Landslide Monitoring with Sensor Networks: a Case for Autonomic Communication Services

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Abstract

Wireless sensor networks can be a very useful technology for monitoring remote and hostile environments. In this paper, we firstly report on our experience with landslide monitoring, and analyze the issues and the challenges we had to face in programming and deploying a suitable and useful wireless sensor network infrastructure. Following, we discuss how, within the CASCADAS project, we are contributing to the development of a novel component-based framework to facilitate the design and development of autonomic and situation-aware communication services for the use in modern network scenarios. Such a framework can become a useful tool to facilitate the development of easy-to-deploy, robust, and flexible sensor-network-based monitoring systems and, in particular, of landslide monitoring systems.

Keywords: *Wireless Sensor Networks, Landslide Monitoring, Autonomic Communication Services.*

1 Introduction

Wireless sensor networks are attracting an increasing interest due to their potentials for applicability in a variety of scenarios [AkySC02, ChoK03, Est02, Cas07]. In particular, sensor networks appear an essential tool for monitoring physical and natural phenomena in hostile and remote environments such as wildlife habitats [Mai02], remote glaciers [Mar04], active volcanos [Wer06] and active landslides [She07].

The number of real-world deployments of sensor network systems is rapidly increasing. From our side, we have experienced with the design, development and deployment of a sensor network infrastructure for landslide monitoring in the Emilia Romagna Apennines. Such infrastructure, which is now at work on site, enables the fine-grained analysis of environmental parameters and of slope movements and aims both at a better understanding of the phenomena and at generating alarms in the case potentially dangerous movements.

What characterizes most of the existing deployments, there included ours, is that they have to rely on a variety of technologies and ad-hoc techniques to deal with scenario-specific problems. From the software viewpoint, this introduces every time notable specific complexities to develop a system and to make it flexible, robust, and capable of adapting to contingencies. Accordingly, the availability of a general-purpose framework to support the development of autonomic applications and communication services over these kinds of environments would be highly desirable.

Against this background, the contribution of this paper is twofold. First, we present the landslide monitoring infrastructure we have developed (Section 2) and analyze the main challenges and problems – some of which of a very general nature – we had to face in this process (Section 3). Second, we present and discuss the autonomic framework being developed within the CASCADAS project (Section 4). Such framework, which aims at supporting and facilitating the development of autonomic and adaptable distributed communication services in modern network scenarios, could effectively address the above challenges and simplify the development and deployment of sensor network infrastructures and associated services.

2 Landslide Monitoring with Wireless Sensor Networks

Existing assessed technologies for monitoring slope stability consist of mostly isolated systems (e.g., multi-point bore hole extensometers, tilt sensors, displacement sensors, and volumetric soil water content sensors), typically very costly, and requiring complex installation procedures.

Sensor networks exhibit several advantages over such technologies, which motivated our efforts towards the deployment of a sensor network infrastructure for monitoring landslides in the Emilia Romagna Apennines.

2.1 Advantages of Sensor Networks

There are several characteristics of wireless sensor networks that make them suitable and highly competitive for landslide monitoring. In particular:

1. Wireless communications allow monitoring an environment remotely, without being in that location. This feature is of basic importance for landslides, which are typically found in difficult-to-be-reached and uncomfortable environments such as sharp mountains and quick slopes.
2. A sensor network can collect, aggregate, and analyze diverse and distributed data, and detect patterns that would be otherwise very hard to identify. In the case of landslides, this could enable (e.g., by analyzing humidity, temperature, pressures and strains on different regions of the ground) to detect changes in the patterns of movement well before these becomes apparent and dangerous.
3. Sensor network could (at least in theory) be deployed without requiring any pre-existing infrastructure and very quickly. For landslides, this could enable putting in place in a few hours an emergency monitoring system whenever new dangerous landslide surfaces appear.
4. Sensor network can be distributed also on wide areas at limited costs. For landslide surfaces, which can extend over several square kilometers, this is a very important characteristic.
5. Energy-efficient algorithms for sensor network have been developed allowing the network to run for months without human intervention at nearly no costs. For landslides, which can stay silent for several months and then suddenly re-vitalize, this is a very important feature to ensure continuous, long-term yet low-cost, monitoring.

2.2 The Calita Infrastructure

The Emilia Romagna Apennines, in Italy, are characterized by the presence of several large-scale landslides phenomena, most of which representing a danger to villages and roads. As the monitoring all such phenomena is costly and unsatisfactory with current technologies, we have started a collaboration with the Department for Environmental Protection of the Regione Emilia Romagna and with the Departiment of Earth Sciences of the University of Modena and Reggio Emilia, aimed at experiencing the usage of sensor network technologies. A landslide by the village of Calita, in the county of Reggio Emilia, has been chosen for the first prototypical development and deployment.

