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MONITORING OF LANDSLIDES AND INFRASTRUCTURES WITH WIRELESS SENSOR NETWORKS IN AN EARTHQUAKE ENVIRONMENT

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ABSTRACT

Besides precipitation triggered landslides, a major thread from landslides is related to earthquake triggered landslides, which account for the majority of catastrophic landslides. This fact is complicated due to the progressive development of urban areas and infrastructure, the dependency of our society on a functioning infrastructure and an increasing number of endangered objects in the affected areas. Therefore there is a need to improve basic understanding of the technical, financial and social risks posed by earthquakes triggered landslides. Furthermore basic understanding of processes and cascading hazards related to earthquake triggered landslides must be improved. For the past two decades an increasing number of landslide warning systems are developed and applied for general public and industrial purposes. On the other side earthquake triggered landslide warning and monitoring has made very little advances and is still under development. Resent research in the area of sensor network development focus on the application of micro sensors (MEMS) in ad hoc wireless sensor networks operated in an interoperable spatial data infrastructure (SDI) according to the sensor web enablement (SWE) guidelines of the OGC (Open Geospatial Consortium) for real-time monitoring of landslides like the SLEWS – Sensor based Landslide Early Warning System. The SLEWS sensor nodes provide next to motion detection also a 3D acceleration data to evaluate direction and value of the peak acceleration. This information can be used in an event case both to monitor endangered slopes or critical infrastructures and to initiate warnings to trigger e.g. rail or road blocks. Furthermore the data from the sensor network can be provided in real-time for shake or alert maps via standardized interfaces.

Keywords: wireless sensor network, MEMS, earthquake, landslide monitoring, acceleration measurements

1 INTRODUCTION

Geohazards, like landslides in soil and rock (Fig. 1), which are induced by earthquakes, rainfall, flooding or human activity, are dramatically increasing world-wide (Munich Re, 2009). Due to the progressive development of urban areas and infrastructure, more and more people settle in environments that are or

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become endangered by different types of natural hazards. This situation is being complicated by the fact that the dependency of our society on a functioning infrastructure and number of human or objects in endangered areas increases at the same time. 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. Because of the points mentioned above, geohazards are in an urgent focus today, especially in the context of climate change and sustainability but also in the sense of disaster prevention and management. There is a need to improve basic understanding of the technical, financial and social risks posed by geohazards. Especially, due to the rising vulnerability of the population to natural hazards the demand and requirements for early warning and monitoring systems continuously grow at the same time.

Figure 1. Head scarp of a landslide in Mayli Say / Kyrgyzstan initially developed after and earthquake, endangering villages sand tailings downslope.

An example is the increased vulnerability of major urban areas to earthquakes due to rapid growth of urban centers with little or no regard to proper construction of residential buildings and land use planning. Therefore, related technologies in general and in particular to monitor and predict geohazards for early warning and fast reaction have become an important research and application area. The high relevance of this topic can be seen from the fact that early warning and early action are selected as the two focus topics of the World Disaster Report 2009. Even so the number of disastrous events over the last 30 years rose, the decline of injuries, loss of livelihood and fatalities is seen at least partly as a result of the improved early warning capabilities in this time span (IFRC, 2009). Over last decade (1999 -2008) still the largest number of fatalities is related to earthquake disasters and related phenomena (IFRC, 12009). Besides precipitation triggered landslides, a major thread from landslides is related to earthquake triggered landslides which account for the majority of catastrophic landslides. Youd (1978) for instance states that about 56% of the total costs of the 1964 Alaska earthquake were related to seismically triggered slope failures. More recent disasters like the Chi-Chi earthquake 1999 and the Wenchuan earthquake 2008 prove this and show the need to extend the efforts for earthquake protection measures on slope and ground instabilities. This is even more relevant as experiences made from these two events indicate that after large earthquakes, affecting large areas and numbers of slopes, also the landslide activity increases after the event (Lin et al., 2004; Cui et al., 2009).

For this purpose a new type of environmental sensor network is necessary, providing on-line real time data retrieval without cable connection. Resent research in the area of sensor network development focus on the integration of micro sensors (MEMS) in ad hoc wireless sensor networks operating in interoperable spatial data infrastructures (SDI) according to the sensor web enablement (SWE) guidelines of the Open Geospatial Consortium (OGC) for real-time monitoring of landslides (Arnhardt et al., 2007; Fernandez-Steeger et al. 2009). An example of this type of modern environmental sensor networks is the here described SLEWS – Sensor based Landslide Early Warning System providing motion detection with position sensors as well as 3D acceleration data.

2 WIRELESS SENSOR NETWORKS AND MICRO SENSORS

One major demand in hazard monitoring is the fast and reliable data retrieval to evaluate the current situation in the monitored area. For various reasons wireless sensor networks (WSN) can provide an important contribution to reach that aim. Therefore, 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 WSN for real-time monitoring (Arnhardt et al., 2007). A WSN consists of a number of so called sensor nodes and a data collecting point, the gateway (Fig. 2).

