Abstract – This work demonstrates a condition-based solution for monitoring the long-term health of a system with moving or rotating parts. This is accomplished through the direct measurement of loads appearing on the structure by means of a synchronized network of wireless sensors. The wireless sensors exhibit extremely low power requirements, allowing high sampling rates while sustaining battery life entirely through means of energy harvesting. In addition, the network utilizes methods of TDMA to organize transmission scheduling and perform real-time error correction.

I. INTRODUCTION

Wireless sensing networks, deployed in scalable arrays, can enable the next generation of prognostic and health management systems for structures. In collaboration with Caterpillar, Inc., (CAT) we have demonstrated battery powered wireless multichannel wireless strain rosettes capable of automatically performing fully related peak valley compression and fatigue estimation using embedded rainflow algorithms on earth moving heavy equipment. Of critical interest to CAT is the ability to predict fatigue of welded structures, based on continuous tracking of strains using a network of wired and wireless sensors [1].

Harvesting the ambient energies of machine strains and vibrations to power wireless sensors has been a logical next step in development. We have utilized piezoelectric fibers, solar cells, and electromagnetic generators to create working energy harvesting prototypes, with support from the US Navy/NAVSEA for shipboard condition based monitoring (CBM) applications. One system used a tuned flexural element for vibration energy harvesting, while the other system harvested strain energy directly from a vibrating (cyclically straining) composite beam [2]. In both cases, we demonstrated that sufficient energy could be harvested to power our wireless strain sensor transceiver [3]. A multi-hop network of wireless heat stress sensing nodes were successfully demonstrated aboard the USS George Washington while docked at Newport News/VASCIC [4].

The US Navy/NAVSEA subsequently funded MicroStrain to adapt its energy harvesting sensor systems to track damage on critical helicopter structures, using wireless strain gauges. The first critical structure selected was the helicopter’s control rod, or “pitch link”. Pitch links are critical rotating elements on helicopters, and are very difficult to monitor with existing technologies, such as slip rings. Pitch link loads in the Sikorsky H-60 have been found to vary strongly with flight regimes: during pull-ups & gunnery turns, the loads were measured at approximately eight times that of straight & level flight [5]. Therefore, pitch link loads are a good indicator of helicopter usage severity.

We demonstrated that the operational strains in the pitch link can generate enough power to allow continuous, wireless operational load monitoring of this critical structure, even during conditions of straight and level flight [6]. In the spring of 2007, the first successful flight test of our energy harvesting wireless pitch link was performed on a Bell M412 helicopter [7]. Strain gauges placed strategically on the pitch link directly measured both static and dynamic loads, while canceling out thermal errors.

To facilitate data collection and time synchronization from arrays of sensing nodes, a data aggregation node was developed, capable of data collection from both wired and wireless sensor networks [8]. Precision time keepers within each node were synchronized by broadcasting a timing reference prior to flight to all the networked nodes, using the Global Positioning System (GPS) as a timing reference. Because each node on the network is equipped with its own precision timekeeper, data collection at each node could be performed without the need for further wireless communications.

The performance of MicroStrain’s integrated structural health monitoring and reporting (SHMR) system for use on Navy aircraft has been recently described [9]. The goal of this effort was to develop and test a versatile, fully programmable SHMR system, designed to synchronize and record data from a range of wireless and hard wired sensors. Wireless nodes included strain gauges, accelerometers, load/torque cells, thermocouples, and RFIDs. Data were collected at multiple sampling rates and time stamped and aggregated within a single SQL database on a base station, termed the wireless sensor data aggregator (WSDA).

The WSDA, in addition to providing a central location for collecting data, also provided a beaconing capability to synchronize each sensor node’s embedded precision timekeeper. Wireless node network initial synchronization in response to a centrally broadcast network command, such as to initiate node sampling, or to synchronize node time keepers, was measured at +/- 4 microseconds. With the time synchronization beacon sent only at the onset of a two hour long test, with simultaneous exposure to temperatures of -40 to +85 deg C, the system’s timing accuracy was ~5 milliseconds, which is sufficient for most aircraft structural monitoring applications.

A major advantage of precision timing lies in its potential to support a large number of wireless nodes on a single communications frequency; while minimizing the potential for collisions. Periodic beaconing, combined with a faster radio link, would allow us to scale up our low power sensor networks. However, our prior work did not describe how many nodes could be supported through a well synchronized TDMA network. Furthermore, although we were capable of flagging data that may have been subject to interference using the
check our previous systems could not perform “on the fly” digital error correction while wirelessly communicating.

