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INTEGRATED SMART WIRELESS SENSORS FOR BRIDGE STRUCTURAL HEALTH AND HOMELAND SECURITY MONITORING

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Abstract

Homeland security requires thorough monitoring of the nation's transportation infrastructure health. Discussed in this paper is research aimed at developing a smart wireless sensor network that is an efficient and practical health monitoring system and is also versatile for security monitoring strategies. At the core of such a system is an integrated network which collects data from a variety of sensors and provides real-time analysis, long-term assessment and decision-making tools. Framework for such a system can be flexible and scalable to include not only one particular bridge but also an entire highway transportation system. The implementation of a wireless sensor system for performance monitoring of a bridge is presented. Used in this deployment is an advanced wireless sensor system, developed at Clarkson University, which allows for Structural Health Monitoring (SHM) of bridge structures. A short-span integral-abutment bridge located in New York State is instrumented with a wireless sensor system measuring acceleration, strain and temperature to monitor the behavior of the structure under various loading conditions.

INTRODUCTION

There is an increasing interest in wireless sensors and sensor networks as replacements for tethered monitoring systems traditionally used for structural monitoring of transportation infrastructure. A key benefit of wireless structural monitoring systems is that installation costs are significantly lower when compared to cable-based systems which allows for the deployment of denser sensor networks. Furthermore, wireless sensor networks provide the opportunity for each sensor node to have multiple types of sensors with independent and local data acquisition and processing capabilities. This allows the wireless sensors greater flexibility in processing structural response data. These features are all very attractive for homeland security monitoring applications particularly because the framework for such a system can inherently be flexible and scalable to include one bridge or an entire highway system.

A new generation of low-power wireless chip transceivers has enabled new possibilities for widespread instrumentation of large distributed civil infrastructure systems for which large-scale testing has been limited to

unique cases due to the economic burden associated with cable-based hardware. However, while the number of unique wireless sensor platforms and proposed applications has continued to rapidly expand, there has been limited success in replicating previous cable-based test programs in regards to the number of deployed sensors and data rates. The system described in this paper has achieved higher sampling rates while maintaining reliable communication within a large, dense array of sensors. The degree of success in replicating the system performance of previous bridge monitoring studies utilizing traditional cable-based instrumentation signals the feasibility of wireless sensing for structural and homeland monitoring of civil infrastructure.

WIRELESS SENSOR SYSTEM

The wireless bridge monitoring system developed within the Laboratory for Intelligent Infrastructure and Transportation Technologies (LIITT) at Clarkson University was designed with consideration of the measurement requirements for assessing the static and dynamic behavior of highway bridges using strain transducers and accelerometers (Fig. 1). However, the flexibility of the hardware and software design yields a more universal platform which could be utilized to address the instrumentation requirements of a variety of geo-structural monitoring tasks.

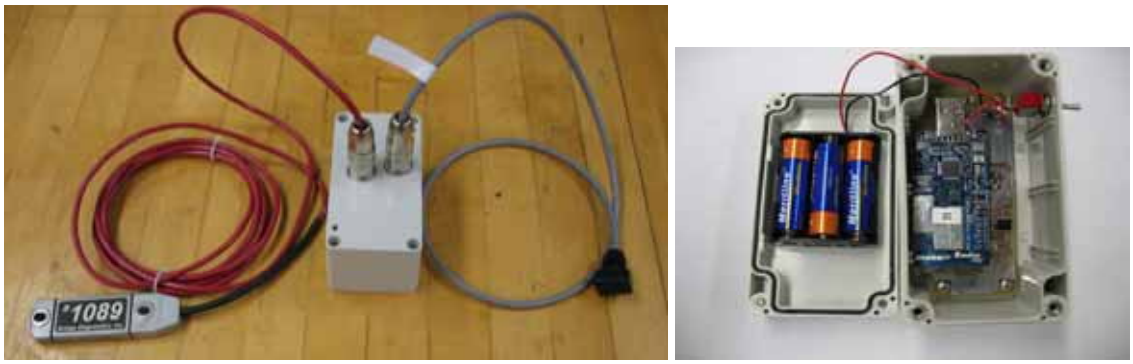

Figure 1. Wireless Sensor Node with Strain Transducer and Dual-Axis Accelerometer

