# Wireless Intelligent Sensor Network for Autonomous Structural Health Monitoring


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## ABSTRACT

Life cycle monitoring of civil infrastructure such as bridges and buildings is critical to the long-term operational cost and safety of aging structures. The widespread use of Structural Health Monitoring (SHM) systems is limited due to unavailability of specialized data acquisition equipment, high cost of generic equipment, and absence of fully automatic decision support systems.

The goals of the presented project include: first, design of a Wireless Intelligent Sensor and Actuator Network (WISAN) and creation of an inexpensive set of instrumentation for the tasks of structural health monitoring; second, development of a SHM method, which is suitable for autonomous structural health monitoring.

The design of the wireless sensor network is aimed at applications of structural health monitoring, addressing the issues of achieving a low cost per sensor, higher reliability, sources of energy for the network nodes, energy-efficient distribution of the computational load, security and coexistence in the ISM radio bands. The practical applicability of the sensor network is increased through utilization of computational intelligence and support of signal generation capabilities.

The automated SHM method is based on the method of modal strain energy, though other SHM methods will be supported as well. The automation tasks include automation of the modal identification through ambient vibrations, classification of the acquired mode shapes, and automatic evaluation of the structural health.



Keywords: wireless sensor networks, structural health monitoring, ambient vibrations, autonomous systems, modal strain energy.


## 1. INTRODUCTION

Life cycle monitoring of civil infrastructure such as bridges and buildings is critical to the long-term operational cost and safety of aging structures. Knowledge of the structure's health, load bearing capacity, and remaining life is the primary goal of any strategy of Structural Health Monitoring (SHM). Maintaining and improving the condition of bridges is critical to the structural integrity and cost effectiveness of the transportation system. Bridges constitute the most vulnerable element of the transportation infrastructure. An out-of-service bridge creates economic losses both for the bridge users (in terms of traffic delays and detours) and for the bridge and road operators [1]. At the end of 2001, the Federal Highway Administration (FHWA) has listed nearly 30 percent of the country's 590,000 bridges as structurally deficient or functionally obsolete, in terms of dimensions, load or other characteristics [2]. The majority of these bridges are small and medium span structures, located on local (secondary) or rural roads.

The FHWA names two main reasons for deterioration of the transportation infrastructure: rapid aging of the bridges and significant increase in traffic levels, placing the wear and tear on many bridges beyond the levels that they were designed to handle. For example, half of the bridges in the federal interstate system are over 33 years old [3]. FHWA estimates show that passenger traffic will increase by 17 percent (from 2.7 trillion vehicle miles traveled to 3.1 trillion) by the end of 2010 and truck traffic will increase by 28 percent. Aging infrastructure and increased traffic levels put more pressure on the issues of bridge maintenance and operational safety.

An objective evaluation of the bridge status can significantly reduce money spent on maintenance, repair and replacement of the structurally deficient components. The key is to have a low cost and reliable way to evaluate structural integrity and to identify deteriorated structural components. This goal can be accomplished by a system that is capable of performing continuous health monitoring and evaluation of bridges. Such a system would complement FHWA-mandated periodic visual inspections of bridges and would provide quantitative measures of the bridge health status. A significant benefit of continuous SHM would be the system's ability to detect and locate damage that is difficult to identify by visual inspections of the bridge, such as fatigue and hidden corrosion. These and other issues of structural health monitoring of bridges has caught attention of many researchers [4].

The same SHM approach can be extended over to other civil engineering structures, such as buildings located in the zones of high seismic activity. A monitoring system would significantly decrease the cost of building maintenance by minimizing the need for visual inspection of welded connections (connected with high costs of removing and reinstalling the cladding and fire retardant) after an earthquake [5].

At the present time, practical use of structural health monitoring systems is limited due to unavailability of specialized data acquisition equipment for structural health monitoring, and high cost of generic, wired instrumentation, coupled with high installation costs. Lynch et al. [6] reported costs of $300,000 per bridge ($5000 per sensor) to install a monitoring system with 60 accelerometers in California and the cost of the 600-channel monitoring system for Tsing Ma Suspension bridge to be over $16 million (over $27,000 per channel). Installation of cables and cable conduits is labor-intensive and constitutes a significant part of the final cost.

Another limiting factor comes from the fact that many structural health monitoring methods do not have fully automatic decision support. A highly qualified expert is usually required to interpret the data and perform damage detection, which slows the widespread introduction of the continuous monitoring systems.

