An Autonomous Landslide Monitoring System based on Wireless Sensor Networks

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ABSTRACT

Landslides cause significant damages to civil infrastructure. Over the years, methods and technologies have been proposed to determine the risk of landslides and to detect hazardous slope movements. There have been increasing interests in developing and landslide monitoring systems to observe movements using sensors installed on the slope. Although providing accurate data, many landslide monitoring systems are not operating in an automated fashion and lack the ability to analyze the collected data in a timely manner. This paper presents an autonomous landslide monitoring system based on wireless sensor networks. Self-contained, autonomous software programs ("software agents") are embedded into the wireless sensor nodes. In cooperation with each other, the software agents are continuously collecting and analyzing sensor data, such as recorded ground acceleration and the orientations of the sensor nodes along the slope. If movements are observed, the collected data sets are automatically transmitted to a connected server system for further diagnoses. The landslide monitoring system presented in this paper is remotely accessible via Internet and provides real-time information about the current state of the monitored slope. Laboratory tests have been conducted to validate the reliability and the performance of the monitoring system.

INTRODUCTION

Landslides are gravitational movements of soil or rock down slopes that can cause severe damage to civil infrastructure. Numerous fatalities and structural failure caused by landslides have been reported over the years (Guha-Sapir *et al.*, 2011). Therefore, efforts to measure and to monitor potential landslides are essential to ensure human safety and to protect civil infrastructure. To observe the behavior of slopes, monitoring systems have been installed or manual inspections by human experts have been conducted.

Several measurement techniques have been proposed to identify slope instability and to estimate the risk of landslides (Lynn and Bobrowsky, 2008). For example, map analyses and aerial reconnaissance are used to assess the risk of landslides based on the interpretation of terrain and geological information. These methods, however, are known to be costly and labor-intensive as well as highly subjective because the results depend on the experience and judgment of the human experts. Furthermore, landslide-indicating features in certain terrains (e.g. forests) cannot be identified by these techniques.

Another approach towards landslide monitoring is based on geotechnical instrumentations using, for examples, inclinometers, extensometers, or piezometers. The instruments are usually installed on the slope and wired to computer systems hosting data analysis software. Several cable-based landslide monitoring systems have been reported (Singer and Thuro, 2006). However, cable-based monitoring systems are costly, require continuous maintenance, and are limited in their communication flexibility. To overcome these limitations, wireless sensor networks are a viable alternative technology. State-of-the-art wireless landslide monitoring systems collect environmental data from the slope and forward it to connected computer systems for persistent storage. The collected data sets are not processed and analyzed automatically (Garcia *et al.*, 2010). Thus, hazardous slope movements are not usually detected in real-time (Zhou *et al.*, 2005; Bertacchini *et al.*, 2009).

This paper presents a preliminary research effort towards the development of an autonomous landslide monitoring system based on wireless sensor networks that is capable to collect and process data autonomously. The prototype system is designed to automatically detect pre-failure slope deformations based on real-time data analyses. The prototype implementation using an agent-based approach is presented in detail. In addition, laboratory tests validating the prototype monitoring system are shown.

SLOPE FAILURE FORECASTING

Several methods for slope failure forecasting have been developed (Busslinger, 2009). In this paper a method based on the inverse velocity of the surface movement is employed. The concept of inverse velocity for predicting slope failure time was developed by Fukuzono (1985), who has conducted large-scale laboratory tests to simulate rain-induced landslides. The conditions in the laboratory were considered to be characteristic of accelerating creep conditions under gravity loading. The assessment of the laboratory data unveiled that the acceleration of surface displacement and the velocity of surface displacement where related, which can be expressed as:

$$\frac{d^2x}{dt^2} = A\left(\frac{dx}{dt}\right)^{\alpha}. \qquad (1)$$

In the above equation, x is downward surface displacement, d^2x/dt^2 is the acceleration, dx/dt is the velocity, and A and α are constants depending on the slope characteristics (Fukuzono, 1987). The laboratory tests also led to the recognition that, when plotting the inverse velocity versus time, the values of inverse velocity approach zero, as the velocity of surface displacement increases towards final slope failure (Fig. 1). Plotted graphically, the slope failure time can be predicted at the point at which the trend line through values of inverse velocity crosses the abscissa axis. This relationship between velocity and failure time, as proposed by Fukuzono (1985), can be described by the empirical equation

$$V^{-1} = \{A(\alpha - 1)\}^{\frac{1}{\alpha-1}} \cdot (t_f - t)^{\frac{1}{\alpha-1}}, \tag{2}$$

where V^{1} is the inverse velocity of surface displacement and t_f is the failure time. Depending on the values of α, the curve of inverse velocity is linear ($\alpha = 2$), concave ($\alpha < 2$) or convex ($\alpha > 2$), as shown on Figure 1.

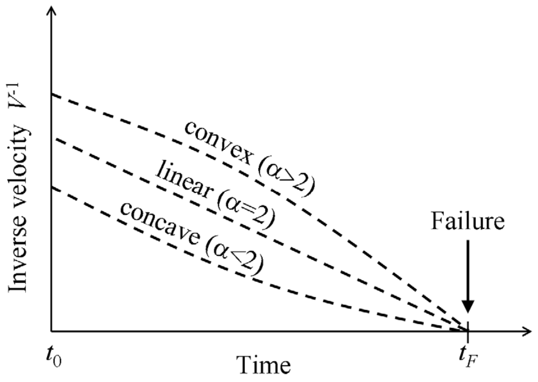

Figure 1. Inverse velocity over time (Fukuzono, 1985).

AUTONOMOUS LANDSLIDE MONITORING SYSTEM

The purpose of the landslide monitoring system is to enable early detection of hazardous slope movements. If having identified pre-failure slope deformations, the system automatically informs human individuals about potential landslides. Relevant measurements taken from the observed slope are continuously stored and available for detailed diagnoses of the slope movements. The landslide monitoring system automatically calculates the inverse velocity, and determines whether and when landslides can be expected. The architecture of the implemented prototype system is shown in Figure 2. The system is composed of two subsystems, a wireless sensor network and a server system.

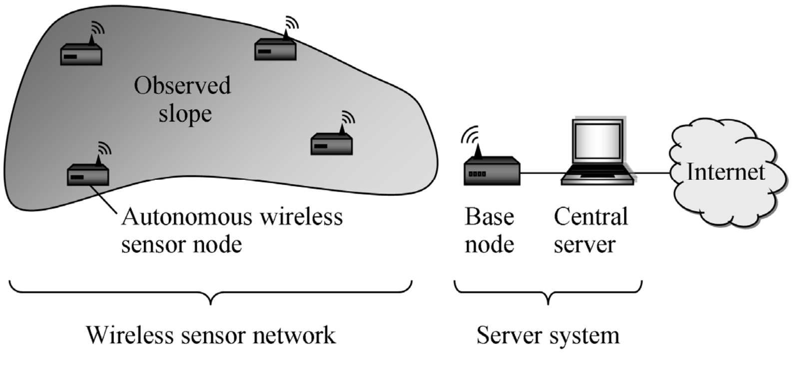

Figure 2. Architecture of the autonomous landslide monitoring system.

Wireless sensor network. A wireless sensor network is comprised of sensor nodes, each has a processor board and a three-axis accelerometer. Mobile software agents are embedded into the wireless sensor nodes to collect acceleration data and to conduct in-situ analyses of the observed slope. A software agent is an autonomous, flexible software program able to complete a specific task without direct human intervention (Wooldridge, 2002). Software agents interact with their environment and respond to environmental changes. Software agents can cooperate with each other to solve comlex problems. Time-consuming data analysis and computation tasks can be performed concurrently by several agents to enhance system performance, which is crucial for real-time monitoring systems.

