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GLACIAL MONITORING USING WIRELESS PEBBLES

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ABSTRACT

Sensor networks for the natural environment require an understanding of earth science, combined with sensor, communications and computer technology. The importance of design factors that influenced the development of the overall system, its general architecture and communication systems are highlighted.

KEYWORDS: wireless sensor networks, radio communications, environmental monitoring, Glaciology.

1. INTRODUCTION

Continuous advancements in wireless technology and miniaturization have made the deployment of sensor networks to monitor various aspects of the environment increasingly feasible. Unfortunately, due to the innovative nature of the technology, there are currently very few environmental sensor networks in operation that demonstrate their value. Examples of such networks include project in deserts, volcanoes and glaciers. The research efforts in these projects are constantly thriving to a pervasive future in which sensor networks would expand to a point where information from numerous such networks (e.g. glacier, river, rainfall, avalanche and oceanic networks) could be aggregated at higher levels to form a picture of the environment at a much higher resolution. This paper highlights real-world experiences from a sensor network, wireless pebbles, which was developed for operation in the hostile conditions underneath a glacier. To understand climatic change involving sea-level change due to global warming, it is important to understand how glaciers contribute by releasing fresh water into the sea. This could cause rising sea levels and great disturbances to the thermohaline circulation of the sea water. The behavior of the sub-glacial bed determines the overall movement of the glacier and it is vital to understand this behavior to predict future changes.

The Briksdalsbreen Glacier in 2001...... and in 2007

Environmental sensor network

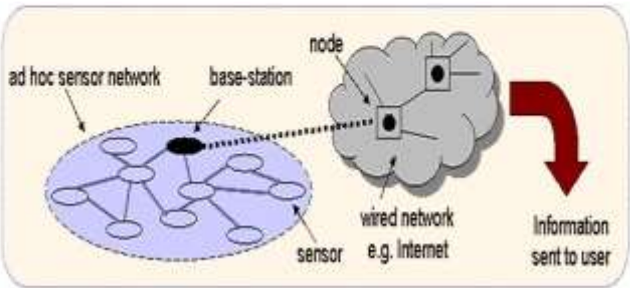
A sensor network is designed to transmit the data from an array of sensors to a data repository on a server. They do not necessarily use a simple one-way data stream over a communications network. Elements of the system will make decisions about what data to pass on, such as local- area summaries and filtering in order to minimize power use while maximizing information content.

2. SYSTEM ARCHITECTURE

The intention of the environmental sensor network was to collect data from sensor nodes (Probes) within the ice and the till (sub- glacial sediment) without the use of wires which could disturb the environment. The system was also designed to collect data about the weather and position of the base station from the surface of the glacier. The final aspect of the network was to combine all the data in a database on the Sensor Network Server (SNS) together with large scale data from maps and satellites. Figure 1 shows a simple overview of our system. The system is composed of Probes embedded in the ice and till, a Base Station on the ice surface, a Reference Station (2.5 km from the glacier with mains electricity), and the Sensor Network Server. Before deployment into the ice, the probes were programmed to wake up every 4 hours and record various measurements that included, the temperature, strain (due to stress from the ice), the pressure (if immersed in water), orientation (in the 3 dimensions), resistivity (to determine if they were sitting in sediment till, water or ice) and their battery voltage. This method provided 6 sets of readings for each probe every day. The base station was programmed to talk to the probes once a day at a set time. It is powered up from its standby state for approximately 5 minutes every day, during which, it collects data from the probes and reads the weather station measurements. Once a week it also records its location with the differential GPS, which takes 10 minutes.. After it has performed these tasks, it sends all the collected information to the reference station PC via long range radio modem. Figure 2 shows the sequence of events occurring during and beyond its operating window describing the communication process between probes, base, reference station and the Server.

3. DESIGN FACTORS

In a sub-glacial environment, nodes can be subject to constant immense strain and pressure from the moving ice. Therefore, a robust sensor design, integrated with high levels of fault tolerance and network reliability was developed. The design of the system was influenced by a comprehensive list of factors including scalability, power consumption, production costs and hardware constraints [8]. These factors served as essential guidelines for the design structure of the network and the chosen protocol for communication. The rest of the section discusses the impact of each factor on the design.