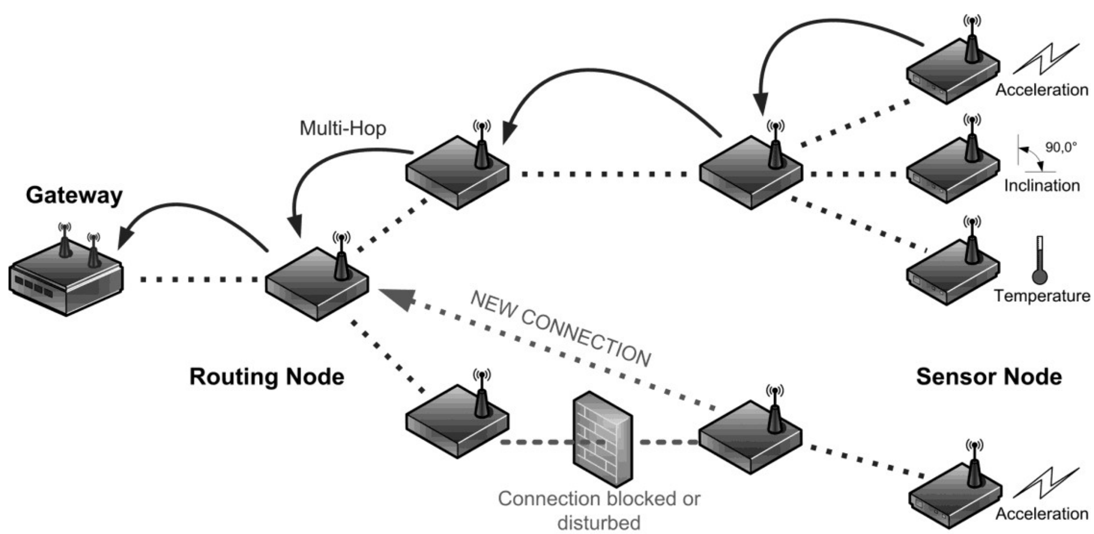

Figure 2: Structure of an ad hoc wireless sensor network (Fernandez-Steeger et al., 2009). The nodes seek independently for the best data routing and if connection fails the routing will be adapted automatically (self-healing). Data from each node is send via radio either directly or via other nodes (multi-hop) to the gateway).

2.1 Ad-hoc wireless sensor network

Modern, so called Ad-Hoc wireless sensor networks are characterized by a self organization and self-healing capacity of the system, without predefined infrastructures. It permits a non hierarchic data exchange and thus allows a very simple adaption of the network to changing conditions. The use of a wireless system eliminates the need of extensive cabling and so reduces material costs as well as the vulnerability of the system (Garich, 2007). Moreover the reliability of the system increases subsequently. The network consists of numerous sensor nodes that can interact with their neighbour nodes (Fig. 2) and perform simple data processing. Each node has its own power supply, transmission and receiving unit, microprocessor, and internal memory. This setup allows an independent working from other nodes of the

WSN and permits a stable runtime. Data packages from each node are sent directly via radio or over other nodes (multi-hop) to a collection point (gateway). The Multi-Hop function reduces the requirement for long-range transmission and in turn also the transmission power (Sohraby et al., 2007). Due to the ad-hoc character of the self organization new nodes or temporarily disconnected nodes can easily connect and synchronize themselves with the system (Fig. 2).

The sensor network used in the SLEWS project uses the 868 MHz frequency band for sending radio signals. Data rates range from 4,8 – 115kbits/s at transmission distances from 10 m to 1,2 km (Fernandez-Steeger et al., 2009). For the detection and direct monitoring of different kinds of landslide processes and deformations, a new sensor board was developed (Fig. 3). It includes the measuring sensors (acceleration, inclination and a barometric pressure sensor) and the node for data and command transfer. Due to the modular setup of the hardware it is easy to adapt or integrate the components in existing solutions. For the power supply of the nodes either batteries (battery pack) or solar powered (solar module) rechargeable batteries (Fig. 3) can be used. The gateway can be connected to a DC energy source (6 or 12 V), fuel cell or solar panel (Solargateway). It is connected either to an existing telemetric unit or via GSM/GRPS to the internet and subsequently to a data infrastructure to process the sensor data (Fig. 4). To extend the stand time and reduce maintenance of the system, the nodes can operate in different energy-saving modes. Bi-directional structure of the system allows remote control and update of the system.

