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Radio frequency enabled soil redox potential sensor networks

Chris Holme

Edith Cowan University

"Radio Frequency Enabled Soil Redox Potential Sensor Networks"

by

Chris Holme

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Supervisors:

Michael Collins and Dr Leisa Armstrong.

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USE OF THESIS

Abstract

There is a need for cost effective tools and data collection methods for field measurements; to increase both productivity and volumes of collected data in the quest for enhanced understanding and management of environmental systems. To such end, various technologies that may be combined into a cost effective soil redox sensor network were explored. Suitability of each technology, as a component of said network was evaluated. A prototype soil redox sensor network was constructed and basic laboratory and field testing was completed. Results indicate that the prototype sensor network functions correctly within bounds. Both laboratory and field testing show that the prototype is capable of capturing the correct redox potential of a soil sample as verified by traditional redox capture methods. Further refinement of the prototype soil redox sensor network, developed as part of this study, is necessary if it is to be useful to soil scientists.

Declaration

I certify that this thesis does not, to the best of my knowledge and belief:

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Table of Contents

1. Introduction

1.1 Background to the Study

The Department for Agriculture of Western Australia (DAWA) undertakes field research into a number of cereal crops (e.g. wheat and barley). The primary focus of the research is an assessment of how such crops are affected by periods of waterlogging and resultant soil imbalances such as are described by Patrick, Gambrell, & Faulkner (1996, p1260, 1261). Patrick et al. state that measuring the **red**uction **ox**ygenation (redox) potential of the soil is an effective method of determining the effects of waterlogging.

Of those methods previously used to measure soil redox potentials, that using a buried platinum (Pt) electrode together with a reference electrode produced the most significant results. The reference electrode consisted of a glass vial filled with potassium chloride or other suitable electrolyte to provide a known potential (Patrick et al., 1996). This may then be compared with the Pt electrode to produce a voltage reading representing the soil redox potential.

1.2 Significance of the Study

Current methods, as practiced by DAWA, of collecting soil redox data from areas of interest involve an operator visiting every measurement location in a given data collection area. Redox potentials must be recorded manually for multiple Pt electrodes installed at each measurement location within the data collection area. Such a manual method of gathering and transporting data consumes resources that may be more gainfully used. Automating collection of soil redox potential data will provide an opportunity to increase the number of measurement points covered per research dollar. Such increased coverage of areas of interest may provide researchers with more detailed knowledge of local soil conditions and improved effectiveness when managing those areas.

1.3 Purpose of the Study

The purpose of this study is to investigate automation via electronic measurement and communication technologies to improve the efficiency of soil redox measurement.

Improved measurement efficiency may increase the effectiveness of management of food producing land, wetlands and catchment areas.

1.4 Research Question

The main question:-

"May soil redox potential data be gathered via a communicating population of automated data loggers?"

The major components of the above are:-

1. *"May commonly available technologies be combined to realise a communicating population of automated data loggers?"*
2. *"Is it possible to construct a prototype soil redox potential collection system using a communicating population of automated data loggers consisting of the technologies identified in sub question 1?"*
3. *"Is the prototype an effective soil redox potential collection system?"*

1.5 Summary and synopsis of the remainder of the study

In this chapter the need for a more cost efficient soil redox data collection system was presented, together with research questions to be answered regarding the construction and utility of a network of sensors that sample soil redox potentials and communicate the collected data via radio for subsequent collection.

Chapter 2 presents research efforts in the form of a literature review while Chapter 3 details the design and construction of a small prototype soil redox sensor network. Chapter 4 recounts the procedure used to test the prototype sensor network and Chapter 5 presents the results obtained along with a discussion regarding the usefulness of the prototype soil redox sensor network. Finally, Chapter 6 concludes this document by recapping the activities undertaken as part of this study and reiterating the main findings.

2. Review of Relevant Literature

2.1 Literature Concerning Suitable Technologies

This Chapter discusses recent technological innovations upon which to base this study and describes the three main areas of interest, namely:

1 current techniques for obtaining soil redox potential data;

2 research aimed at improving soil redox data collection methods; and

3 technologies that may be integrated into an automated soil redox data collection system.

2.2 Discussion

Recent advances and refinements in short-range radio frequency (RF) hardware manufacturing techniques have increased the availability of Original Equipment Manufacturer (OEM) RF communication modules. Such OEM modules, discussed in detail in section 2.5.7, may be combined with data loggers to produce communicating data collection systems (Iftode, Borcea, & Kang, 2003). Many environmental measurement schemes use such combined technologies to measure, collect and report soil-related data (Cogger, Kennedy, & Carlson, 1992; Government of NSW, 1999; Hudnall, Daigle, & Hutchinson, 2001; Sensors Magazine, 2002). However, collection of soil redox potential data using RF sensor networks is one area that is yet to benefit from such automation.

The United States Department for Agriculture - National Resources Conservation Service uses standard redox measurement electrodes connected to data loggers to record redox potentials over time (Hudnall et al., 2001). This automation of soil redox data collection represents an improvement over traditional methods but does not take advantage of the remote configuration and data collection facilities offered by RF sensor networks.

Sensor network technology is available from a number of sources. For example, Crossbow Technology manufactures a sensor network called MICA (Davidson Direct, 2004; Crossbow Technology 2005), based on open source technology developed by

researchers at UC Berkeley. MICA, discussed in detail in section 2.5.6, is used by seismologists to measure a range of data at different locations and relies on an RF network to convey remotely collected data to a central location (Sensors Magazine, 2002). An experimental interface to the MICA electronics, to digitise the input from a Pt/reference electrode pair, has been developed by the author of this study.

The remainder of Chapter 2 details the current situation, current research, and those underlying and supporting technologies to be considered when designing a system to collect soil redox data. Suitability of each technology for integration into a complete soil redox sensor network is discussed in section 2.8.

2.3 The current method of measuring redox potentials

Current soil redox measurement practice involves a Pt electrode and a reference electrode, both of which are in contact with the soil (Patrick et al., 1996). The potential between the two electrodes is recorded via a **D**igital **M**ulti**m**eter (DMM) or data logger (Hudnall et al., 2001).

While Pt electrodes are viable for many months, the reference electrodes are less durable. Extended use of a reference electrode causes its contained electrolyte to deplete leading to drift in the measurement not attributable to changes of redox state (Patrick et al., 1996). According to the results obtained by Bochove, Beauchemin, & Theriault (2002), 1000 hours of instantaneous logging at two minute intervals is the useful lifetime of a silver/silver chloride (Ag/AgCl) reference electrode; this may be calculated to less than ten hours of continuous connection.

Exacerbating the electrolyte depletion problem is the requirement for the reference electrode to remain connected to the circuit until any drift in potential stabilises. The amount of time the operator must wait before the reading is related to the redox state of the soil and is not constant (Bochove et al., 2002).

Another issue, related to the dual electrode method of obtaining soil redox data, is that current collection methods are labour intensive. A technician must visit each measurement site before data may be collected or equipment checked, resulting in significant resource expenditure (Patrick et al., 1996).

In an effort to circumvent such issues with the dual electrode system for obtaining soil redox potentials, some researchers are looking at ways to improve the traditional electrode pair. Other research is aimed at replacing the electrodes with alternate technologies such as a colour change indicator similar to that used to measure the PH of a liquid (Ingle, 2002).

2.4 Current research into methods for measuring redox potentials

Bochove et al. (2002) have investigated the use of electronics to obtain instantaneous, stabilised data when undertaking soil redox data collection. Results indicate that it is possible to use electronics to simulate constant connection of the reference electrode to the measurement circuit (Bochove et al., 2002). However, this simulated connection still causes the electrolyte depletion problem discussed earlier.

Research at Oregon State University (OSU) focused on development of an inexpensive, portable colour-indicator for redox measurement as an alternative to the traditional electrode pair. However, it is known that exposure to oxygen alters the redox state of a sample (Oregon State University, 2002). To overcome this problem, an in-line flow cell was developed which transfers ground water from the soil to the measurement chamber without exposure to air. This colour indicator system was tested both in the laboratory and in an environmental cleanup setting (Oregon State University, 2002) and represents an improvement over traditional methods for measuring soil redox potentials. However, the system relies on the presence of sufficient ground water to be pumped into the measurement chamber. This reliance limits application of the colour change system to those areas where free water is present in the soil.

Measurement is only one challenge confronting redox potential based researchers. Once a redox potential is captured, the data is usually transferred to another device for

storage and/or subsequent interpretation. RF communication may be applied to enhance data transfer within such a system.

2.5 Existing methods and protocols for RF communication

Those RF communications technologies that may be considered suitable for integration into a complete soil redox potential data gathering system will now be described and evaluated.

2.5.1 Controller Area Network (CAN)

Parallel to the development of OEM modules mentioned in section 2.2, protocols have been modified and/or developed to cater for the specific needs of short range RF communication (Kvaser, 2004).

The CAN protocol (ISO 11898) is a protocol designed to facilitate communications between two or more electronic control devices within mobile machinery. CAN was originally developed by Bosch for use within the automobile industry in the mid 1980s. It is intended for use with twisted pair wires, but other media such as radio may be substituted (Kvaser, 2004). CAN was among the first protocols to be modified for short range RF usage. However, CAN does not offer repeater type protocols (ISO 11898), making the standard difficult to implement in an ad-hoc manner, such as that required when deploying sensor networks. A protocol designed specifically for RF communications is Bluetooth.

2.5.2 Bluetooth

Bluetooth is a standard for implementing short-range radio networks and is suited for data rates up to 433.9 kilobits/second (Bray, 2001). However, it is limited to eight devices in any network (Adams, 2003). Any Bluetooth enabled device not 'parked' on the network is forced to resynchronise before requesting a connection (Dunn, 2003), a process that lasts for 3 to 30 seconds. Such latency makes Bluetooth unsuitable for many sensor networks. Smart messaging is another approach to the problems related to RF networks.

2.5.3 Smart Messages

Smart messages are based on a distributed computing model wherein each message is a migratory process that transports itself to nodes of interest (Hurst, Cunningham, & Somers, 1997). This system relies on virtual machines and self routing algorithms running on the nodes (Iftode et al., 2003). Smart messages allow automatic configuration and reconfiguration of radio networks and, as such, are resilient to physical network changes, thereby allowing the physical alteration of the network during operation; an advantage in field sensor networks (Smaldone, 2003). Modern RF communications standards are being segregated from the higher level communications protocols and one example of this segregation is Institute of Electrical and Electronics Engineers (IEEE) standard number 802.15.04.

2.5.4 IEEE 802.15.04

The IEEE standard, 802.15.04 is a standard for short range, low data rate radio communications (Naeve, 2004). It has been developed for battery operated equipment with emphases on energy savings and low operational complexity. The standard specifies details for physical layers, leaving the possibility of defining protocol stacks that implement IEE 802.15.04 to control hardware (Naeve, 2004). One such standard is the Zigbee Standard.

2.5.5 Zigbee Standard

The Zigbee Standard is a set of guidelines for implementing a RF network. Accordingly, it may be thought of as a logical network imposed on IEEE 802.15.04 (Adams, 2003). Zigbee defines the network, security and application profile layers and is set to displace Bluetooth in the commercial sector as it is considered less complicated and superior for battery operated equipment (Dunn, 2003). Adams, the director of Motorola Wireless and Broadband Systems Group Architecture and Systems Organization, and Zigbee Alliance representative, claims that the adoption of the Zigbee standard may reduce the logical design work when developing RF communication systems (Adams, 2003). Adams also claims that many organisations have developed proprietary sensor networks that reduce customer flexibility and that the adoption of Zigbee is an answer to reduced flexibility. One such proprietary system is the MICA Mote.