For modular design of the monitoring system, three classes of software agents are defined and embedded into each wireless sensor node: *ManagerAgent*, *SensorSamplerAgent* and *AnalysisAgent*. The *ManagerAgent* enables the communication between the agents embedded in different sensor nodes, as well as between the agents and the server system. The *SensorSamplerAgent* collects the acceleration data from the slope at a certain sampling frequency and sends the data to the *AnalysisAgent*. Moreover, the *SensorSamplerAgent* determines the sensor orientation and reports tilt changes, if identified. The *AnalysisAgent* determines the motion of the node, thus reflecting deformation in the environment in which the node is installed.

For the communication between the sensor nodes and between sensor nodes and the sever system, radio connections are necessary. Because radio communications consume a lot of battery power, the number of data messages should be kept to minimum. By first sending data to the *ManagerAgent*, which then forwards it to the recipients of other sensor nodes, the *SensorSamplerAgent* and the *AnalysisAgent*, through the *ManagerAgent*, communicate with agents situated on other sensor nodes using just one single radio connection (managed by the *ManagerAgent*) instead of establishing multiple connections.

If a sensor node is in motion, the *AnalysisAgent* sends a command to the *ManagerAgent* to inform all other nodes and the server system. As a direct consequence of a detected motion, all nodes increase the sampling frequency and the server system starts analyzing the global situation of the slope. Furthermore, the *AnalysisAgent* computes the inverse velocity of the sensor node according to the previously described method using the collected acceleration data. The *ManagerAgent* sends the result of the inverse velocity analysis to the server system. A typical monitoring sequence is shown in Figure 3. Due to the multi-agent architecture, the functionality of the wireless sensor network can easily be extended by adding new analysis agents.

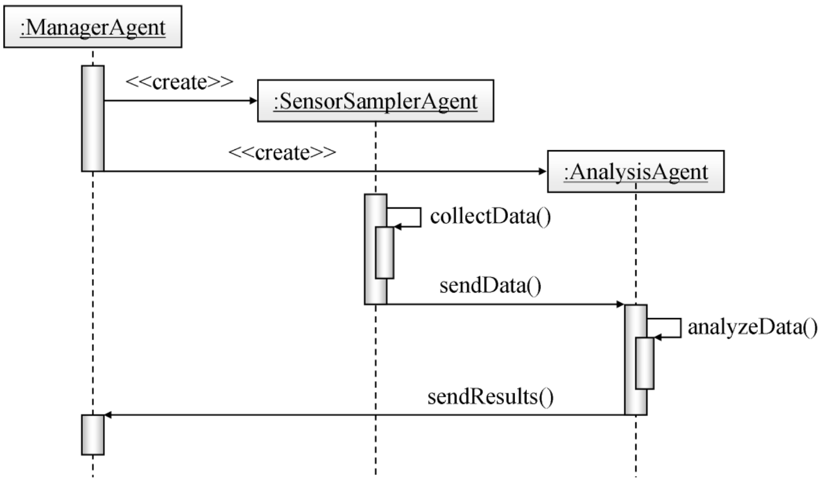

Figure 3. Monitoring sequence executed at system start-up.

Server system. The server system allows human individuals to communicate with the wireless sensor network. The server system is responsible for storing the data and conducting detailed data analyses. In addition, if the server system does not receive the results of the inverse velocity analysis from each sensor node, an attempt to establish a connection to the sensor node is made. If it is not successful, the human experts are informed via email about possible sensor malfunctions. All measured data as well as the results of data analyses can be accessed through a Java application running on the server. Figure 4 highlights the main view of the application showing the functionalities to add or to remove sensor nodes. Data requests can be sent to the wireless nodes to visualize current field data. In addition, the application allows saving data plots in the form of PDF files. In Figure 4, acceleration data is exemplarily shown, collected by two wireless sensor nodes, S_1 and S_2, during laboratory tests.