The developed wireless sensor node incorporates a commercial wireless transceiver platform with a signal conditioning circuit capable of interfacing with a variety of external sensors. The Tmote Sky wireless platform developed by researchers at the University of California at Berkeley and marketed by the MoteIV Corporation was selected as the integrated microcontroller and transceiver device for establishing wireless communication of the sensor data. While this is one of many wireless sensing platforms, commonly referred to as motes, it was selected consequent to several advantageous features. The transceiver utilized functions in the 2.4GHz frequency band with a maximum effective data rate of 250kbps and offers spread spectrum modulation for enhanced performance in this band of increasingly widespread use. The microcontroller is an 8MHz, ultra-low power model with an eight channel 12-bit analog-to-digital converter (ADC), two channel 12-bit digital-to-analog converter (DAC), a direct memory access (DMA) controller and two universal serial buses for communication with a variety of digital devices. The Tmote Sky motes are also compliant with U.S. and Canadian radio frequency regulations and are certified by the FCC and Industry Canada for use in either county.

Single-Ended Sensor Input Conditioning

To facilitate high-resolution acquisition of distributed acceleration measurements for modal analysis, a custom signal conditioning circuit was developed to interface MEMS accelerometers with the mote transceiver board. This section provides analog low-pass filtering, digital offset correction, and digitally programmable gain for up to two analog accelerometer signals. However, since the actual sensor is an external device, the accelerometers can be disconnected to permit acquisition from a wide range of single-ended voltage output sensors, such as inclinometers, potentiometer-based displacement sensors, and temperature sensors (Fig. 2).

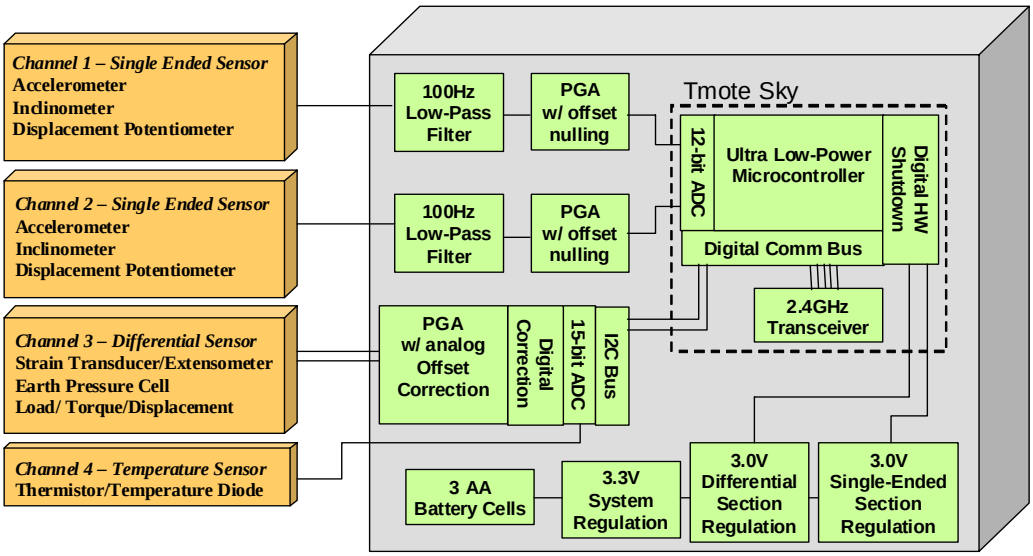

Figure 2. Block diagram of wireless sensor node

A 3V voltage reference is used to provide ultra-low noise, stable power supply to the filter sections and external sensors. The analog filters have a 100Hz frequency cut-off with a Butterworth response and are provided to prevent signal aliasing. Each filter is a 5-pole Sallen-Key design featuring dual second-order sections on the conditioning board and a real-pole section provided within the external accelerometer. Placement of the real-pole filter with a buffer amplifier enables greater noise-immunity through low-impedance output at the signal source and permits the use of other MEMS accelerometers, which generally have different resistance on the signal output, as well as other sensors.

