Remotely Reprogrammable Wireless Sensor Networks for Structural Health Monitoring Applications

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Summary

Wireless sensors can improve our ability to monitor critical civil infrastructure, including highways & bridges. We previously reported on highly miniaturized, wireless strain, acceleration, and inclination sensing systems capable of providing low & high speed data update rates. Signal conditioning, multiplexing, A/D conversion, processing, amplifying, data logging, and bi-directional wireless communications are fully integrated. Each node includes a unique address (RFID), allowing a single base station to orchestrate data collection from thousands of distinct sensing nodes.

In order to enhance these capabilities, we have produced a new base station with remote cellular telephone interface. This allows access to the sensing network from anywhere where cellular communications are available. Key operating parameters such as triggering, data sampling rates, data sampling duration, continuous streaming duration, and number of active channels, and bridge offset balancing may be reprogrammed remotely. These new capabilities allow a remote sensing network to be deployed in the field and remotely reconfigured over time to meet the customer's unique structural health monitoring (SHM) requirements.

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.

Wireless sensing networks can greatly reduce the costs associated with structural health monitoring, because they greatly reduce installation time and cost. 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 [1].

The ability to modify the operating parameters of a wireless sensing network after installation can be critical to success. For example, the triggering parameters of a given

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sensing node or nodes on the network may need to be modified to accommodate changing strain levels, strain rates, vibration levels, or other operating conditions of the structure. The end user should be able to reconfigure the installed wireless sensing nodes without being forced to directly connect to each node. Even better, the end user should be able to reconfigure the wireless sensing network without being forced to leave their office.

Objective

The objective of this paper is to describe the methodology used to develop a modular wireless sensor network capable of wireless reprogramming over a long distance cellular phone network. This system would allow an end user to gain control over a complete wireless sensing network from their office – from distances of thousands of miles away from the monitoring site where the sensing network is actually deployed.

Wireless Sensing Node

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 structural health monitoring (SHM) applications, wireless tri-axial accelerometer nodes and wireless multi-channel strain gauge nodes are frequently deployed. Wheatstone bridge sensor input offsets may be removed using software commands. Bridge completion resistors for quarter and half bridge strain sensors may also be included, allowing a wide variety of strain gauges installations to be accommodated. Modules may also provide software programmable gains.

The bi-directional radio link may be reconfigured in software (frequency and RF power levels) as required for given applications' wireless range requirement and in order to conform to specific radio communications standards for a particular region of the world.

Each node is provides with a unique 16 bit address contained in its non-volatile memory. This scheme allows up to 65,536 (2^16) wireless sensing nodes to be deployed on the wireless sensor network. An important 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 base station broadcast address and/or node specific address commands, including commands to sleep, wake up, log data, and stream data continuously [2,3]. However, our previous base station designs could not be controlled from a remote personal computer platform using cellular phone networks.

These addressable sensing nodes feature two Megabytes 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 rechargeable Li-Ion battery, and on-board temperature sensor. Figure 2 provides a photograph of a wireless strain sensing nodes packaged within an IP67, NEMA 4X rated environmentally sealed outdoor enclosure. The package includes neodymium magnetic mounts to provide easy mounting to steel structural elements. Cable glands allow lead wires from multiple strain gauges to enter the enclosure while maintaining the integrity of the water tight seal. We have used weldable strain gauges (350 ohms, quarter bridge, Micro-Measurements) with good success. These gauges are well protected from the environment and can be installed very quickly using a portable, battery powered spot welder.