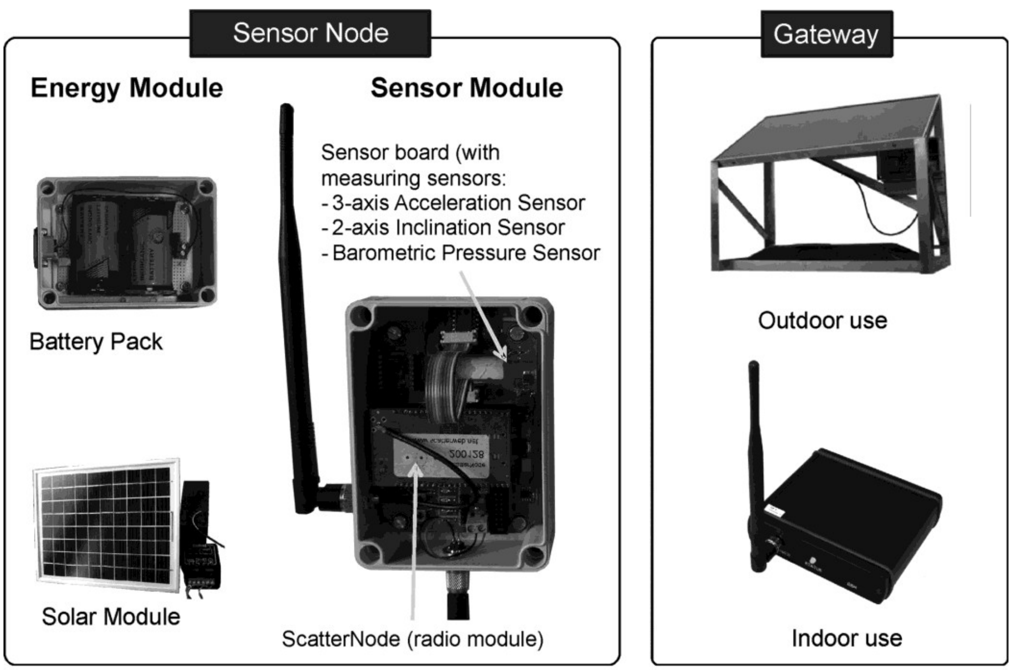

Figure 3: Components of the SLEWS sensor network. The left side shows a sensor node with the ScatterNode mounted on the sensor board and energy modules. The right side shows a solar powered and standard gateway

The signals from the sensor network collected at the gateway and transmitted from there to the server for data retrieval and processing (Fig. 4). Here a special programmed protocol (the transmit receiver unit) feeds the data in a SQL-database. Further feeder applications may be installed to transfer the data to further data applications. To provide and compute the data in a spatial data infrastructure according to Open Geospatial Consortium (OGC) standards a feeder service with an appropriate compiler can be used to store the data in a to a PostGIS spatial database (Fernandez-Steeger et al., 2009). The data base might be used as a source for a Sensor Observation Service (SOS) to retrieve the data standardised (Fig. 4). The advantage of this type of data representation is that any user or application using proper query syntax is able to access data sets without previous knowledge. Furthermore, event-based notification can be pushed asynchronously using a Sensor Alert Service (SAS) to draw user's attention in case of thresholds exceedance or system alerts.

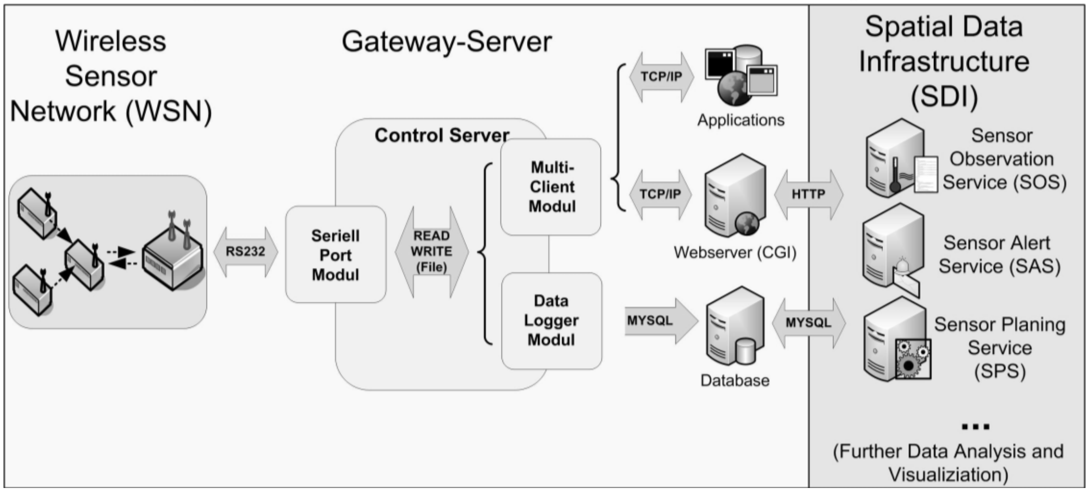

Figure 4: Workflow for data integration of the sensor network into a spatial data infrastructure (SDI) according to OGC standards.

In general the advantages of this type of sensor network are the real-time ability, self-organization and self-healing capacity, energy efficiency, bi-directional communication skills and open data interfaces allowing the easy integration of the system in an SDI (Walter and Nash, 2009).

