An Internet-enabled wireless multi-sensor system for continuous monitoring of landslide processes

Kay Smarsly, Kristina Georgieva and Markus König

Abstract—**Monitoring and early warning systems, although being capable of continuously collecting field data related to landslide processes, are usually unable to autonomously detect and analyze signs of landslides in real time. This paper presents the design and experimental implementation of an autonomous landslide monitoring system. Besides reliably issuing early warnings in case of detected slope anomalies, the monitoring system is primarily designed to support human individuals in assessing the risk of landslide and to improve the understanding of the slope behavior, which may help to reduce economic losses and fatalities caused by landslides. Specifically, intelligent wireless sensor nodes are distributed in the observed slope to autonomously collect, analyze and communicate relevant environmental parameters in real time. Supporting remote analyses of the collected field data, a web application, which is installed on a computer connected to the on-site sensor nodes, enables an automated dissemination of slope parameters through the Internet. Last but not least, geospatial information stemming from external sources is integrated into the monitoring system to provide a comprehensive overview of landslide-related slope conditions.**

Index Terms—**Monitoring of slope movements, wireless sensor networks, early warning systems, artificial intelligence, smart sensors, Internet computing.**

I. Introduction

The world population, which currently numbers more than 7 billion people [1], is growing continuously, and it is expected to reach 10 billion people in the year 2100 [2]. As a direct consequence of the population growth, also the density of population increases rapidly, and therefore unstable, hazardous areas and steep terrains with high risks of natural hazards such as volcanic eruptions, floods or landslides are being developed for settlement [3]. As another direct consequence of the population growth, human activities increasingly trigger natural hazards due to changes in the environmental conditions. For example, landslides are frequently initiated by human-induced factors, such as disturbed or changed drainage patterns, destabilized slopes, or removed vegetation [4]. Landslides, according to the United States Geological Survey (USGS) are defined as "downslope movement of soil, rock and organic materials under the effects of gravity" [4]. Generally, landslides occur in different terrains independently from climate conditions, and they are among the most common but also among the most dangerous natural hazards, because civil infrastructure cannot withstand the forces generated by moving masses of soil, rock, or organic material. Having severe impact both on civil infrastructure and on the natural environment, landslides cause losses and damages of several billion US$ every year as well as numerous fatalities and injuries [4]. As reported by Petley [5], who has investigated fatal landslides between 2004 and 2010, during the 7-year observation period 2,620 landslides have been recorded, which have caused more than 30,000 fatalities.

To investigate landslides and to mitigate their impact on civil infrastructure and natural environments, it is important to obtain detailed knowledge about the causes, the natural phenomena associated with landslides, and the conditions of the slopes. As defined by Crozier [6], the instability of a slope is that condition, which causes landslides. More specifically, two types of contradictory forces exist in slopes, (i) forces that tend to promote slope movement and (ii) forces that tend to resist slope movement. For example, shear stress promotes movement and shear strength is the opposing force resisting movement. The difference between both forces is referred to as "margin of stability". Based on the margin of stability, Crozier has proposed a classification of slope states, categorizing slopes as stable, marginally stable, or actively unstable. A stable slope withstands all forces promoting movement; a slope is in marginally stable state, if no movement occurs and the margin of stability is small; and a slope is in actively unstable state, if the margin of stability approaches zero and signs of ground movement are observed. Three groups of destabilizing factors can be defined that affect the slope states [6]:

- *Preparatory factors* change the state of a slope from stable to marginally stable state without initiating slope movement and make the slope susceptible to movement.
- *Triggering factors* place slopes from marginally stable to actively unstable state by initiating movement.
- *Controlling factors* define form, rate and duration of movement.

In summary, landslides are the result of a variety of aggregated effects of interrelated factors. Besides human activities, as mentioned earlier, seismicity and precipitation are among the most common factors. Petley [7], for example, has reported that more landslides occur during seasons with high precipitation than during seasons with low precipitation. Accordingly, in countries with low precipitation, landslides do not occur as often as, for example, in tropical countries [3]. Extreme weather events, such as intense rainfall, rapid snowmelt, glacier thinning, permafrost degradation or increased groundwater, make slopes more susceptible to landslides. In this context, the groundwater fluctuation is a dominant landslide-triggering factor that substantially affects the stability of a slope, because the slope weight changes with

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the amount of groundwater, which corresponds to the pore water pressure. Pore water pressure, the pressure produced by water in a saturated soil, reduces the shear strength and the margin of stability of the slope.

To understand the effects of groundwater and other causes of landslides, several attempts have been undertaken towards landslide investigation. Traditionally, the first step in landslide investigation is a map analysis [4]. Using various types of maps, such as topographic, terrain, bedrock or engineering soil maps, general information about a terrain on its susceptibility to landslides is gathered. For example, aerial imagery obtained from interferometric synthetic aperture radars (InSAR) as well as light detection and ranging (LiDAR) provide detailed scientific information about a terrain, in which landslides have occurred in the past, and indicate human activities. By merging images of a certain area taken at different points in time, landslide inventory maps can be drawn providing information on past landslide types, frequencies, and impacts. Such information can advantageously be used to estimate potential future landslide hazards at a particular site.