A possible solution to the instrumentation problem lies in the concept of a wireless sensor network, consisting of many inexpensive low-power nodes and performing monitoring of the structural health. Mitchel, Rao and Pottinger [7] used commercially available hardware to design a Web-enabled network of sensors. Lin et.al. [8] used structurally integrated piezoelectric transducers to monitor structural integrity of composite materials. Fraser et. al. [9] plan to utilize a sensor network as a part of a integrated health monitoring system, including computer vision, numerical simulations of complex systems, visualization, risk analysis and statistical decision making. Basheer et.al. [10] looked at the issue of self-organization in a sensor network for structural health monitoring. The authors also highlighted other issues of the design, such as fault tolerance, energy efficient communications and reliable operation. Kotapalli et. al. [11] designed a two-tiered network architecture for structural health monitoring, based on commercially available hardware. Lynch et. al. [6, 12, 13] tested a wireless data acquisition system.

These and other papers describe important issues in the design of wireless instrumentation for structural health monitoring. In this paper we present the design of a fully autonomous wireless system of structural health monitoring.

## 2. THE CONTEXT OF AUTONOMOUS STRUCTURAL HEALTH MONITORING

Design of the data acquisition instrumentation such as a sensor network should provide maximum fit to the particular task. Utilization of a sensor network for long-term SHM is performed in an attempt to minimize cost and maximize utility of the system as a whole. Therefore, resolution of any design issues should be performed by keeping this approach in mind. The sensor network design should be closely tied-in with the design of the monitoring methodology and do not necessarily follow the concepts formulated for other applications. Here we will consider some issues focusing on the task of continuous autonomous structural monitoring of bridges based on modal strain energy.

First, the sensor network should provide capabilities for low-cost autonomous data acquisition. The data acquisition instrumentation of the sensor nodes should be designed specifically for the sensors normally utilized in structural health monitoring and function unattended for long periods of time. The sensor nodes should be inexpensive ($100 per data channel / sensor or less), support heterogeneous senor data, and be easy to install and maintain.

Second, the price of energy used to power the sensor nodes should be minimal, and, preferably, come from a self-sustaining power source. Applications of wireless sensor networks save money primarily by avoiding high costs of wiring and maintenance. Power-hungry sensor nodes may eliminate any cost advantage by consuming significant amount of moderately expensive energy, such as batteries. Normally, sensors are located in hard to reach places and a one-time cost of replacing batteries in a 100 sensor nodes installation may cost anywhere from $1000 and higher depending on the price of batteries, time to replace a battery and cost of labor. If a sensor node can last for just a few months before requiring a battery replacement, the total cost will quickly mount up.

Third, the sensor network system should coexist with other devices functioning in the Industrial, Scientific and Medical (ISM) range of radio frequencies and provide a fault-tolerant, reliable, and secure way of communication in a network containing a large number of nodes. These issues are often overlooked by many researchers.

Fourth, the sensor modules should provide for energy-efficient distribution of computational load and on-sensor intelligence supporting the monitoring methodology. Distribution of the computational load is only meaningful if it minimizes the total energy consumption or minimizes the latency of the system.

Fifth, the sensor network should provide convenient means to self-localization of the sensor nodes. Most of the SHM methods require knowledge of the sensors' position on the structure. The localization capabilities of the network must allow for 3D resolution of the node placements.

Sixth, the sensor network as a whole should be able to acquire data in a manner similar to a wired system, that is with minimal error in synchronization between channels. The sampling synchronization error between any two nodes of the network should be significantly less than the period of the signals being acquired.

Seventh, the sensor network and the SHM system should be built around sensors and monitoring methods that do not require significant energy expenditures to perform measurements and excitation of the structure (for example, the energy to excite a piesoceramic transducer, scaled up to hundreds transducers on a bridge, is very high), but function by capturing and analyzing the ambient response of the structure. By using the ambient energy such as excitation from traffic, wind, and microtremors, we can avoid the cost associated with energy expenditures on forced excitation of the structure.

Finally, the SHM system should not rely on human involvement in any part of the decision making, damage feature analysis, data acquisition and power generation, and be able to function completely autonomous. The structural health monitoring system should process all the data at the location, generate reports on a periodic basis and transmit them to the monitoring agency, and be able to raise alarms when a threatening or an extreme event (such as a rapidly growing crack or an earthquake) is detected.

In this paper we present a framework that conforms to all these requirements.