This diagram shows you how this works

3..1 Probes

Each probe was powered with six 3.6V Lithium Thionyl Chloride cells providing 6AH worth of energy. The cells were chosen due to their high energy density and good low temperature characteristics. The probes were designed to consume only 32 W in their sleep mode, where only the real time clock and voltage regulators are powered. In power mode the probe consumes 15mW when the transceiver is disabled, 86mW when it is on but idle, 370mW when receiving, and 470mW whilst transmitting state. The probes wake up every 4 hours for 15 seconds to take measurements

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and then go back to sleep. They were programmed to communicate with the base station once a day when they power up for a maximum of 3 minutes. During this window they attempt to send their data readings to the base. An approximate calculation of a probe daily power consumption turns out to be 5.8mWH. Theoretically, this means at this rate the probe could last for at least 10 years.

3.2. Base Station

The Base station powered up for a maximum of 15 minutes a day during which it communicates with the probes , takes measurements, reads weather station and sends data to the reference station. The Base Station doubles as a communication relay between the Probes and the Reference Station, and as the controller for autonomous operation that orchestrates the entire system. to allow ice movement to be followed. It also has temperature and tilt sensors, a snow meter and camera. It is controlled by a PIC and uses PICs to interface to some modules. A real- time-clock is used to wake the system up.

3.3 The Reference Station

The Reference Station is a mains-powered Linux-based gateway for transferring data. It is the position reference point and records a dGPS file daily. This PC relays the data from the probes, base station and dGPS to the data server in Southampton on a daily basis (via ISDN). In order to survive for one year most of the system is powered-off between readings and controlled by a real-time clock (RTC). The power-budget allows the probes to wake-up every 4 hours to take readings. However the communication channel is only opened once a day during a system- wide window. The daily sequence of events is shown in Table I. At the end of each period, the probe and base station configure their RTCs to the next "wake-up" time before shutting down. The reference station is configured to upload all unsent data to the SNS via an ISDN dial-up every evening. This data is stored in a database where it is being used by glaciologists to interactively plot graphs for interpretation.

3.4 Transmission Media

The communication module for our probes like most other sensor networks was also based on RF circuit design. There were, however, a few variations to our design to accommodate better transmission through ice. Based on the failure of the previous version of the probes [7], the communication frequency between probes and base station was halved from 868MHz to 433 MHz. Antenna size grows problematically with any further decrease in frequency. The presence of liquid water presents a problem when trying to use radio waves in glaciers especially during summer because the englacial water scatters and absorbs the radio signals making it difficult to receive coherent transmissions [9]. Thus by halving the frequency, one is essentially doubling the wavelength which would be larger than the size of the majority of water bodies that could impede the signal. The radiated RF power was also increased significantly by using transceiver modules that incorporated a programmable RF power amplifier that boosted the transmission power to over 100mW to improve the signal penetration through ice. To further improve communications, base station transceivers were also buried 30-40m under the ice connected via serial (rs232) cables.

3.5 Robust Nature

Most sensor networks are catered to face multiple sensor node failures without upsetting the functioning of the entire network. In a system like ours where only a limited number of nodes are available for disposal in the glacier, it is very crucial that all aspects of the system are robust. The glacier's environment is nevertheless very hostile to allow smooth operation of the system including communication. Therefore some very vital measures were taken in order to sustain the network functionalities, even at the cost of time delay, during breakdown of the system.

3.6 Wireless Pebbles Requirements:

Sensor nodes have the following requirements:

- Low-cost - so many units can be produced.
- Low power - for long-term operation.
- Automated - maintenance free
- Robust - withstand errors and failures.
- Non-intrusive - low environmental disturbance.
- Low pollution

The electronics and sensors are enclosed in a sealed plas- tic cylindrical capsule Each has one 100psi pres-

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sure sensor, two dual-axis micro-electromechanical system (MEMS) tilt sensors and a temperature sensor. The

sensor readings are read and stored (in FlashROM) by the PIC microcontroller. Two PICs were used to enable control and remote reprogramming. Communication with the base station is via a transceiver with an omni directional antenna.