However, due to human activities that change the natural topography or the hydrologic conditions of slopes, landslides often occur in areas that have been considered stable in the past. Therefore, several new methods have been implemented in recent years to detect landslide activity independently from past slope conditions. For example, remote monitoring of landslide-susceptible areas is a common approach that facilitates the assessment of landslide hazard and risk. Monitoring systems are used to estimate type, frequency, extent, and potential consequences of landslides that may occur. Based on analyses of landslide-related data recorded from a slope, monitoring systems are designed to provide information about critical slope states using geotechnical measuring instruments such as inclinometers, extensometers, piezometers and tiltmeters installed in the slopes [8]. Some landslide monitoring systems have been presented in the past years [9-11]; however, these monitoring systems are usually unable to operate automatically, and the collected data is not processed in real time. As a result, even if all relevant data recorded from the observed slope is available, anomalies in the slope condition are detected with significant time delays. Autonomously collecting, processing and communicating landslide parameters can help to overcome this limitations of current landslide monitoring systems.

In this paper, the design and implementation of an experimental Internet-enabled multi-sensor system for continuous monitoring of landslide processes is presented. Providing authorities and decision makers with critical information on actual slope conditions, the monitoring system continuously collects field data through a number of wireless sensor nodes installed in the monitored slope. In particular, soil moisture data, directly related to the pore water pressure, is collected and analyzed directly on the sensor nodes, facilitating real-time identification of anomalies related to landslide initiation due to increased pore water pressure. If an anomaly is detected, tilt and acceleration data is collected used and autonomously analyzed with respect to potential surface movements. Furthermore, additional information from external geospatial sources as well as weather data is integrated into the monitoring system. Warnings are issued by the system in case of high risks of landslides. In addition, the wireless sensor nodes disseminate relevant information via Internet for further data analyses. This paper first describes the architecture of the monitoring system, including its hardware and software components. Then, field tests are presented that are conducted to validate the system. After a discussion of the results obtained in this study, the paper concludes with a brief summary and an outlook on possible future research directions.

II. Design and Implementation of a Landslide Monitoring System

The Internet-enabled multi-sensor system for continuous monitoring of landslide processes is composed of three basic components, as shown in Fig. 1:

i. A *wireless sensor network* consists of sensor nodes that are installed in the monitored slope, and autonomous software programs are embedded into each sensor node to continuously collect and analyze field data.
ii. A *desktop application*, installed on a computer located on site, is designed to persistently store the field data in a remotely connected database. In addition, the desktop application provides diagnostic and visualization functionalities that can be performed on the data sets stored.
iii. A *web application* enables remote access to the database (and thus to the field data); the web application also integrates geospatial and weather information from external sources.

After a brief description of the overall system architecture and the proposed monitoring concept, each component of the multi-sensor monitoring system is described in details in the following subsections.

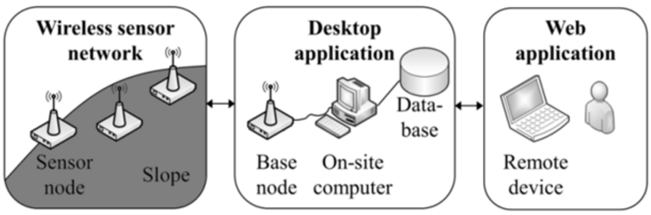

Fig. 1. Architecture of the Internet-enabled multi-sensor system.

To autonomously monitor landslide processes, the concept of “multi-sensor data fusion” is applied. Multi-sensor data fusion refers to the combination of data from different sensors and related data from associated databases in order to enhance the precision of the data analysis. As elucidated previously, groundwater and soil moisture are among the main factors that affect slope states. Therefore, the multi-sensor system continuously collects and analyzes soil moisture to identify the triggers (or causes) of a landslide. However, soil moisture data alone does not provide information on slope movements. For this reason, the multi-sensor system also measures tilt and acceleration data enabling a real-time detection of slope movements.

For implementing the prototype system, data collected by two sensor types, soil moisture sensors and accelerometers (providing tilt and acceleration data) is combined as shown in Fig. 2. The states of the observed slope – stable, marginally stable, and actively unstable – are categorized based on the slope state classification proposed by Crozier [6]. In stable state, soil moisture data is collected and analyzed by comparing a current measured value to a threshold value that is defined by a human expert. If the actual soil moisture value exceeds the threshold value, landslide occurrence is possible. Then, the slope is in marginally stable state and a *warning* is issued. Besides soil moisture data, tilt data is collected in marginally stable state. When a movement occurs, anomalies in the tilt data are detected, and the slope is in actively unstable state. To inform human individuals about the detected movement, an *alarm* is issued. In actively unstable state, the surface displacement of the slope is observed, and the inverse values of the velocity of surface displacement are calculated. The inverse values of the velocity of surface displacement have proven to be helpful in estimating the failure time of a slope [12]. Fukuzono [13] has proposed a graphical method to predict the slope failure time, which is implemented into the monitoring system. If the velocity increases over time, the inverse velocity decreases approaching 0. If the inverse velocity is close to 0, a landslide occurs. Graphically, the time of failure can be predicted if the inverse velocity is plotted over time, as shown in Fig. 3.

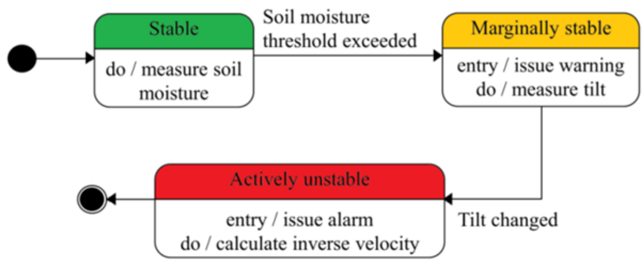

Fig. 2. Landslide monitoring concept.