## 3. WIRELESS INTELLIGENT SENSOR NETWORK

The Wireless Intelligent Sensor and Actuator Network (WISAN, "the sensor network") is designed with the goal of continuous structural health monitoring in mind. The design of the network conforms to the requirements stated in the previous section and provides a sound foundation for practical implementation of health monitoring systems for a variety of civil engineering structures. The intelligent capabilities of limited signal processing, compression, waveform generation and embedded computational intelligence (fuzzy logic and neural networks) make this sensor network almost universally applicable to a variety of SHM methods.

The internal structure of a sensor node is shown in Fig. 1. Data acquisition modules are built around an ultra-low-power microcontroller MSP430F1611 from Texas Instruments [14]. The data acquisition modules each provide up to six 12-bit analog-to-digital channels, two 12-bit digital-to-analog channels, 16 general-purpose digital input/output channels, and up to 16Mbit of non-volatile EEPROM memory. The modular design allows a scalable design with a

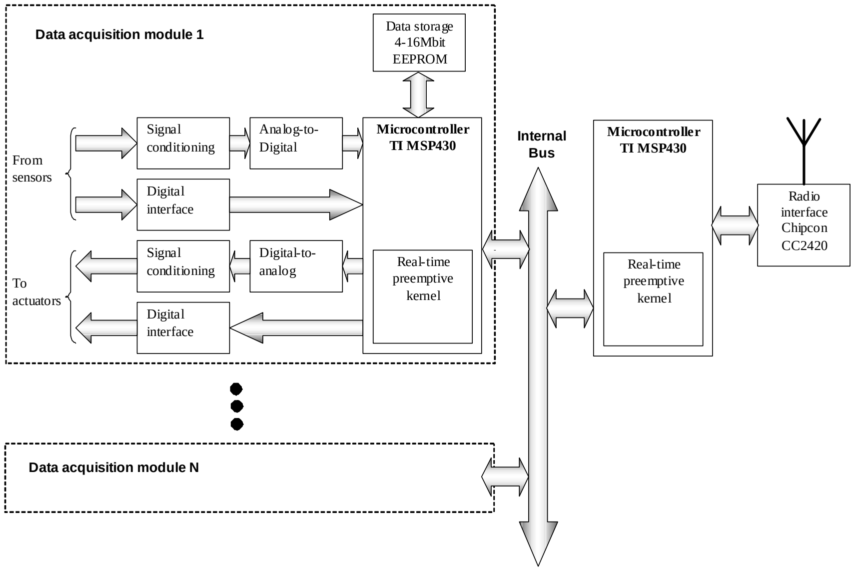


Fig. 1. A WISAN node.

flexible number of input/output channels and relieves the network protocol controller from execution the signal processing tasks.

The data acquisition modules connect to the network interface via an internal bus. The network interface module implements the network protocol based on IEEE 802.15.4 standard. A 2.4Ghz module CC2420 from Chipcon [15] is used for the radio interface. All the components of a sensor node are low-priced, facilitating the target cost of $100 per channel.

Utilization of the MSP430 series of microcontrollers and CC2420 RF chips allows for an extremely low power design of the sensor nodes. A single MSP430 consumes about 0.84mW at 1Mhz or 7.5mW at 8Mhz, which is superior to most other microcontrollers. In addition, MSP430 consumes only about 5μW in the low-power mode, enabling many years of battery life in standby. The CC2420 is a low-power, low-cost, IEEE 802.15.4 compliant transceiver designed for RF applications in the 2.4 GHz unlicensed ISM band. The transceiver module provides 16-channel direct sequence spread spectrum modem with 2 Mchips/s and 250 kbps effective raw data rate, low power consumption (RX: 60 mW, TX: 52 mW), effective range 10 to 75 meters, programmable output power, hardware MAC encryption and authentication (AES-128), signal strength indicator and battery monitor. The maximum total power consumption of a WISAN node with all devices fully on (75mW at 3V) is significantly lower than the power consumption of other sensor networks proposed for the task of structural health monitoring [11, 13].