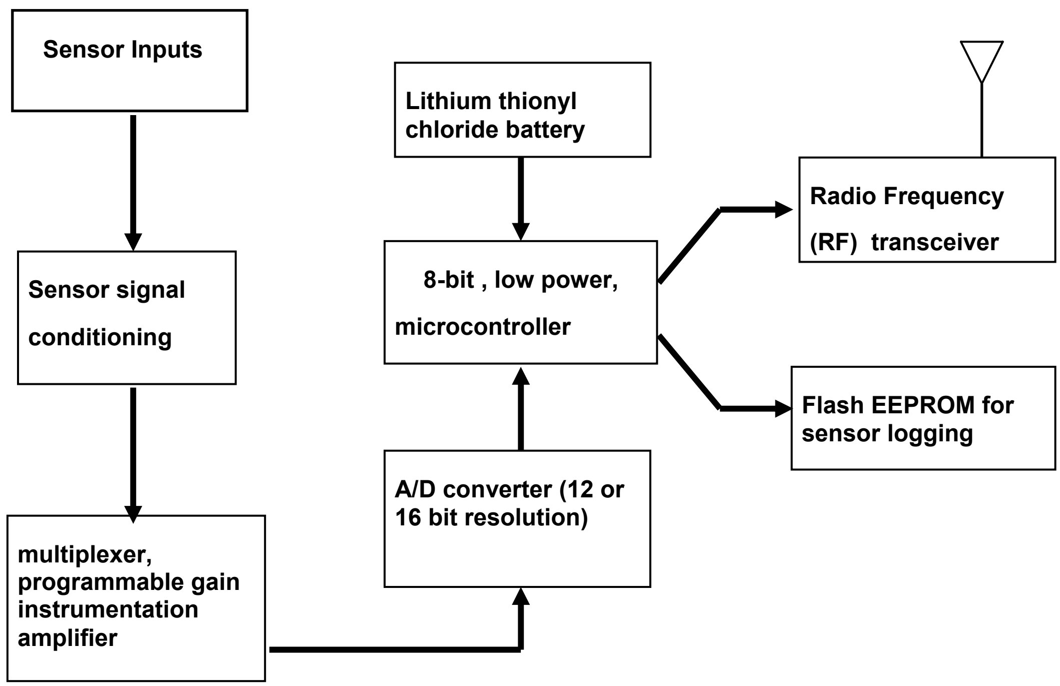

Figure 1. Wireless Sensor Node Block Diagram

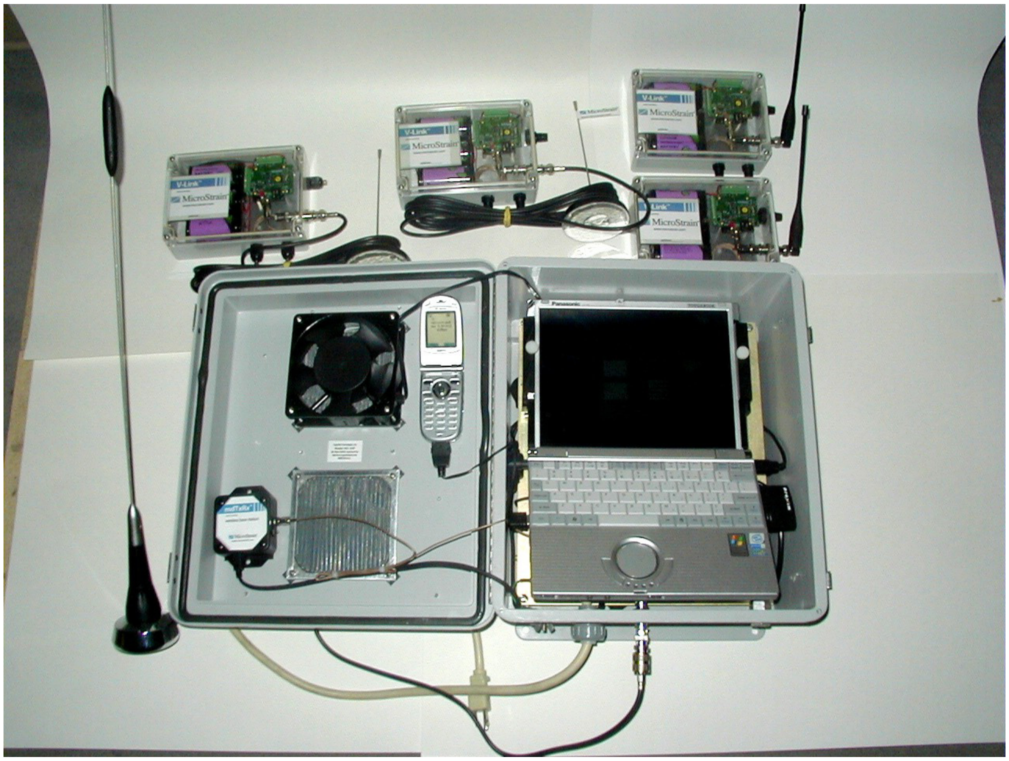

Figure 2. Wireless Sensing Nodes (4) in sealed NEMA 4X enclosures (top). Base Station with Panasonic Toughbook ®, cell phone, 802.11b WiFi card, and narrowband RF Transceiver as packaged within sealed, thermally controlled enclosure (bottom).

Base Station Software Interface

In order to facilitate data collection, triggering, and programming of the wireless sensing nodes, a base station was placed on the structure within 160 meters (500 feet) of the sensing nodes. Figure 2 also depicts the Base Station, which was housed in a heated NEMA 4X enclosure and contained a digital radio receiver with RS-232 output, Panasonic "Toughbook" personal computer (PC), 802.11b WiFi card with PCMCIA interface to the notebook PC, and cellular telephone with modem interface. The base station was connected to a local power source (110 VAC) through an uninterruptible power supply to prevent loss of power during temporary outages and to protect against power drop out and/or surges. The system was deployed on a large civil structure in

North America: the Ben Franklin Bridge, spanning the Delaware River from Camden NJ to Philadelphia, PA.

