Wireless Monitoring of Bridges

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Introduction and Background

The main goal of the project was to build a working prototype unit that collects and stores vibration data from sensors located at areas of interest on the Ron Venderly Family Footbridge (Fig. 1). The wireless sensors use a tri-axial accelerometer, which will measure the acceleration in three dimensions. The data from the accelerometer is sampled via an analog-to-digital converter (ADC) and fed into a single microcontroller. The accelerometer in the sensor will have a low range (*e.g.,* ±2g) to accurately measure the vibrations from the bridge [1]. The acceleration readings are to be transmitted wirelessly to an accessible hub, which is fixed at a location within proximity to the wireless range of the transceivers. The collected data will then be available for further processing to analyze the bridge movements. To achieve self-sustainability the system includes a component to harvest energy from the environment.

Bridge maintenance operations are costly and can even be dangerous. The state of Indiana, USA, has 18,546 bridges, from which 1,927 have been classified as structurally deficient, and 4,111 as functionally obsolete [2]. Inspecting bridges on a regular basis is vital for safety and structural integrity. Compared to physical inspection, wireless monitoring offers reduced maintenance costs and increased safety.

For the case of footbridges important variables to measure are the bridge motions caused by wind and pedestrians crossing the structure. The three main bridge movements of interest in this project are torsion type movements, vertical movements, and lateral movements. The data collected by the sensors will give a better understanding of the bridge dynamics and can be evaluated for maintenance and repair purposes.

Figure 1. The Ron Venderly Family Footbridge

System Architecture

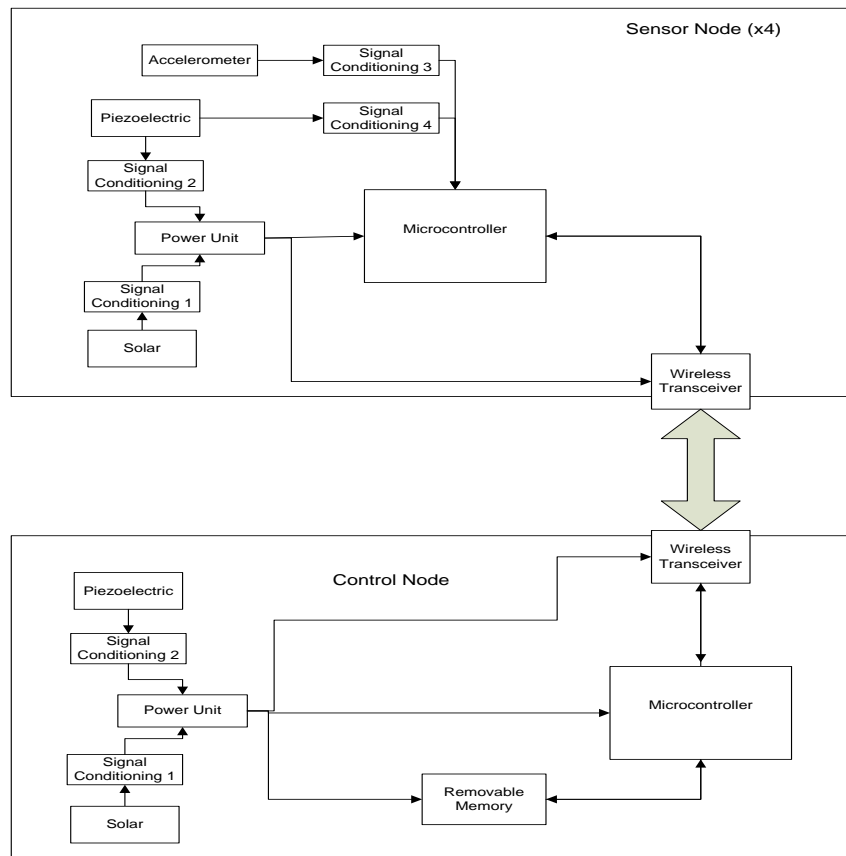The system architecture consists of a control node and sensor nodes as illustrated in Fig. 2.

Figure 2. System Architecture Block Diagram

The sensor nodes measure the bridge dynamics using the accelerometers. The measured data are sampled via an analog-to-digital-converter (ADC) which in our case is integrated into the microcontroller board. The digitized data is transmitted wirelessly to the control node. The system is intended for outdoor use. Specifically, the system is implemented on a bridge, while other civil structures could also be used as practical applications.