Such low power consumption allows prolongation of the battery life and extension of the replacement cycle to several years, or better yet, utilization of the energy of ambient vibrations for powering of the sensor nodes. The peak power consumption of a WISAN node (75 mW), is very short in duration and lasts only for amount of time necessary to synchronize to a beacon and transmit the collected data. All other time the node spends in the low power mode, consuming about 0.1mW of power. For example, continuous acquisition of a 12-bit analog input at 50Hz will produce 2250 bytes of data over a period of 30 seconds. Assuming the worst possible power consumption and conservative acquisition time of 1ms, the acquisition process will consume 50Hz*30s*(1ms*7.5mW+19ms*5μW) = 0.0113925J of energy. Assuming 50% utilization of the wireless link (again, a very conservative estimate) the transmission of these data will last 2250bytes/(250kbps*0.5/8)≈0.14s. Therefore, the transmission will expend approximately 0.14s*(52mW+7.5mw) =8.3mJ of energy. Assuming that a sensor node spends approximately 100ms in the receive mode waiting for a 802.15.4 beacon, the total energy consumption will increase approximately by 0.1s*(60mW+7.5mW) =6.75mJ. Thus, the total energy spent by a WISAN node for a 30-second continuous acquisition of an analog signal at 50Hz sampling rate is 11.4mJ+8.3mJ+6.75mJ=26.45mJ. For comparison, the energy consumption for transmission of the same amount of data in the design presented by Lynch [13] would be 0.9J (vs. 8.3mJ of WISAN), a number two orders of magnitude higher. These numbers directly translate into the battery life of a sensor node and enable battery-free operation from energy-harvesting devices capable of producing as little as 1mW.

The low power consumption enables truly autonomous and continuous operation from an energy-harvesting device, like those described in [16]. In practical terms, a virtually maintenance-free SHM system could be created by utilization of electro-mechanical or piezo-electrical power generating devices for powering of the WISAN nodes.

Selection of the 802.15.4-compatible protocol for the physical and data link layers of the network protocol also resolves the issues with electromagnetic compatibility, reliability and security. The radio frequency (channel) allocation for

802.15.4 devices foresees the coexistence in the presence of other popular network protocols, such as 802.11 (WiFi). Functioning in the presence of electromagnetic interference is supported through utilization of channel sniffing. The communications between sensor nodes can be made secure through Advanced Encryption Standard (AES) encryption and authentication.

The signal strength meter located in the Chipcon RF interface module allows implementation of localization capabilities in the sensor nodes by performing cross-node measurements of signal strength. Such capabilities can be implemented following the procedure described in [17]. The node localization can potentially be used in routing algorithms to minimize the number of hops and evenly distribute the power consumption among the sensor nodes.

The real-time preemptive kernel schedules the execution of every task in the sensor nodes and supports high-precision global time synchronization and timestamping of the sensor data and actuator commands. For example, in order to reconstruct displacement mode shapes from the modal response of a structure, the precision of the mode shapes reconstruction will depend on the accuracy of time synchronization of the sampling events. The time signals for global time synchronization will be transmitted as a part of the 802.15.4 superframe and incorporated into the beacons. Combined with low latency of the real-time kernel, the precision of global time synchronization is expected to be on the order of microseconds.

The services provided by the real-time software of a sensor node implement the embedded intelligence and distribution of computational load. The minimization of bandwidth consumption is achieved through on-the-fly compression of the sensor data. Minimization of the response time is achieved through implementation of fuzzy logic and neural network capabilities that translate into simple ways to perform control tasks without transmitting the data over the network. Considering the low energy consumption by the network interface of WISAN, we do not think that application of fast, high-power computational devices for performing such operations as Fast Fourier Transform on the sensor nodes is justified energy-wise. For example, [13] estimates that computation of 4000 coefficients for an auto-regressive model on a Motorola MPC555 microcontroller consumes approximately 3J of energy. Transmission of the 16,000 bytes of the raw data for that computation without employing any compression scheme in WISAN would consume about 66.75mJ of energy (a conservative estimate). Therefore, that network transmission is potentially 44 times more cost-effective than on-sensor computations. The data will be transmitted to a dedicated node connected to a power source with lower price of energy, such as a power line or a solar cell. Such a dedicated node would provide a more cost-efficient solution to the computational requirements of the SHM system.

All of the above mentioned considerations also dictate the architecture of the sensor network. We propose to utilize a two-level cluster-tree architecture, providing better fault tolerance than a two-tiered architecture [11]. Fig. 2 illustrates the structure of a two-level cluster-tree network.