As can be seen from Fig. 3, the failure of the slope is expected at that time, at which the inverse velocity crosses the abscissa. Three shapes of curves of inverse velocity are distinguished depending on the slope characteristics: linear, convex, or concave. In case of a linear curve, two inverse velocity values at different points in time are sufficient to estimate the failure time of the slope. In most cases, the inverse velocity curve is expected to be linear, but the failure time can also be predicted for convex or concave curves. In the latter cases, the failure is expected when the tangent line of the inverse velocity curve crosses the abscissa. The curves are mathematically described by the following equation:

$$v^{-1} = \{a(\alpha - 1)\}^{\frac{1}{\alpha-1}} \cdot (t_f - t)^{\frac{1}{\alpha-1}} \quad (1)$$

where v is the velocity of surface displacement, v^{-1} is the inverse velocity, a and α are experimental constants, and t_f is the failure time.

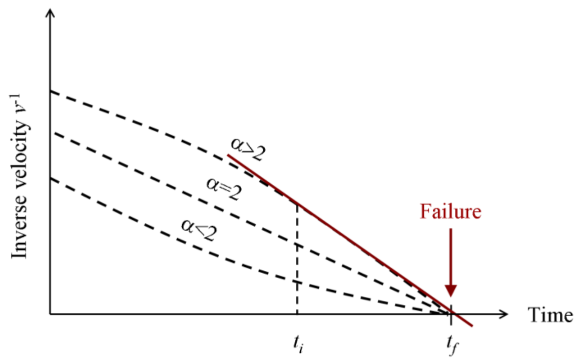

Fig. 3. Inverse velocity plotted over time.

A. *Wireless sensor network*

The primary advantages of wireless sensor networks for environmental monitoring, compared to traditional cable-based monitoring systems, are the flexibility in communication and the low-cost installation of the wireless sensor nodes. First, wireless sensor nodes designed for monitoring are able to process data in a decentralized manner and to identify anomalies in the collected data in real time. Second, unlike cable-based monitoring systems, wireless sensor networks do not require extensive coaxial wires for connecting sensors to data processing systems. As a result, monitoring systems based on wireless sensor networks allow for greater nodal densities than cable-based systems [14]. In this study, a wireless sensor network, composed of several multi-sensor nodes that contain both embedded and external sensors, is designed for continuous monitoring of landslide processes.

1) Hardware of the multi-sensor nodes

For the prototype implementation of the wireless sensor network, Oracle SunSPOT sensor nodes are deployed [15]. A SunSPOT sensor node is a battery-powered device, almost entirely written in Java. Each node has a 400 MHz 32-bit ARM920T core processor with 1 MB RAM and 8 MB Flash memory. The processor runs a specially designed small-footprint Java virtual machine named Squawk. For wireless network communication, each node uses an integrated Texas Instruments CC 2420 radio transceiver. The transceiver complies with the IEEE 802.15.4 standard and operates in the unlicensed industrial, scientific and medical (ISM) band. A SunSPOT sensor node includes an integrated three-axis MMA7455L accelerometer. Beyond that, the nodes provide analog inputs, general purpose I/O connector pins and high current output pins for attachment of external sensors and actuators. Furthermore, several RGB light-emitting diodes (LEDs) are integrated, which can be used as status indicators when being deployed in the field.

2) Soil moisture sensor

To collect groundwater data, Vegetronix VH400 soil moisture sensors [16] are attached to the sensor nodes through the analog input pins. The VH400 is a low-power soil moisture sensor that consumes less than 7 mA for operation. By using the dielectric constant of the soil, the sensor measures volumetric water content (VWC) and produces an output voltage proportional to the VWC. Volumetric water content (Eq. 2) is a numerical measure of soil moisture, expressed as a ratio of the volume of water V_w and soil volume V_t:

$$VWC = V_w / V_t \tag{2}$$

The VH400 sensor is insensitive to water salinity and does not corrode over time. To achieve greater measurement accuracy, the sensor is calibrated in this study using the specific soil type of the slope being monitored.

3) Accelerometer

The MMA7455L accelerometer embedded in each sensor node is used to provide information on slope surface displacement, which is determined by tilt and acceleration measurements. The accelerometer measures accelerations over a scale of either ± 2g, ± 4g or ± 8g, where g is the gravity constant. Using the acceleration along an axis, the tilt of the sensor node with respect to gravity is determined. The tilt angle θ of an axis is computed directly on the nodes according to the following equation:

$$\theta = \arcsin\left(\frac{a_{axis}}{|\bar{a}|}\right) \tag{3}$$

where θ is the tilt angle measured in radians, a_{axis} is the acceleration measured along the given axis, and $|\bar{a}|$ is the magnitude of the total acceleration.

4) Multi-agent system

To collect and to analyze the slope data in a decentralized fashion, a multi-agent system is embedded into the wireless sensor nodes. The multi-agent system is composed of several interacting, autonomous software programs, referred to as "software agents", that communicate with each other through messages. By acting autonomously with a certain degree of flexibility, software agents can enhance the modularity, the flexibility and the extendibility of monitoring systems. According to Woolridge [17], software agents can be characterized by the following features:

- Autonomy: Software agents act without direct human intervention. They are capable to control their own internal states and to decide independently from other software programs which actions are appropriate to achieve their goals.
- Reactivity: Software agents are situated in an environment, being able to perceive and respond timely to events and changes that occur in it.
- Pro-activeness: Software agents do not only act in response to changes in the environment, but take initiative and apply goal-directed behavior to satisfy their objectives.
- Social ability: To achieve their goals, software agents interact with each other, thus being able to cooperate, to coordinate and to negotiate.