2.5.6 MICA and other micro radio systems

The MICA system employs sophisticated hardware design and miniaturisation techniques (Johnson, 2003) to achieve sensing, communications and computing in a single device. The MICA system uses an open source hardware and software design approach (Davidson Measurement, 2000). TinyOS (2002) has been developed as an operating system for sensor networks in general and the MICA system in particular. This operating system is programmed in a C-like language called nesC, consisting of components and interfaces (TinyOS, 2002). Once deployed, the MICA sensor motes communicate with each other to form a self configuring network which is resilient to topology changes (Sensors Magazine, 2002). The MICA system has been modified for this study by the addition of a differential measurement interface and manufacture of a TinyOS executable to read and transport the data provided by that interface (TinyOS, 2002). Please see Appendix E for a description of the adaptation of the MICA system for measurement of redox potentials.

Related research at the **U**niversity of **C**alifornia **L**os **A**ngeles (UCLA) developed a sensor net with a different approach to that of the MICA solution (Huang, 2003). By spreading the computing load across the sensor net researchers have reduced the total amount of transmission time required for network configuration and data transmission. Such reduction is achieved through the use of "network clocks" and network time sharing, thereby enabling larger networks of lower powered devices (Huang, 2003).

Another related area of research, embraced by the commercial sector, is the integration of the various technologies required to realise a radio network. These technologies may be categorised as either physical or logical layer technologies. Physical layer technologies comprise hardware and the low level code that controls it while logical layers refer to guidelines for integration of physical components into a network. In section 2.5.7 hardware developments are discussed that make this proposed research possible.

2.5.7 Original Equipment Manufacturer (OEM) modules

Manufacturers of short range radio devices produce complete modules for other manufacturers to include in their products with minimal design effort. These modules range from basic radios, such as the RWS/TWS434 pair (Reynolds Electronics, 2002), to sophisticated radios like the Spaceport module from Radiometrix (Radiometrix, 2003). This range of available technologies provides the OEM designer with a choice, ie. trade off the increased cost of an expensive module against the cost of implementing protocols that guarantee error free data transmission. Or, purchase simple hardware and develop or implement transmission protocols that provide error free data transmission (Radiometrix, 2003).

Development of both hardware and logical protocols for short range RF networks is an ongoing process (Adams, ; Communications Research Center, 2003; Institute of Microelectronics Singapore, ; Johnson, 2003). Section 2.6 is a discussion of those improvements to RF communications which affect this study

2.6 Current research towards improving existing RF communications

Research studies on radio communication systems have included investigations into a number of areas and include two that are relevant to this study. The first area of study is the protection from and elimination of electro-static discharge (ESD) from sensitive electronics (Institute of Microelectronics Singapore, 2004). This research is relevant to the study in that ESD resistant electronics are more durable than systems that do not utilise such technology. The second relevant area of research is the development of miniaturised radio modules that OEM companies may integrate economically into their designs (Johnson, 2003; Radiometrix, 2003; Reynolds Electronics, 2002). Availability of inexpensive, easily employed communications modules reduces design effort and has resulted in a proliferation of devices which communicate via RF means.

On the logical network level, researchers are focusing on development of higher speed, lower energy systems with high levels of abstraction (Adams, 2003). Results of this research are parallel to those from studies on the physical level. Alongside the reduction in complexity when integrating RF hardware into a design is the ease with

which firmware may be developed that uses this hardware (Adams, 2003). Examples of such advances in logical networking are the development of high speed data networks (OGRE, 2004) and development of the Zigbee standard described in section 2.5.5 (Dunn, 2003).

Previous sections have highlighted research relevant to the measurement of redox potential data and its transfer to a place of storage and analysis. Technology relevant to the interpretation of that data, subsequent to its collection, transmission and storage will now be discussed.

2.7 Data display and analysis

Commercially available data logging devices typically include application specific software for storage, display and occasionally analysis of captured data (Davidson Direct, 2004; MicroDaq.com, 2004). Further interpretation of the data may be carried out through the use of commercially available spreadsheet and statistical packages such as Microsoft Excel or Statistical Package for the Social Sciences (SPSS). These software tools provide a practical means to display and manipulate data contained in files, irrespective of whether those files have been generated manually or automatically.

Sections 2.3 through 2.7 have categorised and discussed those experimental and stable technologies that may be considered when designing a sensor network suitable for soil redox data capture. Section 2.8 is an evaluation for suitability of those technologies for integration into such a sensor network.

2.8 Evaluation of pertinent technologies

The research completed by OSU into redox indicator dyes, discussed in section 2.4, is more effective in context than using platinum and reference electrodes to find a redox potential (Ingle, 2002). However, the cost of outfitting measurement points with spectrometers and on-line flow cells would be in addition to the cost of data logging and radio equipment, thus increasing the cost per measurement point of any solution. The redox indicator dye system, experimental in nature, is yet to be manufactured in quantity and accordingly, was not considered as a component of any integrated

solution to the research questions. Elimination of the radical colour indicator system for obtaining redox potentials left only the traditional electrode system to be considered at the commencement of this research project.

In contrast to OSU's method previously discussed in Section 2.4, measurements of redox potential via the use of traditional electrodes (platinum and reference), allows for redox readings to be taken for soil that does not contain free water (Patrick et al., 1996). In addition, the United States Department for Agriculture (USDA) has shown that it is possible to use standard data logging equipment to record redox potentials produced by these traditional electrodes (Dunkels, 2003). Following the precedent set by USDA, the soil redox potential collection system produced as part of this study employs the traditional electrode system.

Once the redox measurement has been made, an appropriate radio network is necessary to transport readings to a common place for subsequent analysis. Four candidate technologies, CAN, MICA, smart messaging and the Zigbee standard, which may considered for integration into a soil redox potential collection system, are discussed below.

One prospective method for transporting redox potential data is the standard CAN (ISO 11898). This standard has been adapted for use with radio communications, but offers no repeater type protocols (Intec Telecom Systems, 2003). As such, a soil redox potential collection system utilising a CAN based RF communication system mandates use of radios with sufficient range and power to cover the whole test area. Such use of more powerful RF communications equipment may violate radio emissions guidelines set down by the Australian Communications Authority (ACA). ACA's emissions guidelines mandate use of radios with effective range of approximately 150 meters or less, making a CAN based solution to the problem of soil redox potential collection suitable for very small areas only.

An alternative technology is the MICA system which may be configured and adapted to perform redox measurements (Davidson Direct, 2004) as only a simple interface between the electrodes and each micro sensor mote need be developed. However, the

cost of approximately AU $350 per node (Davidson Direct, 2004) limits suitability of the MICA system.

Another alternative is an implementation following the smart message paradigm. Smart messages require significant host resources and may be too complicated for use with economical redox measurement automation (Smaldone, 2003). However, new standards such as Zigbee, having been designed for RF networks, promise reduced demand for resources and greater reliability when used in automated soil redox data collection activities.

Use of the Zigbee standard in an integrated, automated soil redox collection system mandates the use of another technology to accomplish the physical layer functions as it only applies to the logical functions of any network. As previously discussed in section 2.5.4, standard number IEEE 802.14.04 is a standard which defines the logical layers of a RF network and may be used in conjunction with Zigbee.

The Zigbee / IEEE 802.14.04 combination may be used in conjunction with OEM RF communications modules, microcontrollers and other electronics such as data storage modules to provide a complete solution to the problem of automated soil redox data collection.

2.9 Summary

Of the technologies reviewed and using affordability, reliability and useability as selection criteria:

- the most suitable equipment to produce the soil redox potentials is the traditional Pt/reference method;
- OEM RF modules are the best candidate for the transport of redox data; and
- the Zigbee/IEEE 802.14.04 combination, using OEM RF communications modules, promises the most economical use of resources within an RF network suitable for soil redox potential collection.

The issues associated with economic, automated soil redox data collection and the suitability of various technologies for possible integration into a data collection system have been investigated. As a result of this investigation, two benefits were identified:

a. a gain in knowledge from an integration of technologies toward a population of distributed, communicating sensors that collects soil redox potential data; and
b. potential improvements to manual collection methods, specifically:
    a) a reduction in required expenditure for field redox measurement programs,
    b) a reduction in labour required to conduct field redox measurement programs, and
    c) an ability to take many measurements rapidly at multiple locations leading to increased local soil knowledge and management ability.

The following chapters detail the methods used to produce and validate a prototype sensor network capable of collecting and then yielding soil redox data.

3. Design and Construction

3.1 Design

Automated capture of redox potentials simplifies data collection by minimising the need for attendance by a technician. However, such automation introduces a data problem where, in an effort to prolong electrode life, data captured automatically has not necessarily been stabilised (Bochove et al., 2002; Patrick et al., 1996).

Initial experiments, discussed in Appendix A, with simple OEM radio modules revealed low reliability of data transfer. In consequence, RF hardware incorporating error detection and correction mechanisms was selected for this project.

A PIC 18F452 microcontroller incorporating ADC, RTC, RAM and 8 bit core, was chosen in conjunction with **S**erial **E**lectrically **E**rasable **P**rogrammable **R**ead **O**nly **M**emory (SEEPROM) for computing and data storage respectively. The reference electrode was biased by +2.5 V relative to ADC ground, thereby eliminating the need to measure truly negative potentials. To combat the problem noted in section 2.3, i.e. to reduce electrolyte depletion to a minimum, a reed relay disconnects the reference from the circuit when not in use.

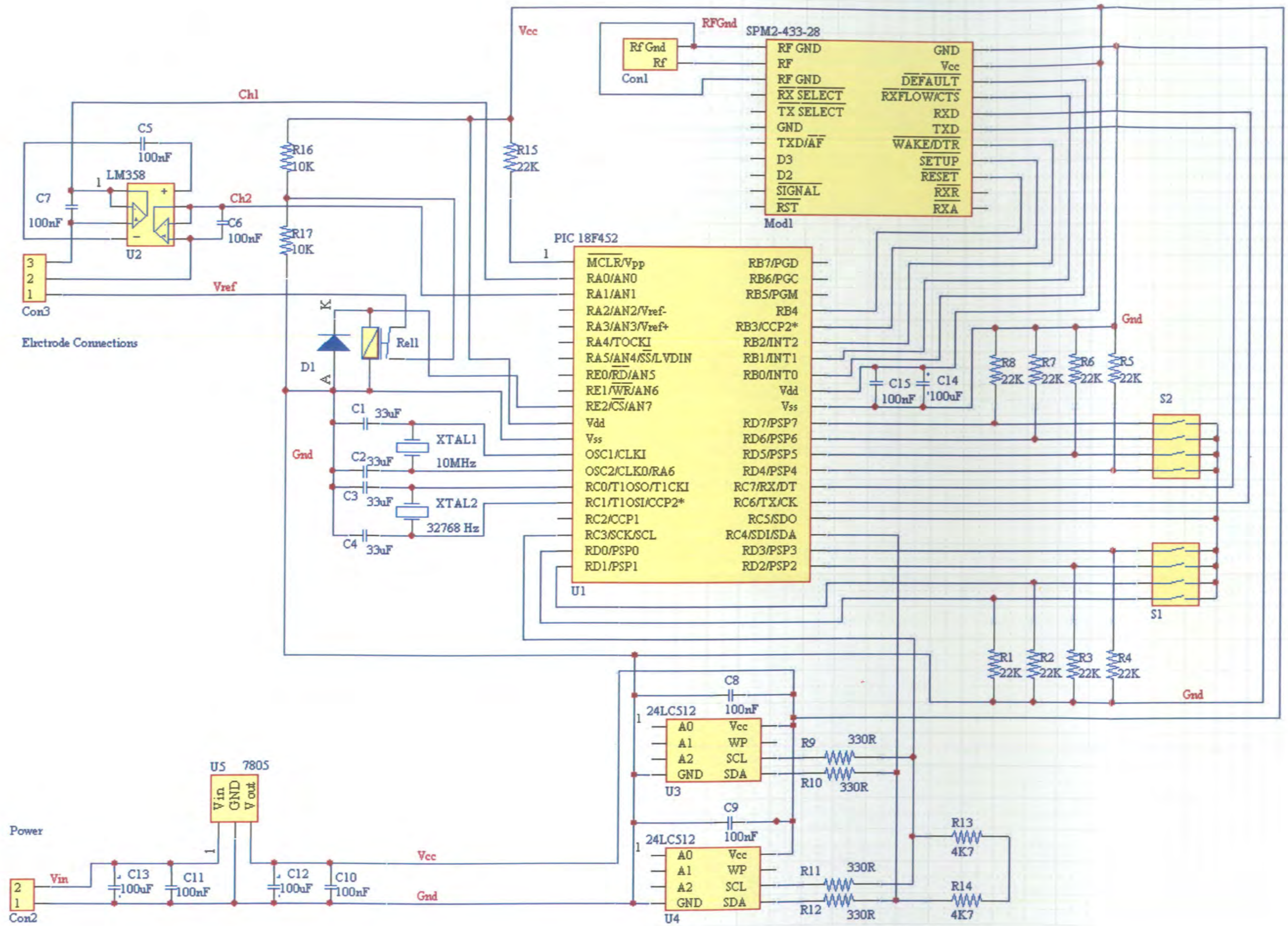

Figure 1: Circuit diagram for prototype node

3.2 Hardware Construction and Basic Testing

This section describes the construction and testing, for basic functionality, of two nodes of a prototype redox sensor network and the RF modem that is the means of communication between sensor net and **P**ersonal **C**omputer (PC) or other device. Construction and testing of the two nodes is described first, followed by construction of the modem.