Communications

The nature of the environment meant the communications must meet the following requirements:

- High-power unidirectional for probes
- Long-range for base to reference
- Low data-rate
- Error-detection and correction
- Backup channels are needed

Because any part of the communication chain can be faulty we use a store-and-forward mechanism for data transfer. The ring-buffer technique in the probes is also used in the base station so that data flows when communication channels are available. A long-range (2.5km) hop between the base and reference stations is linked with a 500mW 466MHz radio-modem with built-in error-handling (9.6kbit/s suffices). If this fails a backup GSM phone is used by the base to send data directly to the server in . This actually occurred when one radio modem failed in the reference station.

One consequence of using PIC microcontrollers is that the use of TCP/ip was ruled out. A custom protocol allowed a lower overhead and a greater degree of experimentation. A packet-based protocol with error detection was devised which also allowed a multi-master bus-like network topology could be employed. An extensive use of store-and- forward, time-outs, checksums and retries allows the sys- tem to tolerate communication errors. Broadcast packets allow system time synchronisation

3.6.1 Probe constraints

A typical sensor node comprises of 4 basic modules. These are a power module, a sensing module, a processing module and a transceiver module. All these units needed to fit into a palm-sized module that could be easily dispatched into the glacier's bed via holes 70m long and 20 cm wide. As shown in figure 4, all the electronics were enclosed in a polyester egg-shape capsule measuring 14.8 x 6.8cm. The round shape simplified insertion into the drilled holes. Our probe electronics was divided into 3 sub-systems: digital, analogue and radio each of which was mounted on separate octagonal PCBs. This efficiently utilized the available volume and modularized the design. PIC microcontrollers are low-cost, small sized RISC computers with low power consumption. The probes used embedded PIC processors to configure, read and store the attached sensors at user-specified times, handle power management and communicate with the base station. The length of the capsule was designed so that it could also accommodate a conventional ¼ wavelength "stubby" helical antenna fixated on the radio module.

3.6.2 Base Station constraints

The base station was one very critical aspect of the network as the entire operation of the network depended on it. Due to its location on top of the surface of the glacier, several measures were taken in order to ensure safety and efficiency. The base station was held together with the help of a permanent weather and movement tolerant pyramid structure as seen in figure 4. The electronics and the batteries were housed in two separate sealed boxes. Their weight in total stabilized the entire base station by creating a flat even surface as they melted the ice beneath. The long pole in the middle of the pyramid was used to mount the GPS antenna, the long range modem antenna to communicate with the reference station and the anemometer connected to the weather station in the box. The solar panels were attached directly on top of the boxes in order to minimize wind-drag.

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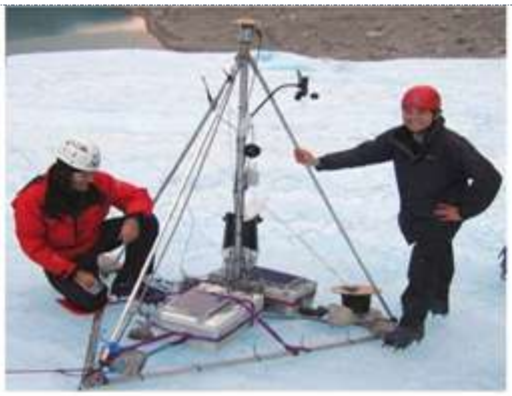

3.7 Topology

Unlike many sensor networks, we decided not to deploy the probes in an arbitrary fashion. The deployment site of the glacier was surveyed beforehand using Ground Penetrating Radar (GPR) to determine any sub-glacial geophysical anomalies (e.g. a river). Based on this survey, the 8 probes were deployed in holes within 20m of a relay probe which was suspended 25m into a central hole. The main reason why this was done was due to the range of the probes. station's polling window. This problem is currently being investigated by a trial and error method where the polling window is shifted slightly every day.

