GLACSWEB: A Sensor Web for Glaciers

Kirk Martinez, *Member, IEEE,* Royan Ong, Jane K. Hart and Joseph Stefanov

***Abstract*—A system is described which is designed to obtain data from various sensors within and on glaciers. The sensors must survive for a year so power management through scheduling and selective control is used. Radio links locally in the glacier and across 2.4km distances are used for data and commands. The first prototype system was installed in Norway in 2003 and this paper describes details of the design.**

***Index Terms*— environmental monitoring, sensor network, glaciers, radio communications**

I. Introduction

Modelling the behaviour of ice caps and glaciers is an important part of our understanding of the Earth's climate. Monitoring the subglacier environment is an ongoing research area which is addressed in this project [1,2]. In order to produce a sensor network capable of producing usable data the classic sensor network issues have to be addressed as well as physical difficulties (also found by other researchers [3]).

To accurately monitor this environment the system must autonomously monitor glaciers over a reasonable geographic area and over a relatively long time. It also needs to be as non-invasive as possible to mimic the movement of stones and till. These systems should have the following properties:

- Non-intrusive – mimicking actual behaviour.
- Low power – long-term operation.
- Automated – long term gathering of data.
- Robust – withstand errors and partial system failures.
- Low-cost – cheap enough for many units to be produced.

II. Overview

The system described here consists of: Probes (PR) inserted in the glacier, a supra-glacial Base Station (BS) that communicates with the Probes, and a Reference Station (RS) that relays data to Southampton, as shown in fig. 1. Nine probes were deployed; a majority at the ice-till boundary (between 50m to 80m deep). Each probe is equipped with pressure, temperature and orientation (tilt in three dimensions) sensors. The probes are not recoverable.

Manuscript received November 14, 2003. This work is supported by the Royal Society and the Department of Trade and Industry, UK. K.Martinez, R.Ong J.Stefanov are members of the School of Electronics and Computer Science, University of Southampton, SO17 1BJ UK. Phone +44 (0)2380594491, email: kirk@ieee.org.

J.K.Hart is a member of the School of Geography.

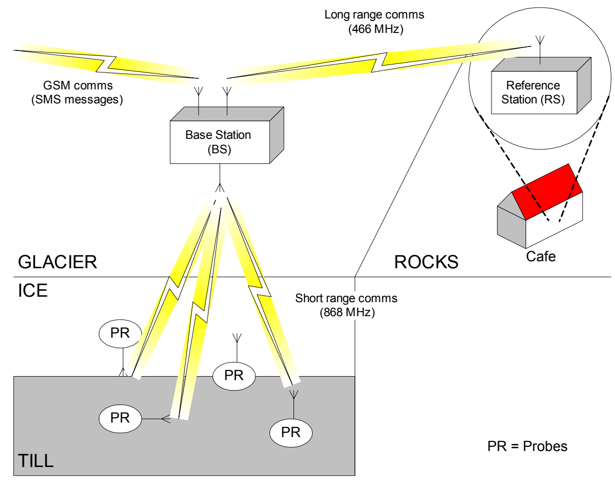

Fig 1. System overview

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.

The Reference Station is the gateway for transferring data and manually controlling the entire system from Southampton. It also acts as a reference point for the differential GPS system for measuring supra-glacial displacement.

Communication between the Probes and the Base Station, and the Base Station and the Reference Station; is carried out over the license-exempted 868Mhz and 466Mhz channels.

III. System Description

A. Probes

The electronics and sensors are enclosed in a cylindrical capsule made from PVC. Each capsule is composed of two halves that were screwed together and water-proofed with O-rings and PVC sealant.

Each probe has one 100psi pressure sensor, two dual-axis 180 degrees micro-electromechanical system (MEMS) tilt sensors and a temperature sensor. The analogue values of the pressure and tilt sensors are converted by the microcontroller (MCU); the temperature sensor is accessed via the inter-integrated communication (I^2C) protocol. This protocol also accesses the real-time clock (RTC) and FlashROM.

Each Probe has a PIC16F876 8-bit microcontroller, responsible for reading and storing sensor data, configuring the RTC, and interpreting commands, as shown in Fig. 2.

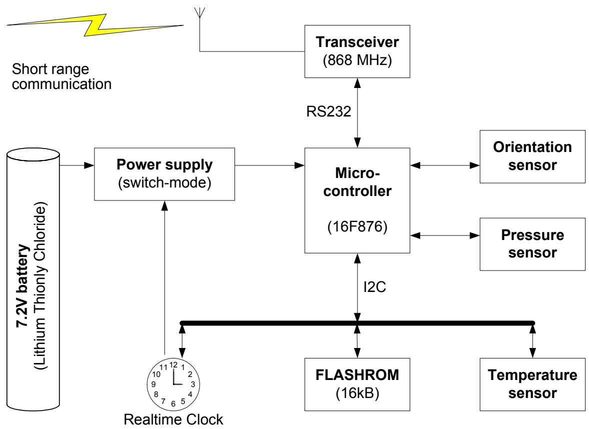

Fig. 2. Block diagram of a Probe

In order to save energy the Probe collects data six times daily (4 hour intervals), although the transceiver is only enabled once each day during the communication window.