Following the circuit diagram shown in Figure 1, two prototype nodes to measure, record and communicate redox potentials were constructed. After construction, simple firmware applications were implemented to test individual modules of the circuit. All tests, except those testing RF communication, ran error-free to conclusion. An explanation of the problems encountered with the RF hardware may be found in Appendix B.

To enable communication between the prototype sensor network and a PC, an RF modem was built according to manufacturer's (Spaceport modules) instructions.

3.3 Firmware and Software Creation

The algorithms developed to collect and transmit redox data appear in Appendix C.

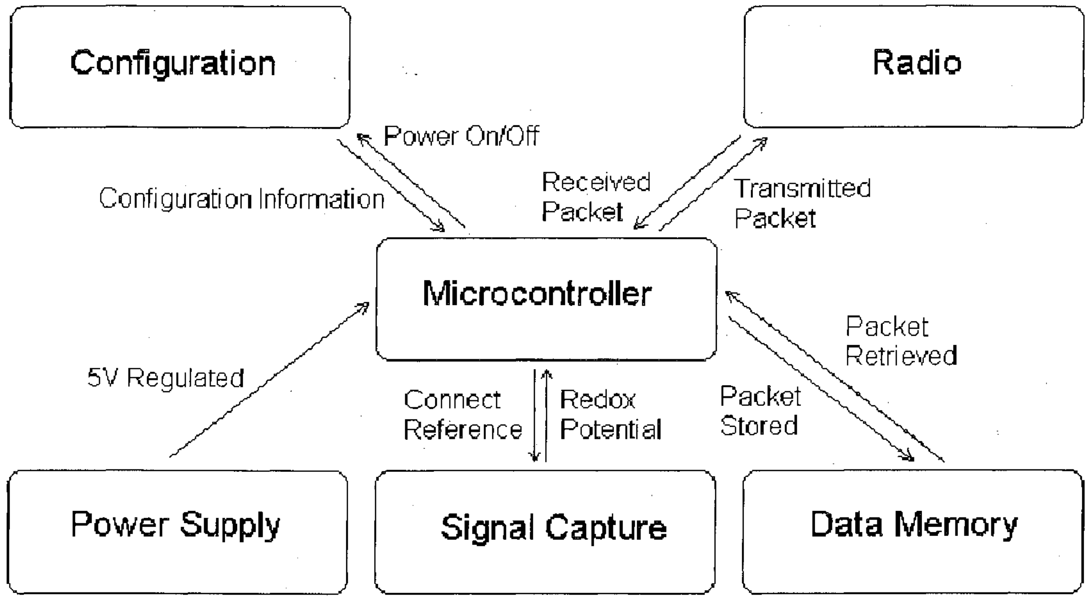

Figure 2: Module diagram for prototype node.

The prototype redox sensor network was reduced to the sub-systems depicted in Figure 2 and mini algorithms were developed to impart functionality to those sub-systems.

Other algorithms not linked to a hardware subsystem were also needed. Tasks such as combining the individual nodes into a functioning soil redox potential sensor network needed to be addressed. To simplify this nodes are arranged in grid pattern each with an address wherein the tuple (1,1) represents the top left node of the network and the tuple (n_1,n_2) represents the bottom right node. Each node is assigned its address upon deployment. The rationale for pre-assigning addresses includes the following points:

- correct position of each redox sensor node must be known before the data collected by those nodes becomes information;
- sensors that may capture soil redox potentials must be situated with care and may not be 'sown' from aeroplanes or by other means; and
- a reduction in labour required to complete the project was realised by elimination of development or adaptation of algorithms to realise a self configuring network.

Time constraints curtailed attempts to produce a multi-hop network. Instead, a system was worked out where each node would report a redox potential at intervals. This redox potential may be gathered by either a PC equipped with a RF modem or by a master node having data memory. Although implementation of a single-hop network reduced effective coverage area of the prototype soil redox sensor network, proof of concept was still possible.

Chapter 3 is an account of those factors that influenced the design and construction of two nodes of a prototype soil redox potential collection system linked by radio to a PC. Chapter 4 reveals the methods used to test the effectiveness of the prototype soil redox sensor network.

4. Method

4.1 Initial Testing

Initial testing of the prototype soil redox sensor network verified that the system reliably takes measurements and transfers them to a PC. The remainder of this section is a summary of the tests performed on the prototype sensor net, a more complete description may be found in Appendix D.

Testing was simplified in the first instance by electrode simulation, thus avoiding the need for a Pt/reference electrode pair. The simulation supplied potentials of ± 1.3 Volts to one node of the prototype sensor net which reported them to a host PC via the RF modem. When the PC received a report from the prototype node it queried a RS232 enabled multimeter for the actual potential supplied by the electrode simulation and stored both potentials for later comparison.

Comparison of potentials captured from the prototype and the multimeter revealed high correlation between the two series of data; indicating that the prototype redox sensor network functions correctly. All data is presented in Appendix D.

4.2 Simulated Field Testing

Although initial testing of the prototype soil redox sensor network had verified that the system captured redox potentials and transferred them to a PC, it was decided to test the prototype in field conditions, and deployed with an actual Pt/reference electrode pair.

In the absence of a precedent, testing was carried out as follows:

(a) Traditional methods as described by (Patrick et al., 1996) and using separate electrodes to the automated equipment, were used to obtain control data. This was used to gauge when the soil within the containers had reached a stable reduced state, indicating the end of the test. Potentials were manually captured from those electrodes used by the automated equipment, thereby providing a point of comparison for the electronically captured readings. Additionally, the

potential evidenced by the Pt/reference electrode pairs when they were first connected to the measurement circuit was recorded. This instantaneous series of data was expected to resemble more the data furnished by the automated equipment than those readings which were stabilised.

(b) To validate the radio communications system implemented in the prototype, a commercial sensor net system was used, namely the MICA2DOT. This commercial system was equipped with a similar measurement interface to that employed by the prototype. The data series provided by the MICA2DOT was used to verify that data emerging from the prototype was unchanged by transport across a radio network. An explanation of the circuit used and the firmware installed in the MICA2DOT nodes may be found in Appendix E.

4.2.1 The Field Test

4.2.1.1 Materials List

- two plastic containers with hermetically sealed lids;
- two 40 mm diameter bathroom plugs;
- eight platinum electrodes for taking redox measurements;
- two Ag/AgCl reference electrodes;
- quinhydrone;
- 30 mls PH 4.0 buffer solution;
- 30 mls PH 7.0 buffer solution;
- a multi meter;
- timber dowel of length 300 mm and diameter 10 mm;
- Selleys Wet Area Silicon Sealant;
- a 12 Volt battery or power supply;
- two prototype redox data capture system nodes;
- a RF modem;
- three MICA2DOT motes;
- MIB510CA interface board;
- 18 pieces of 13 x 0.12 tinned hook-up wire 200 mm long; and
- hand tools.

4.2.1.2 Setting up the test

Following the precedent set by Bochove *et al.*, excavations in soil were made to fit two plastic containers with hermetically sealed lids (Bochove et al., 2002). The containers were placed inside the excavations and the removed soil placed in the containers, as depicted in Figure 3.

Figure 3: Containers set into soil and backfilled

This arrangement minimises the difference in temperature between the soil in the containers and the surrounding soil. Further, it allows manipulation of soil water content and oxygen availability within the containers. Next, the Pt electrodes were tested and installed.

All electrodes were numbered and tested for correct functionality before installation by following the method detailed by Patrick et al., (1996). Redox standards were prepared by adding a "pinch of quinhydrone" (Bochove et al., 2002) to 30 mLs each of PH buffers at PH 4.0 and 7.0. A new reference electrode, acquired from TPS Pty. Ltd. was paired with each of eight platinum electrodes in turn and dipped into each redox standard, rinsing in between. Readings, shown in Figure 4 were made while the

electrodes were immersed in the standards and after potential drift slowed to < 1 mV per 5 seconds.

	Voltage in redox Standard	
Pt Electrode Number	PH 4.0	PH 7.0
1	259	84
2	259	84
3	260	83
4	258	84
5	259	84
6	260	84
7	259	84
8	259	85

Figure 4: Results of electrode tests

Correct function of the electrodes is indicated by readings of 262mV ± 20 mV for PH 4.0 standard and 83mV ± 20 mV in PH 7.0 standard (Bochove et al., 2002).

Once correct function of the electrodes was verified, they were installed in the containers. Figure 5 illustrates placement depths of Pt electrodes. The Pt electrodes were grouped as those used for manual readings, the control series, and those used by the automated equipment. As noted in section 4.2 paragraph (a), a series of manual readings was also captured from the automated group of electrodes.

Platinum electrode numbers in each container, at each depth and included in reading group					
		Container 1			
		Manual		Automated	
Depth in mm	100		6		2
	250	5		1	
		Container 2			
		Manual		Automated	
Depth in mm	100		8		4
	250	7		3	

Figure 5: Depths of electrodes when placed in containers

Holes were made in the soil in the containers with a length of 10 mm diameter timber dowel to the indicated depth and the Platinum electrodes pushed into the holes so that each electrode was in contact with the soil at the bottom of each hole.

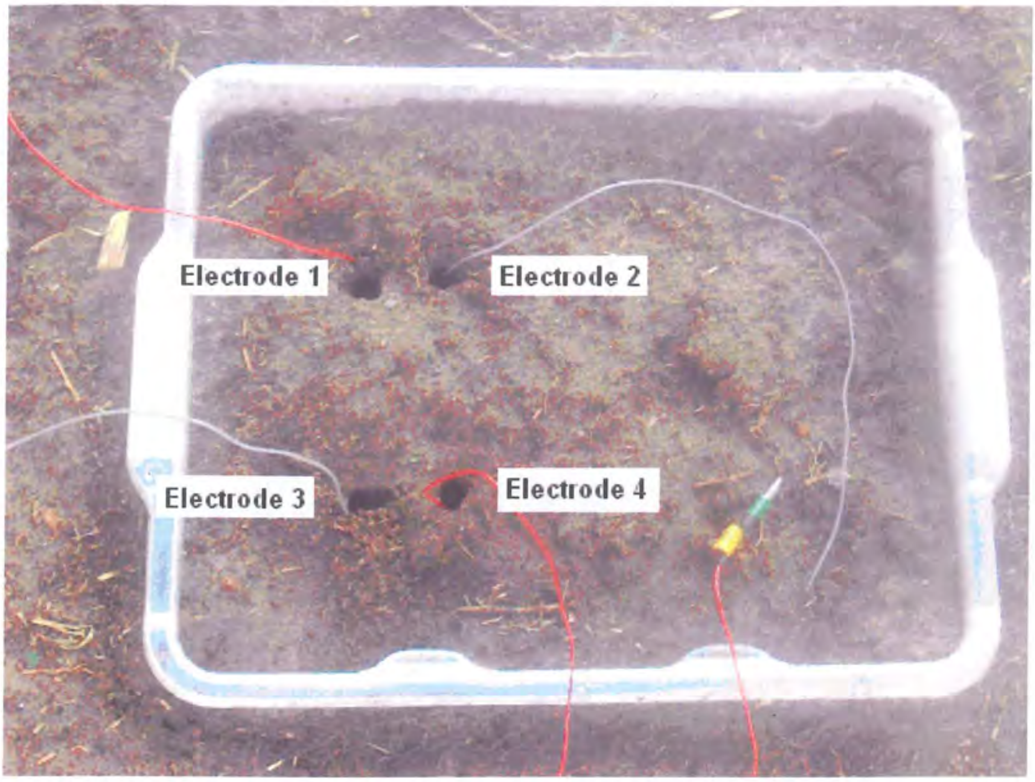

Figure 6: Installing the platinum electrodes

Figure 6 is a photograph of container one after electrode group one was installed.

