Multi-sensor Data Fusion in Wireless Sensor Network for Landslide Monitoring

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Zusammenfassung

Erdrutsche sind eine der schwersten Naturkatastrophen, sie bedrohen Eigentum und Menschenleben. Daher ist es notwendig, sie zu untersuchen und ihr Verhalten zu verstehen, um bereits vor der Katastrophe geeignete Schutzmaßnahmen ergreifen zu können. WSN (Wireless Sensor Network) sind eine seit zwei Jahrzehnten aufstrebende Technologie, welche niedrige Kosten, geringe Größe und wenig Energieverbrauch vereint. Dadurch wurde der zunehmende Einsatz in der Geländeüberwachung möglich. Ein WSN mit Neigungs- und Beschleunigungssensoren wird durch den Lehrstuhl für Ingenieurgeologie und Hydrogeologie der RWTH Aachen zur Erkennung von Hangneigungswinkelvarianten entwickelt. Durch die Verwendung mehrerer Sensoren, deren Datenbanken zusammengeführt werden, anstelle eines einzelnen Sensors, können spezifische Interferenzen gemessen und die Genauigkeit der Daten verbessert werden. Das Datenfusionsmodellen JDL ist aufgrund seiner Konsistenz mit Katastrophen-Überwachungs-Prozessen am besten auf Alarm- und Frühwarnsysteme für einen Erdrutsch anwendbar. In diesem Paper werden ein standardisierter Rahmen für Hangstabilitätsbewertung und -überwachung sowie die Simulation von Hangstabilitäten mit einem numerischen Modell vorgestellt.

Schlüsselworte: JDL Data Fusion, WSN, Erdrutsch Monitor, FEM

Abstract

Landslides are one of the severest natural disasters in the world threatening human lives and property. Hence it is necessary to investigate and understand landslides and their behavior in order to take appropriate protective measures before they happen. Wireless sensor network is an emerging technology in the last two decades and has been progressively applied into the environmental monitoring with its great benefits of low-costing, small size and low-energy consumption. A wireless sensor network with inclination and acceleration sensors is developed by the Department of Engineering Geology and Hydrogeology of RWTH Aachen University and is able to detect slope tilt angle variations. In order to optimize data from multiple sensors and associated databases, multi-sensor fusion is a necessary measure to obtain data with more improved accuracies and specific inferences than using a single sensor alone. Among several data fusion models, JDL data fusion model generated by Joint Directors of Laboratories is applicable to landslide alarm and early warning system due to its consistency with disaster monitoring process. In this paper, a standardized framework for slope stability assessment and monitoring, together with a simulation of slope numerical model is provided.

Keywords: JDL Data Fusion, WSN, Landslide Monitoring, FEM

1 Introduction

By the WORLD DISASTERS REPORT (2011) from International Federation of Red Cross and Red Crescent Societies (IFRC), 3402 people have been killed in 2010 by mass movement (landslides, rock falls, avalanches, subsidence, etc.), and the estimated damage exceeded 1.2 billion US dollars. In spite of improvements in recognition, mitigative measures and warning systems, worldwide landslide activity is rising, and the trend is unavoidably continue because of increased urbanization and deforestation of landslide-prone areas, as well as raised regional precipitation caused by changing climate patterns (SCHUSTER 1996). Therefore, it is necessary to investigate and understand landslides and their behavior in order to mitigate the disaster and reduce losses. The main concern and purpose of monitoring is the protection of people and environment, by detecting potential landslides before they happen, to allow taking appropriate protective measures in time (LAROCQUE 1977). PECK (1969) proposed the Observational Method (OM) as an active design and construction approach for geotechnical structures. During these years, it has been increasingly developed and standardized (EUROCODE 7 2004) based on numerous applications in ground engineering area. Over the years the method found its way in national and European standards to predict geotechnical behavior in situations where it is difficult to apply established numerical solutions. This situation is comparable with a critical slope which has to be monitored for safety reasons. However, some of the requirements defined in the Eurocode 7 and other standards (NICHOLSON et al. 1999) are difficult to provide, like definition of acceptable limits, proof of adequate measurement ranges of the devices at a defined standardized operational framework. Therefore even if the concept of OM is convincingly simple and attractive, it might not cover all requirements to a landslide alarm and early warning system.

This paper will present a concept by implementing JDL Data Fusion Model into landslide alarm and early warning systems, providing a standardized framework to establish a slope stability assessment and monitoring on a high quality level with Wireless Sensor Network (WSN).