Low-noise, low-power programmable gain amplifiers (PGA) provide amplification of the signal to maximize the resolution of the conversion specific to the sensor and the on-site excitation. In-network wireless commands enable adjustment of the gain from zero up to 4096V/V in binary multiples. Independent digital offset nulling for each channel is provided with accuracy of 1mV by low-noise programmable voltage references. This adjusts the sensor input range such that it is balanced in both the positive and negative directions and permits the use of high gain amplification without driving the signal out of range. A 1.25V reference is provided to bias the amplifier output to the mid-span of the ADC conversion range, which is set with a 2.5V external voltage reference. Hardware shutdown of the PGA and voltage reference supply to the sensor and filter sections conserves limited battery resources during periods of inactivity.

Differential Sensor Input Conditioning

The core of this circuit is the ZMD31050 application specific integrated circuit (ASIC) designed specifically for the conditioning and acquisition of full-bridge sensor measurements. However, the flexible digital configurability of the signal conditioning permits the acquisition of data from various differential sensors, such as load and torque cells, earth pressure cells, and linear displacement and angular rotation transducers. The signal conditioning chip features 13 stages of programmable gain up to 420V/V, digitally programmable analog offset nulling, and a 15-bit internal ADC with adjustable input ranges to maximize the resolution of the signal over the ADC range. In addition, signal inputs are provided for either temperature diode or thermistor-based temperature measurement. An internal microcontroller introduces a digital conditioning algorithm for linearization of the sensor signal as well as providing up to 2^{nd}-order polynomial temperature compensation using the external sensor. Temperature compensation is a critical correction for long duration strain measurements using strain transducers, as the temperature-induced expansion of bridge elements often differs with temperature-induced transducer expansion, thereby resulting in a strain output in the absence of applied deck load. This signal conditioning ASIC communicates digitally with the mote's microcontroller through the use of the 2-wire serial (I2C) interface. A voltage regulator is used to provide a low-noise, regulated supply to the external transducer and signal conditioning chip as well as to enable digitally controlled hardware shutdown for power conservation during periods of inactivity.

Software

Embedded software applications were written for both the remote and base wireless transceivers under the TinyOS-1.x open source operating system. While the TinyOS framework and the accompanying assembler code were utilized for programming the motes, the software modules and interfaces were generally found to be incompatible with the requirements of the monitoring task and therefore seldom used. Extensive development of low-level software enabled much higher data throughput, a greater number of nodes per network while maintaining reliable transmission, and other advanced features, such as digital filtering with the hardware multiplier. The embedded software was designed to balance efficiency and throughput with flexibility, so that the same code could be utilized for an array of monitoring tasks and sensor network configurations.

A highly developed LabVIEW host application has been written to operate in conjunction with the remote transceivers to control and coordinate the wireless network. The LabVIEW software establishes bi-directional communication with a base mote through a USB connection operating us if it were a serial port operating at 262,144 baud. A user-friendly interface permits programming of sampling rate, duration of sampling, sampling initiation, component power supply status, and configuration of individual signal conditioning circuits. Sensor nodes can be individually programmed to sample in several configurations: two channels of single-ended sensor data, each single-ended sensor channel and the differential sensor channel, or simply the differential sensor channel. This permits the multi-functional nodes to perform only the tasks specific to the current monitoring program and sensor layout. Programmable gain for the single-ended sensor channels is selected on a per channel basis, while the embedded software handles automatic adjustment of the sensor offset to the mid-span of the signal range. This enables rapid sensor configuration with minimal operator commands and discretion. An extensive digital filter design sub-section of the host software allows the operator to design a custom filter, the coefficients of which can be transmitted to the nodes wirelessly over the network. In addition, network status can be queried through a single command that reports the status of the component power supplies, regulated mote supply voltage, and received signal strength. Upon initiation of sensor sampling, the host software receives incoming data packets, displays the measurements in real-time on a series of waveform charts, and logs the readings to individual spreadsheet files for post-processing.

FIELD DEPLOYMENT

A large-scale network consisting of 40 channels of sensor measurements acquired through 20 remote wireless transceiver nodes was deployed on an integral abutment, single-span bridge in St. Lawrence County, NY (Fig. 3). The bridge is a 17.07 m (56ft) span reinforced concrete deck on four steel girders spaced 2.74 m (9 ft) center-to-center. Both quasi-static, similar to load-rating protocol, and dynamic monitoring of the bridge was conducted using a total of 29 accelerometers and 11 BDI strain transducers. Only ambient loading from vehicular traffic was provided for structural excitation. Each channel of sensor data was over-sampled at 512Hz, passed through a 55-tap digital low-pass filter, and decimated to an effective sampling rate of 128Hz for real-time transmission to the host computer. This network configuration and sampling rate resulted in a transmission overhead in the range of 97kbps to 126kbps depending on the initial packet success and retransmission rates.