LABORATORY TESTS

Laboratory tests are conducted to validate the performance of the prototype landslide monitoring system. Specifically, the functionalities of the software agents are analyzed to determine the accuracy of the inverse velocity method applied. To prove the concept, a sand slope is exposed to flooding, which results in soil movement (i.e. landsliding).

Laboratory test setup. A container is filled with sand as illustrated in Figure 5a. The depth of the container is 42 cm. A sand slope with an inclination of 45 degrees is built with a bulk density of the sand (i.e. the ratio of the mass of the sand particles to the total sand volume) of 1.56 g/cm^3 and a void ratio of 0.7; the void ratio describes how sand particles are packed. A void ratio of 0.7 indicates that the sand is of middle-graded density. The wireless sensor nodes, S_1 and S_2, are installed on the top and at the toe of the slope surface. Every sensor node hosts the embedded agents.

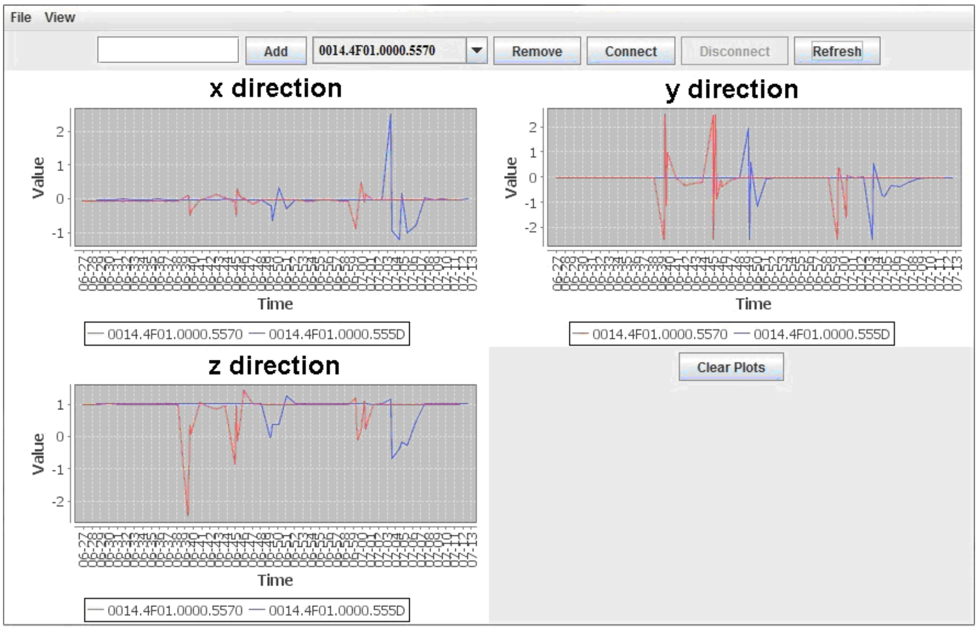

Figure 4. Prototype control and analysis web application.

To determine the initial slope condition, the embedded agents continuously measure the acceleration and the orientation of a node at a relatively low sampling rate of 0.001 Hz; they analyze the data with respect to changes, condense it, and send it to the server system. To simulate heavy rainfall, water is poured slowly at the top of the slope. After pouring 10 liters of water, the soil is saturated and a slow movement starting at the toe of the slope is observed by the monitoring system. Tension cracks also occur because of the weak foundation material. The movement results in changes in the acceleration data, which are identified by the agents. The sampling rate is automatically increased to 0.01 Hz. Based on the acceleration data, inverse velocity values are calculated and sent to the server system for further analysis and visualization. After a total of 14 liters of poured water, cracks occur at the top of the slope as shown in Figure 5b, leading to another movement at the top of the slope and to a total slope failure.