2 Wireless Sensor Network

Wireless Sensor Network (WSN) is an emerging technology originally generated for military application (WANG & BALASINGHAM 2010). Due to the fast development of Micro Electro Mechanical Systems (MEMS) and the optimization of sensor cost, size and energy consumption in the last two decades, WSN has been progressively applied into many areas such as environmental monitoring, industrial sensing, traffic control, health monitoring and public security. WSN is built of "sensor nodes", each of which contains one or several sensors, and the types of the sensors are quite various like tilt sensors, displacement transducers and barometric pressure sensors. Each sensor node possesses its own voltage supply, transceiver, microprocessor and internal memory storage, so it is available of sensing, transmitting, retrieving, and forwarding data in a local area network. The sensed data are sent to a sink node (gateway) that is connected to the internet, and an end user can fetch these data remotely by accessing to the networks. Fig. 1 shows a sketch map about how the WSN operates.

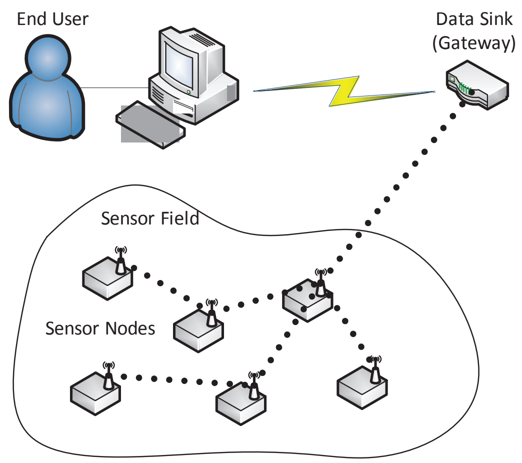

Fig.1: Wireless Sensor Network

The topology of a wireless sensor network could be either star-based or mesh-based (SOHRABY et al. 2007), which are shown in fig. 2. Star-based systems (upper Fig. 2) are deployed with single-hop radio connectivity to sensor nodes, using static routing over the wireless network, so there is only one route from the sensor nodes to the companion terrestrial nodes. Mesh-based systems (lower Fig. 2) are equipped with multi-hop radio connectivity among sensor nodes, dynamically changing the routes from sensor nodes to the sink node (gateway).

A wireless sensor network is developed by the Department of Engineering Geology and Hydrogeology of RWTH Aachen University (Fig. 3), the network of which follows the mesh-based principle, loaded with a 3-axis acceleration sensor and a 2-axis inclination sensor.

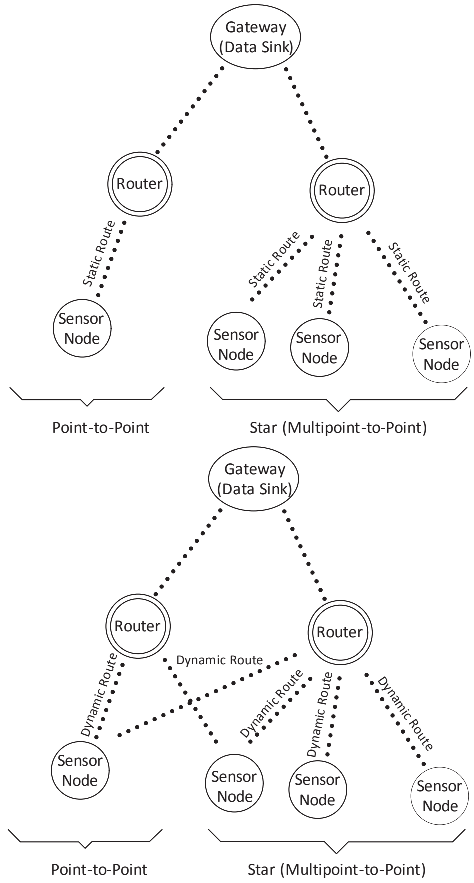

Fig. 2: Wireless Sensor Network Topology (adapted by SOHRABY et al., 2007)

3 Data Fusion

Multi-sensor data fusion is an up-to-date technology which has gained significant concern in both military and nonmilitary applications. By combining data from multiple sensors, and related information from associated databases, one can achieve more improved accuracies and specific inferences than those obtained by using a single sensor alone. Analogous to the ongoing cognitive process used by humans to integrate data continually from their senses to make inferences about the external world, the data from different sources and types of sensors are combined using techniques drawn from a wide range of areas including artificial intelligence, pattern recognition, statistical estimation and other areas (HALL & LLINAS 1997, HALL & STEINBERG 2000).

The Joint Directors of Laboratories (JDL) data fusion working group created the JDL process model for data fusion (Fig. 4), to unify terminology crossing application-specific boundaries and improve communications among military researchers and system developers (KESSLER 1992, HALL & LLINAS 1997).

