

MULTI-CHANNEL STRUCTURAL HEALTH MONITORING NETWORK, POWERED & INTERROGATED USING ELECTROMAGNETIC FIELDS

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ABSTRACT

Structures with the ability to sense operating temperatures, pressures, and strains could potentially reduce the weight and costs of composite materials, and result in improved condition based maintenance. Unfortunately, the ingress and egress points of lead wires or fiber optic “tails”, which emanate from the structure, are often subject to fatigue and breakage. Recent advances in wireless systems allow the realization of highly miniaturized sensing, processing, and communications modules. However, powering of wireless sensing systems remains a barrier to their wide application. This paper reports on a network of versatile, embedded wireless sensing nodes that are powered & interrogated by external electromagnetic (EM) fields. The embedded nodes support a wide range of sensors, and include a factory programmable RFID.

KEY WORDS: Instrumentation/Measurement Technology, Sensors/Sensor Technology, Applications-Medical, Aerospace

1. INTRODUCTION

The goal of this work was to design, build, and test a robust multi-channel sensing network that could be powered and interrogated through a non-contacting, inductive “coupling” at one or more points on the structure. We have previously reported on remotely powered sensing systems for use in critical structural applications, including long term *in vivo* load monitoring of human total knee replacements^{1, 2, 3} and temperature monitoring of fiberglass composite panels during the autoclave cure process⁴. These systems relied on a radio frequency (RF) transmitter to communicate data out of the structure. The technique described in this paper utilizes switched reactance, which eliminates the need for an embedded RF transmitter. This results in an elegant and robust embedded system, capable of extreme miniaturization, and tolerant to high temperatures and high G-forces. Each embedded sensing node (termed “EmbedSense™”) supports bi-directional communications through the inductive coupling, and include a unique radio frequency identification code (RFID), which may be programmed into the embedded node through the inductive communications link.

2. METHODS

The embedded microelectronics module has been reduced to a minimum number of components. A photograph of the embedded microelectronics is provided below in Figure 1. A block diagram of the system is provided in Figure 2. The embedded microprocessor (PIC16C770) controls switch 42, which shifts the reactance of the embedded receiver coil 34'. This shift induces a detectable voltage amplitude change on the external reader coil 38, which is converted to digital data within reader 40.

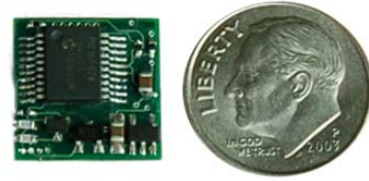


Figure 1. Embedded sensing & RFID microelectronics

A more detailed description of the microelectronics required for embedded structural sensing using bi-directional switched reactance communications has been provided in our recently published US patent application⁵.