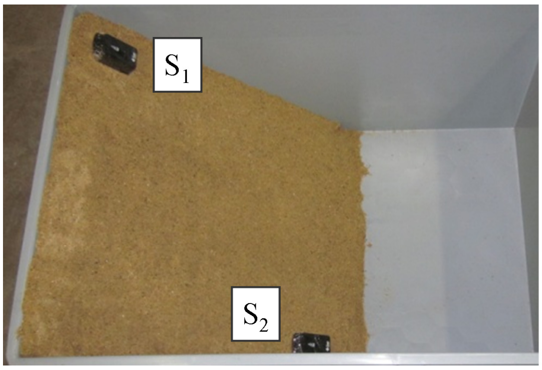

Figure 5a. Sand slope instrumented with sensor nodes before flooding.

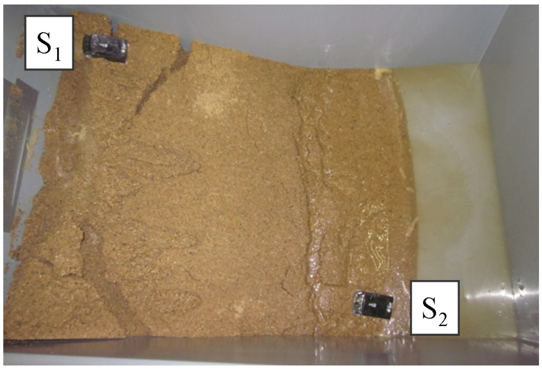

Figure 5b. Sand slope after flooding and landsliding.

Results of the laboratory tests. Slope movements have been detected and, based on the inverse velocity method, the failure time has been calculated by the prototype monitoring system. Relevant information has been forwarded from the wireless sensor nodes to the server system. Figure 6 illustrates the inverse velocity calculated by S_2 before failure. As can be seen, the inverse velocity decreases as failure time approaches. In summary, the laboratory tests have proven that the landslide monitoring system is capable of autonomously identifying anomalies and pre-failure deformations.

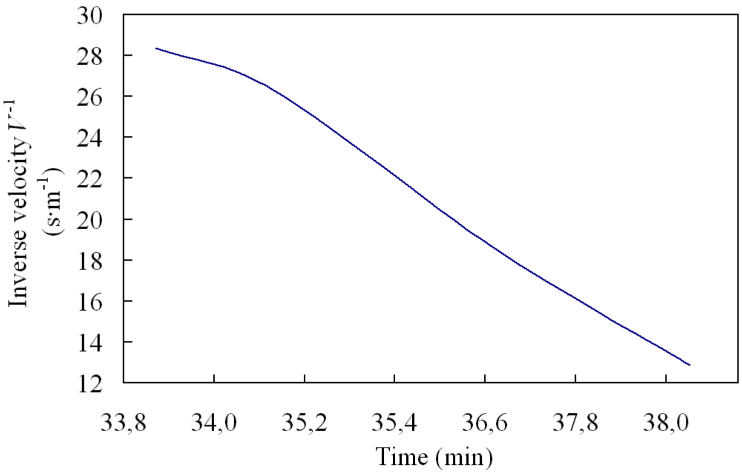

Figure 5. Inverse velocity time history records calculated by sensor node S_2.

CONCLUSIONS

In this paper, the prototype development and implementation of an autonomous landslide monitoring system based on wireless sensor nodes has been presented using a wireless sensor network. Software agents have been embedded into the wireless sensor nodes to continuously collect and analyze ground acceleration data and orientations of the nodes. Within the laboratory experiments, it has been demonstrated that the software agents react appropriately on environmental changes, e.g. by increasing the measuring frequency if anomalies are identified. The collected data can be sent from the wireless sensor nodes to a server system for further analyses and automated email alerts. A distinct advantage, compared to conventional landslide monitoring systems, is that the presented system observes slopes without permanent human interaction. Furthermore, costs for cable-installation and maintenance are avoided because of the utilization of wireless sensor nodes. Due to the flexibility and adaptability of the software agents embedded into the wireless senor nodes, a resource-efficient reduction of measured data is achieved. Future improvements can be made, for example, by incorporating soil moisture sensors into the system. Also, the implementation of additional agent functionalities could further enhance the autonomous monitoring.

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