DEVELOPMENT OF A "SMART" WIRELESS SOIL MONITORING SENSOR PROTOTYPE USING RFID TECHNOLOGY

T. K. Hamrita, E. C. Hoffacker

ABSTRACT. *Radio Frequency Identification (RFID) technology is commonly used for object or animal identification and tracking. In this article, we explore the feasibility of its use in a rapid solution to wireless real−time monitoring of soil properties. A lab prototype system for wireless measurement of temperature was developed using a commercially available 13.56−MHz RFID passive tag. Temperature is sensed by a thermometer Integrated Circuit (IC) that produces a Pulse Width Modulated (PWM) signal. An embedded Motorola 68HC11 microcontroller monitors this signal, produces averaged measurements, and sends them to the RFID "tag" or transponder unit, hence the "smart" feature of the sensor. A receiving unit also called the "interrogator" emits an electromagnetic field, which when detected by the passive RFID tag causes it to transmit temperature data stored in its memory to the interrogator. The latter detects these measurements and sends them to a data collection PC. The architecture of the sensor allows for the addition of other transducers without alteration of the telemetry channel or significant changes to the sensor design. In benchmarking tests using a water bath over the course of several days, measurement error over a range of 0 to 50°C showed a standard deviation of 0.5°C and a max error of 1.5°C. Measurements also showed a high correlation (greater than 99%) with those obtained using a thermocouple. The architecture of the developed wireless sensor prototype allows for additional soil transducers to be integrated into it without changes to the sensor design. Potential applications for this sensor could be in the area of precision farming where soil properties such as temperature might be monitored in a wireless manner. Although limitations in transmission range (less than one meter) would require proximity reading of the sensor, using existing equipment that regularly pass over the field as a mount for the interrogator, such as center pivot booms or sprayers, would increase feasibility of this telemetry strategy.*

Keywords. *Soil telemetry, Wireless temperature monitoring, Passive RFID, Precision agriculture, Smart sensor.*

Radio Frequency Identification (RFID) technology is becoming increasingly viable as a commercial and technological solution to wireless identification. Since its invention, this technology has found numerous applications in commercial areas where remotely powered automated non−intrusive identification of the tagged subject is preferred over more traditional methods of inventory control, or as an anti−theft measure such as in warehousing or retail outlets. RFID is also used in livestock identification, and ISO has established standards ISO 11784 and 11785 to aid the shape and growth of this technology (Finkenzeller, 1999). Millions of RFID tags have been sold since the 1980s (Troyk, 1999).

RFID technology is typically and primarily used for identification and tracking purposes. However, due to the success of commercially available RFID tags, some research labs have explored their use in the development of wireless sensors. Crosslink (Boulder, Colo.), a company that specializes in wireless electronics for the trucking industry, has recently developed a proprietary RFID−based temperature−pressure sensor for wireless monitoring of tires in heavy vehicles (*RFID Journal*, 2003). RFID tags have also been used successfully by medical labs in the development of injectable medical implants (Troyk, 1999).

In this article, the goal was to explore the feasibility of using off−the−shelf passive RFID tags as a telemetry link in a wireless sensor for real−time monitoring of soil properties such as temperature. RFID tags are produced in very large quantities. They are versatile, generic, small, and they don't require their own communication channels. RFID tags are either passive or active. Active tags are powered by internal batteries whereas passive tags operate battery free through power provided by the reading unit or interrogator. This lack of power source on a passive RFID tag makes it much smaller and cheaper than an active one. Some passive tags could be as small as half a grain of sand and as cheap as a few cents (McCullah, 2003). Additionally, active tags have a limited operating life, whereas passive tags have virtually an unlimited lifetime. Moreover, the same RFID system could be used for various types of sensors (Troyk, 1999).

The work presented in this article was motivated by the need for a rapid solution to wireless monitoring of soil properties without having to design telemetry equipment or purchase costly custom hardware. Soil temperature is an important variable, which affects germination and overall health of the soil. Its measurements could be used in determining soil temperature profiles as well as soil thermal conductivity and heat capacity. Additionally, soil temperature is very important in developing crop modeling algorithms (Schomberg et al., 2002; Luo et al., 2001; Irmak et al.,

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2001). Therefore, soil temperature was chosen as the variable of interest for the developed sensor prototype.

