Scalable, Synchronized Network of Lossless Wireless Sensors for Rotorcraft Monitoring

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Abstract

This work demonstrates a condition-based solution for monitoring the long-term health of a system with moving, rotating, or hard to reach parts. This is accomplished through the direct measurement of loads, vibration, displacement, and temperature 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.

What is unique about this system is its ability to maintain 100% communication success rate in harsh environments such as a rotorcraft, where multipath, moving parts, and other anomalies can cause significant data loss. This is accomplished through the use of buffering, acknowledgements, and retransmissions without compromising the energy-constrained nature of these devices. The reliability of this wireless network, coupled with the versatility and low power technology suitable for energy harvesting, make it ideal for complimenting a fully deployed health and usage management system.

Keywords: Wireless, Sensing, Synchronized Networks, Energy Harvesting, Rotorcraft, SHM, HUMS, SHUMS

Introduction

Wireless communications, combined with energy harvesting, have the potential to enable sensors to become very deeply embedded for long term aircraft structural health tracking. The US Navy for example seeks advanced next generation sensing systems that can track the precursors to crack formation and initiation [1]. The ideal monitoring system would directly measure component strains, loads, torques, vibrations, displacement, and/or temperatures over their lifetime to provide a rich data set of information to accurately measure structural fatigue and to enable component lives to be safely extended. This promises to reduce maintenance costs, increase mission readiness, and enhance safety.

MicroStrain has previously reported on flight tests of energy harvesting wireless components (pitch links and mast) aboard a Bell M412 helicopter and Sikorsky MH-60S [2]. MicroStrain has since developed a highly scalable synchronized system for wireless sensor data aggregation and remote reporting [3]. Network scalability and collision avoidance are achieved by time division multiple access (TDMA) [4]. Previously flown flight tests have proven the viability and utility of wireless sensor networks (WSN) to compliment current HUMS [5].

Despite their utility, many current WSN deployments suffer from data loss due to the extremely strict low power and high sampling rate requirements. Missing data can lead to invalid health assessments of the components being monitored, especially if the lost data occurs in large segments. This paper will describe a WSN which complies with these strict requirements and overcomes the data integrity problem.

Objective

The objective of this work was to develop and deploy a practical "lossless" wireless communication protocol for a network of synchronized and very low power wireless sensors to be used in rotorcraft monitoring. In order to conduct a valid health assessment of the monitored parts, the wireless sensors must provide 100% data throughput despite the non-ideal communication environment within an aircraft. In addition, the network must simultaneously support sensors running a diverse range of sampling rates and configurations.

Methods

Wireless Sensor Network

A network of wireless sensors consists of a base station unit and one or more wireless sensor nodes. Sensor nodes report sampled data from one or more sensors to the base station unit, which aggregates this data and passes it to a greater data base source, such as a cloud service or local PC. Many wireless sensor networks can contribute information to this source.

Wireless Sensor Nodes

Each wireless sensor node includes an embedded microcontroller, 2 MB of non-volatile memory, high-speed external RAM, and a 2.4 GHz transceiver chip with power amplifier. The device also contains analog sensor hardware, which may include an instrumentation amplifier, gain amplifier with offset adjust, anti-aliasing filter, and a 16-24 bit analog to digital converter. Sensor hardware can vary greatly depending on what is being measured, as can the desired mode of operation. Two units, described below, employ two distinct modes of operation, "continuous synchronized sampling" and "burst synchronized sampling". Synchronization will be explained further in the next section.

One device, designed to monitor rotor bearing fatigue, employs four displacement sensors and six strain gages simultaneously. With all ten sensor channels active, the wireless node samples continuously at rates up to 128 Hz. At this maximum sampling rate, the node must transmit data packets to the base station at a rate of 32 transmissions per second, occupying 25% of the network bandwidth. This leaves up to 75% of the total bandwidth for three additional similar sensors.

Another device is designed to measure vibration and temperature in order to monitor swashplate bearing degradation (Figure 1). This unit equips two piezoelectric accelerometers and one RTD (resistance temperature detector) per node. The piezoelectric accelerometers are sampled in periodic bursts, at rates ranging from 1 kHz to 100 kHz, while the RTD is continuously sampled at 1 Hz. Data is communicated in the time between the periodic bursts.