The multi-agent system embedded into the wireless sensor nodes consists of a number of software agents that are designed according to the Burmeister methodology [18]. The Burmeister methodology describes the analysis and design phase of developing multi-agent applications and is built upon object-oriented methods. Three task-specific categories of software agents are prototypically implemented in this study to meet the system's main functions, each of which being responsible for one distinct task to be executed in landslide monitoring. These categories are the *controller agents* and the *sensing agents*, where the category of sensing agents is further subdivided into *tilt agents* and *soil moisture* agents. Instances of all agent categories are created on every wireless sensor node.

5) Controller agent

Controller agents are embedded into the sensor nodes to manage the autonomous processing in the nodes. The controller agents are responsible for the instantiation of the tilt and soil moisture agents and enable the interaction between all agents. Moreover, controller agents provide functionalities to send measured data and notification messages from the wireless sensor nodes to the desktop application. Vice versa, controller agents receive commands sent from the desktop application to the sensor nodes.

Fig. 4 shows an activity diagram of a controller agent. Once the controller agent has autonomously been created on a sensor node, it instantiates a soil moisture agent and a tilt agent. The controller agent opens a connection to a base node that is connected to the on-site computer (Fig. 1). Then, the controller agent waits for a message from the desktop application and, thereupon, sends an acknowledgement to perform a connection handshake, which establishes the connection between the sensor node and the base station.

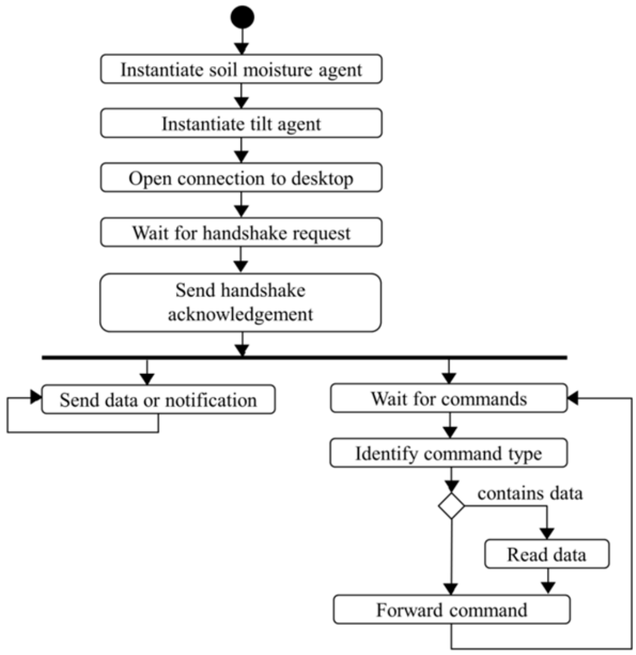

Fig. 4. Activity diagram of the controller agent.

6) Sensing agents

The soil moisture agent and the tilt agent are of type sensing agent. A sensing agent is defined by the following internal states that are related to the states of the observed slope:

1. Initial
2. Stable
3. Marginally stable
4. Actively unstable
5. Terminated

In "initial" state, a sensing agent collects measurements to determine the initial values of the observed slope parameters at system startup. The states "stable", "marginally stable", and “actively unstable” correspond to the global state of the monitoring system. The observed slope and the monitoring system are categorized as stable, marginally stable or actively unstable, according to the classification proposed by Crozier, as described earlier. The first of the LEDs of a sensor node, as shown in Fig. 5, indicates the state of the system by blinking at regular intervals in an appropriate color (Table 1). In “terminated” state, the agents stop collecting data.

TABLE I: LED COLOR DEPENDING ON THE STATE OF THE OBSERVED SLOPE

System state	LED color
Stable	Green
Marginally stable	Yellow
Actively unstable	Red

Fig. 5. LED indicting the state of the observed slope.

a) Soil moisture agents

The internal states of the soil moisture agents are presented in Fig. 6 in terms of a state machine. Upon initialization, the soil moisture agents directly change to “stable” state and measure periodically the volumetric water content of the soil (i.e. the soil moisture). It should be noted that due to the capability of the agents to autonomously analyze the soil moisture data, it is not necessary to continuously send the data to the desktop application every time a measurement is performed. By contrast, the soil moisture data is sent only at specific times, defined by human experts (e.g. once an hour), to reduce the amount of data transmitted through the wireless sensor network. The analysis of the soil moisture data on the sensor nodes includes comparisons of measured soil moisture values to threshold values. If the actual soil moisture value exceeds a threshold value, landslide occurrence is possible. A soil moisture agent reacts on the detected change in the slope condition by informing the controller agent and changing to “marginally stable” state. The controller agent, in turn, sends a notification message to the desktop application and informs the tilt agent that the system state has been changed. In “marginally stable” state as well as in “actively unstable” state, the soil moisture agent collects data with a higher sampling rate than in “stable” state, and data is sent to the desktop application each time a measurement is performed.