2.2 Micro sensors (MEMS) for landslide and peak acceleration monitoring

Landslides are complex ground movements that cause deformation and displacement on the surface but also damage to constructions. In the case of seismically triggered landslides besides the displacement, seismic shaking or ground acceleration can be monitored. Besides high precision, sensors in a WSN have to fulfil further specific requirements. They should be small in size, have low energy consumption, provide digital interfaces and inexpensive to use them in large quantities. Micro-Electro-Mechanical-Systems (MEMS) can support this effort, because they fulfil all of these requirements. The MEMS sensors combine very small mechanical and electronic units, sensing elements and transducers on a small microchip. In the SLEWS system, 3D MEMS silicon capacitive sensors made of single crystal silicon and glass for measuring acceleration, tilting and barometric pressure are used (Fig. 5). The 3D acceleration sensor has a sensitivity of 1333 counts/g and a acceleration range of ± 2g. To monitor changes of sensor inclination a dual axis inclinometer with a measuring range of ± 30°, a sensitivity of 1638 counts/g is used. The digital absolute barometric pressure sensor has a resolution of 1.5 Pa. and an accuracy of ± 50 Pa. All sensors have a standard SPI digital interface, an internal temperature device and automatic compensation mode. The three sensor types are mounted on a sensor board in the sensor node. Besides this sensor node a second type with precise position sensors is used for elongation-measurements (Fig. 5). Two different types can be integrated into the network: potentiometric displacement transducers and linear magnetorestrictive position transducers. According to classical extensometers they are used to monitor the opening and closing of cracks and fissures. The measuring range of the displacement transducer used has a length of up to 1 m with a given linearity of ± 0.05 % of the effective range. The magnetorestrictive transducer used in this project has a measuring range of 1000 mm, with a given linearity of < ±0.01 % of the effective range.

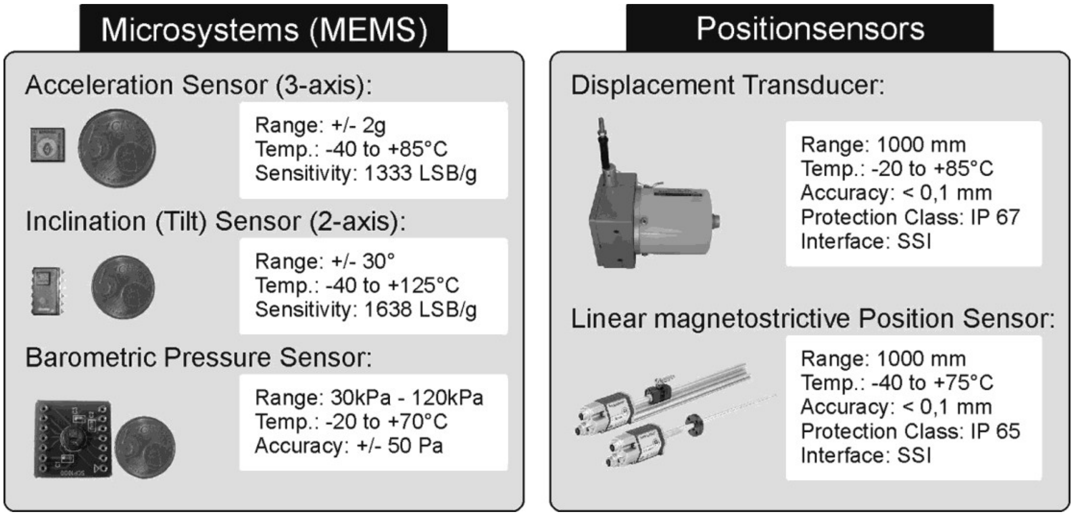

Figure 5: Sensors used in the frame of the SLEWS project. At the left side the MEMS integrated in the standard sensor node like acceleration, tilting and pressure sensor are shown. The right side shows the position sensors used in the project.

To prove the quality of the sensors integrated in the system in laboratory, tests under stable and dynamic conditions were conducted to obtain information about data spreading the accuracy of the different sensors in the setup. The analyses showed that all sensors show very small data variations without measurable data drifts. For example the tilt sensor showed accuracies of about +/- 0.06° (Fig. 4), +/- 0.008g showed the acceleration sensor and accuracies of +/- 0.1 mm are achievable with the displacement transducer. Under dynamic conditions changes of >0.1° for the tilt sensor, of >0.02g for the acceleration sensor of up to 0.1 mm with the elongation sensor can be identified with high precision.