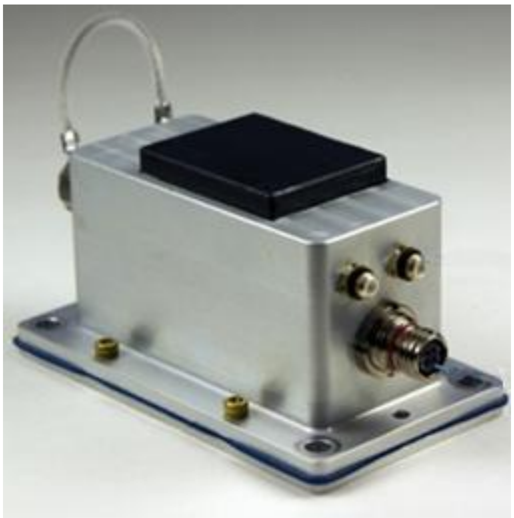

Figure 1. Energy harvesting, wireless sensor node designed to monitor vibration and temperature.

The synchronized burst mode allows this node to sample at much higher rates than can be accomplished through continuous sampling. In addition, it is beneficial in energy harvesting applications because the node can use the time in between bursts to fully recharge batteries or supercaps.

Wireless Sensor Data Aggregator

A wireless sensor data aggregator (WSDA) is used as the base station for remote sensing applications. The WSDA synchronizes all wireless nodes in the network with a "beacon" broadcast, which may itself be synchronized through GPS, Ethernet, or an internal clock. The WSDA collects all data being transmitted by the sensor nodes and stores it locally. This data may be downloaded later, pushed to MicroStrain's secure Sensor Cloud, or pushed to a HUMs box or other third party serial device. WSDA settings and information may also be accessed or configured remotely.

Figure 2. MicroStrain Wireless Sensor Data Aggregator (WSDA)

Synchronization

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

In order to have a tightly synchronized and scalable network of wireless sensors, each of our units utilize a high-precision, temperature compensated real time clock. The drift rate of this part is +/- 3ppm over temperature, requiring the node to re-synchronize at periodic intervals in order to maintain synchronization to within +/- 30 microseconds of the reference.

The image below (Figure 3) illustrates a network of four wireless sensors. Using the beacon as a time source, nodes 1 and 2 sample and transmit continuously. Nodes 3 and 4 perform higher sample rate bursts, and then report this information in the time between bursts. No matter what the sample rate or sampling mode, all nodes can operate on the same frequency band.

