2006

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This is an Author's Accepted Manuscript of: Collins, M. , Holme, C. C., Tan, K.T., & Armstrong, L. (2006). An automated sampling soil reduction-oxygenation RF sensor network for cereal crop management. Proceedings of 2006 IEEE Region 10 Conference (TENCON). (pp. 4p). Hong Kong. IEEE Hong Kong Section. Available [here](#)
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An automated sampling soil reduction-oxygenation RF sensor network for cereal crop management

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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 present the method and results of laboratory and field tests performed. The experiment was conducted by running the prototype RF based equipment alongside a closely matched contemporary control system. Results indicate close correlation between experimental and control data.

1. Introduction

The Department for Agriculture of Western Australia (DAWA) undertakes field research into the management of 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 water logging and resultant soil imbalances [5]. Measuring the reduction oxygenation (redox) potential of a soil yields data that enables detection of the onset of reducing conditions and associated processes such as de-nitrification [2]. 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 [5]. 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. Such measurement techniques exhibit drift in electrode potential yields [5] that may be overcome by incorporating appropriate sampling delays. Current practices, used e.g. by DAWA and others [5], of collecting soil redox data from areas of interest involve an operator visiting each measurement location in a given data collection area. Redox potentials must be recorded manually for multiple Pt electrodes installed at each measurement location within that area. The automation proposed by this study offers economies that improve effectiveness of redox data collection thereby reducing project labour costs. In summary, this paper describes research carried out to investigate gains in soil redox measurement practice efficiency afforded by the use of electronic measurement and communication technologies.

2. 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: Controller Area Network (CAN), Bluetooth, Smart-messaging, IEEE802.15.4 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 pro-

tocol (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 [7]. 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 Australian Communications Authority (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 [3]. However, it is limited to eight devices in any network [1]. Any Bluetooth enabled device that is not 'parked' on the network is forced to resynchronise for 3 - 30 seconds before requesting a connection [4]. 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 [6]. This system relies on virtual machines and self routing algorithms running on the nodes. 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. However, Smart Messages require significant host resources, precluding their economical use with redox measurement automation. The IEEE standard, 802.15.04 is a standard for short range, low data rate radio communications. 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 IEEE 802.15.04 to control hardware. 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 [1]. 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 [4]. 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 [1]. The Zigbee/ IEEE 802.15.04 combination may be used in conjunction with Original Equipment Manufacturer (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. The MICA system has an open source hardware and software design approach. MICA uses a RF network specific operating system called TinyOS, programmed in a C-like language, comprising components and interfaces. Once deployed, the sensor motes communicate with each other to form a self-configuring network resilient to topology changes. 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. 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. However, the significant cost of approximately AU\$250 per node limits applicability of the MICA system. Similar research at UCLA produced a sensor net using a different approach to that of the MICA solution. 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. 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, to sophisticated radios like the Spaceport module from Radiometrix. 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.

3. 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 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. Specifically, a PIC 18F452 was chosen for the following reasons:

1. integrates real time clock, analogue to digital converter (ADC), flash memory, RAM, EEPROM, watchdog timer, UART and brown out detection in a single 40 pin package;
2. large program memory for experiment and development of firmware;
3. large RAM space for communications buffers; and
4. 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 [5]. Operational amplifier (Op amp) and analogue to digital converter (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 mV. 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 [2], 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 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.

4. Field tests

To validate the radio communications system implemented in the prototype, a commercial sensor net system, the MICA MOTE was used. This commercial system was equipped with a similar measurement interface to that employed by the prototype, as shown in Figure 1. As the data series provided by the commercial system was expected to resemble closely that of the prototype and hence show that the data that emerged from the prototype was unchanged by transport across a radio network. Additional control data was derived from manual data collection to provide further true grounded data. Such was necessary to preclude common errors propagating from the common Pt electrode interfaces sampled by both systems, i.e. MICA2DOT and prototype. A testing model following guidelines established by [2] was used, thereby minimising differences of soil temperature and allowing manipulation of such variables as soil water content and oxygen availability. Buried Pt electrodes were incorporated according to procedures established by [5], whereupon the system was then tested for completeness of communication.

5. Results

As shown in Figure 2, all measurement techniques showed an initially oxidised state per representative sample soil type, indicated by positive potential. There followed a chemical reduction of the soil, then indicated

Figure 1. Schematic of Redox collection node.

by decreasing potential. The discrepancy between instantaneous and stabilised measurements [5] was most evident when the soil was oxidised. Those potentials captured with the prototype soil redox collection system are in close agreement with the instantaneous manual series of measurements. Notable actual discrepancies are:

- for a stable redox state, data collected by the MICA2DOT system was approximately 100 mV greater than that collected by both instantaneous and prototype systems.
- MICA2DOT recordings were 100 mV lower when the soil was reducing quickly.

However, as [5] suggest, due to the heterogeneous nature of soil, wherein two adjacent electrode sets may produce differing results, it is the trend that indicates soil redox and not the actual values. Accordingly, as discrepancies were consistent, trend analyses could be applied.

6. 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 and field testing were carried out to verify that the prototype redox data collection system both gathered and transported data correctly. Such automation represents significant

Figure 2. Comparison of various measurement techniques at Pt sensor.

savings over traditional, labour-intensive methods and relieves upper limitations on the amount of data collection points that may be managed simultaneously. Further economies appear in that several adjacent test paddocks may now have data collected from them simultaneously. Advantages stemming from these are that, given the heterogeneous nature of soils, an increase in data collection points for a given test area will increase local soil knowledge and thus provide a means for better management of said area and more effective research practices. Future work will be concentrated toward collecting data via IP and satellite communications, realizing potential further economies in data management.

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