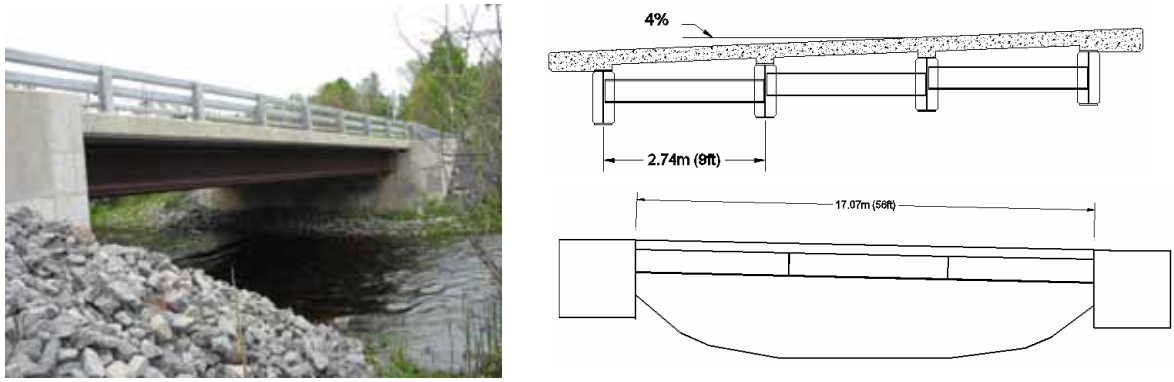

Figure 3. Wright Road Bridge over Trout Brook, Potsdam, NY

Sensors

Accelerometers were utilized to investigate the dynamic response and modal properties of the in-service bridge structure. The LIS2L02AL capacitance-based MEMS accelerometer manufactured by ST Microelectronics was been selected for its low-power consumption, ultra-low noise floor, and low-cost. This dual-axis accelerometer has a $30\,\mu g/\sqrt{Hz}$ noise density with a white-noise distribution, permitting resolution below $240\mu g$ for a 64Hz input bandwidth. These accelerometers were mounted on custom printed circuit boards containing the real-pole section of the analog filter along with a buffer amplifier to reduce the signal impedance for greater noise immunity. The boards are encased in potting epoxy within a small external housing to maintain the high resonant frequency of the sensor and enable direct placement of the sensor on the structure for superior vibration transfer. A short length of cable terminated with a water-tight industrial connector links the sensor to the wireless sensor conditioner and transceiver unit.

For field testing and system validation, reusable strain transducers marketed by Bridge Diagnostics Incorporated (BDI) were selected, as these have been widely utilized for bridge load ratings nationwide. These sensors have a gauge length of 76.2mm (3in) and are housed within a sealed stainless steel case. Sensors are applied to bridge elements using threaded mounting tabs that are adhered to surfaces with high-grade epoxy. The factory length of cable was terminated with a water-tight industrial connector for linking to the wireless sensor node.

An instrumentation layout was developed for concurrent determination of the static response of the bridge members, including end fixity, girder distribution factors, and neutral axis locations, as well as mode shapes with relatively high spatial resolution (Fig. 4). All sensors were temporarily affixed to the structure using quick-setting adhesives. Strain transducers were oriented in the longitudinal direction and accelerometers were oriented in the vertical direction. The complete instrumentation setup, testing, and site disassembly was performed over the course of merely five hours with a crew of only four researchers. Furthermore, this duration would be significantly reduced at a site with easier access to the girders or through the use of a snooper truck.