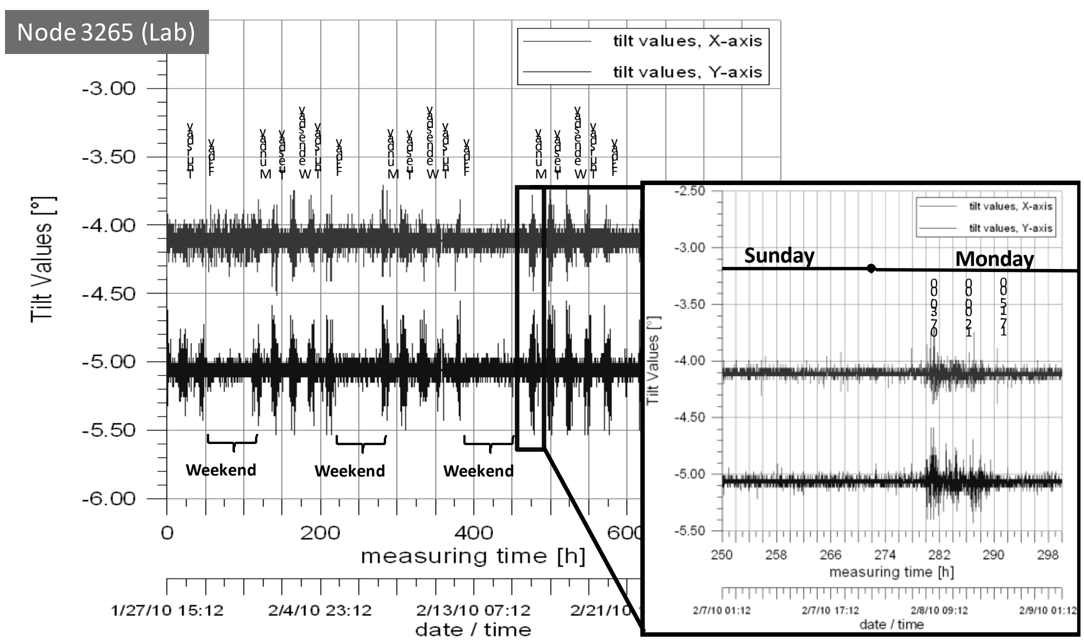

Figure 6: Tiltsensors (which are also acceleration sensors) in the department lab identified construction work at the departments building over 3 floors distance.

Figure 6 shows the performance of the WSN regarding the monitoring of ground motions. A sensor mounted on the roof of the department monitored over a distance of 3 floors vibrations due to construction work in the departments building. As these sources emit comparably small energy in the solid concrete frame building, accelerations of relevant magnitudes for seismic landslide initiation (>4 according to Keefer, 1984) will easily be recognised by the system.

Further filed tests were performed in 2009. A small wireless sensor network with 7 nodes and one gateway was set up on the landslide Super Sauze in the south of France for one week in summer 2009. This complex landslide is located in weathered soft clay shales and is since its initiation in the 1960's still very active. Even though the measuring period was very short and the landslide was not very active at this time smaller movements in the area could be observed. With the displacement transducers crack openings of 1.5 mm in 5 days could be observed and later validated with data from a nanoseismic array. The test showed that the system can be used also in slow moving landslide environments. Also the installation of the system in the previously unknown environment was easy and fast. First data could already be obtained shortly after start up. Since autumn 2009 the system is tested in the "Elbsandstein" mountains in Germany to monitor joint opening in rock pillars to prove the long-time stability and remote data transfer under real conditions.

2.3 Sensor fusion for data enhancement and information retrieval

Another very important aspect in hazard monitoring and early warning is the reliability of sensor signals or information derived from sensor networks. Today existing monitoring systems are very often monolithic solutions with only one or two measuring devices in the field. Due to the small number of instruments, reference systems are missing. Thus it is often very difficult to distinguish if the measured values are initiated by slope deformations or from malfunctions. One solution for this problem is the combination of sensor information (sensor fusion) from different autonomous working devices. Sensor fusion (i.e. combination and comparison) contributes to the decision making of alarm and early warning systems and allows a better interpretation of data.

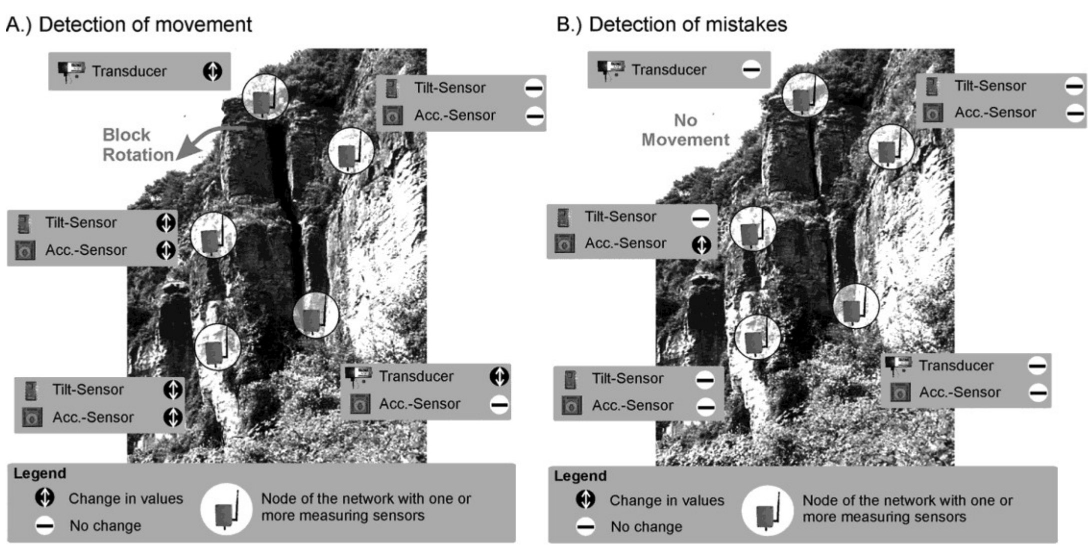

Figure 7: A potential application of complementary and spatial sensor fusion for tilt monitoring of a rock pillar. Case A at the left shows a clear situation where the pattern of sensor information indicates movements. In case B the pattern indicates a malfunction or error, as only one sensor is active and even the complement sensor shows no reaction.