Next, the wires for the platinum electrodes were passed through previously prepared holes in the lids of the containers. Selleys Wet Area Silicon Sealant was used to seal the lids to the containers. A bead of sealer was placed around the flat surface on the top edge of each container and the lids were then pressed on.

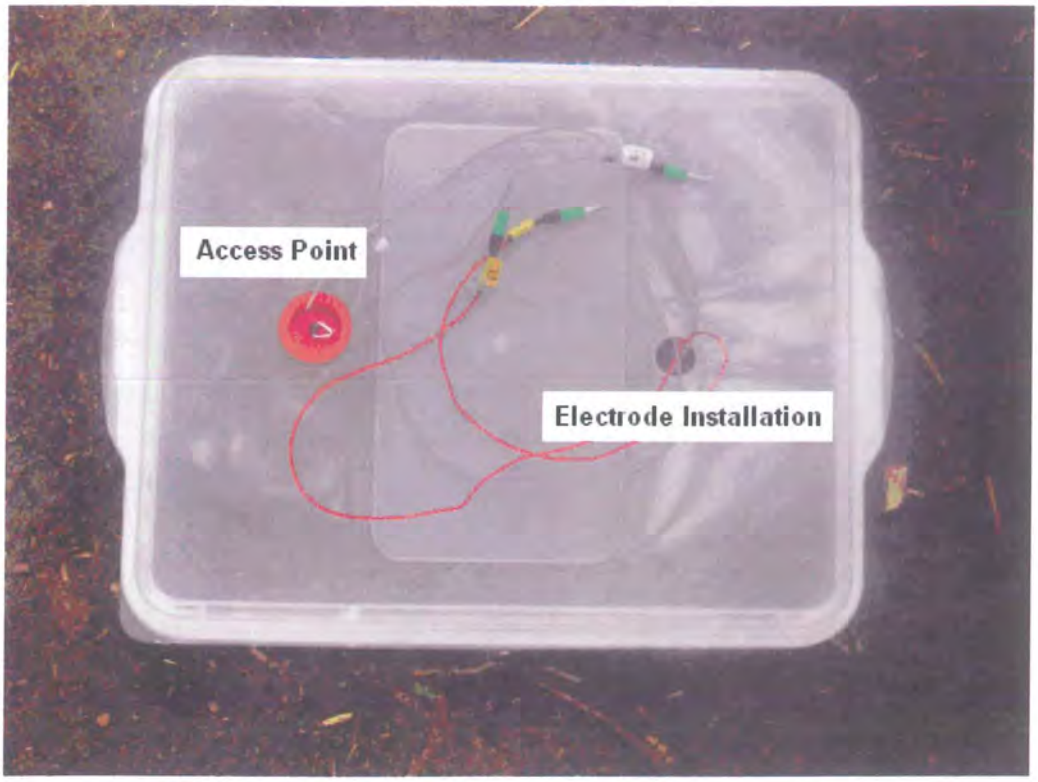

Figure 7: Platinum electrodes installed and lids fitted.

Figure 7 shows container two after its lid was fitted. The second hole was used for access to the soil inside the containers. This hole was sealed with a 40 mm diameter bathroom plug when not used. The reference electrodes were installed next.

New reference electrodes were acquired from TPS Pty Ltd. These electrodes were installed by inserting them through the hole containing the platinum electrode leads. Once the reference electrodes were pushed into the soil inside the containers, Selleys Wet Area Silicon Sealant was used to seal these holes as shown in Figure 8.

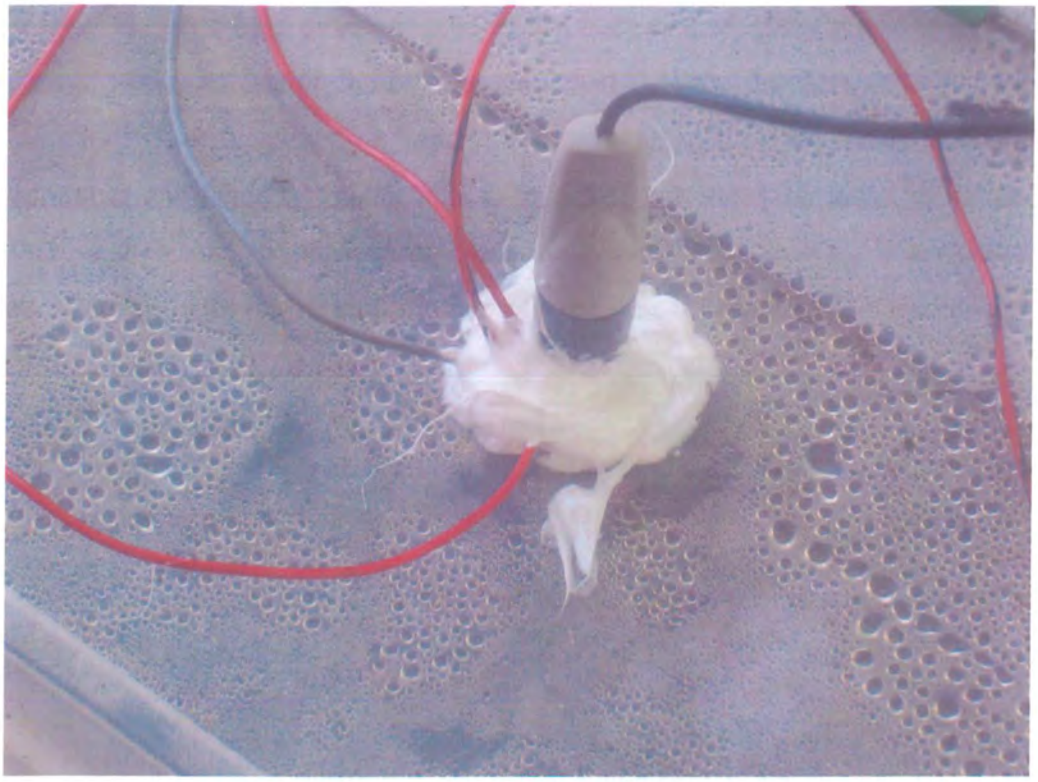

Figure 8: Installation and seal of reference electrode

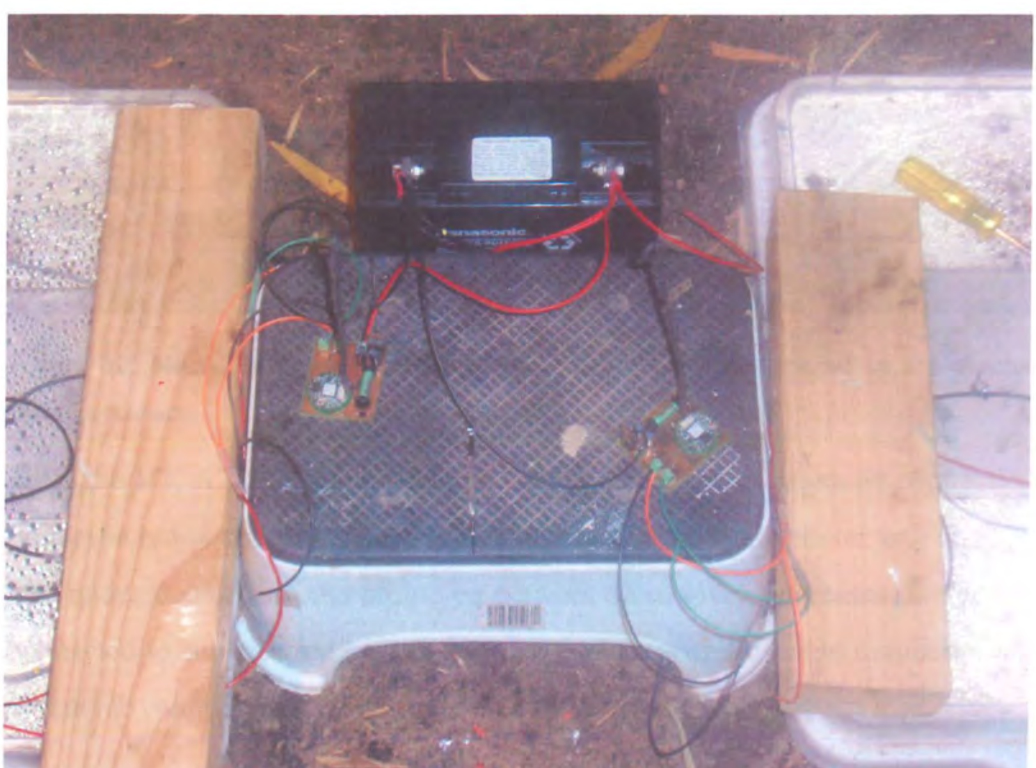

Figure 9: Installation of MICA2DOT sensor network

Next a plastic platform was placed between the containers and the MICA2DOT sensor network was installed as shown in Figure 9. Three lengths of tinned hook-up wire

were soldered to each electrode lead so that each electrode might be connected to both sensor nets and a multimeter simultaneously. Next, the MICA2DOT node with address 101, as discussed in Appendix E, was installed on electrodes one and two in container one while the node with address 102 was similarly installed on electrodes three and four in container two. This arrangement left two other wires connected to each electrode for installation of the prototype sensor network and a multimeter.

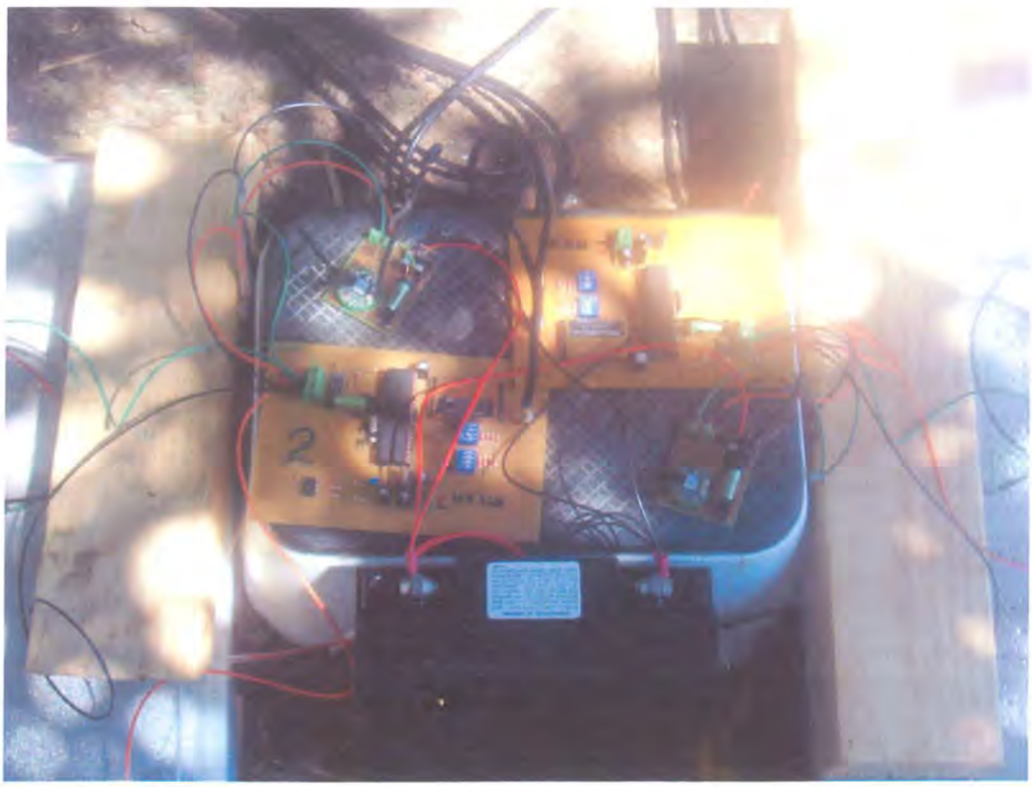

Figure 10: MICA2DOT and prototype sensor networks connected to the electrodes in the containers.