Although the use of off−the−shelf RFID equipment in wireless sensor development is a fairly novel approach, the concept of using radio telemetry for wireless monitoring of soil properties is not new. NASA researchers have recently developed a wireless mesh of radio sensors for monitoring heat, humidity, and soil moisture (Huang, 2003). Cromer and McLendon (1984) developed a wireless soil moisture telemetry system that had multiple individually addressable moisture sensors in the field. The base station would query all the sensors in turn using Radio Frequency (RF) transmission, and the appropriate sensor would transmit data in reply, also over RF.

The long−term goal of the work presented in this article is to expand the developed wireless sensor platform to other types of sensors such as a moisture sensor and use these in precision farming applications. Precision farming is a fast growing farm management practice that has great potential for maximizing crop yields while minimizing waste of resources such as water, fertilizer or pesticides by directing materials where crops need it most (Blahovec and Kutilek, 2003). Historically, application of resources in the field was a matter of anecdotal experience and observation, or based on end of season crop yields. Precision farming requires real−time monitoring of important variables to determine how much resources should be applied and where. As a result of this new direction in agriculture, there's a growing demand for monitoring important soil variables such as moisture, temperature, and nitrogen levels in an automatic and wireless manner.

How Does Passive RFID Work?

For a detailed description of RFID systems, the reader is referred to Finkenzeller (2003) and Lee and Sorrells (2001). An RFID system consists of an RFID tag also called transponder, a reader also called interrogator or transceiver, and a control and data processing computer. The RFID tag acts as a "listener" for radio signals sent by the reader. When it receives a radio query, it responds to it by transmitting information in its memory to the reader.

The reader is connected to an antenna for transmitting and receiving signals. The RFID reader has circuitry that sends and receives signals to and from a tag, a microprocessor that checks and decodes the data, and memory for data storage. The reader can be part of a control and data processing computer or located remotely. The reader emits radio waves in a transmission area, which is dependent on the operating frequency of the system and the antenna size.

Each RFID tag contains a small antenna, modulating circuitry consisting of a specialized integrated circuit chip for controlling communication to the reader, and non−volatile memory containing data to be transmitted to the reader when the tag is activated. The amount of data stored in a tag ranges from 8 bits to 16 Kbits. The tag is queried for stored data by the interrogation device using a RF electromagnetic carrier wave as the communication channel.

In general, RFID devices almost exclusively use backscatter modulation as the method of RF transmission. As a mode of communication, it is dependent upon the level of electromagnetic coupling between the reader antenna and tag antenna. A backscatter system is often likened to an air core transformer, with the reader antenna, or interrogator, being the primary coil and the tag antenna the secondary. The reading device broadcasts a carrier signal (13.56 MHz in this application) that, by Ampere's and Faraday's laws, induces a current on the closed conductive circuit that is the tag antenna. This induced current is proportional to the strength of the broadcast EM field from the reader, the distance between the transmitting and tag antennas, and the orientation of the tag antenna in the generated field. In most RFID applications, this AC current on the tag antenna is rectified and used as the power source for the RFID data retrieval and modulation circuitry. This style is designated as "passive" RFID, while those tags that actively transmit data with an onboard power source are called "active" RFID.

Once the induced voltage on the passive tag antenna reaches a sufficient level to power the tag, the modulation circuitry begins sequentially shorting a section of the antenna tuning circuit in a pattern corresponding to the stored data. Since changing the inductive or capacitive values of a tuning circuit alters the resonant frequency of the antenna, electrically shorting a section of that antenna changes the inductance and reduces the amount of energy conferred to the circuit – essentially de−tuning the antenna. Back at the reader, this causes a small fluctuation in the voltage applied to the transmission antenna since the magnetically coupled circuit (reader and tag together) is experiencing a changing load as the tag antenna goes from resonant to non−resonant. The reader continuously monitors fluctuations in this output voltage, and demodulates any appropriate patterns that emerge, thus reproducing the data transmitted from the RFID device.

Materials and Methods

Hardware

The developed wireless "Smart" temperature sensor consists of (1) a temperature transducer, (2) an RFID system, and (3) a microcontroller for data acquisition and processing.

The Temperature Transducer

The Serial Digital Output Thermometer (TMP04, from Analog Devices, Norwood, Mass.) was chosen as a temperature sensor for this application with an operating range of −25°C to 100°C. An integrated IC that measures its own internal temperature, it produces a PWM output proportional to this temperature with a base frequency of approximately 35 Hz and accuracy of ±1°C. This output is easily integrated with a microprocessor TTL input requiring only software in the microprocessor to measure the duty cycle of the PWM signal, thus eliminating the need for A/D conversion.