The sensor nodes in a cluster are usually powered from a moderately expensive power source, such as batteries or energy harvesting devices. To minimize energy consumption by a node and to minimize number of hops for a message, all sensor node prefer a single hop communications with a cluster head node. If, however, a single-hop path is not available, a multi-hop path can be taken. Various energy-saving routing algorithms can be applied to minimize and equally distribute energy consumption in the sensor nodes routing message from other nodes [18]. However, a single-hop message delivery is normally available to all nodes. The purpose of multi-hop capability is to provide fault-tolerance to the network in a case when a cluster head goes out of service, which could happen, for example, during an extreme event such as an earthquake. The communication in the two-tiered architecture presented by Kottapalli [11] will be completely disrupted if any of the “local site masters” (cluster heads) go out of service.

A cluster head controls the communication in the allocated cluster and has a less expensive and more powerful source of energy such as a power line or a solar cell. The properties of the power source limit the number of locations on the structure where a cluster head could be installed, but allow to accommodate a high-speed long-range communication link, such as 802.11a, operating at 54Mbps in the 5Ghz frequency range. The longer range of the high-speed connection can be achieved by application of directional antennas. A cluster head does not possess additional computational capabilities, but rather serves as a high speed router of the network messages. Previously we have shown that a acquisition of a continuous 12-bit data stream sampled at 50Hz will consume approximately 0.14s of the transmission time every 30 seconds. In practical terms, it means that a single cluster head can accommodate up to $N=30s/0.14s\approx200$

sensors in a cluster (with conservative estimates of 50% bandwidth utilization and no compression). Therefore, for many small-scale applications, the network will essentially consist of a single cluster.

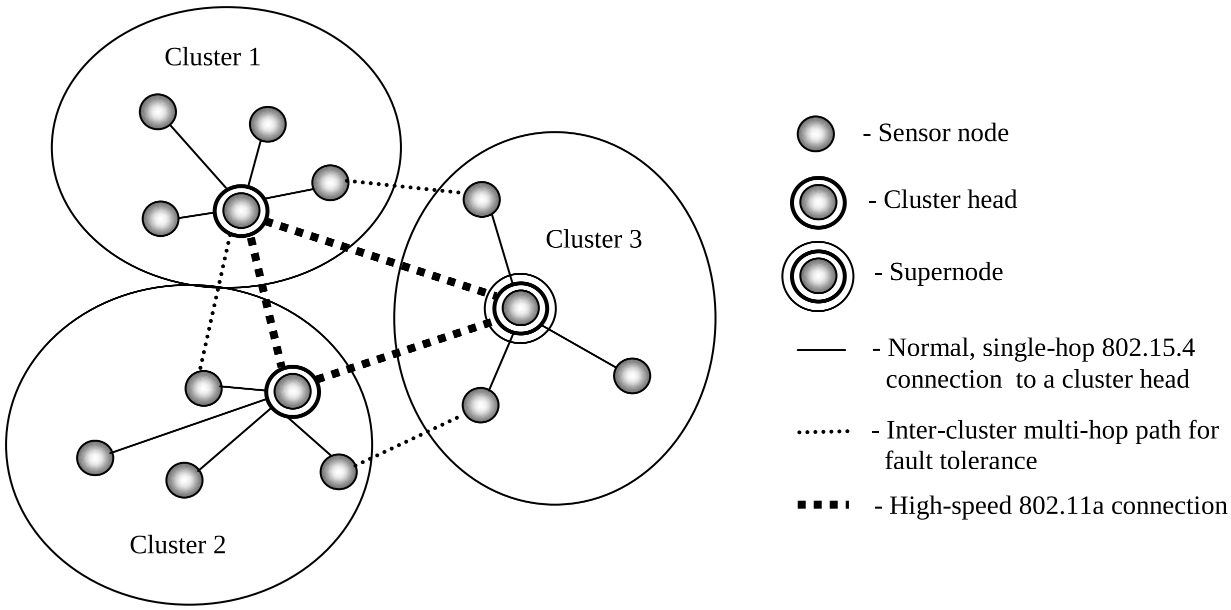


Fig. 2. Two-level cluster–tree architecture of WISAN.

Finally, a supernode combines the functionally of a cluster head with additional computational capabilities that can be used to implement the computational methodology of structural health monitoring. Again, for many small-scale applications the network will contain a single cluster head / supernode.

## 4. THE MONITORING METHODOLOGY

WISAN allows autonomous instrumentation of civil structures, but to be truly autonomous, such an SHM system should not require significant energy for excitation of the structure, but rather rely on ambient energy, and allow for human-free damage detection process. WISAN will be used to utilize the method of modal strain energy for structural health monitoring of bridges.