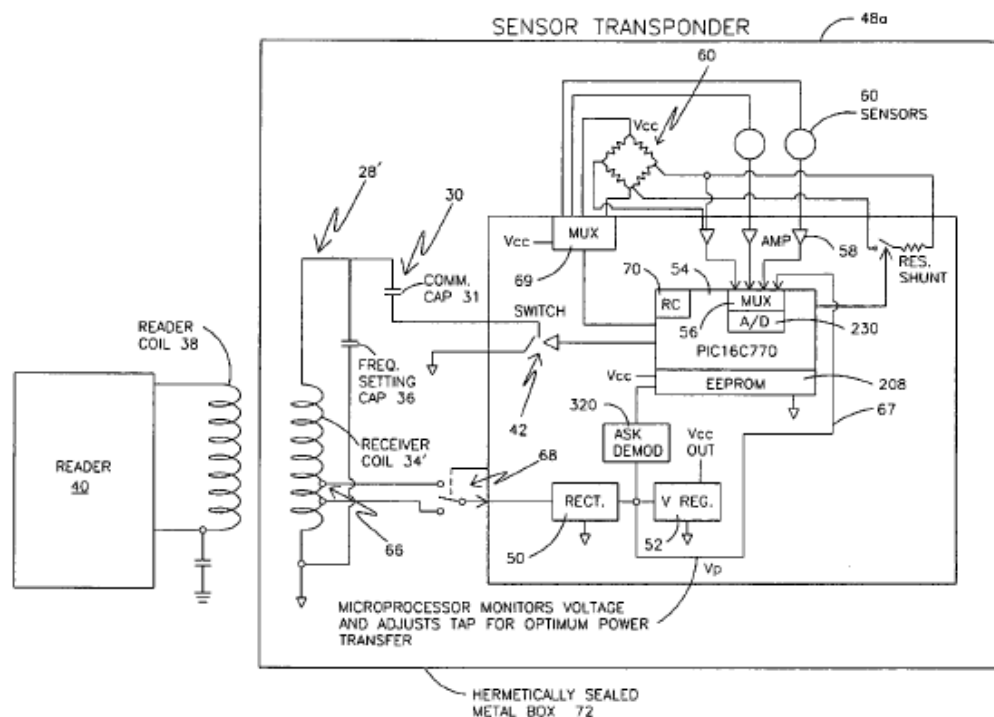


Figure 2. Block diagram of remotely powered and interrogated sensor node

The non-contact powering system operated at 125 KHz, and was optimized to provide a robust link, capable of penetrating several inches into a composite structure. The external powering coil consisted of single turn of copper wire. The epoxy potted embedded node, including the embedded receiver coil for remote powering and communications, consisted of a 5 mm thick disk, 36 mm in diameter (Figure 3). A photograph of the complete system, including the external powering coil and reader enclosure is provided below in Figure 4.

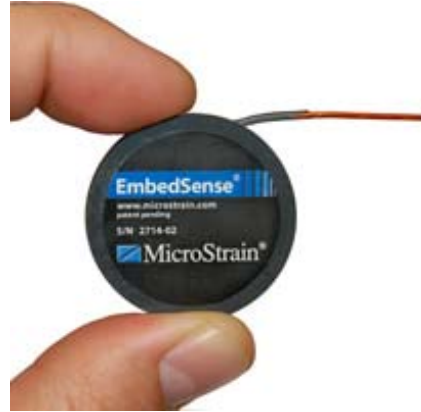


Figure 3. EmbedSense™ RFID node



Figure 4. EmbedSense™ remote powering & interrogation system, including external reader coil, reader electronics, and one embeddable RFID sensing node

The embedded nodes may be configured to support thermocouples, including the cold junction temperature sensor, or they could be configured to support Wheatstone bridge sensors to measure strain, pressure, force, torque, or magnetic fields. Along with sensors, embedded nodes include a pancake coil, signal conditioning (with programmable gains & offsets), multiplexer, 16 bit analog-to-digital converter, microprocessor, and switched reactance communications (under embedded processor control). Data communications used a balanced coding scheme to enhance reliability of the wireless link.

The embedded receiving (Rx) coil was connected to a network of four (4) nodes, which could support up to six (6) sensors each. Each node was capable of changing its impedance state in order to support low power “sleep modes” without draining power from the Rx coil. Each node on the network was also provided with a unique address. Randomized communications timing allowed multi-channel digital sensor data at 4800 baud. This power management strategy allowed us to build a multi-channel embedded sensor network without significantly increasing the overall power requirements for the system.

An addressable network of four embedded nodes was designed, built, and tested. Each node was capable of supporting six (6) thermocouples and one (1) cold junction compensation sensor. Therefore, a total of 24 discrete thermocouples could be sampled through the remotely powered network. The external powering system included an amplitude shift keyed (ASK) demodulator, which provided a serial data stream to a personal computer (PC). A custom graphical user interface was created to display and archive data from the embedded sensing network. The accuracy of the thermocouple measurements was tested using an environmental chamber (Thermotron) along with a hard wired reference (Omega model CL25 thermocouple calibration reference).

