RADIO FREQUENCY ENABLED SOIL REDOX POTENTIAL SENSOR NETWORKS

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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, we explore the various RF technologies that may be combined into a cost effective soil redox sensor network, discuss the merits of each as a component of said network, describe a prototype soil redox sensor network and perform basic laboratory testing. Laboratory results indicate that the prototype sensor network functions correctly within bounds. Subsequent to this, we describe the procedures that we will undertake to test the prototype when it will be migrated to a field setting.

INTRODUCTION

The **D**epartment for **A**griculture of **W**estern **A**ustralia (DAWA) undertakes field research into a number of cereal crops (e.g. wheat and barley). These crops require aerobic (oxidising) soils and do not thrive in anaerobic (reducing) conditions. The primary focus of DAWA's research is to assess how such crops are affected by periods of waterlogging and resultant soil imbalances [PGF96]. Measuring the **red**uction **ox**ygenation (redox) potential of a soil yields data that enables detection of the onset of reducing conditions and associated processes such as denitrification [BBT02].

Of the methods used to measure soil redox potentials, that using a buried platinum (Pt) electrode and a reference electrode produces significant results. It requires a reference electrode comprising a glass vial filled with Potassium Chloride or other suitable electrolyte to provide a known potential [PGF96]. The known potential may be compared electronically to the potential of the soil sensed by the Pt electrode to produce a voltage reading that represents the soil redox potential. Although such measurement techniques are known [PGF96] to have problems of drift in electrode potential yields, addressing these was not the focus of this study.

Current methods, practiced by DAWA and others, 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. The automation proposed in this study achieves economies that improve effectiveness of redox data collection, potentially allowing for either research fund re-allocation or an increased number of measurement points, thereby yielding greater accuracy and/or volume of knowledge/data.

In summary, this paper is a description of research carried out to investigate gains in soil redox measurement practice efficiency afforded by the use of electronic measurement and communication technologies. We start with an evaluation of RF technologies that may be applied as part of such a system, and follow with a short description of the design and construction process followed by an explanation of the initial testing procedures. Next we interpret the results of this testing and describe our plans for formal field testing of the prototype soil redox sensor network.

EVALUATION OF RF TECHNOLOGIES TO FORM A SOIL REDOX SENSOR NETWORK

We identified those RF technologies suitable for incorporation into the sensor network. Logical technologies are considered first; namely: CAN, Bluetooth, Smart-messaging, IEEE802.15.04 and ZIGBEE. Physical technologies and complete systems are described subsequently, namely: the Mica sensor net, research efforts at UCLA and efforts by the private sector to abstract the technologies of RF communications and produce integrated radios for use in electronic equipment.

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 1980's. It is intended for use with twisted pair wires, but other media such as radio may be substituted [K04]. CAN was among the first protocols that researchers modified for short range RF usage. However, CAN does not offer repeater type protocols. 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 **A**ustralian **C**ommunications **A**uthority (ACA). Avoiding this violation of emissions guidelines mandates use of limited power radios with an effective range of approximately 150 meters making a CAN based solution to the problem of soil redox potential collection suitable only for small areas. A protocol designed specifically for RF communications is Bluetooth.

Bluetooth is a standard for implementing short-range (up to 100 meters) radio networks and is suited for data rates up to 433.9 kilobits/second [B01]. However, it is limited to eight devices in any network [A03]. Any Bluetooth enabled device that is not 'parked' on the network is forced to resynchronise for 3 – 30 seconds before requesting a connection [D03]. Such latency makes Bluetooth unsuitable for many sensor networks.

Smart messages are based on a distributed computing model wherein each message is a migratory process that transports itself to nodes of interest [HCS97]. This system relies on virtual machines and self routing algorithms running on the nodes [IBK03]. Smart messages allow automatic configuration and reconfiguration of radio networks. As such, they are resilient to physical network changes and points of failure, thereby allowing for physical alteration and/or recovery of a network during operation – an advantage in field sensor networks [S03]. However, Smart Messages require significant host resources, precluding their economical use with redox measurement automation [S03].

The IEEE standard, 802.15.04 is a standard for short range, low data rate radio communications [N04]. 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 [N04]. One such standard is the Zigbee standard.

The Zigbee standard is a set of guidelines for implementing a RF network that may be conceptualised as a logical network imposed on IEEE 802.15.04 [A03]. Zigbee defines the network, security and application profile layers. Its simplicity and superiority for battery operated equipment render it a viable alternative to Bluetooth in the commercial sector [D03]. Adams, Director of Motorola Wireless and Broadband Systems Group Architecture and Systems Organization and Zigbee Alliance representative, claims that adoption of the Zigbee standard reduces logical design work for RF communication systems [A03].

