MONITORING AND EARLY WARNING OF SLOPE INSTABILITIES AND DEFORMATIONS BY SENSOR FUSION IN SELF-ORGANIZED WIRELESS AD-HOC SENSOR NETWORKS

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Abstract

Geohazards, like landslides in soil and rocks which are induced by rainfall, flooding, earthquakes and human activity are dramatically increasing worldwide. Apart from socio-economic factors, like increasing population and concentrations of settlements on endangered areas, extreme weather conditions are the main reasons for this ascent. But, these occurrences are not only concentrated on the high mountain ranges with steep slopes and strong relief. In February 2003, a landslide in the middle of Germany near the village of Wolfstein-Roßbach damaged some houses (one of them totally). Another example is the Manshiet Nasser failure in Cairo in September 2008, where a large rock tilt buried many houses. This few examples show the devastating effect of geohazards in settlement areas and the need for precise monitoring systems to protect human life and property.

In the frame of the special program “Geotechnologien” of the German Federal Ministry of Education and Research (BMBF), the joint project “Sensor-based Landslide Early Warning System” (SLEWS) aims at the development of a prototypic Alarm- and Early Warning system (EWS) for different types of landslides using wireless sensor networks (WSN) for real-time monitoring. The WSN consists of a number of so called sensor nodes and a data collecting point (gateway). The solar powered gateway is connected either directly or by GSM/GPRS to the internet and subsequently to a data infrastructure to process the sensor data. Each node has a sensor board were the measuring sensors and the communication and processing unit are integrated. Special features of the Network are the real-time ability, self-organization and self-healing capacity, energy efficiency, bidirectional communication skills and data interfaces regarding OGC (Open Geospatial Consortium) specifications. The bidirectional structure of the system enables data transfer not only from each node to the spatial data infrastructure (SDI), but also to transmit commands or software-updates to individual or a group of nodes. Special sensor nodes for the monitoring of surface deformations due to landslides, measuring acceleration, tilting or extension, were developed and tested.

Apart from the detection of direct deformations caused for example by landslide movements, the system also allows the monitoring of indirect deformations on buildings and constructions, like bridge or retaining walls. Furthermore, the remote monitoring of flood control basins, dams or tailings in or close to housing areas becomes easy to set up in a cost-effective way. Open structures of the system enable a very rapid and flexible adjustment to the changed conditions and also permit a simple linkage with other data sources (e.g. climate data) or other sensor networks. Also, temporal deployments for safety purposes in road construction or foundation engineering become possible as the WSN is self-powered, the components are quite small and easy to
set up. In the future other sensors may be integrated into the sensor notes so further tasks in spatial environmental monitoring may be covered.

**Keywords:** Slope instability, deformation, sensor fusion, sensor networks

1 Introduction

Geohazards, like landslides in soil and rock, which are induced by rainfall, flooding, earthquakes and human activity, are dramatically increasing worldwide (Munich Re Group, 2009). Apart from socio-economic factors, like increasing population and concentrations of settlements on endangered areas, extreme weather conditions are the main reasons for this ascent. But these incidents are not only limited to the high mountain ranges with steep slopes and strong relief. In February 2003, a landslide in the middle of Germany near the village of Wolfstein-Rossbach damaged some houses (one of them completely). In May 2009 boulders of about 15 to 20 m³ in size fell down from a rock face of 180 m in height and crashed in a building in the village of Bad Ems (near Koblenz; Germany). Another example is the Manshiet Nasser failure in Cairo in September 2008, where a large rock tilt buried many houses. In June 2009 about 80 miners were killed by a landslide in the southwest of China. These few examples show the devastating effect of landslides in settlement areas and the need for precise monitoring systems to protect human life and property.