The features of the Modal Strain Energy (MSE) make it a perfect candidate for fully autonomous long-term structural health monitoring of bridges. These features include:

- **Damage detection based on the localized changes in mode shapes.** The MSE is a *local* method where a grid of sensors passively listens to the vibration of the structure. If natural frequencies are known, damage detection for a given location can be performed only using the data from the *three adjacent nodes*. In the method's formula $U_{ab} = \frac{1}{2}\int_a^b EI(\phi'')^2 dx$ the integration interval [*a*-*b*] usually (but not always) represents the sampling interval with which the nodes can be positioned on the structure. This interval defines the spatial resolution with which damage can be localized in the structure. If a mode shape has a node at the location of damage, there will be other mode shapes that can detect damage at that location.
- **Autonomous damage detection from ambient vibrations.** The modal data from a structure can be acquired using WISAN to acquire ambient vibrations caused by traffic, wind and microtremors of the ground [19]. Thus, the monitoring system does not have to excite the structure in any way, lowering the total energy expenditure of the system and allowing for truly autonomous operation.

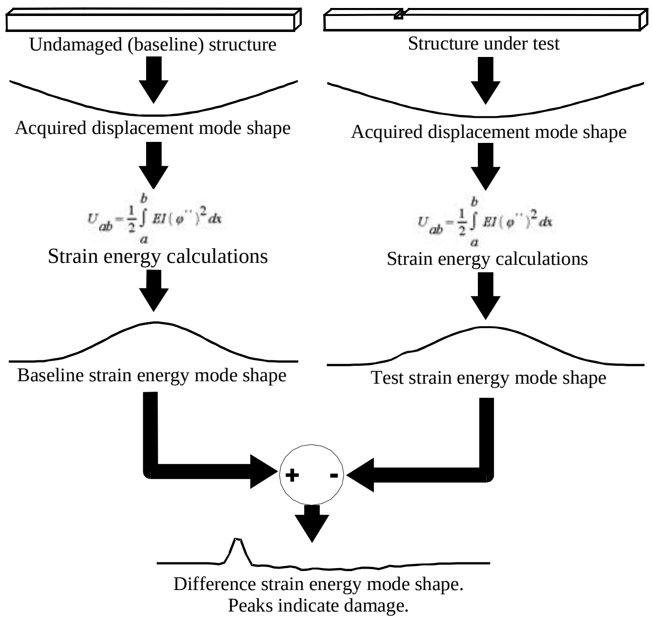


Fig. 3. Illustration of modal strain energy method.

- **High sensitivity to damage and availability of the theoretical background for sensitivity evaluation**. Farrar and Jauregui [20] listed the damage index method (a derivative of the modal strain energy) as the most sensitive method out of 5 tested on a highway bridge. Compared to other modal methods, the method of modal strain energy offers higher sensitivity to damage on the beams (Shi and Law [21], Cornwell et al. [22]). It has been used for damage detection on the plates (Yoo et al. [23]), and has been tested on the actual bridge structures (Wahab and Roeck [24], Yan and Deng [25]). The best sensitivity to damage can be established through the analysis of the measurement noise (Sazonov [26]).
- **Low sensitivity to environmental and operational variations.** Compared to other modal methods, the MSE method is less sensitive to environmental variations. Changes in natural frequencies due to temperature variation may be more pronounced than changes due to damage (Peeters et al., [27]), while changes in the mode shapes are less pronounced. In addition, such changes can be accounted for by having a different baseline (in a baseline-based method) for each temperature range of interest.
- **Ability to detect damage on structures without known response.** Damage index method [20] and frequency-decomposition MSE method (Sazonov [28]) allow detection of damage in structures with unknown damage state. For the MSE method, it can be show that the Fourier series of strain energy mode shapes of an undamaged pinned-pinned beam consists only of two members for any mode *k*: $U_k(x) = \frac{C_k \Delta}{2}(1 - \cos \omega_k x)$, while the Fourier series of a damaged beam contains significantly higher number of harmonics. Damage location in the beam can be established by removing the two harmonics related to the frequency spectrum of an undamaged beam and performing the inverse of the Fourier series. The same technique can be applied to other symmetrical boundary conditions and beams of more complex shape.
- **Model-free method.** The method of modal strain energy does not require an analytical or numeric model of the structure, thus lowering the cost of the monitoring system. As an example, model updating methods require an accurate (and expensive) numerical model of the structure under test. To locate damage in the structure, an inverse problem (changing the model, so that it matches the actual response of the structure) has to be solved. Such a solution may not be unique (Wang [29], Fritzen [30]). The method of modal strain energy can uniquely locate damage in a structure.
- **Automated damage detection algorithms.** Automated damage detection algorithms and software were developed during the design of automated damage detection system for Armored Vehicle Launched Bridge (Sazonov [31]). A well-developed theoretical base implemented in practical software solutions paves the way for a fully automated system of structural health monitoring for bridges.