The system was designed to acquire strain data when trains passed on the bridge, but this required that the trigger levels be optimized for each strain sensor placement. The WiFi card allowed us to gain control of the system from under the bridge, which proved helpful when the triggering parameters were initially set up. The cellular phone interface was intended to provide a greater level of programmability and distant (remote) access into the wireless sensing network. The cell phone interface also allowed data to be copied or moved from the notebook computer platform on the bridge to another computer (or server) located on the local area network where another cell phone was used to establish the connection. The following figures (3-9) are screen shots from the Base Station (PC side) and "Strain Wizard ™ " software used to configure & calibrate the nodes remotely, using bi-directional wireless communications as required for an SHM applications. The software was written for use on Windows 95/98/2000/XP platforms.

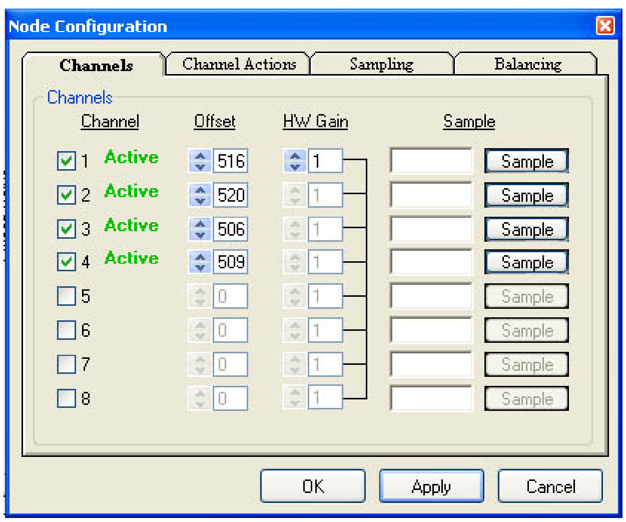

Figure 3. Software interface used to manually set up the number of active channels, as well as the offset and gain values for specific sensors on a channel-by-channel basis. The end user can also request that the software "sample" a specific channel on the wireless node to obtain an instantaneous snapshot.