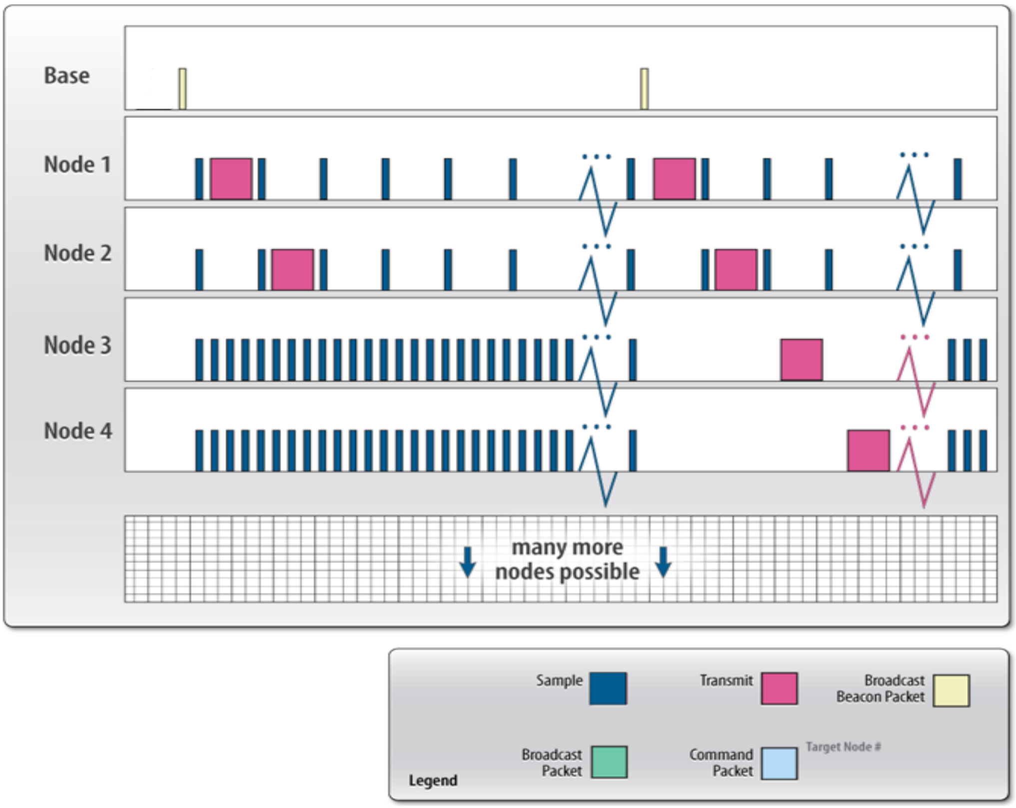

Figure 3. Illustration of four nodes operation in synchronized sampling mode using the beacon as their time source. Nodes 1 and 2 sample and transmit continuously while nodes 3 and 4 perform high sample rate bursts.

The beacon has the added benefit of being able to remotely start and stop a network of wireless sensors. For example, a rotorcraft monitoring application which only cares about collecting data during specific flight times will have its sensor nodes turn on in a low power mode, where they periodically listen for the beacon. The WSDA begins transmitting a beacon only when it would like to start collecting sensor information. Upon hearing the beacon, the nodes all begin sampling and transmitting, and continue doing so until the beacon has been removed. An example application of this feature is a Goodrich HUMS that signals the WSDA to start collecting data when the weight on wheels becomes false.

Lossless

It is expected in a rotorcraft, a metal shell environment with many moving parts, that several wireless packets may be corrupted and dropped. The network created achieves 100% data throughput through the application of buffering, transmission acknowledgements, and retransmissions.

Sensor nodes buffer all collected data and timestamps to high-speed, non-volatile memory. F-RAM is highly suited to this task, as it is very high-speed, low power, and offers an incredibly high number of write-erase cycles. One 2 Mbit F-RAM chip can buffer 10 minutes of data from a 1 channel wireless sensor sampling at 256 Hz.

When the network is configured, a specific number of transmission slots is assigned to each wireless sensor based on their sampling criteria (i.e. number of sensor channels, sampling rate, etc.). But the number of slots allocated to each node grants a greater potential bandwidth than is required by the node.

The sensor node transmits data from its F-RAM buffer to a WSDA, and the WSDA responds with an acknowledgement once it has deemed the packet content acceptable. When the node does not receive a successful acknowledgement it will continue retransmitting this data until it is successful. By taking advantage of the additional bandwidth it was originally allocated, the node can recover from the backed up data.

The image below (Figure 4) shows data collected from two wireless accelerometers, where one is using the lossless protocol (top) and the other has retransmissions disabled (bottom). The data was collected at close range (less than 10 meters) in an environment exhibiting significant multipath and WIFI interference. The node using the new protocol easily handles the situation of recovering from intermittently dropped packets.

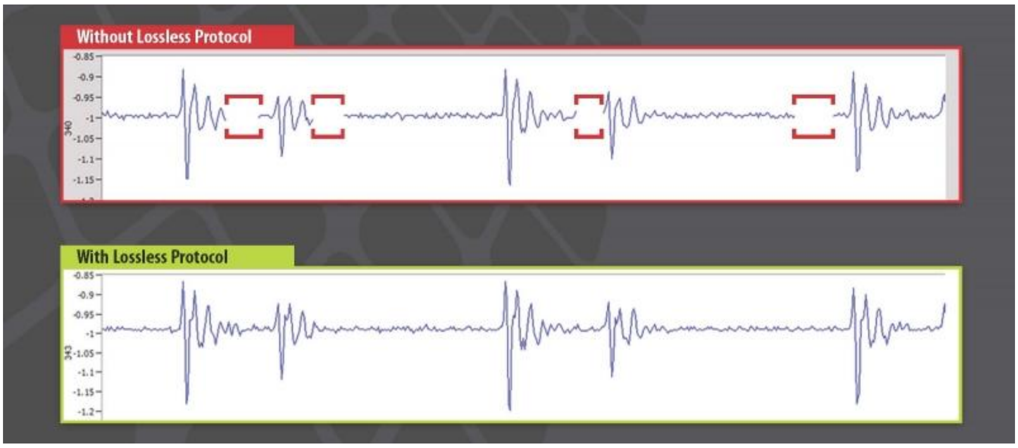

Figure 4. Lost data is recovered when using new lossless protocol.