Wireless Standard Selection

In relation to the selection of the wireless standard for this project, there are two main design criteria. The design must minimize energy usage, and must also be able to allow for minimum number of hops communication between the furthest node and the control node [3].

When selecting the control node location, we assume that the system may expand to monitor the full length of the bridge, and may eventually include an access point at one end. To account for possible future expansion, the control node is placed at the center of the bridge. The selected bridge spans 220 feet (67 meters). By placing the control node at the center of the bridge, and assuming a star topology it is estimated that 34 meters is the maximum distance needed for single-hop communication between the control node and the furthest possible node (at the end of bridge). This estimate provides a general range value to be used in choosing the appropriate wireless standard.

The IEEE standard 802.15.4 (also known as "ZigBee") has been deemed appropriate for this wireless sensor network application for the following reasons:

- It focuses on low-energy communication
- It is designed for applications with transmission range up to 100 meters
- It has data transfer rates of 250 kbps for 2.4 GHz interaction
- It allows for sleep functionality and can wake up in 15 milliseconds, when needed
- It provides the lowest power consumption for our desired talking range, which is 34 meters
- It has features that allow to lower the overall power consumption of the system

Since the control node needs to coordinate the collection of data from the four sensor nodes, it must use a functionality which requests data from the sensor nodes. The control node will request data from one sensor node, receive all data frames successfully, send an acknowledgement for each data frame, and then repeat the process with the next sequential node. The nomenclature for this request functionality is defined as a *"Beacon-enable Network"*, and is described explicitly in IEEE protocol 802.15.4, section 5.5.2.1. [4].

Implementation

The overall system requirements are:

- Vibrations sensing
  - Be able to measure frequencies from 0 to 10 Hz
- Wireless transmission
  - Transmitting range up to 34 meters
  - Saving power capabilities
- Harvest and store energy
  - Be able to harvest at least 100 mW
  - Use a super capacitor (~1F – 10F) or a rechargeable battery (>200 mAh)
- Enclosure
  - Weatherproof
  - Temperature range of -50^0F to 200^0F
  - Tamper resistant
- Access data
  - Via an access point
  - On-site access (e.g. memory stick, proximity transfer)

These requirements are met with the conceptual design summarized in Table 1.

TABLE 1. CONCEPTUAL DESIGN

Factor	Concept
Harvest Energy	Hybrid (solar/piezoelectric)
Topology	Star
Number of Hops	1-hop
Energy Storage	Super Capacitor
Data Collecting	Data gathered at each SN, sent to CN
Data Access	Hub/Laptop relay/Removable media
Sensor	3d Accelerometer, piezoelectric
Transmission Protocol	IEEE 802.15.4
Enclosure	Polycarbonate

Discussion of the conceptual design

- Advantages

  - Using star topology minimizes number of hops to one hop, which uses less energy for data transfer.
  - Super capacitor properties: virtually unlimited lifespan, low cost, ability to charge in less than 20 seconds, fast discharge, and no worry of overcharging.

- Storing data at each sensor node allows data from sensor to be stored while data is being sent from other nodes.
- Using a hub/laptop to gather data from the control node provides the ability to access data from remote locations with internet access.
- Tri-axial accelerometer provides 3-dimensional readings of the bridge's vibrations, while piezoelectric also provides vibration stream data.
- IEEE 802.15.4 has low power consumption, range of 30 m needed to access different sensor locations, and supports power-saving sleep functionality.
- The enclosure made of polycarbonate has twice the impact strength of ABS, has electromagnetic shielding, high heat resistivity and high dielectric strength

- Disadvantages
  - Using hybrid becomes more expensive and also makes the sensor more bulky
  - Super capacitor may only have 1/5 the capacity of a Lithium Ion battery

- Considerations

  - Design requires a hub to be installed for remote access.
  - Lithium-ion batteries are typically used for our type of application.
  - Secondary "fall-back" options for this design include: lithium-ion battery power source and removable media for data storage and access.

Table 2 provides a list of actual components that we found to meet the specifications of our concept.