2 Sensor-based Landslide Early Warning System (SLEWS)

In the frame of the special program “GEOTECHNOLOGIEN” of the German Federal Ministry of Education and Research (BMBF), the joint project “Sensor-based Landslide Early Warning System” (SLEWS) aims at the development of a prototypic Alarm and Early Warning system (EWS) for different types of landslides using wireless sensor networks (WSN) for real-time monitoring (Arnhardt et al., 2007). The WSN consists of a number of so

![Figure 1: Number of disasters reported from 1900 to 2008 (source: EM-DAT: The OFDA/CRED International Disaster Database; www.em-dat.net - Université Catholique de Louvain - Brussels – Belgium). The increasing number of disasters reported shows that more and more people are (and will be) affected by natural hazards. The reasons for this are on one side the growth of population and the population expansion (urbanization) even in endangered areas. On the other side extreme and changed weather conditions contribute to the increase of disasters in many regions worldwide.](image)
Figure 2: Structure of a self-organizing (Ad-Hoc) wireless sensor network. Depending on signal strength the nodes seek for best and most stable connection to other nodes of the system. If a connection fails or is blocked a new route will be established independently without manual intervention. This avoids the collapse of the whole system if some nodes are failing. Data from each node is send via radio either directly to the gateway or via other nodes (Multi-Hop).

called sensor nodes and a data collecting point, the gateway (Figure 2).

The solar powered gateway is connected either directly or via GSM/GPRS to the internet and subsequently to a data infrastructure to process the sensor data. Each node has a sensor board where the measuring sensors and the communication and processing unit are integrated (Figure 3). Special features of the Network are the real-time ability, self-organization and self-healing capacity, energy efficiency, bidirectional communication skills and data interfaces regarding OGC (Open Geospatial Consortium) specifications. The bidirectional structure of the system enables data transfer not only from each node to the spatial data infrastructure (SDI), but also to transmit commands or software-updates to individual or to a group of nodes. Special sensor nodes for the monitoring of surface deformations due to landslides, measuring acceleration, tilting or extension were developed and tested (Fernandez-Steeger et al., 2008).

In laboratory, first tests were conducted under stable conditions to obtain information about data spreading and thus the accuracy of the different sensors in the setup. Even considering the accuracy limitations of the used test environments, the deviation of measuring data is quite low with minor variance. All tests were performed using sensors integrated in the sensor network environment to prove the operational accuracies. For example, the tilt sensor showed accuracies of about +/-0.06° (Figure 4), +/-0.008g shows the acceleration sensor and accuracies of +/-0.1 mm are achievable with the displacement transducer. In order to improve the test environment to be more accurate
and sensitive, test stations with very precise computer control are being developed nowadays. Further tests were performed to obtain information about the measuring resolution of the sensors in the WSN environment. The results are also quite satisfactory. For example, tilt changes of up to 0.1° and displacements of 0.1 mm can be monitored very reliably. Since Autumn 2009, the system is operating in the “Elpandstein” mountains in Saxoney under suitable landslide environment.

Another very important aspect of the project is the sensor fusion. The fusion (i.e. combination and comparison) of all sensor data from the sensor network contributes to the decision making of alarm and early warning systems and allows a better interpretation of data. The comparison of data from different (complementary sensor fusion) but also same sensor-types (redundant sensor fusion) permits a verification of the data (Figure 5). The development of special algorithms allows further analysis and evaluation step namely the combination of data from all nodes of the network (sensor node fusion). Especially the detection of measurement errors and malfunctions is of high interest. A warning system that shows many false alarms lose its acceptance by users, operators and public. Therefore it is very important to detect errors before the whole warning chain is activated. Sensor fusion can be used to find errors and uncertainties and thus avoids the trigger of a false alarm (Figure 6).

3 Application of wireless sensor networks

Apart from the detection of direct deformations caused by landslide movements (Figures 7–8), for example, the system also allows the monitoring of indirect deformations on buildings and constructions, such as bridges (Figure 9) or retaining walls.