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As a two-layer hierarchical model, the top level of JDL data fusion process model is conceptualized by three divisions, which are named source domain, data fusion domain and human/computer interface respectively. Data sources include sensor data, information from databases, input from other fusion processors or smart sensors, or human input and directions. All of the data will be input to the data fusion domain, which is constituted by preprocessing and refinements of "objects", "situations", "threats" and "processes". Thereby the status of the monitored obstacle can be attributed, analyzed and predicted in the data fusion domain.

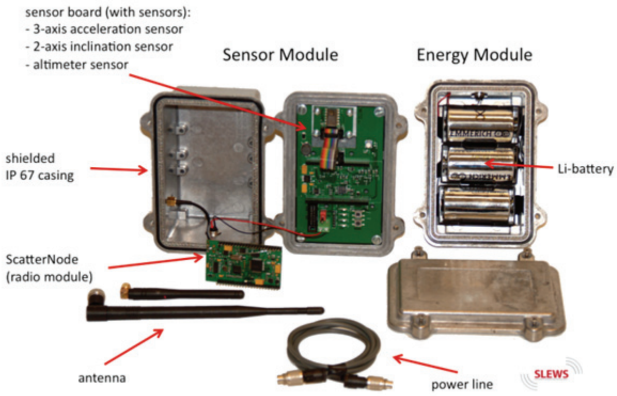

Fig. 3: Wireless Sensor Node (after FERNANDEZ-STEEGER 2011)

Afterwards, the human/computer interface will interact with and control the fusion process, and an alerting decision can be implemented. Besides JDL Data Fusion Process Model, there are also others used to describe data fusion, such as Endsley's Situation Awareness (SA) model (LEE et al. 2012), the Bedworth and O'Brien's Omnibus Process Model (BEDWORTH & O'BRIEN 2000) and the TRIP model (HALL & MCMULLEN 2004). Among all of the fusion models, JDL Model is selected to be adapted into landslide data fusion process due to its consistency with the structure of disaster monitoring and prediction. Fig. 5 shows the specific applied process model for landslide monitoring.

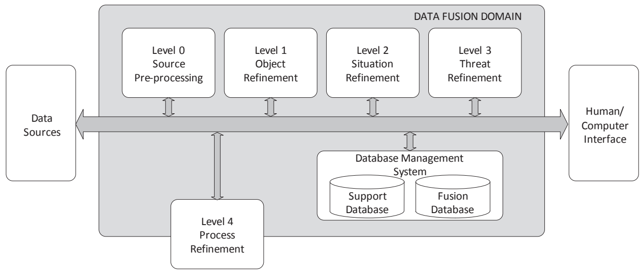

Fig. 4: JDL Data Fusion Process Model (after Hall & Llinas, 1997)

According to the landslide monitoring data fusion process, data received from sensor nodes will be imported into Data Fusion Domain which is composed of six functions, and each of the sub-layers is generally introduced as below:

• Preprocessing: An initial sub-process providing preliminary filtering of input data, assorting of data from multiple sensors by observation time, reported location, data or sensor type, and uniformity of data units.

• Object refinement: This sub-process combines positional and identity information from multiple sensors and sets up a refined database of attributes like identified entities, position, velocity and target tracks.