TABLE 2. COMPONENTS SELECTED

Device	Quick Specification	Model/Part #	Provider
Explorer 16 Dev. Board	100-pin w/PIM	DM240002	Microchip
PIC24 Microcontroller PIM	16-bit MCU	PIC24FJ128GA010	Microchip
PICTail Plus Transceiver	2.4 GHz IEEE 802.15.4	MRF24J40MA	Microchip
Accelerometer	3-axis ±3g, 1.8 to 3.6V	ADXL335	Analog
Enclosure	Polycarbonate	3.120.0556.28	Sealcon
Mounting Plate	1.5mm Galvanized Steel	3.120.0560.69	Sealcon
Supercapacitor	5V, 3 Farad	PM-5R0V305-R	Mouser
Solar Panel	9V 2W	SPE-225-6	SolarWorld
Piezoelectric	Variable Res. Freq., < 70V	0-1002794-1	Parallax

Hardware

The PIC24FJ128GA010 Microcontroller PIM was chosen as the microcontroller for this project and approved for application per Microchip. Its notable features are: low power sleep, fast wake, and fast control functionality. It also has 8192 bytes of internal RAM for storing data at each sensor node until the control node is ready to receive wireless transmission.

The following calculation shows the rate of data collection for this application.

- Nyquist rate for 10 Hz = 20 samples / second
- Accelerometer bits = 3 channels each 10 bit ADC
- Piezoelectric = 1 channel at 10 bit ADC)
- Total = 40 bits/sample, from which,

$$\left(\frac{20 \text{ samples}}{\text{sec}}\right)\left(\frac{40 \text{ bits}}{\text{sample}}\right)\left(\frac{1 \text{ Byte}}{8 \text{ bits}}\right) = 100 \text{ Bytes/sec}$$

Thus assuming no overhead bits 81.92 seconds of data can be collected in those 8182 bytes.

The operating voltage of the microcontroller is between 2-3.6 V and has an operating current of 650 µA/MIPS typical at 2.0 V and sleep current of 150 nA typical at 2.0 V. The microcontroller has 13-channel 10 bit ADC built into the microcontroller allowing for the piezoelectric and accelerometer analog signals to be digitized by the microcontroller directly.

The MRF24J40MA PIC TailPlus 2.4 GHz RF Card was chosen because it is a card package that inputs directly into the Explorer 16 development board. There are three versions of the MRF24J40 (M, MA, & MB). Of these, the MA version was chosen because it has an antenna built onto the card and has a signal range of up to 70 m line-of-sight. The M version has no antenna built in and the MB version consumes more power due to longer signal transmission capability. Typical current consumption for TX is 23 mA and for RX is 19 mA and draws on 2 µA in sleep mode. It is also important to note that the MRF24J40MA is accompanied by the Microchip ZigBee 2006 Protocol Stack.

A micro-SD card adapter will be used to store data that can be removed at the control node. This allows for mass storage of data and will continue to store data even if a power loss occurs. The operating voltage of the SD adapter is 3.3 VDC and is capable of operating in serial or bus mode.

Software

The software used for the microcontroller and the wireless card are compatible with products from Microchip Technology Inc. The microcontroller combined with the wireless card requires the use of C Compiler and MPLAB ICE/IDE. The ZigBee 2006 Protocol Stack allows for the 2.4 GHz RF card to communicate with the microcontroller and is ready to send and receive signals. The MRF24J40 Radio Utility Driver Program allows the user to configure and run tests of basic transceiver functionality such as transmission, reception sleep and Turbo mode using a command-line and menu-driven user interface.

Evaluation Plan

Transmission Testing

The transceiver we chose was the MRF24J40MA 2.4 GHz PICTail Plus RF Card from Microchip. Indoor and outdoor range tests were conducted with this device for up to 35 meters. All tests passed as our data packets were successfully sent from the sensor node to the control node. The outdoor testing included successful transmission of at least one quarter-length of the bridge.

Messages and data were verified by two methods. By the first method, the two nodes were programmed with their respective codes while the Control Node was examined in Debug mode via the Microchip ICD3. The Sensor Node's BYTE Signal array is initialized for the purpose of transmission testing. This initialized signal was sent by the Sensor Node and viewed with the use of software breakpoints in Debug mode. The Sensor Node's Signal array is non-repeating, therefore assuring that the Control Node's incoming data can be viewed for accuracy.

By the second method, the Sensor Node's Signal array was populated with real-time digitized values from the on-board potentiometer. The values were gathered by the user in some recognizable pattern (0→255, 255→0, etc.) and displayed on the Sensor Node LCD screen. At this point the user visually inspects to ensure that these streaming LCD values are appropriate. Once a full, 10 second collection cycle is fulfilled, the data is sent to the Control Node. Control Node's incoming data stream is verified on the LCD screen and in the workspace's Debug mode.