A simplified scenario of structural health monitoring using the modal strain energy method and involving a baseline is illustrated in Fig. 2. Structural damage is detected by identifying changes in the strain energy mode shapes caused by the changes in stiffness at the damage location. The modal response of the structure under test is used to reconstruct the displacement mode shapes. The strain energy formula is used to calculate the test strain energy mode shapes. The test strain energy mode shapes are compared to the baseline, representing the original state of the structure. Any damage to the structure will create damage indicators on strain energy difference mode shapes.

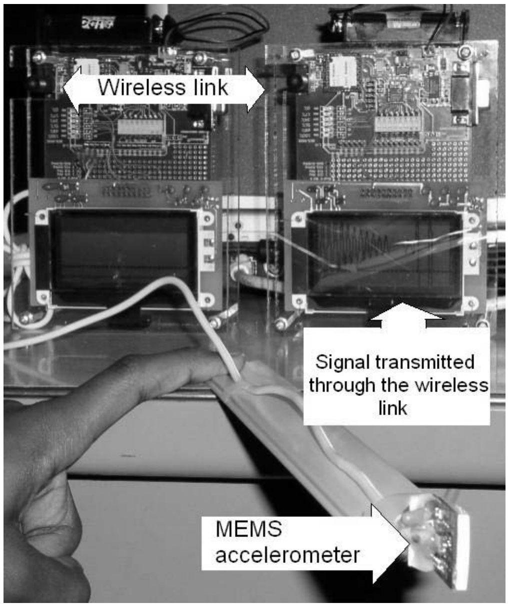


Fig. 4. A prototype of the WISAN nodes.

## 5. IMPLEMENTATION

The Wireless Intelligent Sensor and Actuator Network is currently being developed under a grant from New York State Energy Research and Development Authority (NYSERDA). Fig. 4 shows a functional prototype of the WISAN modules used to test concepts discussed in this paper. Currently we are working on the second generation design, incorporating changes on all layers of the network protocol.

## 6. CONCLUSIONS

The presented concept of a sensor network for fully autonomous structural health monitoring addresses the synergetic issues of integrating a sensor network with a vibration-based SHM method. We have identified some of the critical questions that must be answered before such a system can be practically implemented and suggested a possible solution in the form of WISAN and method of modal strain energy.

The proposed solution resolves the raised issues in a simple and efficient manner:

- The WISAN provides an ultra-low-power instrumentation for inexpensive and continuous health monitoring of structures. Due to low costs of the principle components in a sensor node, we expect to succeed in achieving a low cost of $100 per data channel / sensor or less.
- The very low power consumption of the network nodes allows extending of the battery life or eliminating the batteries from the design altogether by replacing them with an energy harvesting device. Such a solution minimizes the long-term energy costs for the sensor nodes.
- The 802.15.4-compliant physical layer permits coexistence with other devices functioning in the Industrial, Scientific and Medical (ISM) range of radio frequencies and provides a secure way of communication. The two-level cluster-tree architecture enables the network to tolerate multiple faults in the cluster heads and sensor nodes.
- The intelligent capabilities of the sensor nodes minimize energy consumption of the sensor network as whole by performing energy-efficient operations such as data compression, while delegating power-intensive computations to the supernode. The latency of the system is decreased by embedding computational intelligence such as fuzzy logic and neural networks into the sensor nodes.
- The physical (RF) interface of the network supports simple and energy-efficient self-localization of the sensor nodes in the network and establishing sensors' position on the structure.
- The network protocol and real-time operating kernel of the sensor nodes allow for high-precision global time synchronization in WISAN.
- The vibration-based monitoring method utilizes ambient energy of vibrations and does not require energy for excitation of the structure.
- The suggested method of damage detection, among other useful traits, supports fully automatic damage detection and localization, allowing for implementation of a fully autonomous SHM system.

## ACKNOWLEDGEMENTS

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