The comparison of data from identical sensor-types (redundant sensor fusion) but also different sensors that complement each other's observations like tilting and displacement transducers (complementary sensor fusion) permits a verification of the data (Fig. 7A). The development of special algorithms allows further analysis and evaluation steps, namely the combination of data from all nodes of the network (sensor node fusion). Especially the recognition of false reports or malfunctions but also the identification of outliers or errors quantification is of high interest. This is especially important as warning systems that produce many errors and false alarms lose acceptance by users, operators and public. Sensor fusion can help to identify errors and uncertainties and thus avoids the trigger of a false alarm (Fig. 7B). Furthermore the concept of sensor fusion allows to combine different sensor networks to qualify information, e.g. from seismic arrays, rain gauges or different landslide monitoring systems.

3 WIRELESS SENSOR NETWORKS IN SEISMIC LANDSLIDE HAZARD MANAGEMENT

For the past two decades an increasing number of landslide warning systems are developed and applied for general public and industrial purposes. Especially in industrial countries with relevant areas locate in alpine type environments they reach today a considerably high standard. Anyhow these systems are usually monolithic, not flexible and adaptable to other situations, expensive and afford time consuming installation and maintenance work. The issue of earthquake triggered landslide warning and monitoring was initiated at least by the Chi-Chi earthquake in 1999 and more recently by the Wenchuan earthquake in 2008. Anyhow here are like in earthquake early warning very little advances observable. If there are advances, they are usually related to lifeline protection and earthquake monitoring but not landslides. Here the concept of the SLEWS system (Fig. 8) with simple inexpensive and flexible monitoring devices in a wireless sensor network provides some advantages and options for the application in the field of surface deformation and landslide monitoring in a seismogenic environment.

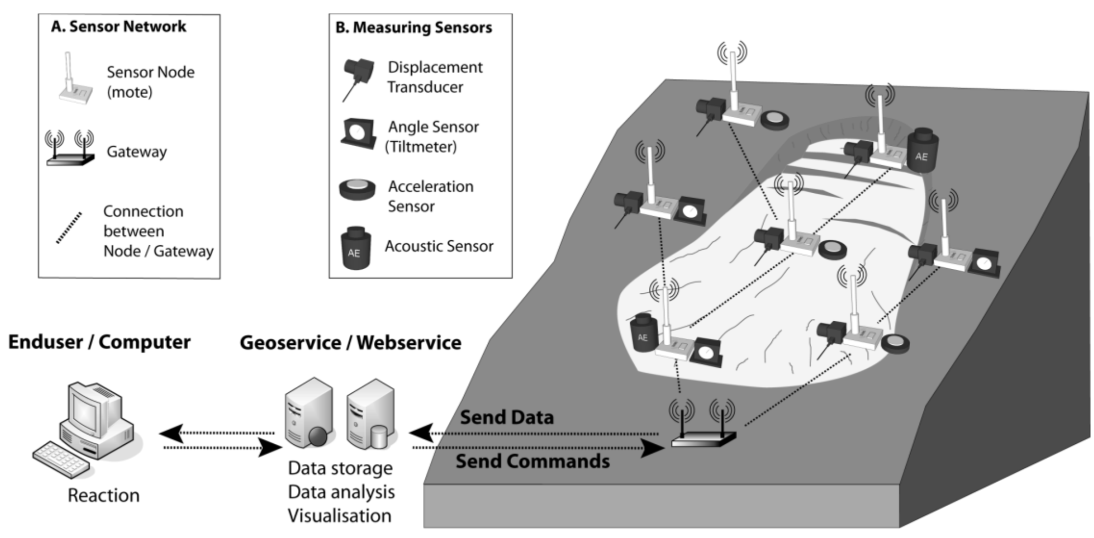

Figure 8: Configuration of a real-time spatial early warning and monitoring system for landslides. The descried configuration with acceleration sensors allows also a monitoring of local ground accelerations exceeding a relevant ground acceleration

Especially the cable less network connection and data routing od WSN based monitoring systems improves the operative integrity of the system in an event case. As above mentioned often supply and lifelines are interrupted due to landslides after an earthquake. The usually larger landslide events related to earthquakes lead also to large surface movements which can destroy cable connections of conventional monitoring systems. Here the ad-hoc reorganization of the WSN allows a self healing of the network, even so some of the sensor nodes might fail or are destroyed in an event case. The only limit is the operational sensor density, which is related to the maximum range of stable data transmission between single nodes in the multi-hop mode. But not only data routing inside the network can be arranged cable less. Also the data uplink to the central data infrastructures for hazard monitoring and management can be arranged cable less by 3G or satellite connections.