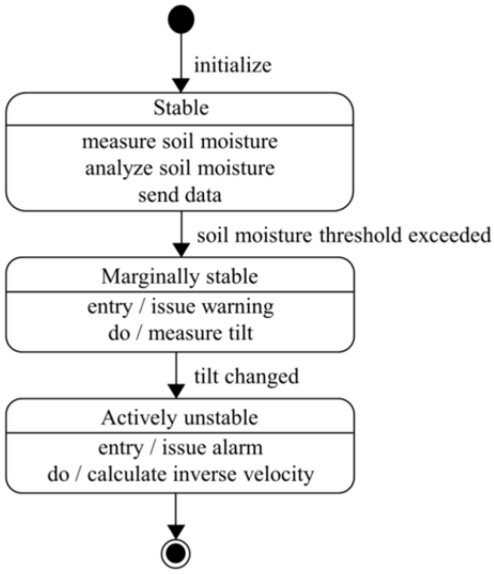

Fig. 6. State machine of the soil moisture agent.

b) Tilt agents

The tilt agents are used for detecting surface displacements. In stable state, the tilt agents are inactive. Internally, tilt measurements are triggered on a sensor node when a soil moisture agent has detected high volumetric water content. In marginally stable state, the tilt agent measures the orientation of the sensor node along its x-, y-, and z-axis using Eq. 3 and sends the result to the desktop application. The actual tilt values are compared to the initial values that represent normal slope conditions. If anomalies are detected, the tilt agent changes to actively unstable state. In actively unstable state, the tilt agent collects acceleration data and sends the data to the desktop application. The acceleration data is used by the desktop application to calculate the inverse velocity values of surface displacement as an indicator of the risk of landslides.

B. Desktop application

The desktop application, written in Java, consists of several software modules and a graphical user interface. A basic overview of the software modules and the interaction paths between the modules are shown in Fig. 7. The software modules are briefly described in the following subsections. As will be shown, different information technologies and software tools are integrated into the modules to achieve the design goals of the desktop application.

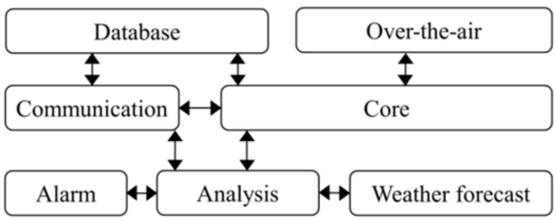

Fig. 7. Architecture of the desktop application.

1) Core module

The core module manages the sensor nodes installed in the slope. The core module comprises sensor node information relevant to monitoring, such as a unique 64-bit network address of every node as well as the geographic coordinates (i.e. latitude and longitude).

2) Communication module

The communication module is designed to provide reliable communications between the desktop application and the wireless sensor network. For that purpose, connections are established to all sensor nodes by connection controllers. A connection controller defines a port number corresponding to the connection and obtains data input and data output streams to receive data or notifications from the wireless sensor node.

3) Over-the-air module

The sensor nodes used in this study integrate embedded software that runs on the nodes and that listens for commands and messages send by other sensor nodes or by human users. The software also provides a so called "over-the-air functionality". Over-the-air functionality allows for locating any nearby sensor node and retrieving information about the nodes' configuration. Through the desktop application, a user can discover all sensor nodes in the range of a certain node that is connected to the on-site computer and, for example, retrieve the battery properties. Thereby, it is possible to update the software running on the sensor nodes or to extend the capabilities of the software agents without manually installing or updating software applications.

4) Weather forecast module

To provide information on weather conditions, weather data from external sources is integrated into the landslide monitoring system. Several weather forecast websites provide such data and application programming interfaces (APIs) to integrate the weather data into applications. A weather forecast module is implemented as a part of the landslide monitoring system. The weather forecast module uses the Forecast API [19] to query a forecast website and to retrieve the current conditions and weather forecasts for a certain location. A forecast is retrieved at regular intervals and used for the analysis of landslide possibility in case of high soil moisture values. The forecast contains several properties, among which precipitation probability, precipitation intensity and precipitation type.

5) Database module

The database module ensures the persistent storage of the measurement data received from the wireless sensor network. Here, a MySQL database system is deployed. To remotely connect the desktop application to a MySQL database system, the Java Database Connectivity (JDBC) technology [20], an industry standard for database-independent connectivity between the Java programming language and MySQL database systems, is used.

An excerpt of the database schema is shown in Fig. 8. In general, the database consists of a *sensornodes* table and several measurement tables. The *sensornodes* table contains the properties of the sensor nodes, i.e. IEEE address, latitude and longitude. The measurement tables differ in the type of the stored data as described earlier. *Soilmoisture* tables are designed for storing soil moisture data, *tilt* tables for tilt data, *acceleration* tables for acceleration data, and *inversevelocity* tables for the inverse velocity. Each type of measurement table is created for every sensor node, whereby tables are identified with a unique name that includes the last 16 bits of a sensor node's network address. To give an example, the tables created for two sensor nodes, whose addresses end with "792d" and "7840", are shown in Fig. 8.

6) Analysis module

The analysis module provides analytical functionalities. If the system is in marginally stable state (i.e. when a soil moisture value exceeds – or has exceeded – the soil moisture threshold), the analysis module checks whether heavy precipitation is expected. For that purpose, the weather forecast module is used to receive the actual precipitation probability and the average expected precipitation intensity.

For example, if the precipitation probability is above 60% and the intensity is above 0.4 inches of liquid water per hour, heavy rainfall is expected. In the latter case, a *warning* is issued and sent via email to the involved individuals.