II OBJECTIVES

The primary objective of this work was to develop and test a practical TDMA implementation for very low power energy harvesting sensors, particularly adapted for aircraft structural loads tracking, and featuring a robust technique for real-time error correction.

III METHODS

Wireless Strain Sensor Nodes

Each wireless sensor node includes an instrumentation amplifier, gain amplifier with offset adjust, anti-aliasing filter, 16-bit analog to digital converter, embedded microcontroller, 2 MB of non-volatile memory, and a 2.4 GHz transceiver chip.

A block diagram of the strain sensing node is provided in Figure 1.

![Block diagram](image)

Figure 1. Block diagram of wireless sensor node enabled for energy harvesting.

Embedded firmware within each node was programmed to support the following features:

- Wireless data transmission
- Data logging to non-volatile memory
- Up to 4 multiplexed sensor channels which support wide array of Wheatstone bridge type sensors
  - 10, 12, or 16-bit analog to digital conversion
- Synchronized sampling within +/-30 microseconds (theoretical worst case is +/-60 us using 20 second resynchronization rate)
- Programmable sampling rate 32 to 512 Hz
- Buffered transmissions for power conservation
- Base stations respond with acknowledgment
- Automatic retransmission of dropped data packets
- TDMA transmission scheduling
- Extremely low power allows for energy harvesting

In the following sections, we will discuss some of the major contributing attributes to this system. These topics include power optimization, data collection, synchronization, transmission scheduling, and energy harvesting.

Power Considerations

To enable energy harvesting it is important to minimize the power required by the electronics. The largest contributor to power consumption is generally the radio used to transmit data. In this project we considered a number of radios, presented below in Table 1. The most important parameters were the amount of energy required per bit of data transmission and the ability to rapidly turn on and off the radio to save power. Bluetooth and WiFi were ruled out because of the amount of time to turn on and transmit data. The Nordic radio clearly had the lowest energy/bit and the transmission range was adequate for our system. For these reasons, the Nordic NRF2401 2.4 GHz FSK radio was chosen.

<table>
<thead>
<tr>
<th>Radio Transceiver</th>
<th>Network Size</th>
<th>Transmit Power</th>
<th>Bit Rate</th>
<th>Energy/bit</th>
<th>Wireless Range</th>
<th>Turn-on Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE802.15/WiFi (Garmin)</td>
<td>&gt;100</td>
<td>153.6</td>
<td>0.25</td>
<td>122.4</td>
<td>70</td>
<td>5 mS</td>
</tr>
<tr>
<td>IEEE802.15/Bluetooth (CSR)</td>
<td>&gt;100</td>
<td>30.6</td>
<td>0.7</td>
<td>12.4</td>
<td>70</td>
<td>1 mS</td>
</tr>
<tr>
<td>Proprietary (Nordic)</td>
<td>&gt;100</td>
<td>66.6</td>
<td>2</td>
<td>95.1</td>
<td>15</td>
<td>5 mS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9.8</td>
<td>5 mS</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Comparison of radios.

Utilizing the high speed, low power Nordic radio has shifted the primary source of power usage from data transmission to sensor sampling. Methods were explored to further reduce power consumption of the sensor and signal conditioner. High resistance (4.7kOhm) foil strain gauges were to used minimize the power consumption of the sensor. The amplifier signal chain was designed to be turned on in under 20 microseconds, which minimizes the amount of time the system is powered. A precision 32 kHz clock timer IC is used to wake the microprocessor from sleep to sample, log, and transmit data. The following plot documents the power required of the sensor node for different sample rates and numbers of active sensors.

![Power consumption plot](image)

Figure 2. Power consumption of wireless sensor node with respect to sampling rate and number of active sensor channels.

Data Collection

The wireless sensor data aggregator (WSDA) is responsible for data collection and timing management within the wireless sensor network. The WSDA features a GPS receiver, timing engine, microprocessor core running Linux 2.6, CAN bus controller, and wireless controller. It provides large on board data storage, as well as an Ethernet, Bluetooth, or cell link used to direct data to an online database. Figure 3 displays archived data collected from a wireless sensor node positioned on a helicopter mast test stand. The plot displays perpendicular and parallel bending loads as well as torque (green, orange, and blue plots, respectively).
Figure 3. Data collected by WSDA wireless strain sensor node sensing perpendicular and parallel bending loads, as well as torque.

**Beacon**

A wireless beacon packet is broadcast every second, on the second, by the WSDA base station. This beacon is used by the wireless sensor nodes to synchronize sensor sampling and schedule transmissions.