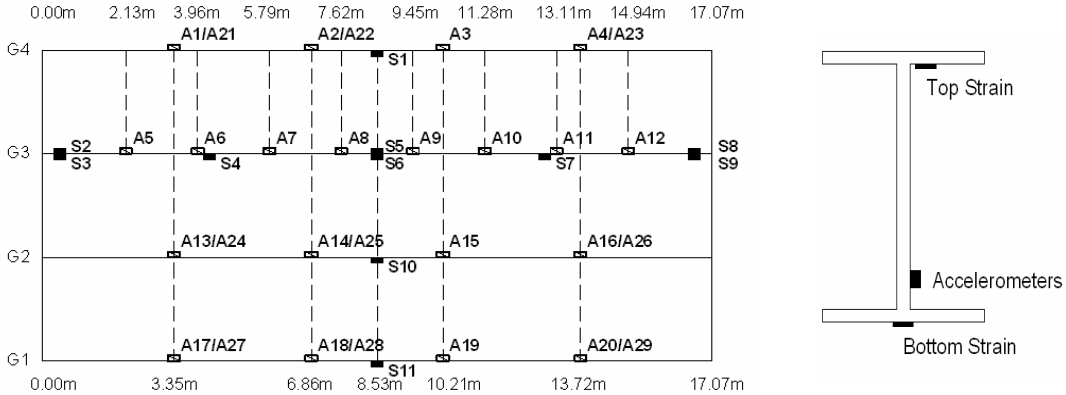

Figure 4. Instrumentation layout across bridge girders

Measurements and System Performance

The integral abutment bridge design was beneficial for investigation of the sensor performance on a full-size structure, as the relatively high stiffness created a demanding measurement scenario. Peak accelerations from vehicle loading ranged from less than 2mg to only nearly 10mg. However, the sensors, which were amplified either by 64V/V or 128V/V depending on location from the abutments, provided clear representations of the time-history data and distinct peaks within the frequency spectra, even with only ambient loading (Fig. 5 & 6). Investigations of the distributed acceleration measurements during traffic events where the vibrations are distinct confirm that the wireless sensors maintain phase amongst themselves, thereby substantiating the assumption of the using an accurate crystal oscillator for time synchronization. Given the exceptional system response with such low excitation levels on a relatively stiff structure, even enhanced performance on longer-span structures with lower natural frequencies can be inferred.

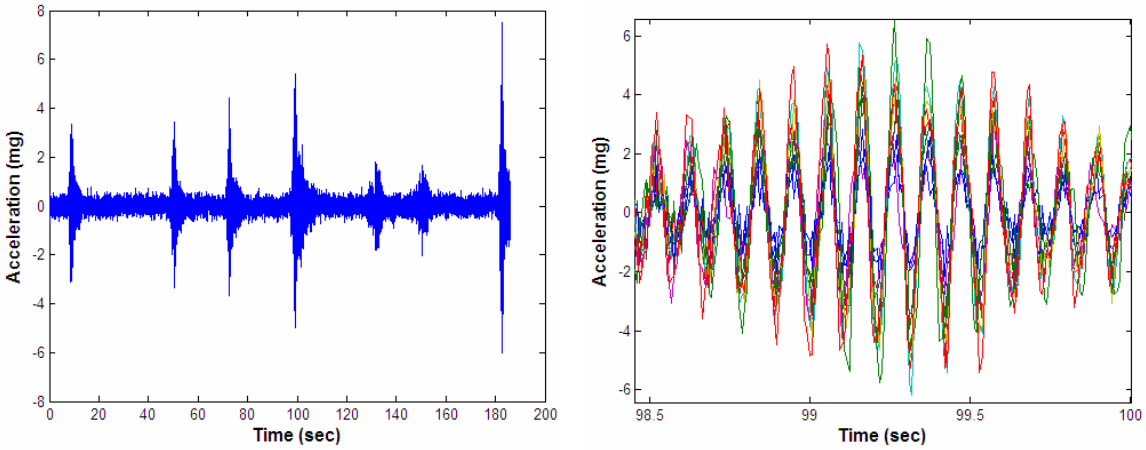

Figure 5. a) Typical acceleration time history toward midspan, and
b) overlay of accelerations during a traffic event