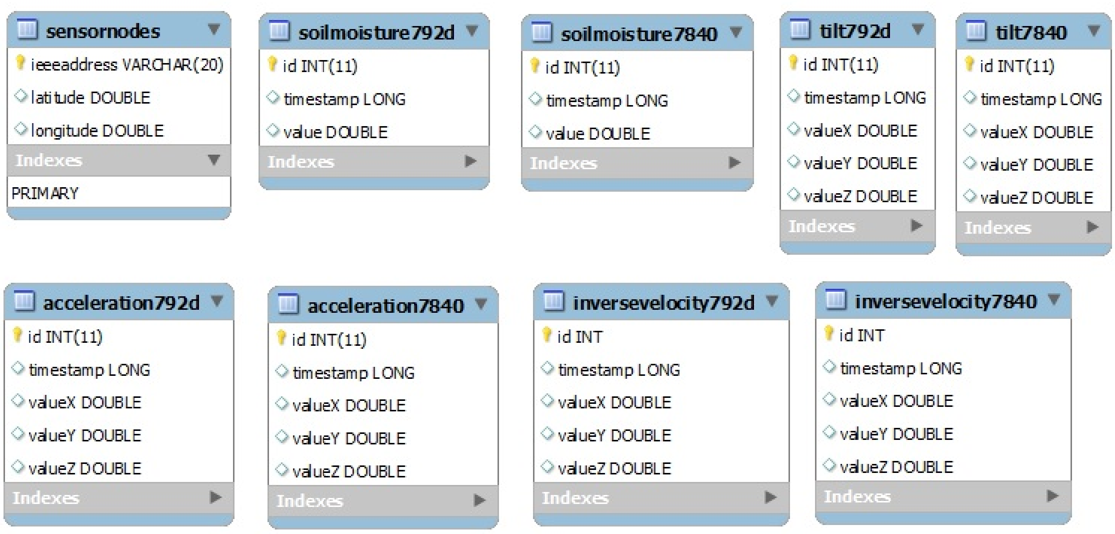

Fig. 8. An excerpt of the database schema.

Furthermore, the analysis module uses the acceleration data collected by the wireless sensor nodes to compute the inverse velocity of the slope surface. To calculate the inverse velocity, the analysis module computes the velocity by numerically integrating the acceleration data. Specifically, the trapezoidal rule [21] is applied to approximate the acceleration. The velocity v_i is calculated according to the following equation:

$$v_i = v_{i-1} + (a_{i-1} + a_i) / 2 \cdot (t_i - t_{i-1}) \qquad (4)$$

where v is the velocity, a is the acceleration, and t is the point in time.

7) Alarm module

To automatically send emails to human individuals for issuing warnings and alarms, the alarm module utilizes the JavaMail Application Programming Interface (JavaMail API) [22]. The JavaMail API provides functionalities that can be integrated into software programs for sending emails based on Internet standards such as MIME, SMTP, POP3, and IMAP. Two types of email messages are sent by the alarm module. First, a warning message is sent if the slope is in marginally stable state and heavy precipitation is expected. Second, an alarm message is sent if the slope is in actively unstable state.

C. Web application

The web application is designed to provide remote access to the database and to the desktop application of the monitoring system. The web application is implemented utilizing Java Server Pages technology (JSP). In essence, the web application retrieves sensor data from the database and visualizes the data using the Google Charts library [23] that is used to display the data in terms of charts. A chart is created for every sensor node and for all available sensor readings, i.e. soil moisture, tilt and acceleration (Fig. 9). In addition, the velocity and inverse velocity values, calculated by the desktop application, are also presented graphically by the web application.

To visualize geospatial information about the wireless sensor nodes, a map is implemented into the web application. As can be seen from Fig. 9, the sensor nodes installed in the slope are displayed as points on the map being characterized by the latitude and longitude. For the map implementation, the Google Maps API is integrated into the web application.

The web application also provides a feature allowing users to subscribe for warnings and alarms issued by the landslide monitoring system. As described above, the monitoring system automatically generates alarms and warnings when the state of the slope changes, and it sends email messages to previously specified recipients. Through the subscribe feature of the web application, a user can be added to the list of the recipients. While access to the sensor data is provided to all visitors of the web application website, access to the desktop application is provided only to authorized users.