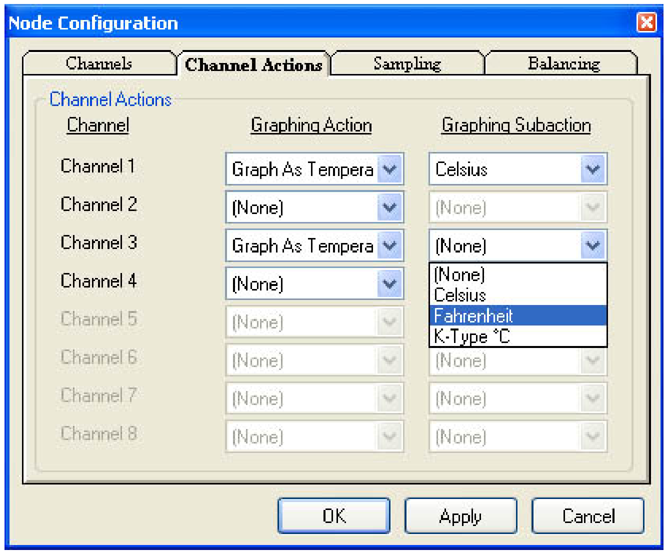

Figure 4. Software interface used to apply linear and nonlinear scale factors to convert digital sensor outputs (in bits) to physical units on a channel-by-channel basis. This example shown is for thermocouples, but can be extended across other sensor types.

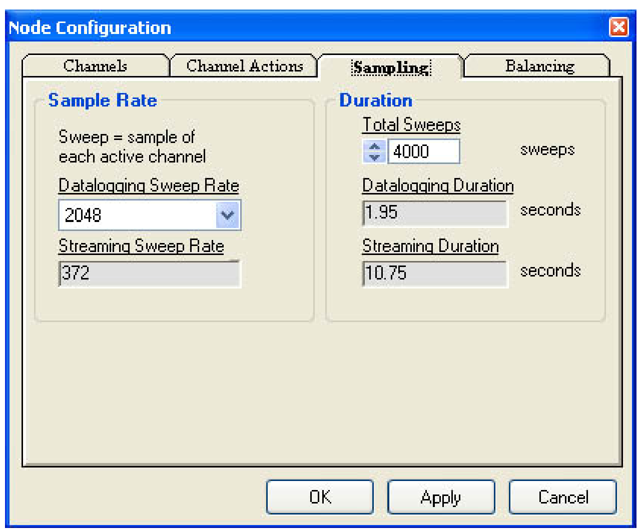

Figure 5. Software interface used to set up the sampling parameters of a specific wireless node on the network, specifically the sweep rate and total number of sweeps. The program automatically calculates the duration of the sample based on these two parameters

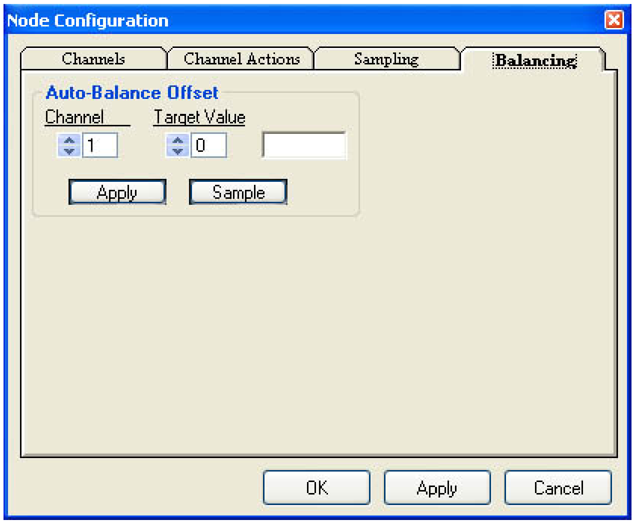

Figure 6. Software interface used to apply automatic balancing of the strain gauge offsets for a specific node address on a channel-by-channel basis.