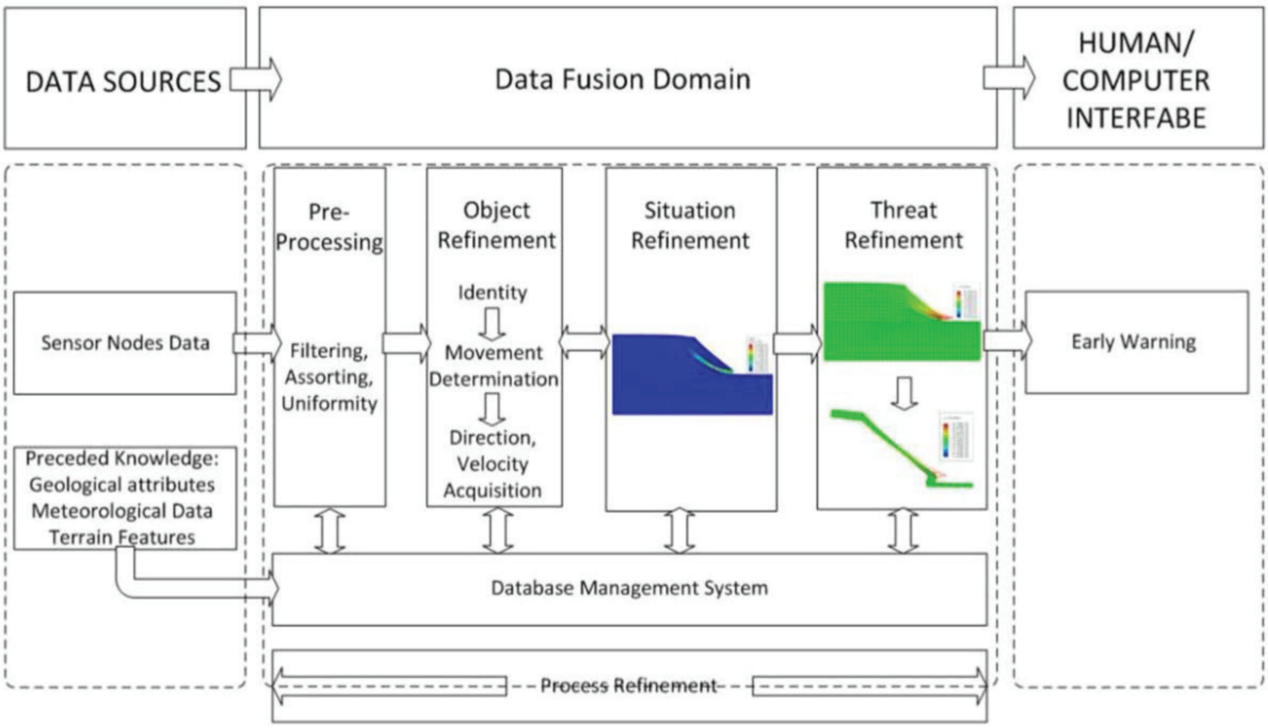

Fig. 5: JDL Data Fusion Process for Landslide Monitoring Systems

Situation refinement: A sub-process to understand the context of the products based upon the results of Object Refinement. It focuses on the relationship among entities as well as that between the entities and environment, and the aggregation of entities in time and space area. For the case of landslide monitoring, Finite Element Method (FEM) can be applied to numerically modeling, mechanical analyzing and result visualizing. During monitoring, the measurements of the sensors could be used to back-calculate the input parameters for a FEM model, and ultimately the consistency between simulation and observation will be reached.

• Threat refinement: This sub-process draws the current situation into the future to describe inferences about enemy threats, vulnerabilities, and operational opportunities. It deals not only with computing possible engagement outcomes, but also assessing the enemy's intent according to preceded knowledge. For a civilian application like landslide alarm and early warning, the tilt angle variations along the surface of the slope when it fails will be analyzed and calculated from FEM model; hereby a threshold value can be set as an alerting limit before the landslide occurs.

• Database management: The database management system is the most extensive support function, which provides access to, and management of databases, including data retrieval, storage, compression, relational queries, and data protection. Preceded knowledge and the processed data from each fusion function will be managed here.

• Process refinement: Considered as a meta-process, this sub-process concerns about other processes, and seeks to optimize the ongoing data fusion process. Process refinement is partially inside and partially outside the data fusion domain, the display of which indicates the optimization of the ongoing data fusion process accounts for both needs of the fusion system and operation.

4 Demonstration

For this paper, we have established a soil slope model using finite element method by the software application Abaqus/CAE. Basic parameters and the primary model are shown in Tab.1 and Fig. 6.

The failure of the slope is realized by Shear Strength Reduction (SSR) method, which has been proposed by GRIFFITHS & LANE (1999) and increasingly being applied into FEM slope stability analysis in the last 20 years. The factor of safety of the example slope model is deduced as 1.3, and vector symbols at the critical status are shown in Fig. 7.

As a homogeneous soil slope, the toe and foot are often obviously varied. In this case, the unit at the top of the slope is taken as an observing point. The tilt angle variation until the slope fails can be calculated by using trigonometric function to convert the change of coordinate values to angles; Tab. 2 shows the calculated data based on the simulating result, which are corrected to 4 decimal places. From the table, we can conclude that when the slope fails, a variation of about 4.4˚ will be monitored at the top. Therefore, the end user could set a threshold value at 4.4˚ as an alert limit; when the detected tilt angle variation by the wireless sensor node deployed at the slope top reaches the threshold, the monitoring system will announce an alert and early warning, and then corresponding means and strategy will be implemented.