The Calita's sensor network infrastructure (see Figure 1) has been deployed in May 2007 and it's still at work. It exploits 15 Crossbow Micaz motes and covers a surface of about 500 square meters. It exploits accelerometer sensor boards for capturing slope movements, and environmental boards for the monitoring of ambient parameters like temperature, pressure, humidity and light depth.

Over the landslide surface, Micaz each node has been assigned either the role of “Data” or “Bridge” nodes. Data nodes are in charge of sampling data from the environment and sending it to bridge nodes. Bridge nodes, following a predetermined static routing table, forward packets to a base station placed in a safe position, 50 meters far from the observed landslide.

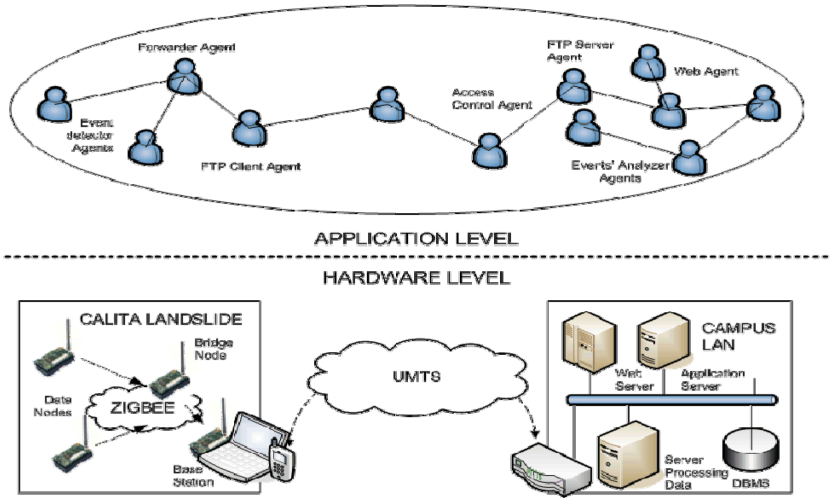
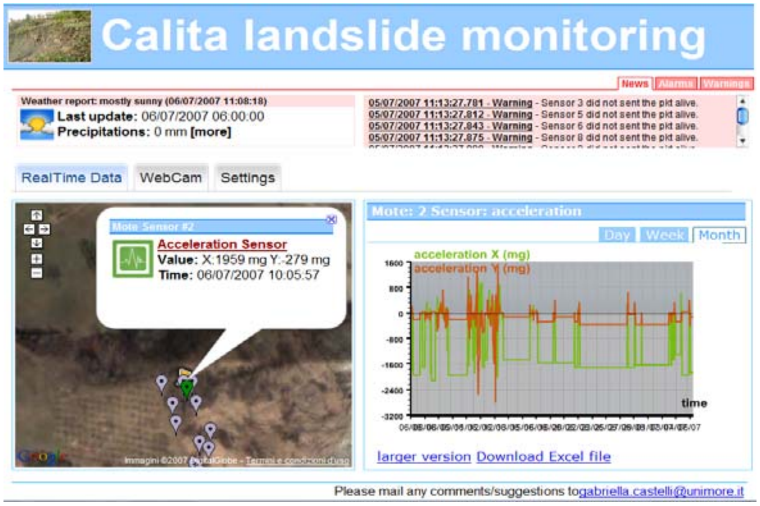


Figure 1. General architecture of the landslide monitoring application.



Weather report: mostly sunny (06/07/2007 11:08:18)
Last update: 06/07/2007 06:00:00
Precipitations: 0 mm **[more]**

05/07/2007 11:13:27.781 - **Warning** - Sensor 3 did not sent the pkt alive.
05/07/2007 11:13:27.812 - **Warning** - Sensor 5 did not sent the pkt alive.
05/07/2007 11:13:27.843 - **Warning** - Sensor 6 did not sent the pkt alive.
05/07/2007 11:13:27.875 - **Warning** - Sensor 8 did not sent the pkt alive.

Acceleration Sensor
Value: X:1959 mg Y:-279 mg
Time: 06/07/2007 10:05:57

Please mail any comments/suggestions togabriella.castelli@unimore.it

Figure 2. A screenshot of the monitoring Web site (http://155.185.228.148/calita).

A base-station mote, cable-connected to a laptop retrieves network packets. The laptop, exploiting FTP over a UMTS connection, sends data to our servers at the university. There, a Java application elaborates data and stores it in a MySQL database. More in general, application agents running on both sensor nodes and on the backend server infrastructure take care of retrieving sensor data, collect it to a central base station, and deliver it to our campus' server cluster.