Control and Sensor Nodes Interactions

Fig. 3 shows the message-based interaction between the Control Node and Sensor Nodes. All of the sensor nodes simultaneously gather data for 10 seconds. Then, the message "SN1ready" is issued by Sensor Node 1 to the Control Node. This starts a chain of messages, which are shown in a counter-clockwise manner below, starting with "SN1ready".

Summary

A prototype to monitor the movements of a footbridge has been built. The designed system consists of a control node and sensor node. Each sensor node has a triaxial accelerometer, a microcontroller, an 802.15.4 transceiver, and an energy harvesting unit whose main component is a solar panel. The developed software can support multiple nodes and for each node the harvested power meets the power budget requirements.
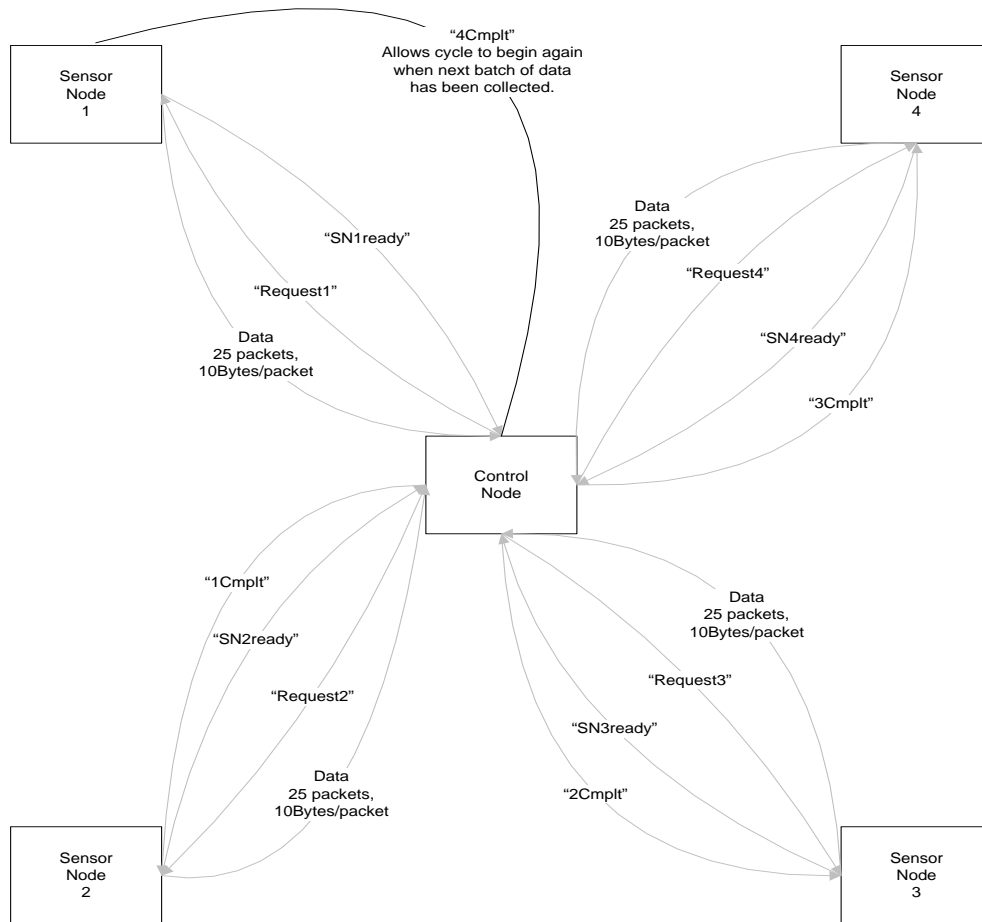
Figure 3. Star Topology Node Interaction

References

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[2] US Department of Transportation. Federal Highway Administration http://www.fhwa.dot.gov/bridge/nbi/county09.cfm   (accessed June 10, 2010).

[3] J. P. Lynch, "Overview of Wireless Sensors for Real-Time Health Monitoring of Civil Structures," *Proceedings of the 4th International Workshop on Structural Control (4th IWSC),* June 10-11, 2004, New York City, New York, USA.

[4] standards.ieee.org/getieee802/802.15.html, (accessed on 10/15/2009).