Wireless Strain Measurement Systems – Applications & Solutions

S.W. Arms & C. P. Townsend

Williston, Vermont USA

Abstract

This article summarizes the development of wireless strain sensing systems for a variety of customer driven structural health monitoring (SHM) applications. By combining advanced, low power microprocessors, flexible software operating modes, and low power signal conditioners, these systems were optimized for very low power operation, while permitting high speed data logging and wireless communications capabilities. Solutions deploying wireless strain sensors are described, along with the appropriate citations.

Introduction

Sensors integrated into structures, machinery, & the environment, coupled with the efficient delivery of sensed information, could provide tremendous benefits to society. Potential benefits include: fewer catastrophic failures, conservation of natural resources, improved manufacturing productivity, improved emergency response, enhanced homeland security. However, barriers to the widespread use of sensors in structures and machines remain. Bundles of lead wires and fiber optic “tails” are subject to breakage and connector failures. Long wire bundles represent a significant installation and long term maintenance cost, limiting the number of sensors that may be deployed, and therefore reducing the overall quality of the data reported.

Wireless sensing networks can eliminate these costs, easing installation and eliminating connectors. The ideal wireless sensor is networked & scaleable, consumes very little power, is smart & software programmable, capable of fast data acquisition, reliable & accurate over the long term, costs little to purchase & install, and requires no real maintenance.

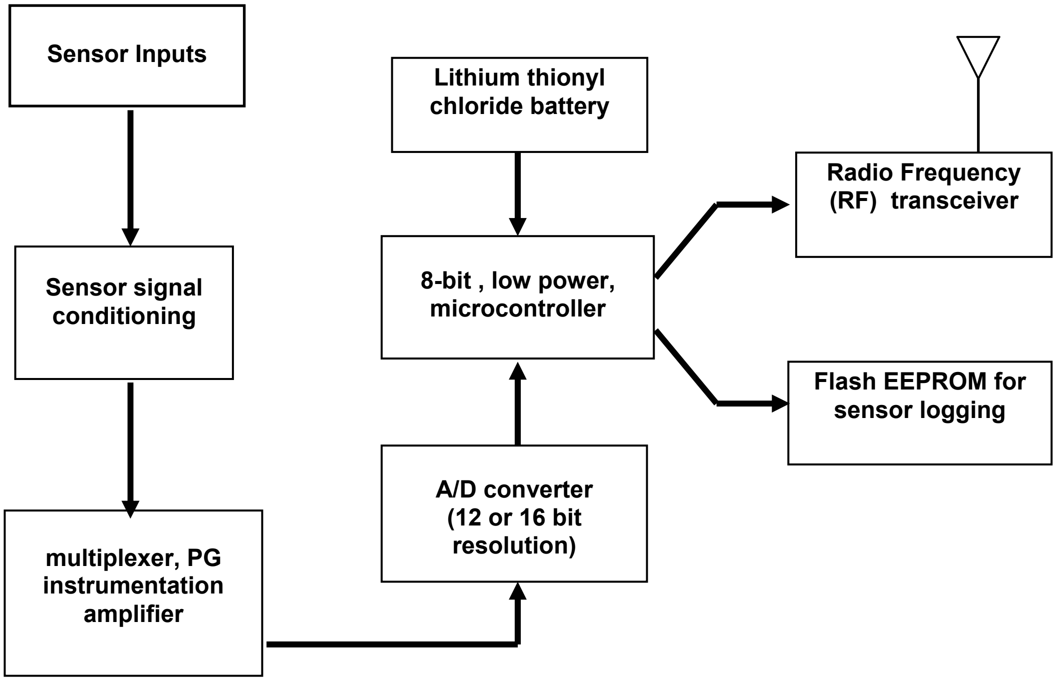
Selecting the optimum sensors and wireless communications link requires knowledge of the application and problem definition. Battery life, update rates, and size are all major design considerations. Examples of low data sensors include temperature, humidity, and peak strain captured passively[1]. Examples of high data sensors include strain, acceleration, vibration, and peak strain captured actively[2]. Strain is a very useful and general measurement that is very important for structural integrity and machine condition monitoring. High strain levels may indicate fatigue or yielding in the material, strains can be used to compute a structure’s loads, moments, and stresses; frequency analysis can be performed on strain data, and arrays of strain gauges combined with careful design can be used to create very accurate transducers of torque, load, pressure, and acceleration.