The RFID System

Several manufacturers of RFID products are in the market, with their offerings ranging from basic components to complete systems. The MCRF355 device from Microchip Inc. (Chandler, Ariz.) was selected for this application due to its availability in IC form (as opposed to only being offered in full tag form), its low cost (less than $1 per RFID tag and less than $2000 for the whole system), as well as its adaptability to the application at hand. The MCRF355 is an 8−pin 13.56−MHz passive RFID device with 154 bits of user configurable EEPROM that is programmed with 20 VDC (18−mA current load) along with TTL level voltages. Like all RF transmissions in the United States, 13.56−MHz devices are regulated by the FCC and operate under limitations of the reader's interrogation signal transmission power. The reading range provided by this system is between half and one meter. For a longer range, reader transmission power must be increased.

THE MICROCONTROLLER

A Motorola MC68HC811E2CFN2 microcontroller (Northbrook, Ill.) was used in this application for temperature measurement and data transfer to the RFID chip. The HC11 is one of the most widely used microcontrollers in industry and it was selected for this application for several reasons. The chip allows for simultaneous measurement of multiple inputs, both TTL and analog using an on−board A/D converter. This allows for the addition of other sensors in the future to the same wireless sensor prototype without having to make any significant changes to the sensor design. Additionally, the chip is equipped with timer interrupt capabilities, which makes it easy to handle PWM signals. Moreover, the chip's processing power and on−board RAM and EPROM make it possible to expand the “smart” feature of the wireless sensor in the future with further on−board signal processing capabilities.

Power for sensor operation and data acquisition circuitry was provided in this experiment using standard lab DC power supplies. A 5−V signal was required to power the temperature sensor as well as the HC11 microcontroller. A 20−V signal was required to write temperature measurements to the EEPROM in the RFID device with an 18−mA current load.

IMPLEMENTATION

A block diagram of the developed wireless sensor prototype is shown in figure 1. The microprocessor is the heart of the system, acting as a data collection hub for the sensor as well at the programming source for the RFID transmitter. For this prototype the Motorola MC68HC811E2CFN2 was mounted in a JDR Microdevices CGN−1001 stand−alone microcontroller board (San Jose, Calif.). The stand−alone board provides all the necessary support circuitry needed by the microcontroller (e.g. 8 MHz oscillator, startup delay circuit, ModA/B select, etc.) so that it could automatically commence operation when supplied with 5Vdc.

The RFID chip requires a resonant antenna circuit that is tuned to the EM field frequency generated by the external RFID reading module, in this case 13.56 MHz. A commercially available solution from the RFID manufacturer that consisted of an antenna with pre−selected tuning capacitors was used (Microchip INC, MicroID 13..56−MHz PDIP Hard Tag).

The Analog Devices TMP04 Serial Digital Output Thermometer generates a PWM signal proportional to its temperature at approximately 35 Hz. The PWM duty cycle is directly proportional to the temperature measured internally in the IC, and the signal line is monitored through port A of the HC11. Configured as a real−time interrupt, this I/O line induces a capture of an internal free running counter value each time the PWM signal rose or fell.

Programming the RFID chip is accomplished by manipulating four dedicated RFID outputs on the chip to place the device in programming mode and send it the serialized programming codes and data to be retained and transmitted. To program the EEPROM in the RFID chip, it is placed in hardware read/write mode and command code sequences are clocked to it through Port A of the HC11. The 20−V signal required for erasing or writing to the EEPROM array is triggered by an HC11 line, which is connected to the gate of a FET circuit for amplification to the required level. All signals out of the HC11 are routed to the RFID IC through a diode to eliminate backfeeding current. When the data write is complete, the RFID modulates the signal on its antenna circuit with the newly written data whenever the interrogator is within reading range.

The RFID device has a limited data capacity of 154 bits, therefore an efficient data handling structure had to be adopted to optimize the use of this memory space. Numeric resolution of temperature measurements was limited to 8 bits and the functional temperature range of the sensor was limited to 0.0 to 51.0°C. An 8−bit incrementing counter was used to identify when new data had been written to the EEPROM array. Depending on how many bits are available to be dedicated to this purpose in future implementations, it could be used for both identifying the age of the data read by the interrogator as well as predicting the remaining functional life of the sensor.