Retrieved data is processed and elaborated by other application software agents that present their result via a Web 2.0 graphical user interface. The site displays the sensor network as an overlay over Google Maps, through the Google Maps' marker the user can access aggregated sensors data (based upon day, week or month time range). Moreover, the site provides weather reports and precipitation data, coming from a weather station sited in the landslide area. An alarm windows displays alarms and warnings about the landslide status. Figure 2 shows a screenshot of the Web site that is reachable at **http://155.185.228.148/calita**.

Early analysis of data confirms that our infrastructure has to able to identify most slopes' motion patterns detected by the other traditional tools already in place there. Whether it can do more is still to be evaluated. However, the analysis of these results is beyond the scope of this paper.

3 Challenges

The deployment of the above described wireless sensor network for landslide monitoring have posed us several challenges, either related to sensors' inherent characteristics, or to the characteristics of the target scenario [ChoK03], or both.

Fast Deployment and Reconfiguration Time

One of the main challenges belonging to the first category is the necessity of designing networks fast and easy to deploy, no longer involving human collaboration. In these networks, nodes have to self detect each other, and self organize in a operating data-collection system.

In our experience deploying a 15 nodes network, and testing the whole system, can last up to 6 hours. Moreover, necessary maintenance operations could lead to additional hours of "on-the-site" work.

Robustness – Fault Tolerance

Another common challenge is the research for robustness and reliability. A sensor network should cope gracefully with the fault of some nodes. Fault tolerance can be obtained either by replicating devices in a static routing table or, in a more flexible and interesting way, by making nodes self adaptive, capable of dynamically finding new paths to the base station bypassing network faults. Robustness and fault tolerance mean also the ability of recovering from network errors, when, for example, the exploited connections (in our case UMTS and zigbee) could momentarily break down.

During our deployment we've experienced several broken communication links due mainly to: (i) a bad alignment between motes' antennas, (ii) faults on mote programmed routines, (iii) batteries exhaustion and (iv) water infiltration inside sensor boxes.

Energy Consumption

A challenge more strictly related to application context is the definition of the right trade-off between performance and node consumption. Sampling slope motions at high-rates certainly produces more accurate and meaningful data but also an even increasing traffic of packets over the network. A network featuring real-time services makes the monitoring activity more effective but obviously it weighs heavily on motes' life expectation. In addition, maintaining a balanced energy consumption between nodes is fundamental in order to extend the average network life.

The wasteful power consumption of bridge motes forced us to perform several minor deployments for replacing exhausted batteries.

Devices Heterogeneity & Interoperability

From a technical point of view one of the main challenges is related to devices heterogeneity and the problems associated to their interoperability. Sensor network scenarios are typically composed by different kind of devices ranging from micro-sensors for fine-gain readings, to large backend servers to process and store retrieved data. When developing applications, it is important to take such differences into consideration and thus wrote software for a lot of different platforms having very different resources and constraints.

For example, in our implementation:

- Sensor nodes are micaz devices with TinyOS operating system. We developed their software with the nesC programming language [GayL03].
- The base station runs Linux with software written in Java and C. The application we developed has to bridge packet from a Zigbee network to a UMTS one (overcoming networking heterogeneity).
- Backend servers have WinXP operating system and run software written in Java.

Naturally, such a plethora of technologies pose several integration challenges.

4 The CASCADAS Approach

The CASCADAS project attempts to define a general-purpose paradigm for the development of autonomic and situation-aware communication services. The component at the root of CASCADAS is the ACE (Autonomic Communication Element) [Hof06]. Such a component model presents a number of interesting features supporting the development of autonomic and flexible services.

1. ACE components can run both on server computers as well as on tiny devices like sensors. Moreover ACEs can be dynamically relocated to different devices at run time by making use of mobile code techniques [QuiL06].
2. Communication between ACEs is message based and decoupled. This allows both to supervise the ACE behavior, since communication between ACEs can be intercepted and decoded, and to enable flexible interaction in open environments. In particular, a flexible discovery mechanism called GN-GA has been developed [Hof06].
3. ACE services are semantically described and suitable interaction mechanisms can be contracted on the fly.

4. The behavior of an ACE is formally and explicitly represented by means of a finite state automaton (FSA). This allows to trace and supervise the behavior of an ACE from an external application.
5. The ACE model supports context-awareness by allowing to change the ACE behavior on the basis of the current system configuration.

The above characteristics are a good match for the presented sensor network scenario in that they provide autonomic features that would make the landslide monitoring application more robust and flexible. In particular, in this section we describe how the ACE component model can address effectively the challenges described in the Section 3.