B. Base Station

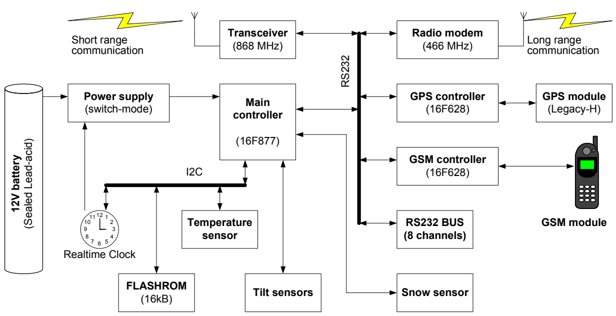

Fig. 3. Block diagram of the Base Station

The Base Station is controlled by a PIC16F877 MCU (main controller) and two ancillary PIC16F628 MCUs (GPS and GSM controllers), as shown in Fig. . The FlashROM, RTC, temperature and tilt sensor sub-systems are identical to the Probe's. The Snow sensor uses an analogue input.

Communication between the MCUs and the long and short-range transceivers is via RS232. To overcome the point-to-point limitation of RS232, a switch between four nodes – the main controller, long-range transceiver, GSM controller and RS232 BUS – was developed (the GPS controller and transceiver is part of the RS232 BUS). This switch ensured that data from any node would be received by the others. Data corruption when multiple nodes transmit simultaneously is not possible as commands are only issued by the main controller.

The GPS and GSM controllers act as proxies for the GPS and GSM modules. This arrangement allows both modules to conform to the communication protocol used (described in Section III), and the controllers also provide additional functionality such as GPS channel selection.

The GPS system is used in conjunction with the GPS unit in the Reference Station to reduce the spatial errors caused by the surface movement (aprox 30m/year). The GSM modem serves as a backup link to Southampton if long-range communication fails.

C. Reference Station

The Reference Station is a mains-powered Linux-based EPIA-PC located in a café. It is connected to the Base Station via the radio modem, and periodically to the internet via ISDN. It is the position reference point and records a GPS file daily. This PC relays the data from the Probes, Base Station and GPS to the data server in Southampton on a daily basis.

IV. Challenges

Extracting data gathered by the Probes buried under a glacier involves some unique challenges. The major obstacles faced in this project, and the employed solutions, are now described:

A. Miniaturisation

Miniaturisation reduces the intrusiveness of the Probes, and the diameter of the bore-hole needed to implant them. The largest components of the Probe are the batteries and antenna. Lithium Thionyl Chloride batteries were employed due to their high capacity-to-volume ratio and good characteristics at low temperatures. Dielectric antennas measuring only 5x7x0.5mm were used instead of metallic antennas.

B. Power Management

Power management is essential for continuous operation over a year. The Base Station and Probe's circuitry remain unpowered until they are "woken" by their real-time clock. In the sleep state, they only consume 200µA. The RTCs are responsible for enabling the power to the systems according to a time schedule. Both systems power-down automatically after a specific duration. In addition, they actively control the supply to various modules (e.g. transceiver, GSM) and employ high-efficiency regulated switch-mode power supplies. The schedule shown below in table 1 was determined by the power budget available.

C. Radio Communication

The short-range communication has to penetrate up to 100m of glacier ice and some sediment. Under these conditions, RF signals degrade significantly. In view of this, powerful 868MHz transceivers with good sensitivity and efficiency were chosen. The chosen centre frequency is a compromise between antenna size and RF losses. In addition, the omni-directional characteristic of the antennas avoids problems with varying orientation.

The distance between the Base and Reference Stations is 2.4km without line-of-sight. For reliable communications 466MHz high-powered (500mW) radio modems were employed.

A 9600 baud rate is used in all radio communications in this system. This is sufficient for the amount of data handled and will only lead to delays when a camera is mounted on the base station.

D. Communication Protocol

A robust communication method is essential to prevent noise from interfering with system operations and to maintain data integrity. To achieve this, a packet-based communication protocol with error detection was devised.

The packetising of data also meant a multi-master bus-like network topology could be employed.

The packet structure comprises six data fields which vary between 5 and 20 bytes, as shown in Fig. . The first byte contains the header and the size of the data field. The second byte is the ID of the destination. This ID is unique for single-MCU devices. The command (CMD) field allows up to 256 different commands to be defined. The data (DATA) field varies between 1 and 16 bytes and the checksum (CS) is used to check the validity of the packet.