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

The MICA system employs sophisticated hardware design and miniaturization techniques to achieve sensing, communications and computing in a single device [J03]. The MICA system has an open source hardware and software design approach [DM00]. MICA uses a RF network specific operating system called TinyOS which is programmed in a C like language, comprising components and interfaces [TOS02]. Once deployed, the sensor motes communicate with each other to form a self-configuring network resilient to topology changes [SM02]. The MICA system may be adapted for redox potential measurement by addition of a simple differential measurement interface and creation of a TinyOS component to read the data provided by that interface [TOS02]. MICA implements a number of network configurations; of which the most interesting is a multi-hop sensor net that has no theoretical limits to either area or number of nodes [TOS02]. However, the significant cost of approximately AU$250 per node [DD04] limits applicability of the MICA system.

Similar research at UCLA produced a sensor net using a different approach to that of the MICA solution [H03]. By spreading the computing load across the network researchers have reduced the total amount of transmission time required for both network configuration and data transmission.

Such reduction is achieved by "network clocks" and network time sharing, facilitating larger networks of lower powered devices [H03].

Original Equipment Manufacturers (OEMs) typically incorporate modules produced by other manufacturers into their own products. Often such modules cannot be produced by the OEM and their purchase is seen as a cost-effective means to produce the final, composite product. There exist manufacturers of short range radio devices who produce complete modules for OEMs to include in their products with minimal design effort. These modules range from basic radios, such as the RWS/TWS434 pair [RE02], to sophisticated radios like the Spaceport module from Radiometrix [R03]. Such a range of available technologies furnishes OEMs with a choice of a trade-off of a sophisticated, expensive, off-the-shelf module against the cost of developing/implementing software and hardware protocols coupled with low-cost hardware [R03].

DESIGN AND CONSTRUCTION

When automating soil redox potential measurement, there is a need for a directing intelligence, such as a microcontroller, to perform such sub tasks as time keeping, measurement and formatting communications. Microcontrollers are readily available, cost between four and fifty dollars and, of those available, the PIC was chosen due to its widespread, reliable use [ET03] and suitability of included peripheral devices. In addition, cost effective development tools such as programming suites, debuggers, emulators and programmers for PIC microcontrollers are available from many sources worldwide [SSS04]. Specifically, a PIC 18F452 was chosen for the following reasons:

(a) integrates real time clock, **a**nalogue to **d**igital **c**onverter (ADC), flash memory, RAM, EEPROM, watchdog timer, UART and brown out detection in a single 40 pin package;

(b) large program memory for experiment and development of firmware;

(c) large RAM space for communications buffers; and

(d) power saving modes that may reduce current consumption to nano-amps.

The ADC incorporated in the 18F452 is used, along with support circuitry, to capture voltage information from the Pt/reference electrode pair. Under field conditions, these electrodes produce potentials in the range ±1.5 Volts [PGF96]. **Op**erational **amp**lifier (Op amp) and **a**nalogue to **d**igital **c**onverter (ADC) circuits that allow amplification or measurement of negative potentials require dual power supplies and more complicated circuitry than single supply counterparts. To avoid this extra complication, the potential of the reference electrode was raised by 2.5 volts relative to ADC ground, by connecting the reference electrode to a resistor divider network which effectively raises the required measurement range to [1..4] volts. The modified voltage range covers 60% of the available measurement of the ADC within the PIC 18F452, providing a resolution of 4.88 millivolts. The impedance of the signal supplied to this ADC must be of 10 kilo-ohm or less to meet signal capture timing requirements, requiring an op amp configured for unity gain to lower the impedance of the signal provided by the electrodes.

Another problem related to use of PT/reference electrodes is that reference electrodes have limited life [BBT02], constant connection to a circuit depletes the solution contained within causing a drift in potential not attributable to redox state. Use of a reed relay to switch the reference in and out of circuit overcomes this problem.

Once taken, measurements are time stamped and stored in EEPROM for later communication to a PC or similar device. Due to time constraints a decision was made to trade off the time required to develop or implement robust data transmission protocols for simplified modules such as nRF401 from Oatley Electronics against the cost of RF modules that integrate this technology. Spaceport modules, from Radiometrix [R03] were chosen for availability and reliability. Use of Spaceport modules eliminated resource requirements for development or integration of standards such as ZIGBEE into the prototype. One further advantage is the inclusion of a reference circuit for a RF MODEM in the data sheet supplied with the Spaceport modules. Construction of this circuit further reduced resource requirements for the project by eliminating design time for a RF link between the prototype sensor net and a PC or similar device.