In addition to handling intermittently dropped packets, the network handles situations in which a device is expected to move in and out of coverage range. While the node is out of range it will buffer data for minutes or hours, depending on the amount of data being sampled. And when it moves back into range, the node will push its data through without negatively affecting other nodes in the network.

The recovery time after dropping packets is dependent on how much bandwidth overhead the node is granted. For example, if a node is given 20% more bandwidth than it requires, then it will take 5 seconds to fully recover from 1 second of lost data. Networks must be designed to assure the percent of additional bandwidth reflects the maximum expected data loss a node will see. In past applications, nodes have dropped between 1-5% of data collected when given no retransmissions despite remaining well within communication range. In these cases, 20% of additional bandwidth is more than adequate to overcome short term losses.

Network Scalability

Networks may be scaled to include many wireless sensor nodes operating on any given frequency. The plot below (Figure 5) displays the example number of nodes one could fit in a network if all of the nodes are configured with the listed number of active channels sampling at the given sample rate. This plot assumes that all measurements are communicated as 16-bit values. The percent of bandwidth overhead associated with nodes in these default configurations is 20% when 1 or 8 sensor channels are active, and 40% with 3 active channels. This overhead allows the nodes to retransmit lost data as described in the previous section. Additional overhead may be granted in cases where connectivity is very poor, at the expense of decreasing the maximum node capacity.

Sample Rate	Number of Channels			Aggregate Capacity*
	1	3	8	
512 SPS Continuous	3 nodes	1 node	0 nodes	1536 SPS
256 SPS Continuous	15 nodes	3 nodes	1 node	3840 SPS
128 SPS Continuous	31 nodes	7 nodes	3 nodes	3968 SPS
64 SPS Continuous	63 nodes	15 nodes	7 nodes	4032 SPS
32 SPS Continuous	127 nodes	31 nodes	15 nodes	4064 SPS
16 SPS Continuous	223 nodes	55 nodes	27 nodes	3568 SPS
8 SPS Continuous	479 nodes	119 nodes	59 nodes	3832 SPS
4 SPS Continuous	991 nodes	247 nodes	123 nodes	3964 SPS
2 SPS Continuous	2015 nodes	503 nodes	251 nodes	4030 SPS
1 SPS Continuous	2031 nodes	1015 nodes	507 nodes	4056 SPS

Figure 5. Network scalability chart, displaying the maximum number of nodes one could fit in a network if all nodes are configured alike.

Multiple WSDA's may synchronize to each other using GPS or Ethernet, creating a much larger system of localized networks. These local networks are isolated from one another by using one of 16 frequency channels, and a managed 16-bit PAN ID. Adjacent networks using the same frequency, but different PAN, will overcome loss caused by radio interference using the lossless data protocol as long as these networks do not remain within close proximity for an extended time.

Results

The lossless protocol described has been used in many field applications to date with successful results. Wireless sensors deployed in similar environments as a rotorcraft, such as in wind turbines, high-speed trains, and on heavy earth movers have yielded data throughput consistently greater than 99.9% success rate, where previously it was not uncommon to experience loss of up to 10% or greater.

Flight tests incorporating MicroStrain's lossless wireless sensors are planned to occur in December 2012. Among these applications is a pitch link strain sensing wireless sensor on a Boeing Apache AH-64 (Figure 6). Pitch link loads will be used to extrapolate load cycles and therefore fatigue, on many components in the rotating frame. Due to its remote location, and highly dynamic loads, the unit provides its own power through energy harvesting.

Figure 6. Apache pitch link energy harvesting wireless sensor.

Another of these flight tests planned for December 2012 will be performed on a V-22 Osprey, where wireless strain sensors in the landing gears are used to evaluate weight on wheels and landing pulse. Other flight test ready products include gear box and swashplate vibration measurement systems, as well as a rotor bearing fatigue monitoring node.

Conclusion

A network of wireless sensors has been developed for tracking aircraft structural health. 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 many distinct sensor nodes utilizing a variable arrangement of sensors and sampling rates. Under typical operating conditions, the sensor nodes may accomplish near lossless data throughput while maintaining low power restrictions.

Acknowledgements

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