4. CHALLENGES FOR ENVIRONMENTAL SENSOR NETWORKS

Extracting data gathered by the sensor nodes in remote locations involves some unique challenges. GLACSWEB has tackled many of these issues and led to a greater under- standing of the solutions.

Miniaturisation

Miniaturisation is essential as many systems are deployed in confined spaces and may have to be unobtrusive. For low frequency radio the antenna size can be a limitation. Dielectric antennas measuring only 5x7x0.5mm were used to save space as well as for their properties. Surface mount components were used together with double-sided boards but some further integration could be achieved through the use of programmable logic for example. The miniaturisation of subsystems has to be balanced: the limiting factors are still battery size and radio power requirements.

Power Management

Power management is essential for long-term operation. In common with other projects we used a time schedule in order to manage power and employed high-efficiency regu- lated switch-mode power supplies. We felt it was risky to use an extremely adaptive scheme from the start, due to the unknown communication losses and reliability issues. However a rate of change driven data capture system and inter-probe ad-hoc communications would theoretically reduce power use further. Systems requiring a long boot or resume time have to be avoided as this can become the dominant factor.

Scalability

Not only do groups of sensors need to be added regularly to environmental systems, but potentially large num- bers need to be managed. Our initial network topology allowed up to many unique devices to be connected to one base station. The use of a communications window could reduce the scalability because if many probes had to send a back-log of data the time could be insufficient. However in our case they would simply send more data the next day or commands can be sent to probes to keep them awake for longer. Arrays of base stations or gateways will typically be needed in order to increase scalability.

Remote Management

Systems in isolated locations cannot be visited regularly so remote access is essential. Bugs need fixes, subsystems might need shutting down and schedules changed. In our case we found that a camera on the base station would be needed in order to monitor the physical status of the site and systems. Power control to completely isolate subsystems was found to be essential not only for power management but for

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workarounds (the Duck Island project found that their sensors could short circuit their power when wet). Custom communications make remote access more complex because normal logins and routing are not available. More software development and failure scenario testing is required in order to achieve good remote management.

Usability
If sensor networks are to be deployed by teams who buy them off the shelf they need to become easier to install, maintain and understand. In the prototype an earth-scientist could not install the system because of the range of computer and electronics technologies exposed without simple interfaces. This can be compared to installing a scanner, printer and network at home. Plug-and-play style developments will help in this area As more data becomes available a major issue is how re- searchers actually access effectively.

Standardisation
Compatibility between off-the-shelf modules such as d GPS units or weather stations is very low and in practice separate code needs to be written for every module that is integrated. In some cases drivers are available, for a web cam for example, but without the correct operating system this is unusable. A future challenge will be to standardise the interface and even some radio networking to allow in- teroperability between different sensor network vendors Standardising the publication of the final data is essential and can be done using semantic web technologies. This would essentially join sensor networks into the *semantic web* but will be complex unless the community can agree on some common ontologies to describe the domains.

Security
Security issues are important at all levels of a sensor network from physical to data interference. Systems need to blend into the environment and where appropriate carry warnings, information and possibly alarms. This may be less problematic in remote areas. Some systems can cope with the loss of one or more nodes due to failure or dam- age. Data may need to be protected against deliberate and accidental alteration. However security should not be used to hamper public access to information. A balance between security and information needs to be reached so that all parties can trust the systems, this will dramatically affect their development and implementation

5. CONCLUSION AND FUTURE WORK
Environmental sensor networks provide exciting technical challenge The data sets of different types and scales can be merged together to enhance our under- standing of the Earth as a whole. Designing sustainable sensor networks for the natural environment is a demanding task. Communications engineering, power management, deployment, weather-proofing, stability and remote diagnostics have all provided interesting problems. This was a significant achievement that demonstrated that this system is robust and can be operated in the hostile environment of a glacier. Our future aim is to implement a multiple hop, self-organising ad- hoc network of probes that would not only ensure scalability but also reduce power consumption. These aims are fostered by keeping into consideration that a future network would involve more nodes covering a larger area and more than one base station. Use of a much more standardized protocol would improve communication with more probes and ensure a better understanding of the sub-glacial environment.

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