Use of Spaceport modules raises the cost of each prototype node to about AU$220 per node, still AU$30 cheaper per node than a MICA solution as outlined above. However, Mica sensor networks are supplied with a significant code base, reducing firmware development time to a few hours when experienced C programmers are used. Porting or developing code to implement a multi-hop sensor network using the prototype nodes would drive the cost of this solution well above that of the MICA alternative. Future iterations of the prototype will include cheaper radio hardware such as the nrf401 transceiver IC which may be included on the circuit board, eliminating expensive radio modules and reducing cost per node significantly when compared to a MICA solution.

A second iteration of the prototype that uses a nff401 transceiver IC would reduce cost per node by AU$150. Development of a less expensive hardware platform than the MICA system is preferred because it is expected that many nodes will be manufactured over time, thereby realising large savings over purchase of a third party system. Firmware development is expected to have little impact on final node cost as it will be developed as project work and will be spread over many nodes,

It is noted that all prices have been based on a completed circuit board only and no electrodes or housings were included in the figures. This has been done to maintain a real comparison with the MICA system which is supplied without these items.

INITIAL TESTING

Data Capture

Initial testing of the prototype soil redox sensor network has verified that the system takes measurements and transfers them to a PC. 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 testing by eliminating the need to manipulate soil redox values over time. The circuit used for the simulation is shown in Figure 1, 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 1.5 Volts.

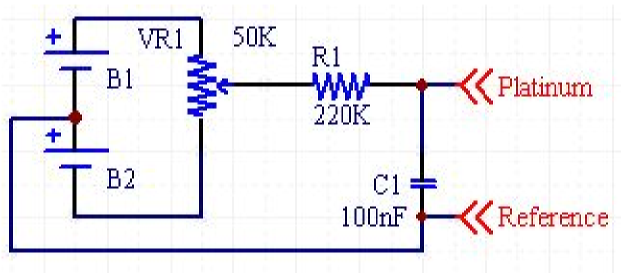

Figure 1: Pt/Reference Electrode Simulation

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

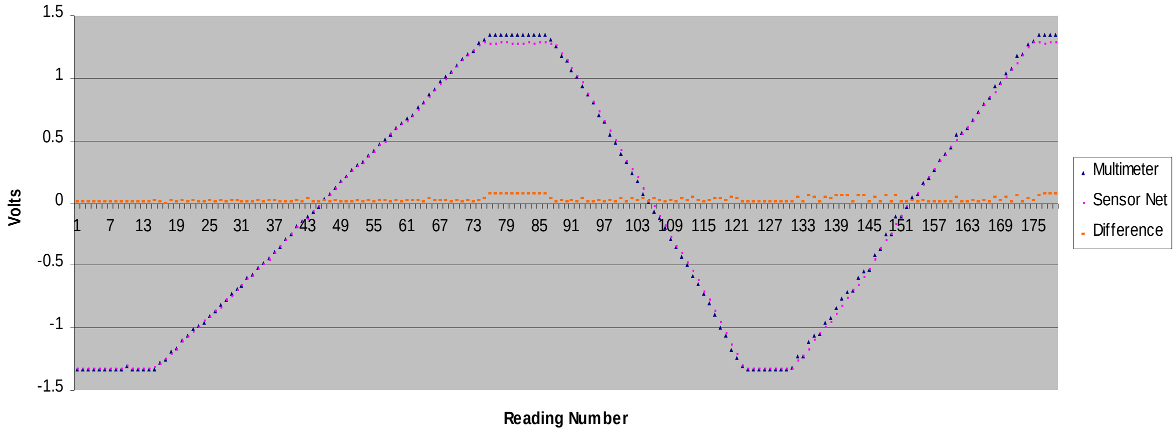

Figure 2: Comparison of Actual and Measured Voltages

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 2. 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 3 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. We conclude 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.