Furthermore, the remote monitoring of flood control basins, dams or tailings in or close to housing areas becomes easy to set up in a cost-effective way. Open structures of the system enable a very rapid and flexible adjustment to changed conditions and permit a simple link-
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Figure 5: Sensor fusion for the detection of movement of a toppling rock tower (upper picture) and for the detection of errors and mistakes (Figure 6). To monitor the movements, several sensor nodes may be attached directly or near the moving block, but also on the stable not moving rock face. If the block moves, the sensors are affected and show changes in their measuring values (presuming that the movement exceed the sensor resolution). The combination of identical sensor types mounted at different positions of the moving block provides already information about movement intensity, but also the type and direction of movements (foot rotation or head rotation). Further information obtained from other sensors at the stable rock face should normally indicate no changes.

Figure 6: Detection of mistakes and measuring errors. One of the sensors (acceleration sensor in the middle of the tower) indicates changes, while the sensors nearby show no changes. Also the tilt sensor on the same sensor node shows no changes. Thus the data from the acceleration sensor must be irrelevant.

Figure 7: Example of a surface deformation in landslide areas that can be monitored by the SLEWSwireless sensor network. The spreading movement of the block leads to an opening of cracks and fissures. Nodes with displacement transducers can be used here to detect the movement.
Figure 8: Breach in a retaining wall in a landslide area.

Figure 9: Usage of a wireless Ad-hoc, Multi-Hop sensor network for bridge monitoring (source: ScatterWeb 2008). Strain gauges and pressure sensors are used to detect deformations and distortions along the bridge. The data of different sensors are sent via radio to the gateway (Scattergate) and from there via GRPS/UMTS to the operator.

As geohazards like tsunamis, earthquakes and landslides are endangering more and more for the population and its infrastructures, it is important to develop monitoring and alarming systems that are reliable and can warn in time. The environmental conditions in such areas are often inhospitable and sometimes difficult to reach, hence measuring systems have to be able to cope with these difficulties. Infrastructures often do not exist or can be damaged or destroyed completely when such an event occurs. Therefore, it is reasonable to use robust but also self-sustaining instruments that can work before, during and also after the event. Wireless self-organizing sensor networks can be setup very easily in such area and present a cost-efficient solution in comparison to current special systems. Due to the usage of wireless communication lines, no cable have to be deployed and thus cannot be damaged or destroyed. Consequently the collapse of the data connection can be avoided. The small size of the node is another advantage and allows a flexible and easy to setup applicability. The self organizing structure of the system is another very important aspect, as no administrative intervention or regulation or manual control of the system is necessary anymore. Depending on signal strength of the communication line, each node finds independently its best connection to the gateway or to other nodes of the system. Therefore, the operation of the system is guaranteed even if some nodes are not operating anymore. The individual energy-supply of each node allows an autonomous operation of each node.

4 Conclusion

As geohazards like tsunamis, earthquakes and landslides are endangering more and more for the population and its infrastructures, it is important to develop monitoring and alarming systems that are reliable and can warn in time. Also temporal deployments for safety purposes in road construction or foundation engineering become possible as the wireless sensor network is self-powered, the components are quite small and easy to set up. In the future, other sensors may be integrated into the sensor notes so that further tasks in spatial environmental monitoring may be covered.
Due to the usage of the Multi-Hop data transfer, data packages from each node can be transported over long distances from node to node to the gateway. This transmission chain allows the monitoring of large areas. This spatial monitoring is very important to understand the areal interrelations and thus permits better and more precise interpretations of the movement process. The system described here uses a wireless ad-hoc multi-hop sensor network to monitor landslide processes and the surface deformations. It has a modular setup to be as flexible as possible concerning energy supply and environmental conditions. Different small low-cost sensors (Micro-Electro-Mechanical Systems (MEMS)) are integrated in the system to detect the movements like tilting, acceleration or spreading. Due to the fast data transfer, processing and visualization process, monitoring and also warning in real-time is possible. The combinations of sensor data (sensorfusion) allow cross-check and evaluate the sensor signals according to decision theory. This contributes essentially to the enhancement of data quality but also to the reduction of false alarm rates. The application of wireless sensor networks in combination with low-cost, but precise microsensors provides an inexpensive and easy way to set up intelligent monitoring system for spatial data gathering in large areas.

References