**Sensor Synchronization**

The energy-harvesting wireless sensors are designed and programmed to spend most of their lives in a low power sleep mode. During this sleep mode, they periodically wake and listen for a start-up command, which is initiated from the base station. Upon start-up, all sensor nodes within the network synchronize their sampling intervals to the broadcast beacon signal. The wireless sensors use a high precision real-time clock (+/- 3 parts per million over a temperature range of -40 to +85 degrees C) to maintain time stability between beacon resynchronizations, which occur every 20 seconds.

Tests were performed to insure that several distinct wireless sensors would maintain synchronous measurements over extended periods of time. In this test, three sensor nodes were connected to differential strain gauges and set into a 256 Hz synchronized sampling mode. An oscilloscope was used to capture square pulses, as shown in Figure 4, marking the start of a sample on each of the three sensors.

Figure 4. Three distinct wireless sensor nodes with synchronized sampling. Pulses represent sensor measurement.

Additional synchronization tests were performed using this setup in order to gain a more accurate impression of the relative time drift. In this test, the analog to digital converter (ADC) sample timing waveforms from each of the three nodes were collected over one hour using the persistent graphing mode of a multi-channel oscilloscope, thus creating a drift envelope as shown in Figure 2. With each node sampling at 256 samples/second, this one hour test recorded a total 921,600 ADC sampling pulses per node. Results from this test yielded a maximum relative time drift of +/- 30 microseconds.

Figure 5. Relative sampling times of three distinct wireless sensors. Time drift is within +/- 30 us.

**Transmission Scheduling**

Data is time-stamped and then buffered for a short duration before transmission. By buffering, as opposed to transmitting data after each sample, we allow the sensors to save power on radio start-up and packet overhead. In addition, we grant versatility to the network in organizing transmission times such that many wireless sensor nodes may transmit data on the same radio channel without interfering with one another.

Time Division Multiple Access (TDMA) is used to avoid transmission collisions and maximize the number of wireless sensors supported by one base station. This method allots a unique time slot to each sensor node in the network. The sensor may transmit data only within its allotted period of time, assuring that no collisions will occur.

Tests were performed to verify time division stability over an extended period of time. The oscilloscope capture in Figure 6 displays three sensors operating in a synchronized network while utilizing a TDMA transmission scheme. In this case, the shorter duration spikes represent sensor samples occurring at 256 Hz, while the longer duration pulses represent transmissions. These sensors were set to maintain TDMA locations at a distance of two sampling periods (or two time slots) apart from each other.

Figure 6. Three sensors operating in a synchronized network while utilizing a TDMA transmission scheme.
Strain gauges. Currently support 32 wireless sensor nodes, or 96 separate sampling at 256 Hz and supporting error correction may shows that a network 3
takes into consideration error correction. For example, this model shows that a network 3-channel wireless sensor nodes sampling at 256 Hz and supporting error correction may support 32 wireless sensor nodes, or 96 separate strain gauges.

Figure 6. Wireless sensors exhibiting synchronized sampling and TDMA transmission scheme.

For our network, it was decided that time slots should remain a fixed size, while transmission frequency would vary based on sampling rate and the number of active sensor channels. In this way, sensor nodes using different configurations may be easily supported within the same network. The time slot size was selected to be 1/256, or about 3.9 ms. This size slot allows sufficient time for the transmission duration, with enough buffer before the next time slot to allow for an acknowledgment.

Error Correction

Due to a limitation of the Nordic radio, each data transmission, or “super-packet,” is actually made up of a stream of 32-byte “sub-packets.” Each sub-packet contains its own 16-bit checksum and index value. The base station has been configured to automatically recognize corrupted or missing data through inaccuracies in either of these values. The base station quickly responds to each super-packet it receives with either an acknowledgment of successful delivery or a request for retransmitted data.

In addition to a time slot dedicated to data transmission, each sensor is also allocated a time slot for retransmissions. In the case of lost or bad data, the wireless node temporarily stores the data into a buffer until retransmission is allowed.

Scalability

Each base station may support a variable number of sensors based on the required bandwidth of each sensor node. A node’s bandwidth is dependent on its sampling rate and number of utilized sensor channels, which determine how many time slots per second it will require to get all its data across. In the case that all nodes are utilizing error correction through retransmission, the required bandwidth doubles for each. The table below gives the real-world associated “bandwidth” for each node as a percent of the total bandwidth, taking into consideration error correction. For example, this model shows that a network 3-channel wireless sensor nodes sampling at 256 Hz and supporting error correction may currently support 32 wireless sensor nodes, or 96 separate strain gauges.