After the MICA2DOT sensor network was installed, work began on connection of the prototype redox sensor network to the electrodes within the containers, see Figure 10. The nodes comprising the prototype network were given addresses one and two and connected to the electrode group in the container with the same number. Connection was made using one of the unused wires soldered to each electrode lead.

Power for all nodes in both sensor nets was drawn from a single 17 Ampere hour lead acid battery.

4.2.1.3 Conducting the test

After all automated equipment was installed; it was switched on and checked for functionality. Small problems with individual nodes were quickly fixed, see Appendix G; leaving both soil redox collection systems functioning correctly.

The first manual readings were taken once both sensor networks were functional; a multimeter was adjusted to the mV range and its common lead was attached to the reference electrode installed in container one. Once the common lead was attached, soil redox potentials were recorded following the method described by Patrick et al. (1996) for platinum electrodes one, two, five and six, i.e. those installed in container one. Soil redox potentials were recorded for container two in the same way. Manual readings were continued at 4 hourly intervals until the conclusion of the test.

Since the soil in the containers was exposed to air during excavation, initial soil redox readings indicated a highly oxidised state. Studies by Bochove et al. (2002) have used glucose solutions to stimulate aerobic microbial activity and thereby reduce a sealed container of soil from its oxygenated state. In order to manipulate the redox potential of the soil over the full range of expected field conditions, this method was employed for field testing.

A solution containing 250 mL of glucose dissolved in 8 L of distilled water was added to the containers, saturating the soil within. Subsequent redox measurements indicated that the soil reduction process had started.

When manual stabilised redox measurements indicated that the soil in the containers had been reduced, the data provided by each control method was compared with that of the prototype redox sensor network. As stated in section 4.2, it was expected that data from the prototype would have high correlation with those control series provided by the commercial sensor net and the instantaneous manual readings due to the complicated relationship between instantaneous and stabilised readings (Bochove et al., 2002).

4.3 Summary

In chapter 4, the method used to test the utility of the prototype soil redox sensor network, constructed as part of this study, has been presented. First, laboratory tests were conducted by using an electrode simulation to provide potentials and a multimeter to provide a control series of data. Results provided by laboratory tests were encouraging so a field test, utilising a reference/Pt electrode pair was performed; this test closely followed a method communicated by Bochove et al. (2002).

Two containers were buried in soil such that their tops were protruding; the removed soil was placed back inside the containers and the lids were sealed on. Four Pt electrodes and one reference electrode was installed in each container. These electrodes were connected to the various automated and manual systems used to capture redox potentials during the test. Glucose solution was added to the containers, all breaches were sealed and initial redox potentials were sampled.

Measurements continued until manual readings indicated that the soil within the containers had reached a stable reduced state, indicating the end of the test. Section 5 follows with a description of the results obtained from field test described in Section 4.2.

5. Results

5.1 Results and the Research Question

A comparison of potentials sampled by the four different systems used for data capture revealed that all methods tend to agree on redox trend but that there are inconsistencies of measurement between systems. A complete set of those results appears in Appendix A.

The data set taken from container one shows a steady reduction of the soil within. By contrast, all methods of redox data capture installed on container two reveal an erratic reduction process. Reasons for this erratic reduction process are not apparent and results from container two will be ignored.

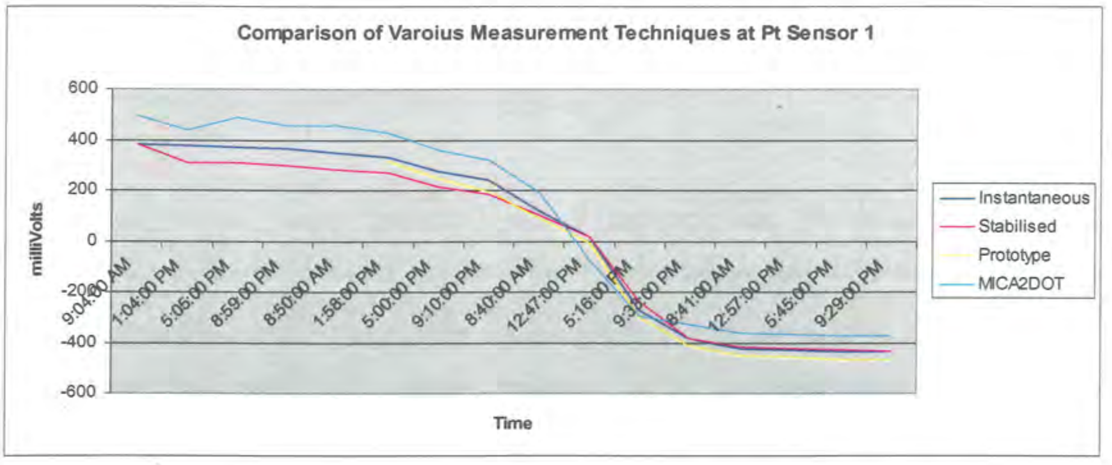

Figure 11: Comparison of Various Measurement Techniques at Pt Sensor 1.

Figure 11 shows that all measurement techniques yielded an initial oxidised state for the soil in container one, indicated by positive potentials, followed by reduction of the soil as indicated by the decreasing potentials reported. The expected discrepancy between instantaneous (the dark blue line) and stabilised (magenta) measurements was most evident when the soil was oxidised. Those potentials captured with the prototype soil redox collection system (yellow) are in close agreement with the instantaneous manual series of measurements. The data collected by the MICA2DOT (light blue) system was approximately 100 mV greater than that collected by the instantaneous and Prototype systems while redox state is stable but was 100 mV lower when the soil

was reducing quickly. Reasons for this discrepancy are not apparent and will be the subject of future study.

Recall the research sub question (a):

a. What commonly available technologies may be combined to realise a communicating population of automated data loggers?

Section 2 of this document is an account of those technologies discovered and evaluated for possible integration into a solution to the research question. In section 2.8 is an evaluation of their suitability and provides an answer to research sub question (a).

Research sub question b asks:

b. Is it possible to construct a prototype soil redox potential collection system using a communicating population of automated data loggers consisting of the technologies identified in sub question (a)?

The prototype soil redox potential sensor network and the MICA2DOT redox potential sensor network, used as part of the control apparatus, were constructed from readily available technologies. It is concluded that it is possible to construct a soil redox potential collection system consisting of a communicating population of automated data loggers from commonly available technologies.

Research sub question c follows:

c. Is the prototype an effective soil redox potential collection system?

When compared with the MICA2DOT sensor net, the prototype sensor net exhibits less sophistication and costs approximately 100 Australian dollars (AU$100) more in single quantities. Further refinement of the prototype soil redox data collection system would see the prototype system become (AU$100) cheaper; through replacement of the Spaceport radio modules with non error handling modules and development of suitable error detection firmware. Usability of the prototype sensor net may be increased to rival that of the MICA2DOT sensor net by installing firmware to enable

multi-hop radio communications between nodes. Although the prototype functions effectively in areas less than 200m square it is not an effective sensor network when compared with the MICA2DOT system.

5.2 Summary

The main research question asks:

> *"May soil redox potential data be gathered via a communicating population of automated data loggers?"*

Results provided by field testing indicate that the prototype soil redox sensor network is capable of providing a measure of the redox state of a soil. Correct function of the prototypes data capture mechanism was verified by the manual series of data captured during the test. Correctness of the sensor network component of the prototype was verified by use of a separate sensor network adapted to sample redox data. It is concluded that it is possible to gather soil redox data via a communicating population of automated data loggers or sensor network.

The effectiveness of the prototype redox sensor network is questionable when compared to commercially available sensor networks such as the MICA2DOT used as part of the control apparatus for the field test. If the prototype is to be of use to soil research workers and competitive with commercially available sensor networks then it must undergo further development.

Section 5 is a discussion of the results obtained from the field test, Section 6 summarises this research project, provides further discussion about the utility of the prototype sensor network developed as part of the study and details possible future extensions to this research.

6. Conclusion

With increasing ecological pressure on the world's remaining arable and wetlands comes the need for more effective management of such land and better understanding of the processes that occur in soils. One factor that affects the health of food crops and wetland plants alike is the redox potential of the soil they grow in. The redox potential of a soil is an indicator of the amount of oxygen available to plant roots and soil dwelling organisms and may also indicate when a soil is water logged.

Currently, no automated technique for gathering soil redox potential data is known to the authors and technicians engaged in the collection of such data must use manually operated equipment. This traditional equipment includes a Pt/reference electrode pair and multi-meter (Patrick et al., 1996). It is labour intensive and therefore expensive (Bochove et al., 2002). At present, the amount of data collected is limited by the few resources available to a point where it's utility is questionable. Automation of soil redox potential data collection is one way of reducing the resources required to collect a specific amount of data and will provide an opportunity to collect much more data with the same resources.

Automation was achieved using established technologies. Figure 2, reproduced below for convenience, is a model of a single node of the prototype soil redox data collection system that has been developed.

The model shows the sub modules comprising the node and the data flows between them. Almost all of these sub modules were constructed using a single active component and as few as two supporting passive components, all readily available. A schematic diagram was constructed and two PCBs were designed and manufactured. Hardware testing revealed no errors of design so a simulation of a Pt/reference electrode pair was devised and a node was connected to it, thereby emulating a field installation.

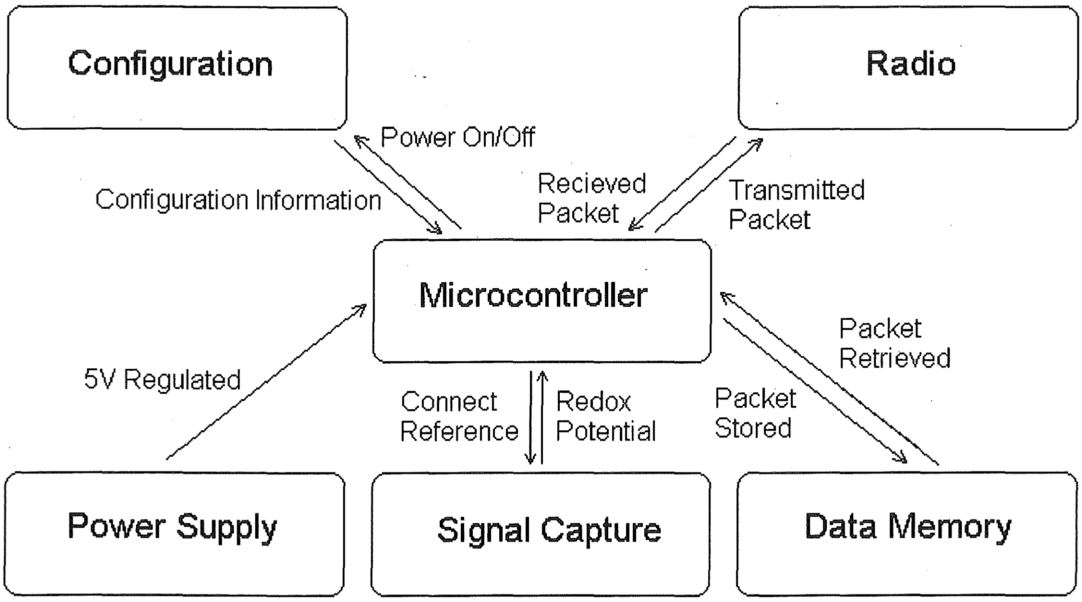

Figure 2: Module diagram for prototype node.