Tab. 1: The Slope Model Calculation Parameters

Material	$\rho(kg/m^3)$	$c(kPa)$	$\varphi(^\circ)$	$E(kPa)$	μ
Siltsoil	1820	15000	25	100000	0.3

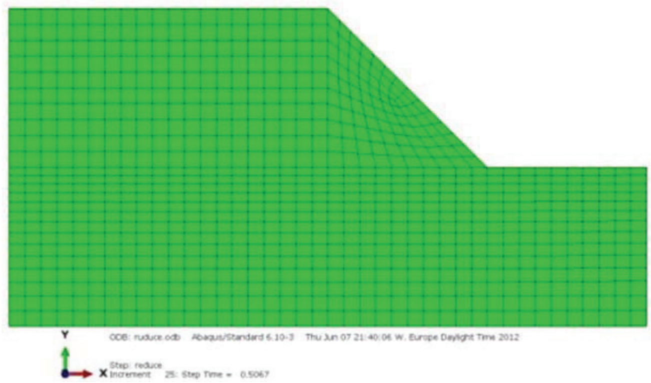

Fig. 6: Primary Slope Model

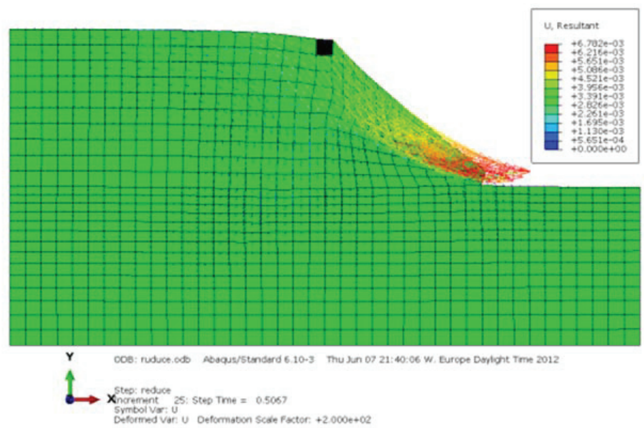

Fig. 7: Deformed Slope Vector Plot Symbols

5 Conclusion

This paper provides a concept of using JDL Data Fusion Model to optimize the process of landslide monitoring with wireless sensor networks, and establishes a standardized framework for landslide alarm and early warning (Fig. 5). Data detected by wireless sensor nodes could be progressively processed and analyzed in Preprocessing and Object Refinement fusion function, followed with the implement of a FEM numerical simulation that repeatedly compared with the monitoring data and adjusted step by step. When the observation and simulation draw in consistency, the Situation Refinement is accomplished. Further on, in the Threat Refinement function, the accurate FEM model will be able to calculate the slope stability and obtain the critical parameters such as tilt angle. At last, an early warning could be achieved when the monitored data reach to the preset threshold value.

A demonstration is provided in this paper, and a real case study is needed in the next step to prove this standardized framework for landslide alarm and early warning system.

Fig. 7: Deformed Slope Vector Plot Symbols

Tab. 2: Tilt Angle Variations of Observing Point

Increment	Δx (m)	Δy (m)	Slope	Tilt Angle (˚)
0	1.0000	0	0	0
1	1.0000	-0.0001	-0.0001	-0.00572958
2	1	-0.0003	-0.0003	-0.01718873
3	1.0006	-0.0023	-0.0023	-0.13170104
4	1.0016	-0.0079	-0.00789	-0.45190423
5	1.0026	-0.0137	-0.01366	-0.78286789
6	1.0041	-0.0291	-0.02898	-1.66003451
7	0.9919	-0.0767	-0.07733	-4.42167427
8	0.9911	-0.0764	-0.07709	-4.40798897
9	0.991	-0.0762	-0.07689	-4.39693693
10	0.991	-0.0762	-0.07689	-4.39693693
11	0.991	-0.0762	-0.07689	-4.39693693
12	0.991	-0.0762	-0.07689	-4.39693693
13	0.991	-0.0762	-0.07689	-4.39693693
14	0.991	-0.0761	-0.07679	-4.39118926
15	0.991	-0.0762	-0.07689	-4.39693693
16	0.991	-0.0762	-0.07689	-4.39693693
17	0.991	-0.0762	-0.07689	-4.39693693
18	0.991	-0.0762	-0.07689	-4.39693693
19	0.991	-0.0762	-0.07689	-4.39693693
20	0.991	-0.0762	-0.07689	-4.39693693
21	0.991	-0.0762	-0.07689	-4.39693693
22	0.991	-0.0762	-0.07689	-4.39693693
23	0.991	-0.0762	-0.07689	-4.39693693
24	0.991	-0.0762	-0.07689	-4.39693693
25	0.991	-0.0762	-0.07689	-4.39693693

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