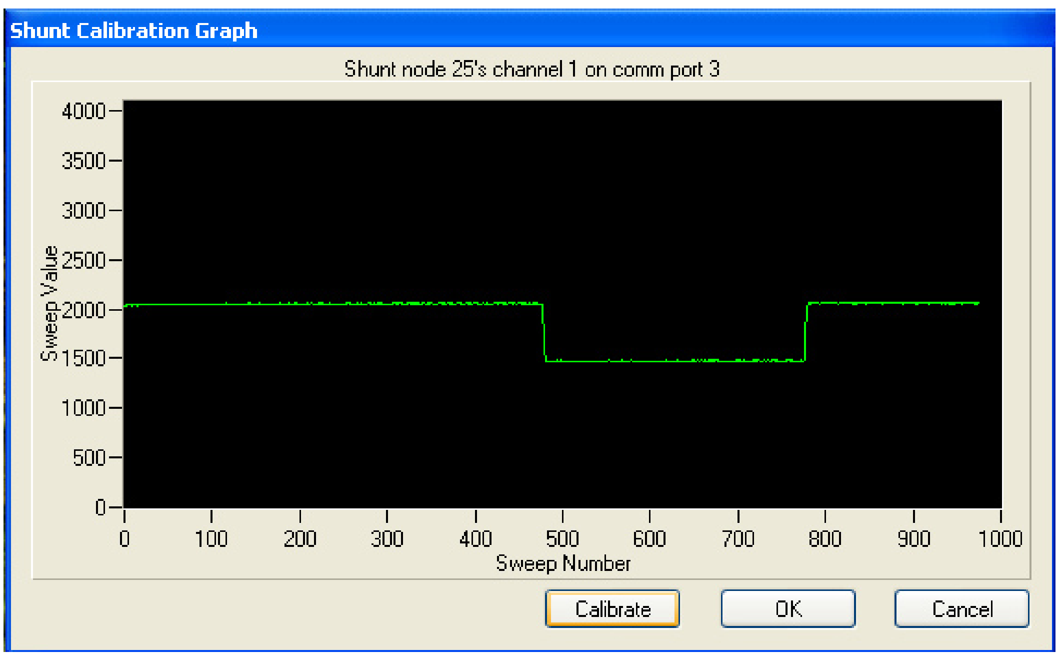

Figure 7. Software interface to indicate results of remote (wireless) shunt calibration of a specific node on the wireless network. In this case, node 25 has been shunt calibrated.

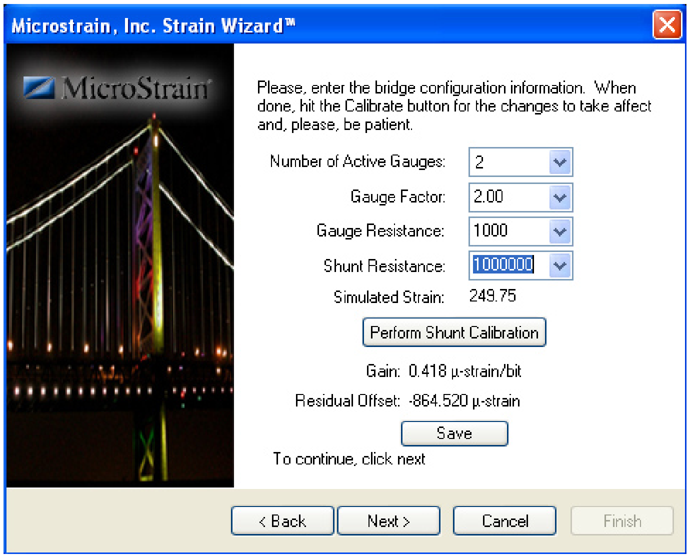

Figure 8. Software interface to provide the user with requisite gain and offset values after the remote balancing & shunt calibration steps have been performed.