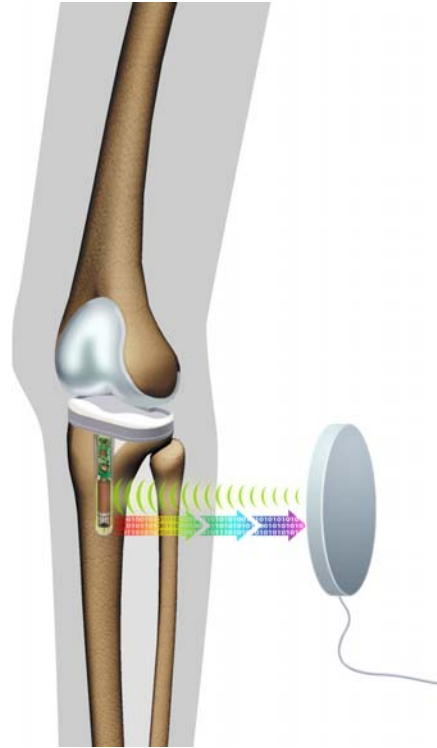
3. RESULTS

The RF powering and communications range, defined as the separation distance between the external coil and the embedded mother node coil, was measured at 75 mm (~3.0 inches). Power into the embedded node decreased exponentially with increased separation distance.

All 24 thermocouple channels were updated every second. The full scale range of temperature measurement was +25 to +1200 deg C. The accuracy of the temperature measurement was measured at +/- 2.5 deg C (+/- 0.2%), with a resolution of ~0.1 degree C. The system was successfully deployed during spin tests of jet turbine engines, where the operational environment was 125 degrees C and the embedded network sustained up to 55,000 G's of continuous inertial loading.

The versatility of these systems enable them to be adapted to a wide range of monitoring applications including: smart medical implants, improved process control “on the fly”, loads monitoring of composite civil structures and strain/temperature monitoring of composite aerospace structures.

Figure 5. System for powering & communicating with a medical implant. The embedded coil and microelectronics module is hermetically sealed within the titanium implant. The implanted system is capable of monitoring the in vivo static and dynamic forces and moments that act across the knee joint.



A diagram for a remotely powered and interrogated total knee replacement is provided above in Figure 5. In this application, the switched reactance method provides the advantage of eliminating the need for a hermetically sealed RF antenna feed-through. Figure 6 provides an example of a monitoring application for process control. In this case, the embedded modules communicate temperature and pressure data through the remote link as materials pass under the reader coil on a conveyer belt.

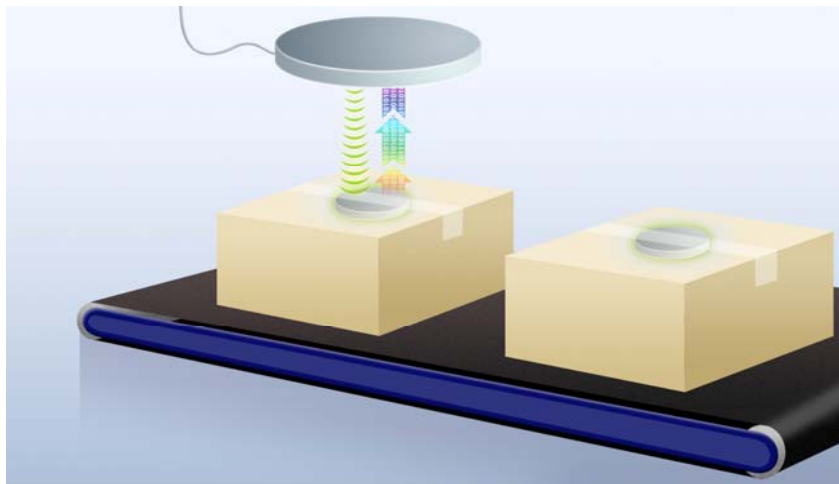


Figure 6. Remote powering & interrogation of RFID and sensor information from completely sealed enclosures while the materials are moving along a conveyer belt.

Figure 7 depicts an application for monitoring the live loads on the reinforcement bars of concrete. In this case, strain sensors mounted on the reinforcement bars are connected via shielded cables to the EmbedSense™ nodes, which are interrogated by a portable inductive reader “wand”.