A second aspect is the easy installation and start up of the system in the field. The sensors have just to be placed at points or situations in the field that have to be monitored. After switch on and initialization, the nodes automatically connect to the gateway or neighboring nodes. Even in larger setups, 10 minutes after installation the nodes operate in the network and transmit sensor data through the network. The same applies to the gateway, where the internet and server connections have to be established and tested. This means that the system can also be used as a mobile component for relief operations to monitor e.g. endangered road cuts, slopes or landslide dams. After completion of the operation the system can also be easily dismounted and used for new tasks.

Besides this operational aspects which are more relevant while or after an event there is a general need to derive on-site acceleration data after a seismic event in landslide environments. One reason is that there is a general need for affordable systems to monitor peak ground accelerations (PGA) for landslides. Due to the integration of precise but cheap MEMS technology accelerometers it becomes affordable to derive much more spatial distributed acceleration data. Furthermore the acceleration data from the sensors can be provided in real-time through standardized interfaces for other applications like shake or alert maps.

The other reason is that there is a strong need for further research and especially data sets from ground failures and landslides related to earthquakes. Earthquake triggered landslides are thoroughly studied and described by Keefer (1984, 2002). The most common methods to investigate the landslide susceptibility on a regional or sub-regional scale is the deterministic approach based on the Newmark's sliding rigid-block model (e.g. Jibson et al., 2000). As ground acceleration is one input of the Newmark model this data are usually predicted based on potential events. Here a broader application of sensor networks might provide more accurate data in the future. Furthermore additional data will help to calibrate these methods for different environments, improve them and develop new approaches. For example there are only for few seismically triggered landslides on-site or close to site acceleration data available. Contrary to the assumptions of the Newmark model recent research indicates that besides horizontal acceleration/shaking also vertical might have in some situation a relevant impact on slope stability (Aoi et al., 2008; Tang et. al., 2009). Additionally there is a considerable need for research regarding site effects and amplification in highly structured topographic environments.

4 EXAMPLES FOR POTENTIAL APPLICATIONS

Even so systems like the SLEWS system are not as precise as seismic arrays or accelerometers designed for a specific purpose, the flexibility and ability to cover different tasks parallel shows their specific value. This flexibility allows a wider application and even if the WSN is not installed for PGA observation it will collect this data. As in the case of seismically triggered landslide events the trigger is not predictable the applications of the WSN for early warning and monitoring purposes is shifted to an event or post event situation. While e.g. for precipitation triggered landslides usually the trigger and its influence on observable slope stability affecting forces is observed to predict an landslide event, in the case of seismically triggered landslides the system will be used to minimize the effects from an event that has already occurred. Therefore, possible and promising applications of the SLEWS system will be:

- **monitoring**, e.g. integrity of sensitive infrastructures or constructions, data input for shake or hazard maps, data collection.
- e**arly warning and monitoring**, e.g. to monitor landslide dams or instable slopes after an event
- **alerting**, e.g. triggering supply line, road or rail blocks
- **post event warning**, e.g. to support relief operations regarding logistics, integrity of life lines

One special aspect from landslides triggered from large earthquakes in mountain regions is that not only the initial event bears considerable risks and consequences, but also following cascading hazards may cause large or even larger losses. One reason is that the landslides act often an amplifying factor in the earthquake disaster scenario. E.g. the failure of reservoirs or landslide dams may endanger much larger areas and people than the primary landslide. Furthermore, while landslides themselves cause less frequently structural damages and collapses of buildings, they often cause major disruptions of life-lines (e.g. roads, railway, power lines, water supply and communication infrastructure) and are therefore crucial for rapid response of relief operations and later rehabilitation.