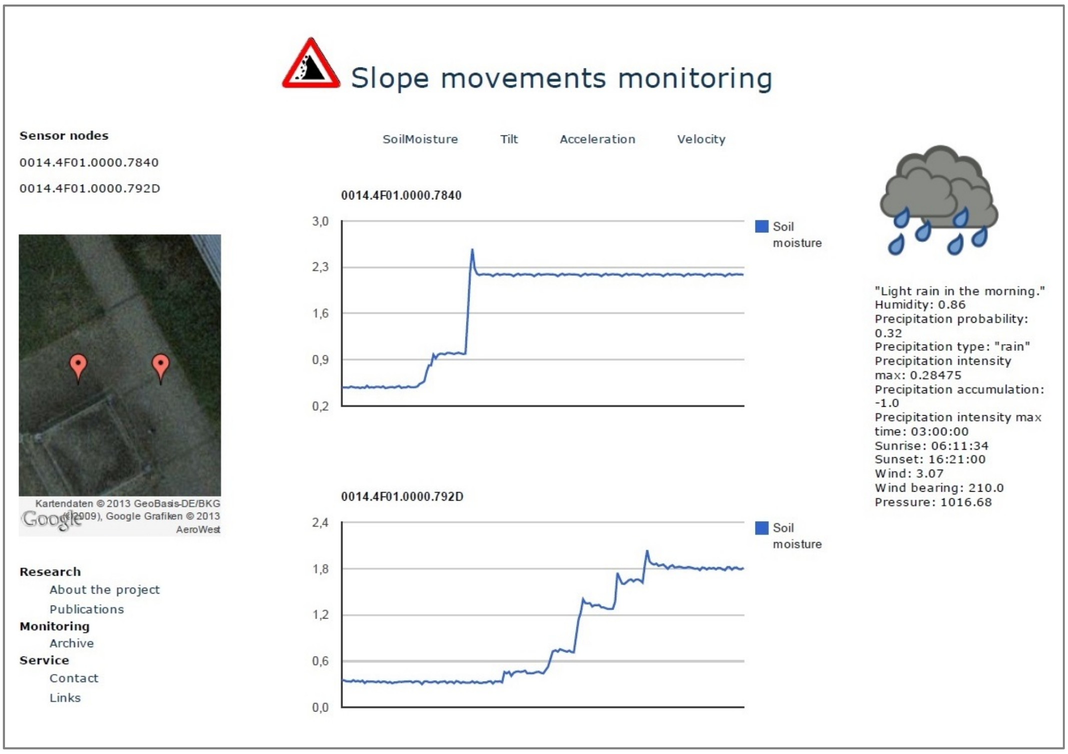

Fig. 9. Web application with experimental data.

III. FIELD VALIDATION

For the proof of concept of the experimental landslide monitoring system, a validation experiment is conducted. The main objectives are

1. to verify the capabilities of the monitoring system with respect to autonomously collecting, integrating and communicating data from the observed slope, and
2. to obtain data for investigating the relationship between changes in the slope condition, particularly groundwater changes, and landslide-related slope deformations.

A. *Calibration*

Prior to conducting the validation experiment, the monitoring system is calibrated depending on the site-specific soil type used in the experiment in order to ensure accurate soil moisture measurements. For that purpose, the soil used for the experiment is baked in an oven until the moisture is baked out. Thereupon, several small containers are filled with an equal amount of soil, having the same weight and volume. Varying amounts of water are added to the containers such that the actual volumetric water content is known. The containers are left for a few hours to let the soil distribute evenly in each sample. Then, the VH400 soil moisture sensors are installed in the containers and the voltage readings are recorded for each sample being related to the actual volumetric water content of the samples.

B. *Validation experiment setup*

For the experiment, a flume is filled with sand, as illustrated in Fig. 10. The length of the flume is 190 cm, the width is 40 cm, and the depth is 15 cm. The flume angle is approximately 40°, which is typical in terrains where natural landslides occur.

Three wireless sensor nodes (S_1, S_2, S_3) are installed in the slope, as shown in Fig. 10, and connected to an on-site computer through the base node. Each node hosts the software agents introduced in the previous section: a controller agent, a soil moisture agent, and a tilt agent. The multi-agent system is thus composed of three *controller* agents, three *soil moisture* agents and three *tilt* agents. During the experiment, the agents collect data from the slope, analyze the data and communicate with agents running on other sensor nodes.

C. *Autonomous landslide monitoring*

The experiment is conducted in three phases that are described as follows.

Phase 1: Initialization of the monitoring system

At system startup, all agents are automatically initialized. The controller agents of the nodes establish connections to the desktop application running on the on-site computer in order to enable data communication. The soil moisture agents and the tilt agents collect data to determine the initial (i.e. stable) state of the slope. The initial data is sent with corresponding timestamps (indicating the time at which measurements have been recorded) to the desktop application. This data is automatically stored in the MySQL database and published online through the web application.

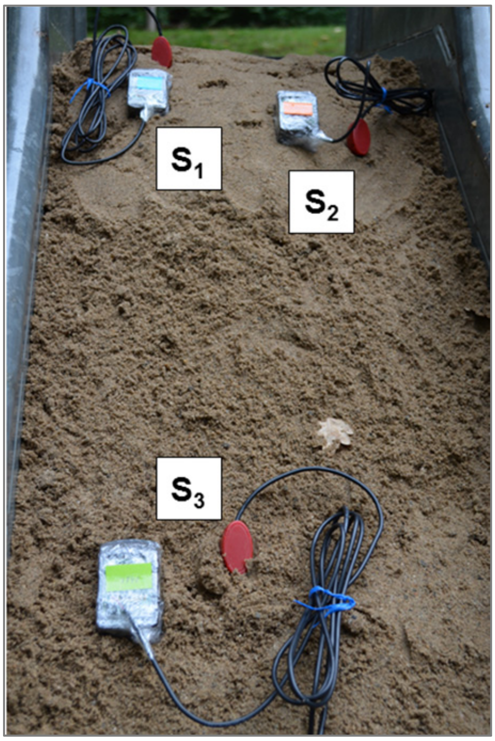

Fig. 10. Sensor nodes installed in the flume.

Phase 2: Landslide initiation

To initiate the landslide process, heavy rainfall is simulated. Water is continuously poured onto the sand surface while the soil moisture agents periodically measure the volumetric water content of the soil. The actual water content is analyzed directly on the sensor nodes by the soil moisture agents. After approximately four minutes, the soil moisture agent running on S_3 is the first agent to detect a high water content of the soil (Fig. 11) and informs the desktop application as well as all other sensor nodes by sending a message. Upon receiving the message, the desktop application issues a warning. Upon receiving the warning, the controller agents running on the sensor nodes forward the warning to the tilt agents. Then, the tilt agents running on all sensor nodes start measuring the orientation of the nodes. The water content and the tilt data are continuously communicated over the network to the desktop application and are stored in the database. The web application continuously updates all online information about the slope including the visual representations of the collected data.