<table>
<thead>
<tr>
<th>Sample rate (Hz)</th>
<th>32</th>
<th>64</th>
<th>128</th>
<th>256</th>
<th>512</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensors channels</td>
<td>1</td>
<td>0.2</td>
<td>0.39</td>
<td>0.78</td>
<td>1.56</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.39</td>
<td>0.78</td>
<td>1.56</td>
<td>3.13</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.39</td>
<td>0.78</td>
<td>1.56</td>
<td>3.13</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>0.78</td>
<td>1.56</td>
<td>3.13</td>
<td>6.25</td>
</tr>
</tbody>
</table>

Table 1. Percent of total bandwidth required by wireless sensor node with respect to its sampling rate and number of active sensor channels.

Frequency Division Multiple Access (FDMA) allows the aggregate capacity of a local network to expand linearly with additional frequency channels. Multiple base stations may be synchronized through the same source, and each operate a family of sensors on a unique frequency channel (FDMA). The current system requirements permit 62 separate frequency channels within the 2.4 GHz band, allotting 2 MHz bandwidth per channel. Expanding the network to incorporate just 8 base stations would expand the capacity of the network to 256 synchronized sensor nodes, each sampling 3 strain gauges at 256 Hz.

Energy Harvesting

For this application, the sensor nodes are required to be active only while the helicopter is running and measurable loads are being generated. While the helicopter is inactive, the sensors nodes remain in a low power sleep mode where they draw an average 12 uA, or 36 uW. During this time, power is provided through a thin-film battery, protected from total depletion by a cutoff switch.

When the aircraft becomes active, the power harvesting circuitry immediately begins generating electrical energy from the readily available ambient strain. The converted electrical energy powers the sensor node while using any excess energy to support background recharging of the thin film battery. Tests were performed to assure that the power collected from bending strain imparted on a helicopter mast would satisfy the requirements of a wireless sensor node. For testing, data collected from the mast of the Bell 407 was used as a model.

The mast of a Bell 407 produces an average bending strain of +/- 500 µε during straight and level flight. We have shown on a spinning mast test stand that piezoelectric patches measuring ~2cm x 5cm, and loaded in bending, each produced ~2.5 mW of harvested power. In our current application, we have fitted a mast with 8 of these small patches. This energy-harvesting configuration has provided ample power for running the 3-channel, strain monitoring sensor nodes at 512 Hz, with enough excess energy to support background recharging of the thin film battery.

Conclusions

A network of wireless sensors has been developed for tracking aircraft structural load. Testing has revealed that the sensors successfully synchronize sampling and transmission timing, while performing real-time error correction. The system has demonstrated that it is scalable to support several distinct sensor nodes utilizing a variable arrangement of sensors and sampling rates. In
addition, under typical helicopter operating conditions, the sensor nodes may accomplish sample rates up to 512 Hz while still consuming less power than the amount energy harvested.

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References


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Mr. DiStasi received his Bachelor’s and Master’s Degrees in electrical engineering from the University of Vermont in 2006 and 2008. He is currently an electrical engineer of wireless systems at MicroStrain, Inc. in Williston, VT. He has made contributions to the field on topics including multipath fading, mesh networking, synchronized wireless sensor networks, and power optimization within embedded systems.

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Mr. Townsend received his Bachelor of Science Degree in Electrical Engineering from the University of Vermont in 1990. Mr. Townsend is currently EVP Engineering at MicroStrain, Inc. His research focus is in the development of analog and digital microelectronics and optimization of embedded firmware for integrated processing, sensing, data logging, remote powering, & wireless data transmission. Areas of special interest include smart medical implants, machines, and structures.

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Mr. Galbreath received his Bachelor's Degree in Mechanical Engineering and Master's Degree in Electrical Engineering from the University of Vermont in 2000 and 2005. Mr. Galbreath currently serves as VP of Wireless Systems at MicroStrain, Inc., developing wireless sensing systems for real-world structural, machine, and environmental monitoring applications. His research contributions have explored multi-path fading, wireless channel allocation strategies, wireless sensor network time synchronization & scalability, and web-connected sensing systems.

Steven Arms:  
Mr. Arms received his Master’s Degree in Mechanical Engineering at the University of Vermont in 1983. He has been awarded 33 US patents, and has contributed to 23 journal publications in areas of advanced instrumentation, wireless sensing, and energy harvesting. Mr. Arms is founder and President of MicroStrain, Inc., a manufacturer of micro-displacement sensors, inertial sensing systems, and wireless data logging nodes for recording and transmitting vibration, temperature, orientation, and strain data.