4.1 Fast Deployment and Reconfiguration Time

One of the main challenges we experienced with the landslide application scenario is the need for a fast deployment and reconfiguration time of the sensor network. Especially at the early experimental stages, a sensor network has to be frequently reconfigured and redeployed. This cause a lot of efforts for many reasons:

1. Physical deployment and sensor placement. The sensors should be located on steep and difficult-to-be-reached areas.
2. The implemented static routing schema, other than being inflexible, requires a lot of effort: sensors cannot be easily programmed on the fly, so routing data has to be decided and coded into sensors a priori.
3. Book-keeping activities alone require a lot of efforts. For each deployment it is important to record where the sensors have been placed, and which kind of devices (e.g., accelerometer, humidity, etc.) were active. Then, collected data has to be effectively sorted, compared with each other and stored in a suitable repository.

The ACE model can support and simplify some part of this process notably.

1. Code migration is an important technology implemented in the ACE model. An ACE can be relocated on different devices on the fly [QuiL06] drastically reducing the number of reconfigurations. New experiments can be set up without physically accessing the sensor nodes: new ACEs can in fact move to the sensor nodes and start executing in there.
2. Flexible communication services, there included dynamic routing, are at the core of the ACE technology. ACEs can dynamically discover each other (via the specific GN-GA protocol) and establish multi-hop communication routes.
3. ACE services can be semantically annotated to enable high-level and flexible access to them. This kind of semantic annotation can be really useful to support book-keeping activities in that semantically annotating collected data would drastically improve data organization.

4.2 Robustness – Fault Tolerance

Another important challenge we faced in the landslide application scenario is supporting robustness and fault tolerance. ACEs can deal with this kind of problem by reconfiguring their activities on the basis of the current system situation.

Network reconfigurations, possibly leading to partitions are the most severe treats the ACEs has to deal with, in particular:

1. ACEs can detect individual broken links and fix routing-table lines accordingly.
2. The addition of new sensors on the fly can be taken into account by having ACEs run discovery protocols to detect new neighbors.
3. Network partitions or massive node faults can trigger specific autonomic services for network reconfiguration. For example, in case of network partitions, ACEs can control the low-level hardware of the network card to increase the power of the wireless signal to detect far away neighbors.

This kind of autonomic behaviors drastically increase the robustness and the life span of a sensor network.

4.3 Energy Consumption

Reducing and balancing the energy consumption over a the sensor network is one the main challenges to create a viable landslide monitoring application. ACEs effectively support this process, in 3 important ways:

1. From the networking point of view, ACEs can run autonomic algorithms to balance the overall energy consumption of the network. Accordingly, the routing tree to collect data to the base station can be reconfigured optimizing the overall energy expenditure. For example, an almost discharged node can be left out from the routing tree and become a leaf node. Vice versa, a fully charge node can be exploited to route traffic to the base station.
2. From the data acquisition point of view, ACEs can dynamically tune sensor sampling rate to optimize the overall budget versus data precision. For example, ACEs can decide to increase the sampling rate during probable landslide periods (e.g., if it is rain, or whether accelerometers detect some high values) and reduce it to save energy otherwise.

3. ACEs can also run algorithms to automatically filter noisy, corrupted, and in general not significant data before transmitting it to the base station. On the one hand, this saves energy in that useless data is not sent. On the other hand, it simplifies data analysis process by producing a cleaner data set.

Overall the ACE architecture can simplify and support the activities required to manage the energy budget of the network in an effective and unsupervised manner.

4.4 Devices Heterogeneity and Interoperability

From a general point of view, the ACE component model is directly applicable to the presented landslide monitoring application in that ACEs can run both on the nodes composing the sensor network, and also in the back-end servers dealing with the collected data. The fact of dealing with a uniform component model running seamlessly on all the heterogeneous platforms in our scenario notably simplifies interoperability problems.

5 Conclusions and Future Works

Wireless sensor networks are useful for monitoring rural environments such as remote and isolated landslides. In this paper we presented our experience with landslide monitoring via sensor network and we discussed the issues and the need for a flexible approach to program such infrastructures. In particular, we highlighted how the ACE component model (developed within the CASCADAS project) greatly facilitates the design and development of complex communication services in sensor network applications, enabling the deployment of robust and flexible landslide monitoring systems.

In our future work we will try to complete the development of our sensor network application by exploiting the ACE infrastructure and by integrating all the CASCADAS features like security and supervision.

From the mote sensors point of view, we are considering to migrate from our cheap accelerometer sensors towards more application dependent instruments (e.g. tiltometer), able to collect data in a more accurate and meaningful way and suitable for more sophisticate purposes. In addition, to overcome the problems regarding the high power consumption of bridge nodes, in conjunction with an electronic engineering group in our department, we are planning to face the challenge of equipping bridge motes with photovoltaic panels scavenging sun energy for recharge accumulators and power the nodes at the same time. Finally, we are thinking how to make our algorithms for slope motion patterns identification more advanced and effective.

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