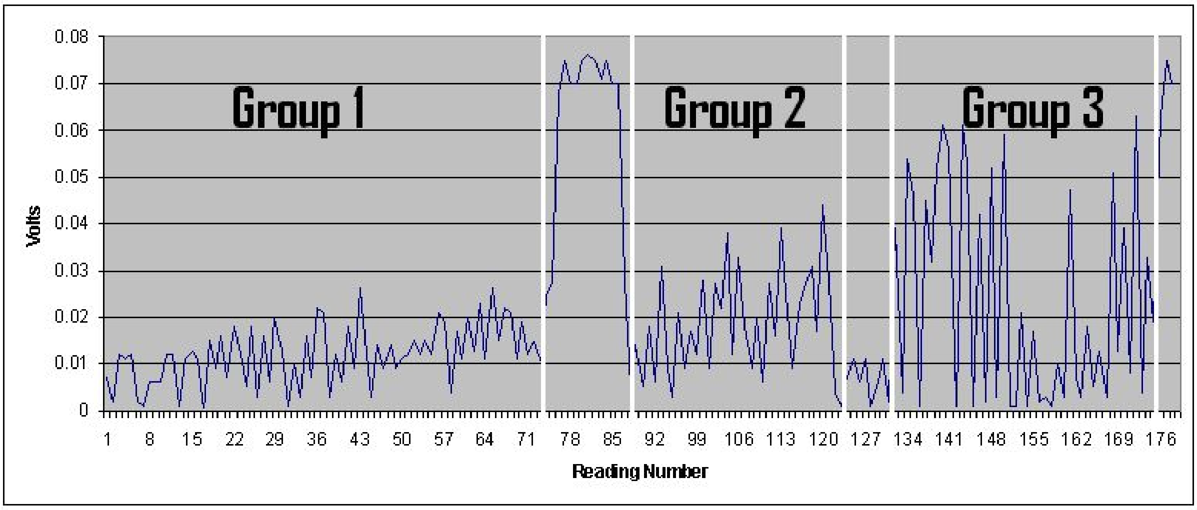

Figure 3: Difference in Potentials Reported by the Sensor Net and the Multimeter at Each Data Point

Interference cancelling techniques were *not* used for this test resulting in the erratic appearance of differences charted in Figure 3.

FUTURE WORK

Although initial testing of the prototype soil redox sensor network has verified that the system takes measurements and transfers them to a PC, it has not yet been tested in a field setting, nor has it been tested for accuracy, repeatability or usability when deployed with an actual Pt/reference electrode pair.

Accordingly, future work by the authors involves field testing of the prototype. In the absence of a precedent, testing is proposed as follows:

(a) Traditional methods as described by Patrick et al. [PGF96] will be used to obtain trusted redox potential measurements as a control. Additionally, the potential evidenced by the Pt/reference electrode pair when they are first connected to the measurement circuit will be recorded. This instantaneous series of data is expected to resemble more the data furnished by the automated equipment than those readings which have been stabilised.

(b) To account for the difference between instantaneous readings such as those made by automated equipment and stabilised readings achieved through traditional methods [BBT02]. A data logger will also be used to take redox measurements. The data series provided by the data logger is expected to resemble those provided by the prototype system and the instantaneous manual method.

(c) To validate the radio communications system implemented in the prototype, a commercial sensor net system such as the MICA MOTE will be used [SM02]. This commercial system will be equipped with a similar measurement interface to that employed by the prototype. The data series provided by the commercial system is expected to closely resemble that of the prototype and hence show that the data emerging from the prototype is unchanged by transport across a radio network. The remainder of this section is a description of the method to be used to obtain data for comparison.

Following the precedent set by Bochove *et al* [BBT02], excavations in soil will be made to fit two plastic containers with hermetically sealed lids, the containers will be placed inside the excavations and the removed soil placed in the containers. This arrangement minimises the difference between soil temperature and that of the containers and allows manipulation of such variables as soil water content and oxygen availability. Automated equipment which includes (a) the prototype redox sensor net, (b) a commercial sensor net and (c) a data logger will each be configured to record the potentials evidenced by two groups of electrodes, one in each container. Each group of electrodes will consist of one reference and three Pt electrodes. Provision will also be made to take manual measurements of the redox potential for the soil in the containers.

Since the soil in the containers will have been exposed to air during excavation, it is expected that initial readings will indicate a highly oxidised state. Studies by Bochove *et al* [BBT02] 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 will be employed for this test.

Once manual stabilised redox measurements, being the accepted method of obtaining redox potentials, indicate that the soil in the containers has been reduced; the data provided by each control method will be compared with that of the prototype redox sensor network. As previously stated, it is expected that data from the prototype will have high correlation with those control series provided by the commercial sensor net, the data logger and the instantaneous series of manual readings. Due to the undefined relationship between instantaneous and stabilised redox potentials, high correlation between these data series is not expected.

CONCLUSION

We proposed the notion of achieving economies of soil redox data collection through RF enabled automation, then discussed the knowledge and methods required to construct, test and evaluate the suitability of such an automatic system. Laboratory testing was carried out to verify that the prototype redox data collection system gathered and transported data correctly and field testing was planned.

Such automation would represent significant savings over traditional methods in that those methods are heavily labour intensive. This labour intensiveness also limits the amount of data collection points that may be managed simultaneously. It is expected that, given the heterogenous nature of soils, an increase in data collection points for a given test area will increase local soil knowledge and thus provide a vehicle for better management of said area and more effective research practices.

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