The PWM signal generated by the digital thermometer is monitored by the microcontroller on a real−time interrupt basis. When the first positive edge is detected, the 2−byte value (0000−FFFF hex, 0−65535) that is contained in the HC11's free running counter is captured and stored in memory. The same occurs on the next negative edge and its following positive edge. These three 16−bit numbers form the basis of one temperature measurement. The conversion equation of the PWM signal to temperature, provided by Analog Devices, is:

$$235 - 400 \times \left({}^{T1}\!/_{T2} \right) = {}^{\circ}\mathrm{C} \qquad (2)$$

where

T1 = time duration of high level of PWM signal (5 Vdc)

T2 = time duration of low level of PWM signal (0 Vdc)

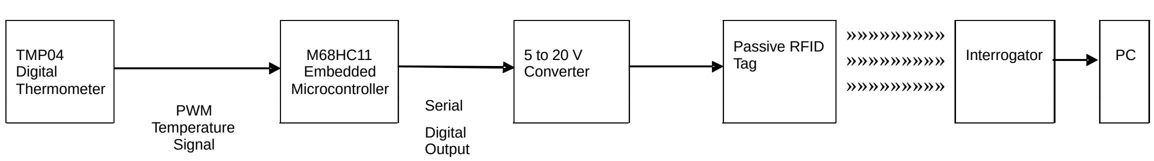

Figure 1. Wireless sensor block diagram.

T1 is the difference between the captured time of a positive edge and the subsequent negative edge, while T2 is the difference between that negative edge and its subsequent positive edge. T1 and T2 are two bytes long since the free running counter is two bytes long. After computation, temperature value's resolution is reduced to an 8−bit register and is offset and scaled based on calibration data. The value is stored, and the process is repeated 255 more times over the span of 17 s and average temperature for that particular sampling sequence is computed. This value is formatted for writing to the RFID and transmitted by the HC11 to the RFID's EEPROM.

The integration of other transducers to the sensor prototype is a straight−forward process. The transducer would interface with the microcontroller either through the on−board A/D converter or though a digital input line. The microcontroller would then transfer the data to the RFID tag following the same mechanism described previously. The latter would transmit the data from the various sensors in a time multiplexing fashion according to user specifications.

Benchmark Tests and Performance

The programming code for the microcontroller was assembled with Axiom Manufacturing AxIDE v3.61 software (Garland, Tex.), and the op−code file provided to the EEPROM programming software of a BP Microsystems BP1200 Universal Device Programmer (Houston, Tex.). After writing the program to the EEPROM of the microcontroller, it was mounted in a JDR Microdevices CGN−1001 daughterboard, and appropriate electrical connections were made. The remaining components of the system, excluding the digital thermometer, were mounted in a 4− × 7−in. (10.2− × 17.25−cm) Archer breadboard. The leads for the digital thermometer IC were left long, approximately 40 cm, so that it could be placed in a plastic bag for immersion in a temperature−controlled water bath and separate from the rest of the sensor assembly. A thermocouple probe was inserted into the bag as well, and was connected for measurement to a Fluke (Everett, Wash.) 16 multimeter to collect calibration data. A 1.5−in. (3−8 cm) microID 13.56−MHz PDIP Hard Tag from Microchip Technologies was wired onto pins 3, 5, and 6 of the MCRF355 so that it could act as the antenna for the sensor. RFID EEPROM programming voltage (20 Vdc) and logic bus (5 Vdc) were supplied by bench DC voltage supplies.

The bag containing the digital thermometer and thermocouple, with leads connected to their appropriate terminations, was immersed in a Thermo Neslab GP−100 water bath (Waltham, Mass.). Water bath temperature was set at increasing levels within the sensor's desired operational range, with temperatures below room ambient (15°C to 20°C) achieved with the addition of ice directly into the bath. Measurements were taken approximately five minutes after each temperature change to allow for temperature stabilization. Results of each successful read by the Microchip Technologies 13.56−MHz Interrogator of the RFID memory were displayed on a PC running RFLAB v3.4 (supplied by Microchip Technologies with the interrogator), which communicates with the reader over an RS−232 serial link. After initial tests, calibration data was collected and applied to the program within the microcontroller, and final data collection took place with similar procedures.