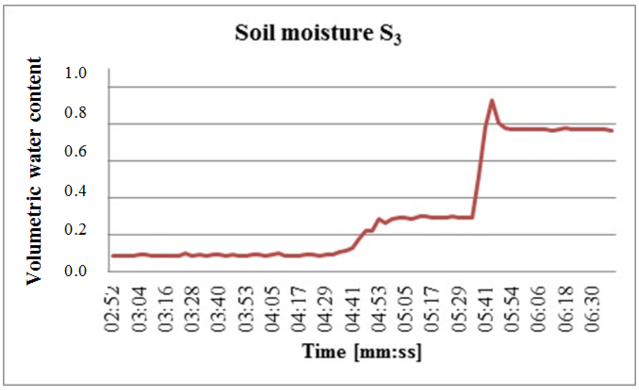

Fig. 11. Soil moisture data collected by sensor node S_3.

Phase 3: Landslide detection

The tilt data is autonomously analyzed by the tilt agents. Several minutes after the soil moisture agent running on S_3 has detected the abnormal high water content, the orientations of the sensor nodes in the slope change, as first identified by the tilt agent on S_2 (Fig. 12).

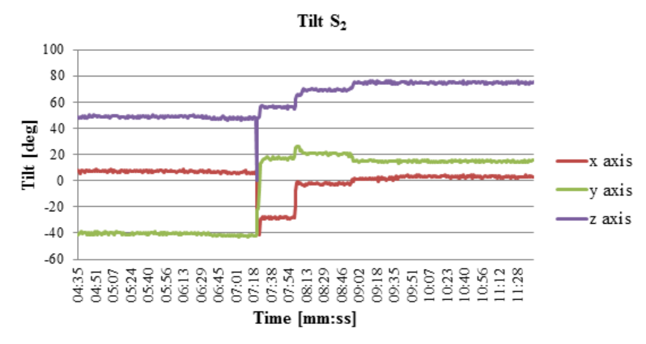

Fig. 12. Tilt data collected by sensor node S_2.

To compute the inverse values of the velocity of surface displacement, the tilt agents collect acceleration data. Fig. 13 illustrates the inverse velocity calculated by S_2. As a result of the changes in the acceleration of the sensor node, the velocity of the sensor node increases. Accordingly, the inverse velocity decreases with time approaching 0. The inverse velocity curve is convex and crosses the abscissa approximately eight minutes after start of the experiment. This is exactly the failure time of the slope as can be roughly predicted from the collected field data.

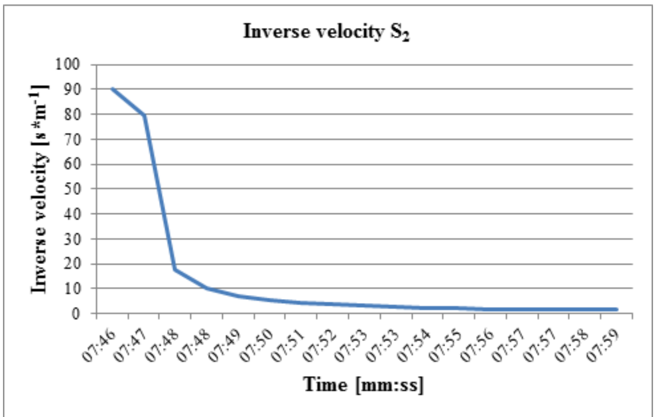

Fig. 13. Inverse velocity calculated by S_2.

D. Experimental results

In summary, the field test has demonstrated that the monitoring system is capable of autonomously collecting and processing slope data. The experiment has also corroborated that groundwater changes are related to landslide processes; the increased volumetric water content of the soil has led to slope failure. It has been shown that the system identifies abnormal slope deformations (e.g. changes in the orientation of the sensor node and the acceleration of the slope surface) without any human interaction. Warnings have been issued automatically. The inverse velocity concept applied to analyze slope surface deformations has successfully estimated the time of the landslide before landslide occurrence. In addition, data and relevant information have been made available remotely through the Internet.

IV. Summary and Conclusions

The design and prototype implementation of an Internet-enabled multi-sensor system for continuous monitoring of landslide processes have been presented. The system comprises of three major components: a wireless sensor network, a desktop application, and a web application. The wireless sensor network, composed of a number of wireless sensor nodes, is designed to collect local field data from the observed slope based on autonomous software programs embedded into the sensor nodes. As a distinct advantage compared to conventional monitoring approaches, the field data is analyzed directly on the sensor nodes in a fully decentralized fashion. The desktop application stores the data obtained from the wireless sensor network in a database system, provides diagnostic functions, and visualizes the recorded data sets. The web application, finally, integrates external geospatial and weather information relevant to assessing the risk of landslides, and it provides remote access to the field data.

A field test, serving as a proof of concept of the proposed monitoring approach, has been conducted in this study. In summary, it could be demonstrated that the autonomous software programs embedded into the wireless sensor nodes reliably collect, processes, and analyze the field data. Also, slope anomalies relevant to landslides, as simulated in the field test, are detected and early warnings are autonomously issued.

In total, it has been shown in this paper that autonomous wireless sensor nodes have the potential to substantially enhance the reliability and efficiency of landslide monitoring as compared with traditional systems. In particular, merging local groundwater, tilt and acceleration information provided by the sensor nodes with geospatial and weather information, as in the prototype monitoring system, supports human individuals in landslide risk assessment. Although the feasibility of implementing the newly proposed monitoring approach could be demonstrated, there is still room for improvements in a number of areas. For example, future work may include integrating further diagnostic functionalities into the monitoring system, and additional sensors may be connected to the wireless sensor nodes installed in the slope (such as extensometers and GPS sensors). Besides long-term field deployments, future work may also include the integration of model-based simulations of the slope condition in order to better understand the landslide dynamics.

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