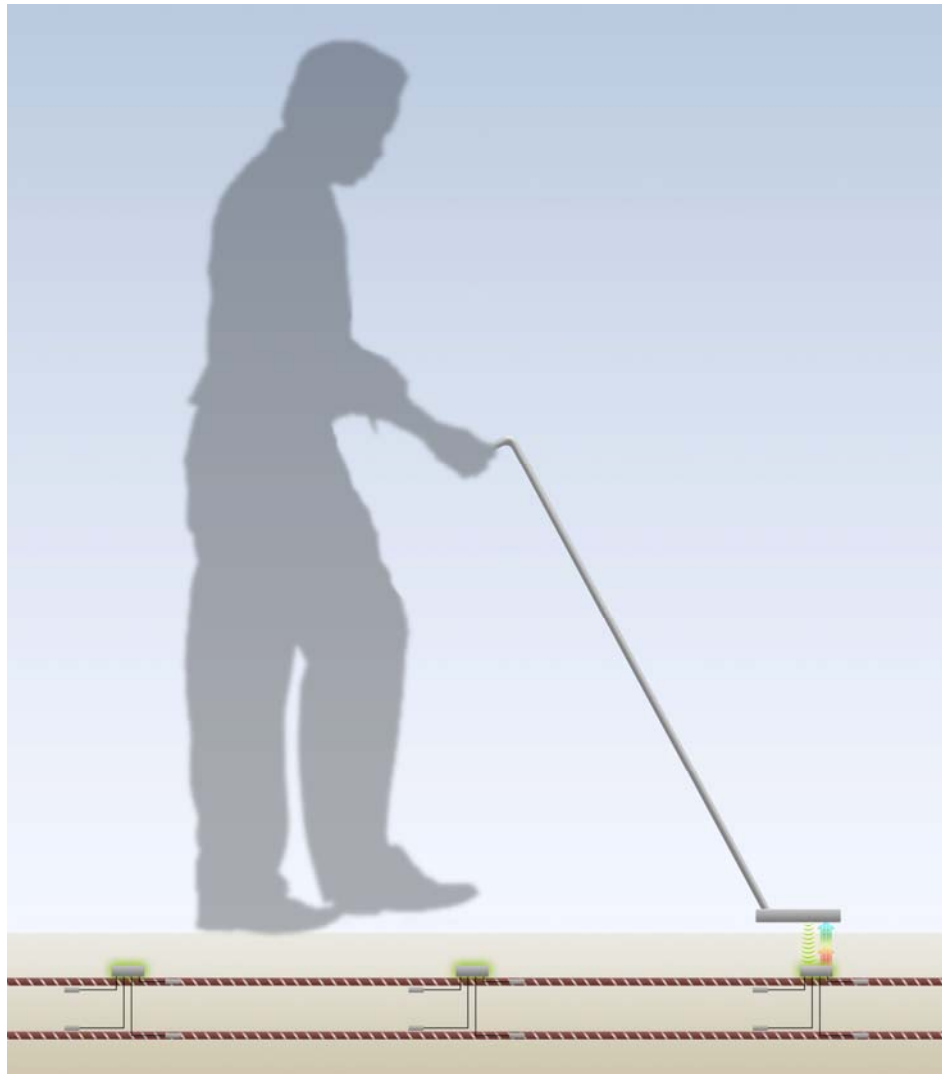


Figure 7. Remote powering & interrogation of RFID and sensor information from embedded sensor nodes for monitoring strains on reinforcement bars within a concrete structure

Figure 8 provides a graphic illustration of remote interrogation of a network of thermocouples embedded within a composite structure. The network of four EmbedSense™ nodes may be interrogated through a single embedded inductive coupling. Each node supports up to six separate thermocouples, for a system total of 24 thermocouples. In this application, a time division multiple access scheme was used to facilitate data collection from a single reader coil. Applications include composite materials production, for temperature monitoring during the curing process without wires exiting from the protective “bagging” used during autoclaving. After the composites are deployed onto the structure or machine, the sensors may be powered & interrogated in the field, to provide data on operational temperatures and strains. The specifications for current EmbedSense™ systems are provided in Table I.