There are a variety of strain sensors available, including: bonded foil piezoresistive, semiconductor piezoresistive, capacitive, inductive, and fiber optic. The most popular and lowest cost strain gauges are the bonded foil piezoresistive type, but these require very careful bonding and environmental protection to survive in an outdoor environment. Inductive strain sensors, including magnetoelastic types, have the potential to be placed in an outdoor environment with greater ease and at lower cost, because inductive sensors are inherently insensitive to moisture ingress. This paper covers a range of applications for foil, semiconductor, and inductive strain sensors, and the systems used to deploy them wirelessly.

Research

A functional block diagram of a versatile wireless sensing node is provided in Figure 1, below. A modular design approach provides a flexible and versatile platform to address the needs of a variety of applications. For example, depending on the sensors to be deployed, the signal conditioning block can be re-programmed or replaced. Similarly, the radio link may be swapped out as required for a given applications wireless range requirement and the need for bi-directional communications.

Figure 1. Wireless Sensor Node Block Diagram



For strain sensing applications, the ability to wirelessly program sensor offsets and gains has been an important feature of the signal conditioning, because strain gauges typically exhibit significant offset due to changes in resistance induced during installation. Furthermore, gain programmability is important because in many applications the full scale strain output is not known, and therefore the system gain must be set “on the fly”.

Another key feature is the requirement for controlling the power consumed by the sensors and sensor signal conditioning. Multi-channel, wireless strain sensing power levels can be greatly reduced by the judicious use of microcontroller sleep modes. To illustrate this point, we compare the power required for three distinct modes of operation:
1) transmission of RF data: 45 milliwatts; 2) processing/logging of sensed data: 5.0 milliwatts; and 3) sleep mode: 0.02 milliwatts.

In order to best take advantage of these extremely low sleep currents, the microcontroller’s built-in firmware was programmed to operate in a mode which automatically pulses power to the sensing portions of the electronics, while synchronously performing analog to digital conversions and RF communications. We have demonstrated this using a three channel, 1000 ohm/gauge, wireless strain gauge system. The system, if continuously powered, would draw, on average, ~25 milliamps from a three volt regulated power supply. By pulsing energy to the electronics & communications link at a rate of 10 samples/sec, the average current draw can be reduced by a factor of 100, down to ~ 250 microamps. This low power capability is enabling for long term battery operation, remote powering by external fields, and energy harvesting.

Another strategy to save power is to remotely command the wireless sensing nodes from a base station as required by the specific application. We have previously reported on addressable, wireless strain sensing nodes that respond to the following base station broadcast address and/or node specific address commands[3]:

- Wake up, listen for commands, log or send data as commanded (or back to sleep)
- Wake up, log information when an event or threshold crossing is detected
- Wake up, transmit data periodically, go back to sleep

These addressable sensing nodes feature 2 Mbytes of on-board, non-volatile memory for data storage, 2000 samples/second/channel logging rates, 1700 samples/sec/channel over-the-air data rates, bi-direction RF link with remote offset and gain programmability, compact enclosure, integral

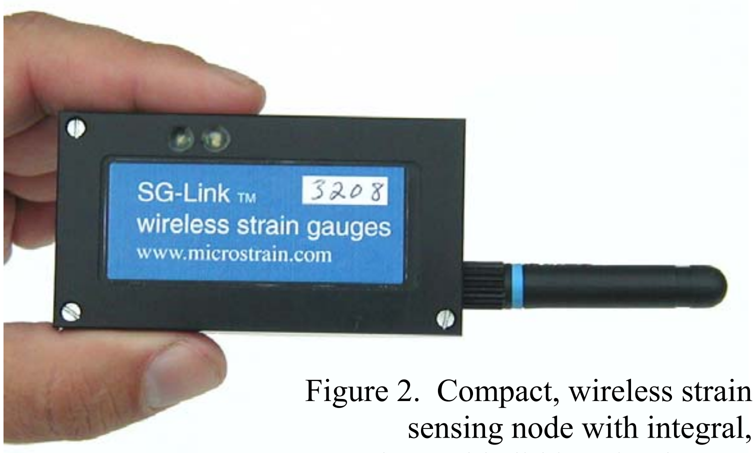


Figure 2. Compact, wireless strain sensing node with integral, rechargeable lithium-ion battery

rechargeable Li-Ion battery, and on-board temperature sensor. Figure 2 provides a photograph of the packaged wireless strain sensing node. Typical performance specifications for the wireless strain sensing node combined with conventional piezoelectric foil strain gauges (1000 ohm) are provided below:

- Temperature coefficient offset 0.007%/deg C (tested from +20 to +50 deg C)
- Temperature coefficient span 0.004%/deg C (tested from +20 to +50 deg C)
- Operating temperatures -20 to +85 deg C
- Programmable full scale range: 1000 to 5000 microstrain
- Resolution +/-2.5 microstrain (tested w/ anti-aliasing filter bandwidth 0-500 Hz)

These advances have allowed batteries to be deployed in a wide range of wireless sensing applications, including civil structural monitoring, automotive quality control, and medical research. For civil structural monitoring, automatic event driven triggering and the ability to place the sensing nodes in/out of sleep as required by civil structures engineers was critical to squeeze the most energy possible from remote batteries but still provide for high data acquisition rates as required by well controlled bridge testing protocols [4]. A diagrammatic representation of this system is provided in figure 3, below.

Figure 3. System for civil structures monitoring with multiple strain sensing elements

In sharp contrast, due to the relatively slow data rates required, concrete and asphalt cure monitoring was well served by a periodic, time division multiple access (TDMA) transmit-only system combined with web-enabled base station[5]. For automotive quality control, the ability to broadcast a command to all the nodes in the network to log data and then to subsequently command specific nodes to send data (by address) was critical to efficient use of RF bandwidth and to extending battery life [6]. In a specific medical research application, the ability to sleep the implanted strain sensing nodes with periodic wake up was critical. Once awake, the nodes' automatic RF data transmission at relatively high data rates enabled new information about the nature of mammalian bone growth rates to be collected for the first time[7].

However, batteries exhibit a shelf life (5 to 10 years), and therefore many monitoring applications require the elimination of batteries altogether, because the application requires that they cannot be replaced. One strategy to achieve this is by inductive coupling of magnetic field energy from an external coil into an embedded coil within or on the structure under test. A system block diagram for this methodology is provided below in figure 4. Power is delivered at a low frequency to facilitate transmission of magnetic energy through metallic materials. Digital RF data is communicated through an antenna feed-through at higher frequencies.