An RS232 enabled multi-meter was also attached to the electrode simulation to provide a control series of data. A PC, in communication with both the multi-meter and the prototype node, was used to record data provided by both devices while the potential provided by the electrode simulation was varied over the range ±1.3 V. Comparison of these two data series revealed high correlation so field testing was planned.

Field testing involved the manipulation of the redox potential of a soil over time. Bochove et al. have made similar field tests and their methods have been adapted to suit present requirements (Bochove et al., 2002). Two containers were buried in soil with the removed soil placed back inside them, aerating and oxidising that soil. The containers were flooded with water and glucose to stimulate the reduction process and Pt/reference electrode pairs were installed. After electrode installation the containers were sealed and the prototype soil redox potential data collection system was connected to the electrodes along with various control equipment.

Soil redox potentials captured from the containers showed a reduction of the soil within. When captured data from the control apparatus indicated that the reduction process had finished the test was concluded and the collected data examined.

Charting the data captured by the prototype system with the data provided by the traditional method used as a control revealed high correlation between the two series. This correlation demonstrates that soil redox trends may be revealed by use of the prototype sensor network developed as part of this study. However, another factor was also investigated as part of this research, namely the effectiveness of the developed prototype as a research tool.

Utility of the developed soil redox potential sensor network is limited by several factors, these are:

1. absence of multi-hop networking protocols severely restricts the area that the sensor network may operate in,
2. the radio modules chosen for integration into the prototype are expensive and cost more than seventy five percent of a complete node; and
3. no power conservation techniques have been employed in the production of either the node hardware or the firmware that controls it.

Accordingly, further iterations of the prototype soil redox potential sensor network would involve:

1. implementation of multi-hop networking protocols increasing the effective coverage of the prototype sensor network many times;
2. use of cheaper radio modules and development of error detection and retransmission mechanisms which would lower cost per node by approximately fifty percent; and
3. implementation of power saving strategies when designing a second iteration of the hardware and firmware used, allowing extended operating times on batteries.

After improvements are made to the prototype soil redox sensor network, a field trial where many nodes are deployed in a soil redox data gathering exercise by soil scientists is advocated. Once the data gathering exercise has concluded, discussion with the soil scientists will reveal areas where the second prototype may be improved further. It is the aim of the authors to provide a tool that may be used to increase the

effectiveness of soil science in the conservation and management of arable and wetlands worldwide.

6.1 Summary

This study integrated two areas of research: namely,

1. capture of soil redox potential data, and
2. sensing and subsequent communication of data via low powered RF sensor networks.

The study's innovation lies in its exploration of methods required for soil redox potential data capture and communication via a network of RF enabled devices (a sensor network). In it, candidate technologies and equipment were investigated, their suitability was evaluated and a prototype soil redox sensor network was constructed. Initial testing involved the successful use of a Pt/reference electrode simulation leading, in turn, to field testing alongside a control system based upon MICA2DOT technology. Field test results indicate that the prototype redox sensor network developed as part of this study reliably captures, transfers and records redox potential data in a reliable manner. This basis enabled each of the research questions posed in chapter one to be answered with affirmation.

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8. Appendix A: Experiments with Simple Radio Modules

Initial radio communications experiments used the RWS/TWS434 pair, consisting of transmitter and receiver modules, from Reynolds Electronics. Circuits constructed on breadboard and utilising two PIC18F452 microcontrollers as communicating intelligences revealed low data transfer reliability. Connecting the transmitted signal and the received signal to channels one and two respectively of a cathode ray oscilloscope showed that the received signal was corrupted by static.

Next, a slightly more expensive module was tried; two NRF401 transceiver modules were acquired from Oatley Electronics. These modules were installed on the breadboards in place of the RWS/TWS434 pair. Communications attempts again revealed low data transfer reliability. A CRC8 algorithm was applied to the data stream in an effort to filter out errors; this had the effect of reducing data transfer to almost nothing.

The poor performance of cheaper radio modules forced the incorporation of more expensive modules into the prototype redox sensor network. The Spaceport transceiver modules used for radio communications incorporate error detection and packet resending mechanisms. Use of sophisticated radio modules eliminates the need to develop algorithms for reliable radio communication.

9. Appendix B: Problems Encountered with Space Port Modules

Initial attempts to communicate with the Spaceport modules chosen to manage radio communications failed. This failure may be attributed to not realising that the Spaceport modules mimic a dumb terminal when communicating with the host controller. Test firmware was written with the assumption that the RS232 link was full duplex with transmit and receive buffers operating within the Spaceport module. In fact, communication is half duplex with characters echoed by the Spaceport module as they are received. This means that instead of sending a whole string to the Spaceport module at once, one character at a time must be sent with a wait after each in order to receive and verify that the character is correctly received. Once this procedure was understood, basic RF communication between nodes of the prototype sensor network was quickly realised.

10. Appendix C: Subsystem Modules and Algorithms

The following is a compilation of the algorithms used by the prototype sensor net hardware during the field test described in this document.

Interrupt Handler

For real time interrupt handling to occur within PIC BASIC Pro programs it is a requirement that the interrupt handler be written in assembly language as PIC BASIC Pro has non re-entrant statements. This interrupt handler must appear before all other code.

```
Declare
        Queue – Array of character
        Pointer to back of queue – integer
        Depth of queue – integer
        Queue full flag – Boolean
        Seconds counter – integer
        Minutes counter – integer
        Hours counter – integer
        Days counter – integer
End Declare
Save used registers
If this is a UART, byte received interrupt AND queue is not full then
        Retrieve the byte from the UART and place it at the end of the queue
        Increment the pointer to the back of the queue
        Increment depth of queue
        If queue is full then
                Flag queue is full
        End if
Else if this a timer 1 interrupt
        Increment seconds counter
        If seconds counter greater than 59 then
                Make seconds counter zero
```

Increment minutes counter

If minutes counter greater than 59 then

Make minutes counter zero

Increment hours counter

If hours counter greater than 23 then

Increment days counter

End if

End if

End if

End if

Restore used registers

Start up chores

Most hardware included with the chosen microcontroller, the PIC18F452, has multiple uses or modes of use. For example, almost all IO port pins are multiplexed with special functions such as ADC inputs or PWM outputs. It is necessary to configure, or turn off, all integrated modules so that the microcontroller exhibits correct behaviour.

Configure Port A as analogue inputs to capture redox potentials

Configure Port B as Spaceport Modem interface

Configure Port C for UART and I2C operation

Configure Port D to read data from configuration module

Configure Port E as outputs to operate redox capture module

Configure Timer 1 as a real time counter

Configure UART for full duplex RS232 communications at 9600 baud

Enable UART receive and Timer 1 interrupts

Capture Configuration Byte

Provision has been made, on each node, for manual programming of parameters such as addresses or group numbers.

Declare

Configuration – byte

End Declare

Turn on the configuration module

Wait for circuit capacitance to charge to Vcc

Read the byte supplied by the configuration module

Turn off the configuration module

Initialise Radio Modem

The Spaceport radio modules require setting up before use. Parameters, such as Channel numbers and operating modes, need to be set. In addition, the address of each node needs to be programmed into its radio.

```
Declare
    Address – byte; the configuration byte
End Declare
Wake up the modem
Enter modem configuration process
While new address not confirmed
    Send new address
    Attempt confirmation of new address
While End
Reset the modem
```

Main Loop

Once all initialisation tasks have been completed, the microcontroller will begin to loop through tasks such as checking the time.

```
Declare
    Redox potentials – array of word data
    Data packet – array of character data
End Declare
If it is time to capture redox potentials
```

Connect reference electrode to the data capture circuit

Wait for potentials to stabilise

Capture potentials from all connected Pt electrodes

Disconnect the reference electrode from the data capture circuit

Construct a data packet containing captured potentials and node address

Send the packet

End If

11. Appendix D: Initial Testing

For these initial tests, it was decided to inject voltages into the prototype system using a model of the Pt/reference electrodes that are used for field measurements. Use of simulated electrodes simplified initial testing by eliminating the need to manipulate soil redox values over time. The circuit used for the simulation is shown in Figure 12. A 25 turn trimming potentiometer was used for VR1 to reduce sudden large voltage changes. Adjusting VR1 from one extreme to the other yields potentials of ± approximately 1.3 Volts.

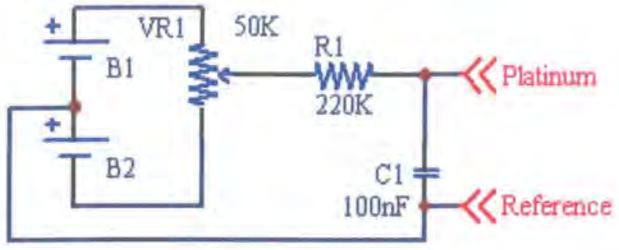

Figure 12: Pt/Reference Electrode Simulation

To obtain test data, one of the prototype sensor network nodes was configured to sample voltages at two second intervals; communicating them directly to a purpose built application running on a PC via the RF modem. By way of control, when the application receives data from the sensor node it queries an RS232 enabled multimeter for the actual voltage applied to the sensor node and records both voltage readings in a text file.

Referring to Figure 12, the simulated electrodes were installed on the test node such that the point labelled reference was connected to the reference electrode while the point labelled Platinum was connected to an input channel of the ADC. The multimeter was connected in parallel to these points. All equipment for the test was switched on and initialised. The electrode simulation was then adjusted from one voltage extreme to the other three times while the prototype node and the multimeter reported the potentials produced by it:

1. starting at approximately -1.3 V the potential supplied by the electrode simulation was raised smoothly to its maximum of around +1.3 V;

2. after a brief period the simulated potential was lowered smoothly, but more rapidly, to its minimum; then, after noticing that the difference between potentials reported by the node and the multimeter appeared to be related to the rate of change of the applied potential;

3. the simulation was again raised to its maximum potential at random rates of adjustment.

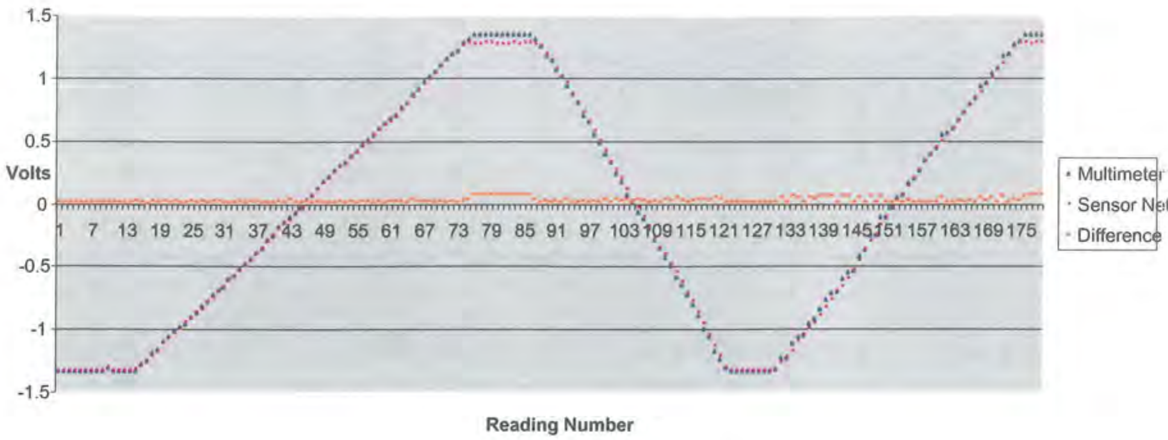

Figure 13: Comparison of Actual and Measured Voltages

Discussion

Once the test was completed, the text file generated by the purpose built application was opened with Microsoft Excel and the values charted, see Figure 13. The chart shows very close conformity between readings taken by the sensor net node and the multimeter except that readings made by the sensor net would not follow the electrode simulation above 1.28 Volts – normal rail clamping for the op-amp selected and a situation that will not affect field readings.