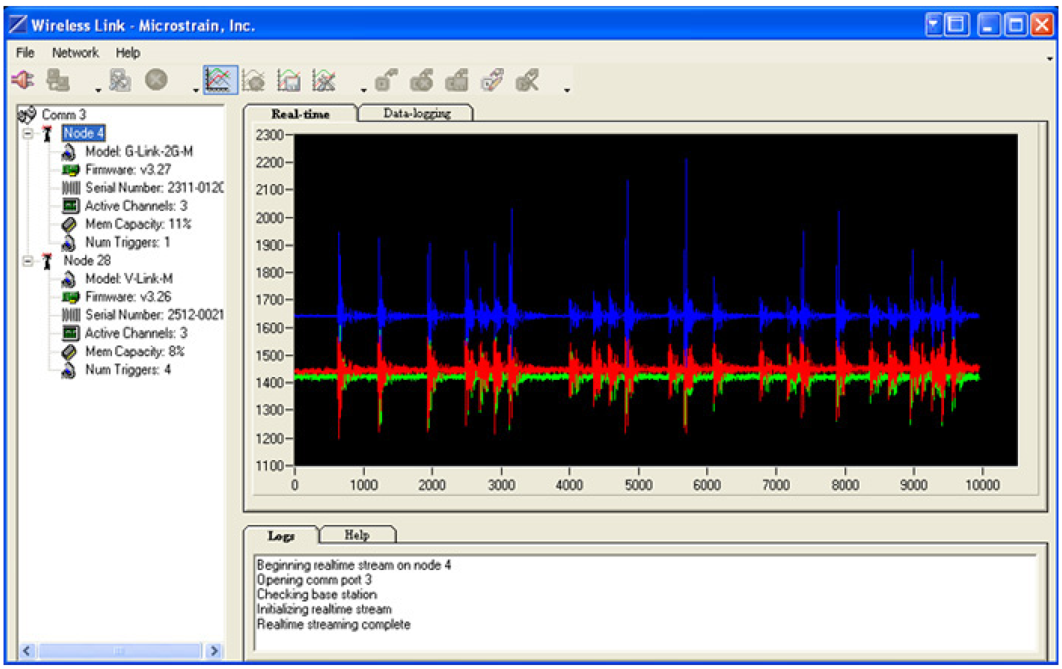

Figure 9. Software interface to display real time streaming data on a continuous basis from a specific node on the wireless network. In this case, node 100 reports in real time.

Cellular Telephone Link

Integration of cell phone and PC display redirection technologies provide remote base station control and node configuration options wherever cell phone coverage is available. Through the use of time-scheduled software, a simple cell phone link directly connects to the internet at set time intervals. During each connection session, a user-defined email address receives information on the node's whereabouts on the internet. The user then has a pre-defined window of opportunity to establish a connection to the machine through the use of virtual network computing software. At connection time, users may operate on any aspect of the wireless network available to them as though they were in physically in front of the base station's PC. Should no connection be made, the software simply disconnects the PC and reconnects at the next scheduled time in a manner similar to an established remote session with the PC which is later disconnected pending session completion.

Discussion

A versatile wireless sensing system with remote reprogramming capabilities has been built and demonstrated. The graphical user interface may be controlled remotely using a cellular telephone interface. This system has potential to be used for advanced, remote condition based maintenance & structural health monitoring for a wide variety of machines and civil structures. A full system installation including ten wireless strain & temperature sensing elements, and two cell phone enabled base stations has been completed on the Ben Franklin Bridge, which is a major span crossing from Camden NJ, to Philadelphia, PA (Figure 10, below). The bridge is remotely accessible via remote software as described in this paper and is currently reporting strain data when passenger trains cross the bridge.

Figure 10. Instrumented Ben Franklin Bridge spans the Delaware River

References

1 Arms, S.W., Townsend, C.P. (2003): *Wireless Strain Measurement Systems, Applications & Solutions,* Presented at NSF-ESF Joint Conference on Structural Health Monitoring Strasbourg, France

2 Galbreath, J.H, Townsend, C.P., Mundell, S.W., Hamel M.J., Esser B., Huston, D., Arms, S.W. (2003): *Civil Structure Strain Monitoring with Power-Efficient High-Speed Wireless Sensor Networks*, Proceedings International Workshop for Structural Health Monitoring, Stanford, CA

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