Figure 2 shows a scatter plot of sensor−measured temperature versus thermocouple−measured temperature for five different runs. The results show a greater than 99% correlation between sensor−reported temperature and thermocouple response. Although the maximum measurement error was 1.5°C in this data set, standard deviation was less than 0.5°C. The sensor−performed as expected, but calibration proved cumbersome and time consuming as modifying the calibration parameters required altering the program stored in the microcontroller's EPROM. Transmission range

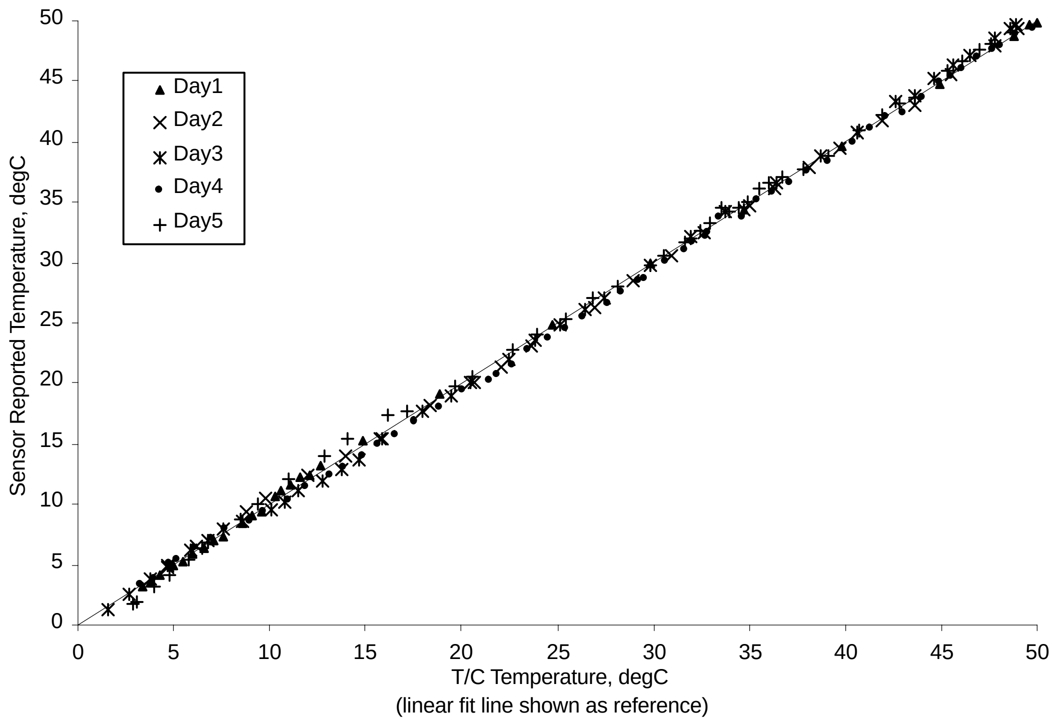

Figure 2. Reported sensor temperatures vs. thermocouple response.

of the sensor was limited to less than 1 m. The limitation is dictated by the transmission frequency of the RFID unit, amount of power delivered by the reader unit, and the reader antenna used. Potential changes to FCC code increasing the current transmission power allowed under Section 15.225 by approximately 50% (FCC, 2001) to bring U.S. standards in line with other international regulatory agencies, as well as future improvements to the design of the reader and its antenna will inevitably lead to improvement of the sensor transmission range. Additionally, for precision farming applications, using existing equipment that regularly pass over the field as a mount for the interrogator, such as center pivot booms or sprayers, would increase feasibility of this telemetry strategy.

CONCLUSIONS

The use of passive RFID, a technology typically used for identification and tracking purposes, was explored in this article for a rapid solution to the development of a wireless sensor prototype for monitoring soil properties. Measurements collected from the sensor using a temperature transducer showed a high correlation with data collected using a thermocouple. Transmission range achieved using the wireless sensor was limited by the selected RFID reader to less than 1 m. The embedded microcontroller in the wireless sensor platform was used to process temperature measurements and download them to the RFID tag. This embedded processing power within the sensor makes it "smart" and offers the capability of integrating other sensors on the same wireless platform without altering the telemetry channel or changing the sensor design. Even though averaging was the only processing performed on board the embedded microcontroller, this sensor architecture offers the possibility of adding other signal processing functions allowing the sensor to output ready−to−use information instead of raw data. The benefits gained by the ease, low cost, and fast design of the wireless sensor prototype using low−cost off−the−shelf components provide an exciting opportunity for wireless "smart" sensor development and warrant further research into improving the sensor design and performance.

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