Figure 13 shows the difference in the potentials reported by the multimeter and the prototype for the duration of the test. In it, groups 1, 2 and 3 correspond to the periods when the potential supplied by electrode simulation was varied as described above. Groups 1 and 2 were recorded while the potential supplied by the simulated electrodes was adjusted smoothly from one extreme to the other. Group 2 was recorded at a greater rate of adjustment than group 1; the difference in the data reported varies with rate of change of measured potential. Group 3 was recorded while the electrode

simulation was being adjusted erratically from one extreme to the other and resulted in periods where the difference in readings was as much as 0.06 V and other periods where the difference was less than one third of this. It is supposed that the differences indicate that both meter and prototype require a different amount of time to settle on and yield a true reading. However, in the context of the anticipated maximum rate of change of field redox potentials this is not expected to affect results.

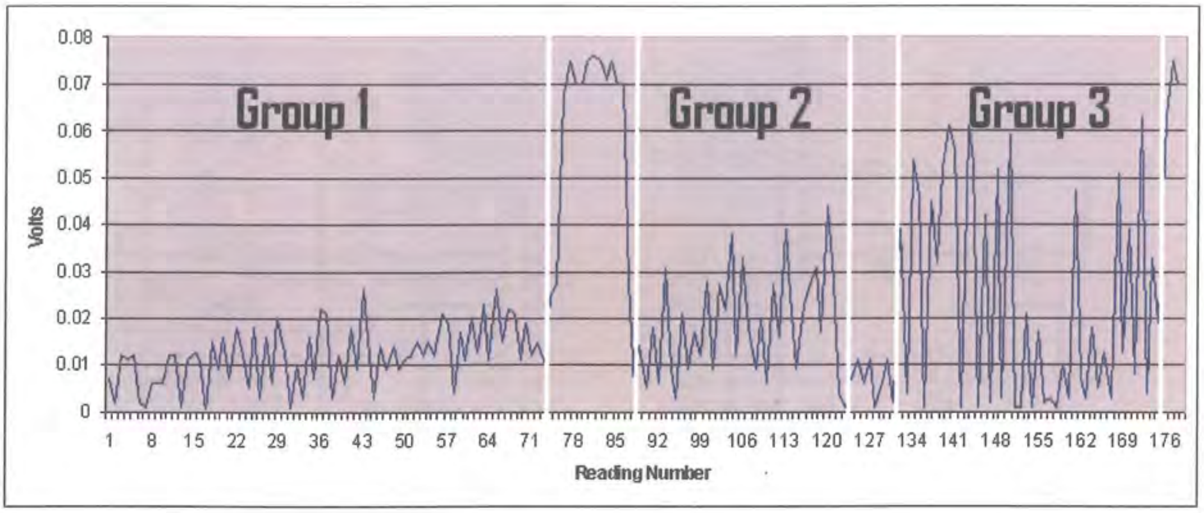

Figure 14: Difference in Potentials Reported by the Sensor Net and the Multimeter at Each Data Point

Interference cancelling techniques were *not* used for this test resulting in the erratic appearance of differences charted in Figure 14.

12. Appendix E: Adaptation of the MICA2DOT nodes for redox data capture

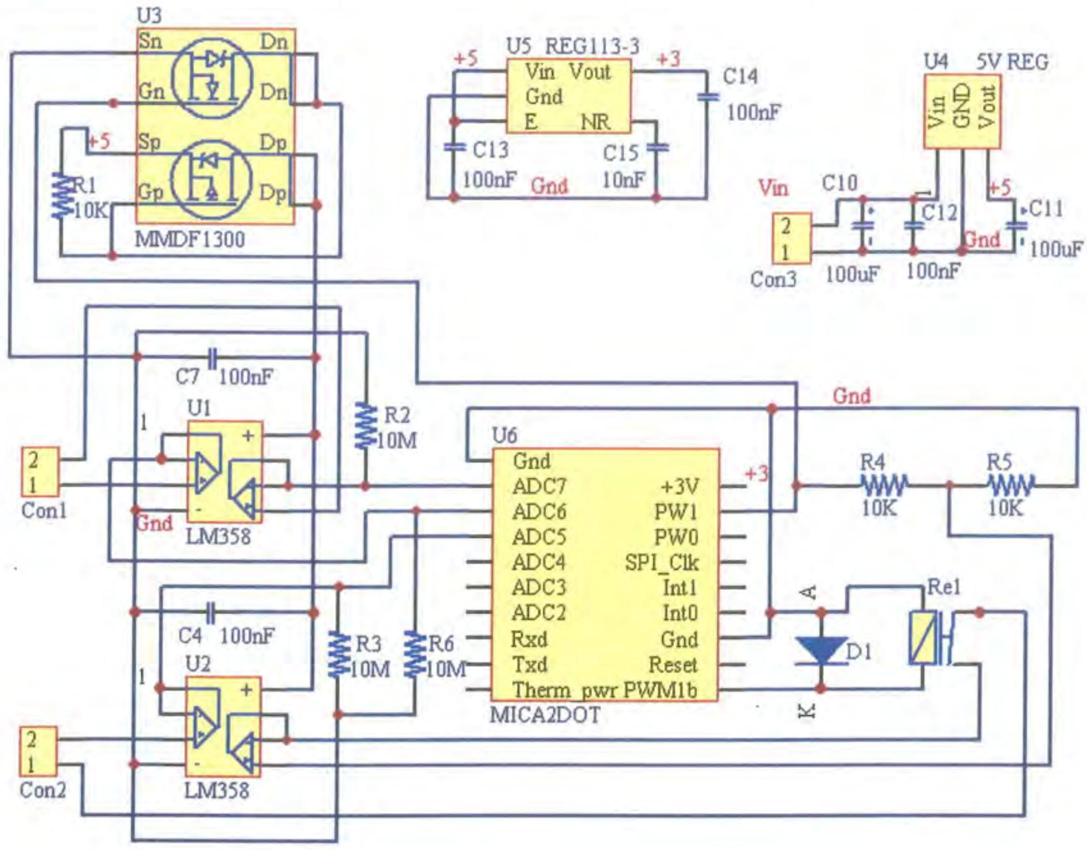

Figure 15: Adapting the MICA2DOT Network

MICA2DOT nodes may not measure redox potentials directly. Accordingly, the circuit depicted in figure 15 was applied to adapt them for measurement and transferal of these potentials. This circuit differs from that used in the prototype in three ways:

1. for the MICA2DOT sensor net, the reference electrode was biased by +1.5 V relative to ADC ground as opposed to +2.5 V for the prototype sensor net;
2. the MICA2DOT system uses an op amp to lower the impedance of the signal supplied by the reference electrode where the prototype does not, this should make no difference to the function of the MICA2DOT and prototype sensor nets; and
3. the MICA2DOT system uses MOSFETs to remove power to the op amps and reference circuits when not in use where the prototype sensor net does not.

Initial programming attempts involved modifying demonstration applications supplied with the MICA2DOT motes. All functionality was removed from application XsensorMDA500M.nc, available from the crossbow contribution directory (Crossbow Technology, 2005), except that required to take and transmit ADC readings from channels 5, 6 and 7. This code was installed into both nodes that would represent the sensor network. Each node was also given an address, addresses 101 and 102 were used. TOSBase.nc, part of the Tiny OS (TOS) installation, was installed on the base station node to enable communications with a PC. Figure 16 represents the resultant network topology, showing two network nodes in radio communication with another MICA2DOT node acting as a base station. The RS232 communication between base station and PC enables communication between PC and sensor node.

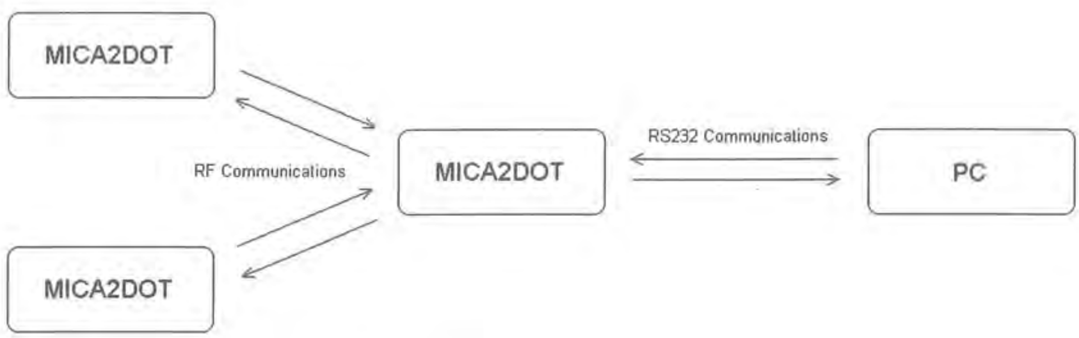

Figure 16: Topology of the MICA2DOT sensor network

TOS is supplied with a JAVA application called "serial forwarder". When running on a PC, the application listens for network connections on a given TCP port and transfers data between the serial port and the network connection. Those packets failing the error detection tests are not forwarded. Attempts to use this application resulted in failure; all packets received from the MICA2DOT network failed the error detection tests and were not forwarded. To resolve this problem a Visual BASIC 6 (VB6) application was constructed.

This VB6 application receives the packets sent to the PC by the MICA2DOT node running TOSBase.nc via a serial port. When a packet is received, the application checks for data corruption and, if the check shows no corruption, extracts the data from the packet and stores it in text files on the hard drive of the receiving PC. There

now follows a listing of the code installed in the network nodes of the MICA2DOT network during the field test described in Chapter 4.