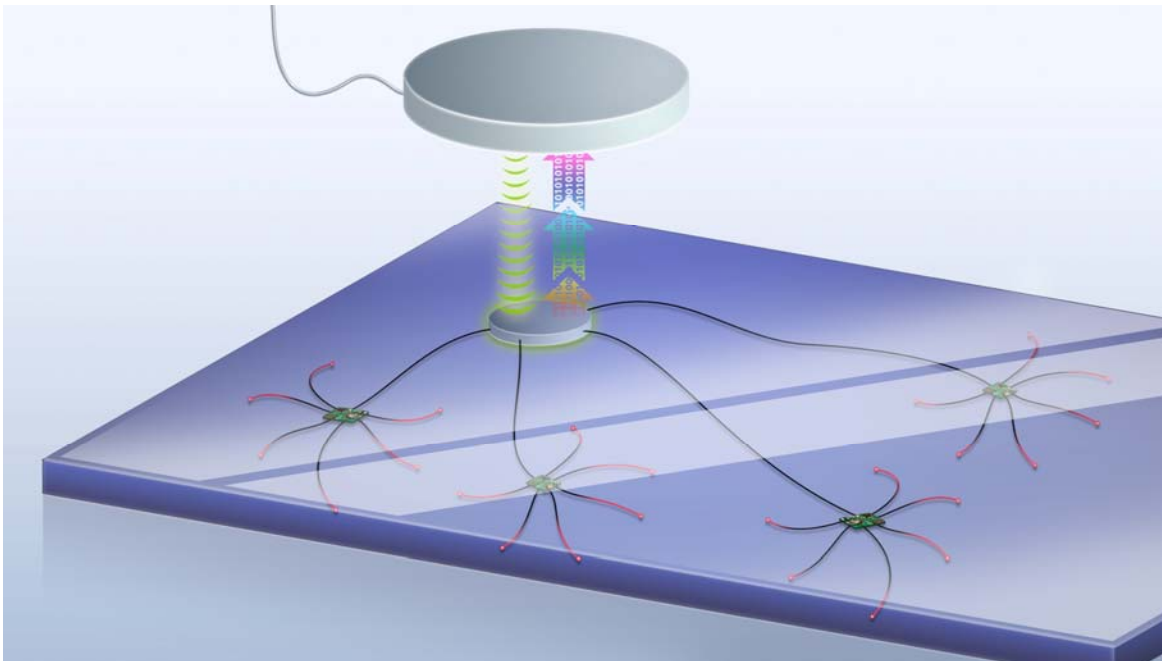


Figure 8. Remote powering & interrogation of RFID and sensor information from embedded sensor nodes for monitoring temperatures of a composite structural panel. The 2-conductor cables running from the embedded nodes to the embedded coil may be up to 6 feet in length. The cable from the reader coil to the reader enclosure may be up to 30 feet in length.

Table I. EmbedSense™ Specifications

Number input channels	2 Channels. 1 differential input and 1 internal temperature sensor (Other configurations available as custom options)
Input amplifier	Instrumentation amp, 110 dB CMRR, hardware programmable gain from 1 to 1000
Bridge excitation	3 VDC, regulated to 0.1%, up to 10 milliamps at 3 VDC available for 10 millisecond duration pulsed bridge excitation
Sensor types	Piezoresistive bonded foil & semiconductor strain gauges, pressure/load/torque transducers, thermocouples
A/D converter	16 bit resolution successive approximation type (standard)
Update rates	50 Hz/channel w/ 125 kHz operating frequency with 16 bit A/D
Communication method	Switched reactance, pulse code modulated serial (RS-232), clocked synchronous
Coil-to-coil separation	Coil geometry dependent, 37mm min. 50mm typical
EmbedSense (embedded node) powering requirements	200 microamperes at 3 VDC, not including bridge excitation, obtained by rectification of external AC magnetic field
Operating temperatures (for nodes)	-40 to +125 degrees C
Operating temperatures (for sensors)	+25 to +1200 deg C
Temperature measurement accuracy	+/- 2.5 deg C (+/- 0.2%)
Temperature measurement resolution	0.1 degree C
Operating G levels	Independently tested to 50,000 G's

4. CONCLUSIONS

A network of remotely powered and interrogated sensors has been demonstrated. The embedded system has no batteries to maintain and no wires exiting from the composite. An added advantage of these systems is that power may be provided through one or more inductive “coupling points” where access is less restricted, but sensors may be extended on or within the smart structure to allow data to be sampled from remote, hard to access areas.

The nodes support a wide range of sensors, and include a unique, remotely programmable RFID.

5. REFERENCES

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