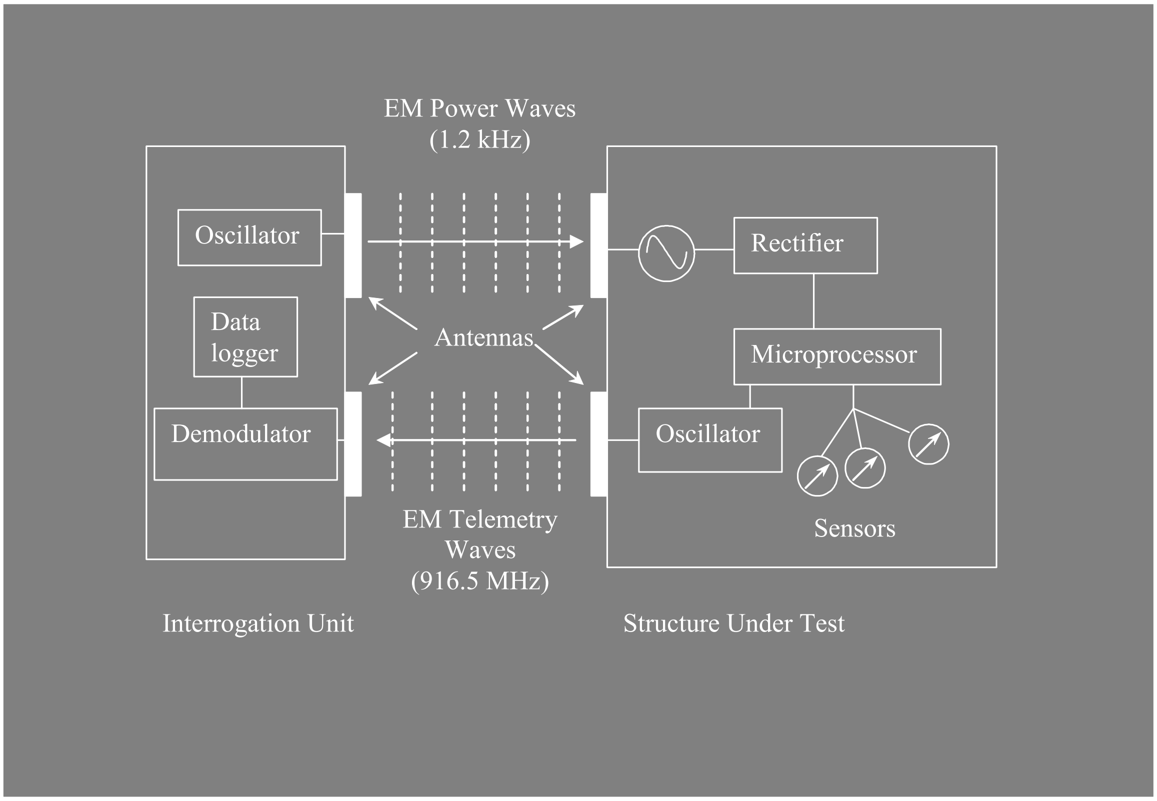


Figure 4. Inductively powered wireless sensing system block diagram.

One drawback of these systems is that very close coupling of the external excitation/interrogation coil and the embedded coil is required. However, this limitation is acceptable for many applications, including: monitoring of composite material properties during their cure cycles; monitoring of medical implant strains, loads, and moments *in vivo*; and monitoring of rotating shaft exposure to strain, fatigue loads, and excess operating torques in the field.

In the composites monitoring applications, temperatures and capacitances of the epoxy/glass laminate material are routinely recorded over time during cure to insure high material quality. However, the ingress/egress of sensing leads can allow steam from the autoclave chamber to enter the material (by tracking along the lead wires), generating scrap material. A solution to this problem is to monitor with low profile, embedded wireless sensors. We have reported on the validation of our magnetically powered sensing nodes for composite cure monitoring during autoclave cure with excellent correlation between hard wired vs. wireless test results[8].

For medical implants in humans, such as total knee replacements, the implanted device must achieve a lifespan in excess of 20 years. Batteries were therefore eliminated in this smart implant design approach. A four channel strain monitoring system was developed, including pulsed sensor excitation and remote powering with an external field. A cavity within the stem of the tibial component of the total knee replacement implant provided a good location for our electronics module, along with a hermetic feed-through antenna, which was placed at the tip of the stem (where stresses on the implant were essentially zero). The entire system was designed to be hermetically sealed using laser welding techniques. This system was successfully deployed during total knee surgery and is expected to be implanted in humans long term in first quarter 2004[9],[10]. A photograph of this system is provided in figure 5 below.

Figure 5. Remotely powered, hermetically sealed, smart total knee replacement (left) along with external powering coil and receive antenna (right). Photograph courtesy Scripps Institute.

More recently, our efforts have focused on simpler RF powered nodes, called EmbedSense systems. These systems use a switched reactance methodology to allow the elimination of many components, including the RF oscillator components, crystals, and feed-through antenna. This is an enabling development for many medical applications, where the added size, cost, and complexity of the components and the hermetic feed-through limits the potential applications for wireless strain sensing.

This simplified switched reactance design has also proven itself to be useful for jet turbine engine monitoring, because this approach eliminates the delicate components which are prone to failure at elevated temperatures and high inertial loads. Multichannel, networked EmbedSense systems have been successfully deployed during turbine engine spin tests by Pratt & Whitney at temperatures up to 150 deg C and inertial loads of 60,000 G’s.

A photograph of the embedded temperature and strain sensing node is provided in Figure 6. By combining this technique with passive peak strain sensors, scaleable arrays of addressable sensors may be interrogated for their maximum strain levels after a potentially damaging event, such as an earthquake[11].

Figure 6. Switched reactance EmbedSense sensing node shown with embedded coil around periphery of circular printed circuit board module.

Future Developments

The most general and versatile deployments of wireless sensing networks demand that batteries be deployed. We're actively working on systems which exploit piezoelectric materials to harvest ambient strain energy for energy storage in capacitors and/or rechargeable batteries. By combining smart, energy saving electronics with advanced thin film battery chemistries that permit infinite recharge cycles, these systems could provide a long term, maintenance free, wireless strain monitoring solution[12].

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Patents

The authors represent that many of the ideas and methodologies presented in this paper may be protected by one or more US patents assigned to MicroStrain, Inc. In addition, the authors have several patent applications pending at the time of this writing. This review article does not convey any license or any other right to an invention or process. For additional information regarding the patents issued to MicroStrain, Inc., please call or write to our main office at: MicroStrain – Patents, 310 Hurricane Lane, Williston, Vermont, USA (phone 802.862.6629, fax 802.863 4093).

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