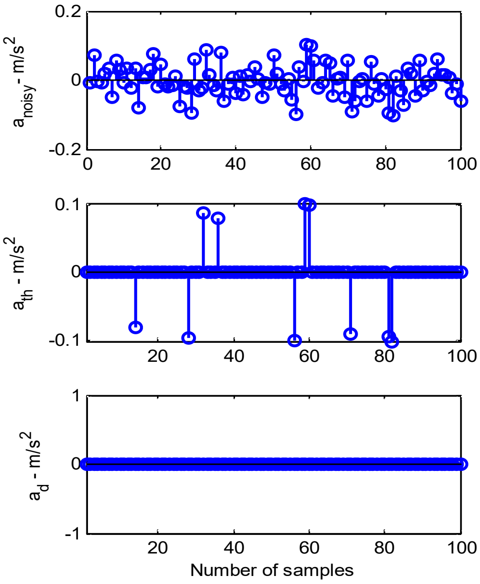
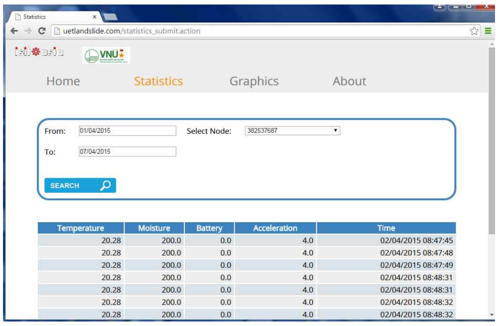


Figure 14. In the case of complete unmovement, the acceleration signals are presented in the forms of: a) direct sampling from the sensor, b) pre-processing by applying the silent zone, c) treating abnormal values.



From: 01/04/2015
Select Node: 382537687
To: 07/04/2015

Temperature	Moisture	Battery	Acceleration	Time
20.28	200.0	0.0	4.0	02/04/2015 08:47:45
20.28	200.0	0.0	4.0	02/04/2015 08:47:48
20.28	200.0	0.0	4.0	02/04/2015 08:47:49
20.28	200.0	0.0	4.0	02/04/2015 08:48:31
20.28	200.0	0.0	4.0	02/04/2015 08:48:31
20.28	200.0	0.0	4.0	02/04/2015 08:48:32
20.28	200.0	0.0	4.0	02/04/2015 08:48:32

Figure 15. Remote monitoring the landslide through the website

4. Conclusion

In this paper, a smart wireless accelerometer network is developed to remotely monitor and automate the warning about the possibilities of the landslide. This is a low-cost solution when an accelerometer can be used to provide the vibration, the inclination, and the displacement concurrently. By introducing the silent zones, the accuracy in the displacement estimation is enhanced. Moreover, if the sensor is in the silent mode, the sensor would not need to transmit the data to the gateway node, and thus, it will save the power. In the movement mode, the data is sent to the gateway node using the Zigbee communication protocol, sent to the data logger, uploaded to the web server for remote monitoring. The vibration, the inclination, and the displacement is automatically compared with the determined thresholds in order to make an alert about the possibilities of the landslide.

5. Acknowledgment

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