Code used in MICA2DOT Nodes

```
/*                                                              tab:4
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```

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 *  CONTRIBUTORS BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL,
SPECIAL,
 *  EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED
TO,
 *  PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA,
OR
 *  PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY
THEORY OF
 *  LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT
(INCLUDING
 *  NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE USE OF
THIS
 *  SOFTWARE, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE.
 *
 * $Id: XsensorMDA500M.nc,v 1.0 2004/10/07 04:41:09 mturon Exp $
 */
/* *-------------------------------------------------------------
------------
 * Modified from XsensorMDA500M.nc
 * Application to read three redox potentials on ADC channels 5, 6
 * and 7 and report it over the radio, for use with MICA2DOT redox
 * Sensor Board version 2
 * connects reference to circuit by driving pin PWM1B high
 * powers opamps and reference by driving PW1 high
 *-------------------------------------------------------------
----------
 * Data packet structure  :
 *  msg->data[0] : sensor id, MDA500 = 0x1
 *  msg->data[1] : packet id
 *  msg->data[2] : node id
 *  msg->data[3] : reserved
 *  msg->data[4,5] : Unused
 *  msg->data[6,7] : Unused
 *  msg->data[8,9] : Unused
 *  msg->data[10,11] : Unused
 *  msg->data[12,13] : Unused
 *  msg->data[14,15] : redox sensor 1
 *  msg->data[16,17] : redox sensor 2
```

```
 *  msg->data[18,19] : redox sensor 3
 */

module redoxNodeM {
  provides {
    interface StdControl;
  }
  uses {
    interface ADC as ADC5;
    interface ADC as ADC6;
    interface ADC as ADC7;

    interface ADCControl;
    interface Timer;
    interface Leds;

    interface StdControl as RadioControl;
    interface BareSendMsg as RadioSend;
    interface ReceiveMsg as RadioReceive;
  }
}

implementation {
  enum { SENSOR_ID = 0,PACKET_ID, NODE_ID=2,RSVD,
         VREF=4,
         THERM = 6,
         ADC2_D = 8,
         ADC3_D = 10,
         ADC4_D = 12,
         ADC5_D = 14,
         ADC6_D = 16,
         ADC7_D = 18};

   #define MSG_LEN  29

   TOS_Msg msg_buf_radio;
   TOS_MsgPtr msg_radio;
   uint8_t i, sec, min;

/**********************************************************************
********
 * Task to xmit radio message
```

```
***********************************************************************
*******/
   task void send_radio_msg(){
    msg_radio->data[SENSOR_ID] = SENSOR_BOARD_ID;
    msg_radio->data[PACKET_ID] = 1;       // Only one packet for MDA500
    msg_radio->data[NODE_ID] = TOS_LOCAL_ADDRESS;
    msg_radio->data[RSVD] = 0;
    msg_radio->addr = TOS_BCAST_ADDR;
    msg_radio->type = 0;
    msg_radio->length = MSG_LEN;
    msg_radio->group = TOS_AM_GROUP;
    msg_radio->crc = 1;
    call RadioSend.send(msg_radio);
    return;
  }
/**********************************************************************
********
 * Initialize the component. Initialize ADCControl, Leds
***********************************************************************
*******/
  command result_t StdControl.init() {
    atomic{
      msg_radio = &msg_buf_radio;
  };
// set atmega pin directions for mda500
      MAKE_THERM_OUTPUT();              //enable thermistor power pin
as output
      MAKE_BAT_MONITOR_OUTPUT();        //enable voltage ref power pin
as output
      MAKE_INT0_OUTPUT();
      MAKE_INT1_OUTPUT();
      MAKE_PW0_OUTPUT();
      MAKE_PW1_OUTPUT();
      MAKE_PWM1B_OUTPUT();
      MAKE_GPS_ENA_OUTPUT();
      call ADCControl.init();
      call Leds.init();
      call RadioControl.init();
      call Leds.init();
      return SUCCESS;
  }
```

```
/**********************************************************************
********
 * Start the component. Start the clock.
**********************************************************************
*******/
  command result_t StdControl.start(){
      call RadioControl.start();
      sec = 0;
      min = 0;
      call Timer.start(TIMER_REPEAT, 1023);
      return SUCCESS;
  }

/**********************************************************************
********
 * Stop the component.
 *

**********************************************************************
*******/
  command result_t StdControl.stop() {
     call RadioControl.stop();
     return SUCCESS;
  }
/**********************************************************************
********
 * Start measurement sequence
 *

**********************************************************************
*******/
event result_t Timer.fired()
{
         sec++;
      if(sec > 59)
      {
        sec = 0;
          min++;
        }
      if(min == 15)
      {
        min = 0;
```

```
        call Leds.redOn();                    //turn LED on

            CLR_PWM1B();                                  ///connect
reference to circuit for redox readings
            for(i=1;i <= 250;i++)             //wait 250 milliseconds to
make sure slow old
            {                                             //mechanical
bits have done there thing
                    TOSH_uwait(1000);
            }
            CLR_PW1();                               //turn on reference
circuit and op amps
            for(i=1;i <= 100;i++)             //wait 100 milliseconds for
things to settle
            {
                    TOSH_uwait(1000);
            }
            call ADC5.getData();            //get first redox sensors
data;
    }
            return SUCCESS;
 }
/**********************************************************************
********
 * ADC data ready
 * Read and get next channel.

**********************************************************************
*******/
  async event result_t ADC5.dataReady(uint16_t data) {
       msg_radio->data[ADC5_D] = data & 0xff;
         msg_radio->data[ADC5_D+1] = data >> 8;
         call ADC6.getData();           //get second sensor data;
       return SUCCESS;
   }

/**********************************************************************
********
 * ADC data ready
 * Read and get next channel.

**********************************************************************
*******/
```

```
  async event result_t ADC6.dataReady(uint16_t data) {
       msg_radio->data[ADC6_D] = data & 0xff;
         msg_radio->data[ADC6_D+1] = data >> 8;
         call ADC7.getData();          //get third sensor data;
       return SUCCESS;
   }

/*********************************************************************
********
 * ADC data ready
 * Read and get next channel.
 * Send data packet

**********************************************************************
*******/
  async event result_t ADC7.dataReady(uint16_t data) {
       msg_radio->data[ADC7_D] = data & 0xff;
         msg_radio->data[ADC7_D+1] = data >> 8;
       post send_radio_msg();
         SET_PW1();                    //turn off the reference and op
amps
         TOSH_uwait(25000);     //wait 25 milliseconds for charge to
drain
         SET_PWM1B();                  //turn off redox reference
       return SUCCESS;
  }
/*********************************************************************
********
 * Radio msg xmitted.

**********************************************************************
*******/
  event result_t RadioSend.sendDone(TOS_MsgPtr msg, result_t success)
{
    atomic msg_radio = msg;
      if(success == SUCCESS){         //if packet was successfully
transmitted
        call Leds.redOff();           //turn LED off
      }
      return SUCCESS;
  }
/*********************************************************************
********
```

```
 * Radio msg rcvd.
 * This app doesn't respond to any incoming radio msg
 * Just return

***********************************************************************
*******/
  event TOS_MsgPtr RadioReceive.receive(TOS_MsgPtr data) {
     return data;
  }

}
```

13. Appendix F: Results Obtained from Field Experiment

Readings at Pt Sensor 1 in millivolts				
Time	Manual		Automated	
	Instantaneous	Stabilised	Prototype	MICA2DOT
9:04:00 AM	381	381		491
1:04:00 PM	375	308		435
5:05:00 PM	371	305		485
8:59:00 PM	363	298		456
8:50:00 AM	345	278		453
1:58:00 PM	332	268	315	423
5:00:00 PM	276	213	246	356
9:10:00 PM	239	184	193	318
8:40:00 AM	118	96	85	186
12:47:00 PM	15	13	-7	-77
5:16:00 PM	-271	-241	-300	-297
9:33:00 PM	-386	-384	-413	-332
8:41:00 AM	-424	-422	-456	-362
12:57:00 PM	-431	-428	-461	-370
5:45:00 PM	-435	-432	-471	-373
9:29:00 PM	-438	-435	-471	-376

Readings at Pt Sensor 2 in millivolts				
Time	Manual		Automated	
	Instantaneous	Stabilised	Prototype	MICA2DOT
9:04:00 AM	294	293		400
1:04:00 PM	275	253		385
5:05:00 PM	268	247		382
8:59:00 PM	259	239		347
8:50:00 AM	235	215		338
1:58:00 PM	217	202	198	288
5:00:00 PM	169	152	144	250
9:10:00 PM	138	124	90	206
8:40:00 AM	-20	-18	-51	30
12:47:00 PM	-103	-96	-129	-109
5:16:00 PM	-259	-233	-290	-265
9:33:00 PM	-396	-395	-422	-332
8:41:00 AM	-410	-407	-437	-341
12:57:00 PM	-410	-407	-437	-344
5:45:00 PM	-414	-411	-447	-350
9:29:00 PM	-415	-411	-447	-347

Readings at Pt Sensor 3 in millivolts				
Time	Manual		Automated	
	Instantaneous	Stabilised	Prototype	MICA2DOT
9:04:00 AM	250	224		335
1:04:00 PM	249	216		318
5:05:00 PM	238	207		291
8:59:00 PM	232	204		291
8:50:00 AM	205	179	158	280
1:58:00 PM	193	168	56	197
5:00:00 PM	151	136	46	200
9:10:00 PM	142	138	41	180
8:40:00 AM	1	1	-31	86
12:47:00 PM	-4	-4	-56	89
5:16:00 PM	22	20	-36	101
9:33:00 PM	13	12	-36	98
8:41:00 AM	-21	-18	-65	54
12:57:00 PM	-35	-32	-95	36
5:45:00 PM	-50	-44	-119	13
9:29:00 PM	-75	-61	-139	-45

Readings at Pt Sensor 4 in millivolts				
Time	Manual		Automated	
	Instantaneous	Stabilised	Prototype	MICA2DOT
9:04:00 AM	320	273		400
1:04:00 PM	332	256		356
5:05:00 PM	301	254		365
8:59:00 PM	294	247		365
8:50:00 AM	276	226	227	362
1:58:00 PM	269	221	124	171
5:00:00 PM	27	26	-85	57
9:10:00 PM	71	69	-90	10
8:40:00 AM	-234	-209	-271	-165
12:47:00 PM	-289	-264	-344	-218
5:16:00 PM	-268	-258	-349	-362
9:33:00 PM	-411	-410	-466	-365
8:41:00 AM	-414	-411	-466	-368
12:57:00 PM	-412	-410	-476	-370
5:45:00 PM	-412	-409	-486	-376
9:29:00 PM	-415	-412	-486	-376

14. Appendix G: Problems found with nodes on initial power up

When the MICA2DOT sensor network was initialised, the node with address 101 did not appear to be transmitting data to the host PC. This PC was situated 17 meters away inside a building. Bringing the node into the same room as the host PC showed that the node was indeed working but had poor radio range for an unknown reason. The node was reinstalled on container one and the host PC relocated to the room closest to the test site. The host PC was now located five metres from the test site. Communication with both nodes of the MCIA2DOT sensor net was established with no further problems.

Similar problems were encountered when power was applied to the prototype sensor network. No data was received by the host PC from node one of the prototype. This node was disconnected from the test apparatus and basic fault finding techniques were used. No faults were found so the node was reinstalled in the test apparatus whereupon it immediately established contact with the host and functioned as expected for the remainder of the test. The missing data from the Automated Prototype sets presented in Appendix F is a consequence of this failure to establish communication.

15. Appendix H: Definitions of terms used in this document

redox	In pure inorganic chemical systems, oxidation-reduction (redox) reactions proceed with a flow of electrons between the oxidized and the reduced states until equilibrium is attained. A substance is oxidized if it loses electrons and reduced if it gains electrons (Araya, 2004).
ORP	**O**xidization **R**eduction **P**otential, an alternate name for redox potentials.
DAWA	**D**epartment for **A**griculture of **W**estern **A**ustralia
RF	**R**adio **F**requency, generally referring to communication by means of a modulated radio wave using a transmitter and a receiver (Intec Telecom Systems, 2003).
ESD	**E**lectro-**S**tatic **D**ischarge
OGRE	**O**n-silicon **G**igahertz **R**adio **E**xploration
OEM	**O**riginal **E**quipment **M**anufacturer
MICA	Crossbow Technology named their device after the mineral that the internals of the device resemble (Sensors Magazine, 2002)
Virtual Machine	An abstract specification for a computing device that can be implemented in different ways, in software or hardware. You compile to the instruction set of a virtual machine much like you'd compile to the instruction set of a microprocessor. The Java™ virtual machine consists of a byte-code instruction set, a set of registers, a stack, a garbage-collected heap, and an area for storing methods (UNCW, 2004).
Firmware	The combination of a hardware device, e.g., an Integrated Circuit, and computer instructions and data that reside as read

only software on that device. Such software can not be modified by the computer during processing (labcompliance.com, 2004).

Open Source All hardware and or software components of an application are freely available (Open Source Initiative, 2004).

Ag/AgCl Silver/Silver Chloride, pertaining to the chemicals found inside a reference electrode suitable for measurement of soil redox potentials (Patrick et al., 1996).

SPSS Statistical **P**ackage for the **S**ocial **S**ciences; a software package consisting of statistical and charting tools

VB6 Visual **B**asic **6**; a software environment used for manufacture of PC programs.