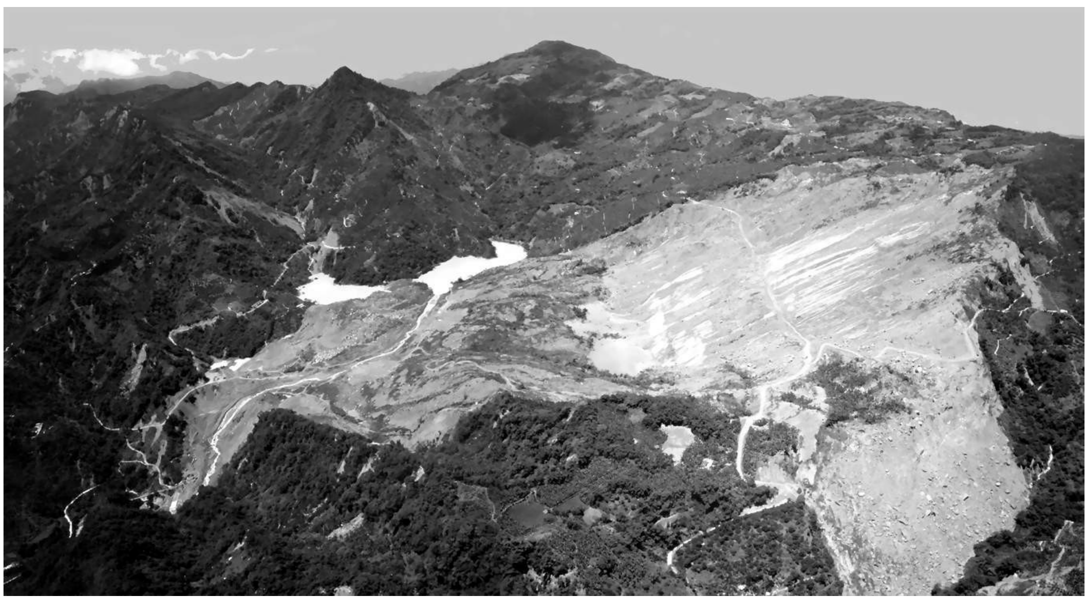

Figure 9. Chiufengershan landslide from northeast (from Shou and Wang, 2003). Two landslide lakes might be recognized at the left side).

As the following example shows not only in typical landslide prone areas like in Wenchuan in China the application of landslide monitoring systems can help to manage landslide hazard situations. On September 21, 1999, a large earthquake with magnitude of 7.3 (ML) occurred in central Taiwan. The epicenter was about 30 km south of Taichung City near a small town Chi-Chi. It was caused by reactivation of the Chelungpu Fault, a thrust fault with is about every 150 years active. Due to geological conditions the major destruction and losses are more or less linear orientated along this fault. Those include structure damages related to surface ruptures along the fault line (1-5m displacement), liquefaction and landslides. The Chiufengershan landslide is one of the major landslides, causing not only 39 casualties, but also formed two landslide dammed lakes (Fig. 9). As unlike other major landslides due to the Chi-Chi earthquake, the Chiufengershan area does not have any written record of landslide for the past 100 years and therefore, the area would not have been the choice for the installation of a landslide monitoring system. Furthermore, the investigations of Shou and Wang (2003) show that today's situation is even more stable than the one before the landslide. Anyhow two monitoring applications for easy to install WSN could have been useful even after the event. On is he monitoring of the embankments of the quake lakes, as failure might have undesired effects even for more fare areas. Here especially the easy and fast installation of the system helps to set up immediately an early warning and monitoring system to control dam integrity while remediation. The other application might be a temporal monitoring to gain data to calibrate and prove slope stability analysis for further hazard management.

5 CONCLUSION

Besides precipitation triggered landslides, a major thread from landslides is related to earthquake triggered landslides which account for the majority of catastrophic landslides. Furthermore in the case of large earthquakes not only the risks and damages from the landslides themselves, but also cascading effects as consequence of the initial landslide like reservoir or landslide dam failure may cause even larger losses. Due to the rising vulnerability of the society to natural hazards like earthquakes and landslides the requirements for early warning and monitoring systems continuously grow. Especially reliable real-time data for the detection of hazards, fast warning and quick response are of special relevance to protect humans and infrastructure in the course of hazard management. Although, the environments in which this systems have to operate are often inhospitable for the technology and by far not ideal the systems have to cope with these difficulties. Therefore it is reasonable to use robust but also self-sustaining instruments that can operate before, during but also after the event.

To manage this task a new type of environmental sensor network is necessary, operating independently and providing on-line real time data retrieval without cable connection. The Sensor based Landslide Early Warning System - SLEWS 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 low-cost micro-sensors (MEMS) are integrated in the system to detect movements like tilting, acceleration or spreading. Due to the fast data transfer, processing and visualization process, monitoring and also warning in real-time becomes possible. The combinations of different sensor data (sensorfusion) allow to 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. Application of interfaces according to the sensor web enablement OGC guidelines allow to easy set up web based modular monitoring or early warning structures and to integrate the system in existing spatial data infrastructures. Finally wireless self organizing sensor networks can be setup very easy and present a cost efficient solution.

While for the past two decades an increasing number of landslide warning systems are developed and applied for general public and industrial purposes, regarding earthquake triggered landslide warning and monitoring very little advances are observable. Here the combination of up to date WSN like SLEWS together with modern and appropriate hazard and risk management strategies provides some advantages and new options for future applications. Due to the flexibility together with the currently integrated and tested sensors the system can be easily used with little or no modifications for monitoring, early warning, alerting or post event warning. Besides others the main operative advantages related to earthquake environments are the cable less network connection and data routing as well as the easy installation, operation and recovery of the system. From a scientific and technical view the in future potentially higher number of measuring networks and sensors allows a spatially higher distributed and affordable option to derive peak ground accelerations (PGA) data in general and for landslide sites in special. This acceleration data may also be used for detailed real-time shake or alert maps.

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