0	1	2	3 … 18	19
HD/SZ	ID	CMD	DATA	CS

Fig. 4. Communication packet format (maximum length)

In the current set up, three types of packets are recognized: command, reply and broadcast packets. Command packets are sent by the Main controller (or from Southampton) to any other device. The device in question responds with a reply packet. If a valid reply packet is not received within a preset duration, this signifies communication (e.g. checksum error) or topology (e.g. unknown device) error. The only packets sent by the Main controller which do not cause a reply are broadcast packets: they are used to disseminate information to all devices simultaneously (e.g. command for setting RTCs).

E. *Sequence of Events*

The daily sequence of events for recording and transferring data is shown in Table I. At the end of each period, the Probe and Base Station configures their RTCs to the next "wake-up" time before shutting down.

TABLE I. COMMUNICATION SEQUENCE

Time	Probe	Base Station	Ref. Station
0000	Data log		
0300		GPS log	GPS log
0400	Data log		
0800	Data log		
1200	Data log		
1600	Comms	Comms	Comms
1900			Transfer
2000	Data log		

Probes only record their sensors during *Data log* periods. During the *Comms* period, they enable their transceivers for a fixed duration after recording their sensors. The Base Station powers up during this period and reads its own sensors, broadcasts the system time and requests unseen sensor readings from the Probes. In addition, the Reference Station connects to the internet to allow communication between Southampton and the entire system. This *communication window* opens for a short duration once the systems are idle.

The Base Station and Reference Station also "wake up" during the *GPS log* period to read GPS data. The packets and GPS data that has been recorded over the day are transferred to the data server in Southampton during the *Transfer* period.

F. *Control and Scalability*

Although the entire system is autonomously controlled by the Main controller in the Base Station, additional commands can be issued when the *comms window* opens. These commands can be sent by the Reference Station, or from Southampton. This extends the flexibility of the entire system.

The network topology allows up to 256 unique devices to be connected within the same domain. Additional modules such as a weather station and sensors would seamlessly integrate with the system as long as they adhere to the protocol. Future systems may need several base stations and inter-probe communications.

V. PRELIMINARY RESULTS

The entire system was installed at Briksdalsbreen, Norway, in August 2003. Holes were drilled with a modified high pressure hot jet-wash after a ground-penetrating radar survey to map out englacial rivers. A mission was carried out in October 2003 to upgrade the Base Station and check the system's condition. The front 50m of the glacier is extremely fragile and surface streams had a severe impact on some holes. Fig. 5 shows the base station.

Fig. 5 Base station and antenna tripod.

A. *Results from Probes*

Temperature (Fig.) and pressure (Fig.) readings were received from one Probe (Probe 8) for nine days after deployment within the glacier. The temperature is not expected to vary much from zero and this is confirmed. The tilt readings were constant throughout this period and are not shown.

Probe 8 was tightly wedged approximately 20m into the glacier. The cessation of data after the 7th of August is attributed to the loss of communications when the Probe slipped into the water-filled zone at the bottom of the hole. Under such circumstances, communication is impossible until the water freezes in the winter. It is expected that communications will be enabled in the winter and each probe will transmit their back-log of data.

The drop in pressure seen in Fig. (error is approximately ±3psi) is still being analysed.

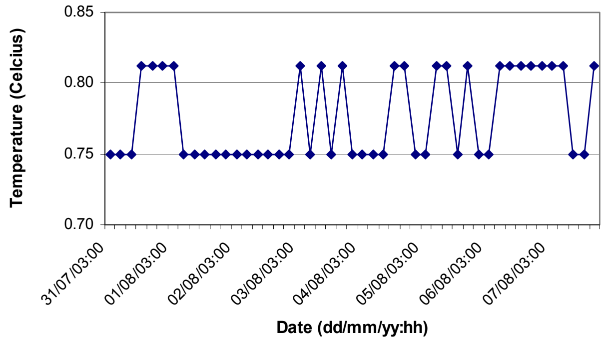

Fig. 6. Probe 8 Temperature Recordings

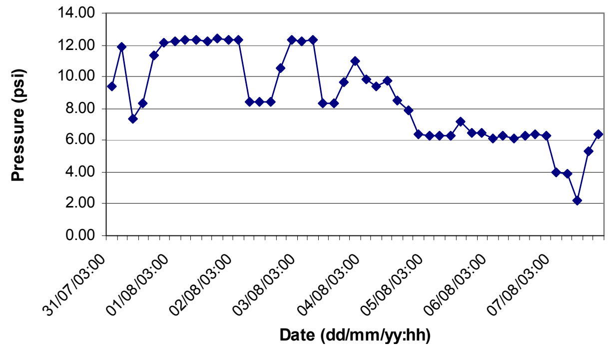

Fig. 7. Probe 8 Pressure Readings

B. *Results from the Base Station*

The Base Station has two sets of data: one each before and after replacement of the main board. The first set of data shows its battery voltage (Fig.) and the second the tilt (Fig.) and temperature (Fig.).

The battery level fluctuated between 12.3V and 14.2V over the course of 65 days. This ripple is due to the solar panels charging the batteries on bright days and it can be seen that overall battery charge remains high during the summer.

The tilt sensors indicate that the Base Station is firmly attached to the glacier at an 11.5 degree slope. The X-axis was initially more erratic before the Base Station settled. The temperature on the glacier is slowly decreasing due to the onset on winter. The equipment itself remained stable for two sunny/rainy months and is anchored using rocks and a backup anchor to a submerged pole. The ice surface melted down around 2m over the summer so drilled poles can not be used.

VI. CONCLUSIONS

Designing a sensor network for glaciers is a challenging task. Weather-proofing, radio signal losses, unstable mounting on ice, maintaining accurate timings and remote diagnostics have all provided interesting problems. The solutions we have found so far have involved the use of fall-back systems, timeouts, retries and redundant storage of data. Future work includes designing a position measuring system to locate the probes and miniaturising their electronics further. Inter-probe communications and extra sensors are also planned for the second system to be installed in 2004.

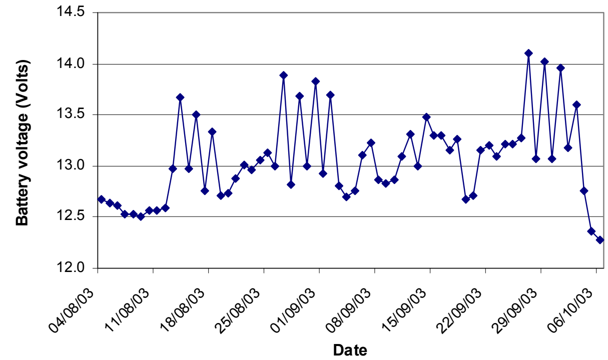

Fig. 8. Base Station battery Voltage

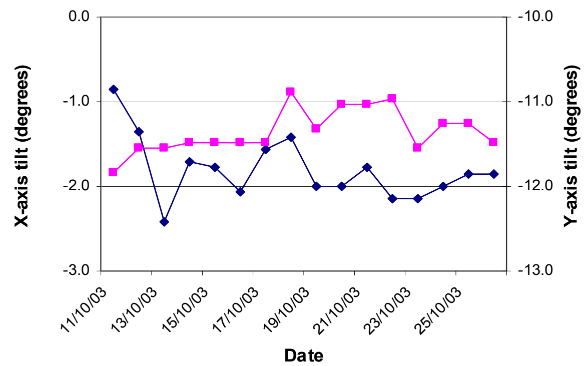

Fig. 9. Base Station tilt

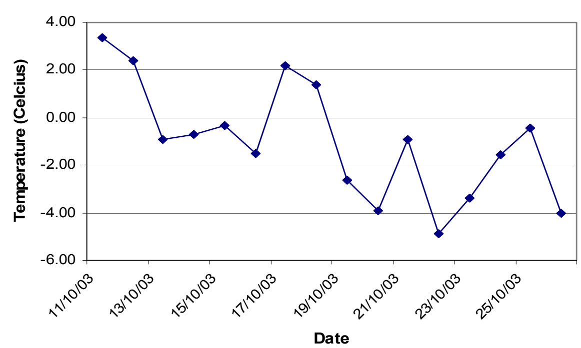

Fig. 10. Base Station temperature

ACKNOWLEDGMENT

The authors thank Intellisys, BTExact and Topcon for their support and Sue Way for field assistance.

REFERENCES

[1] Alley, R. B. "Continuity comes first: recent progress in understanding subglacial deformation", In: Maltman, A. J., Hubbard, B., and Hambrey, M. J. (Eds.). *Deformation of Glacial Materials*, Geological Society Special Publication, Vol. 176, pp.171-180. 2000.

[2] J.K. Hart and J. Rose, "Approaches to the study of glacier bed deformation", *Quaternary International*, Vol. 86, pp. 45-58, 2001.

[3] K.A. Delin, R.P. Harvey, N.A. Chabot, S.P. Jackson, Mike Adams, D.W. Johnson, and J.T. Britton, "Sensor Web in Antarctica: Developing an Intelligent, Autonomous Platform for Locating Biological Flourishes in Cryogenic Environments", *34th Lunar and Planetary Science Conference*, March 2003.