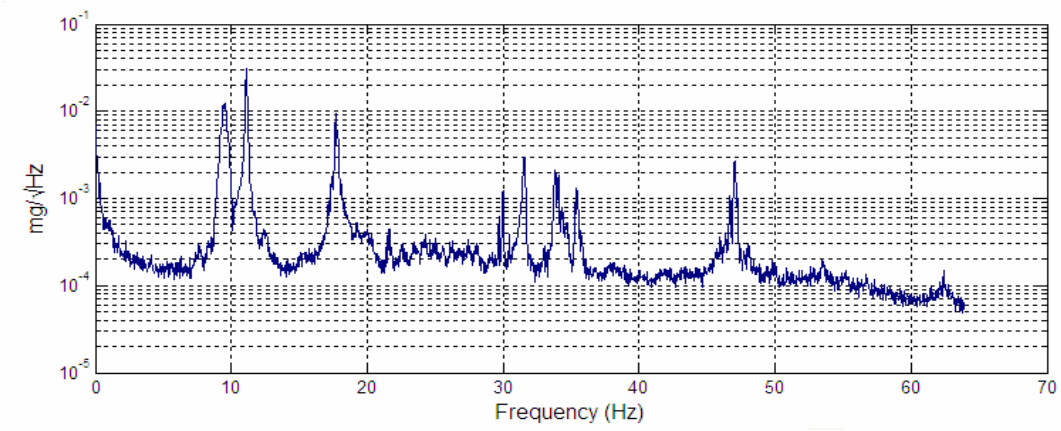

Figure 6. Average normalized power spectrum for vertical acceleration

Strain measurements also verified high-quality performance, despite significantly lower applied loads than typically imposed during a scheduled load rating. The development of bending strain in the girders during a crawl-speed pass of a large sports utility vehicle was well captured at most locations (Fig. 7). The localized tension spike recorded at the top of the girder occurs when the vehicle wheel is directly overhead the sensor. However applied loading was not sufficient to induce significant enough strains to deem the near-abutment measurements valid within the manufacturer specifications. During a typical load rating, much larger vehicles with additional loads would be utilized and such an issue would not occur. Strain profiles were found to be consistent with vehicle loading patterns, composite action of the deck and girders was verified, and calculated neutral axes locations correlated well with theoretical calculations.

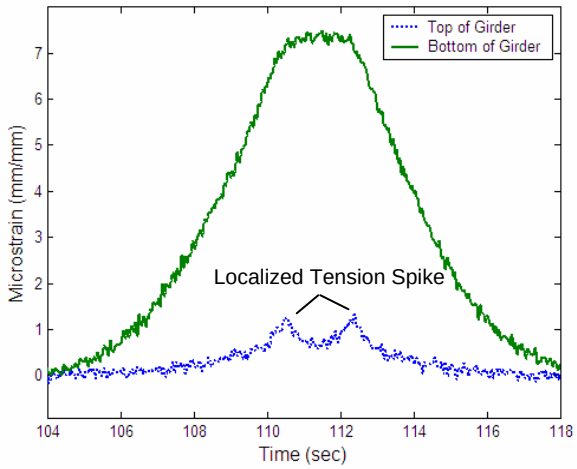

Figure 7. Strain response at midspan of girder during light vehicle pass

The average packet success rate across all of the sensor nodes over ten 3 minute test cycles was 99.91%, with 92% of the nodes reporting 100% packet delivery success. The minimum packet success rate over these tests was 98.0%. The small loss of data is attributed to a software bug in the portion of the code responsible for transmitting any packets in the transmission queue after sampling was completed. It is anticipated that correction of the software section responsible for transmitting packets remaining in the queue will result in complete data sets; however at the current level of packet success over the sampling time, the quasi-static and dynamic modal analysis suffered from no noticeable or adverse distortion. This degree of transmission reliability at the high data throughput rate attained in this testing reveals that wireless sensor networks are currently capable of performing large-scale structural health monitoring tasks with real-time transmission.

Analysis of Field Data

System identification through both classical peak-picking as well as stochastic subspace identification (SSI) methods was used to analyze the vibration data using the commercial software package, Modal Analysis of Civil Engineering Constructions (MACEC) (Van den Branden, 1999). In addition, a finite element model of the Wright Road Bridge was developed for mode shape and natural frequency comparison with the experimental results. The model consists of the steel structure of the bridge, the concrete deck, and the abutments and was drafted from the as built Department of Highways drawings. The experimental mode shapes (Fig. 8) and natural frequencies were found to correlate well with the finite element analysis provided through the ALGOR software package.

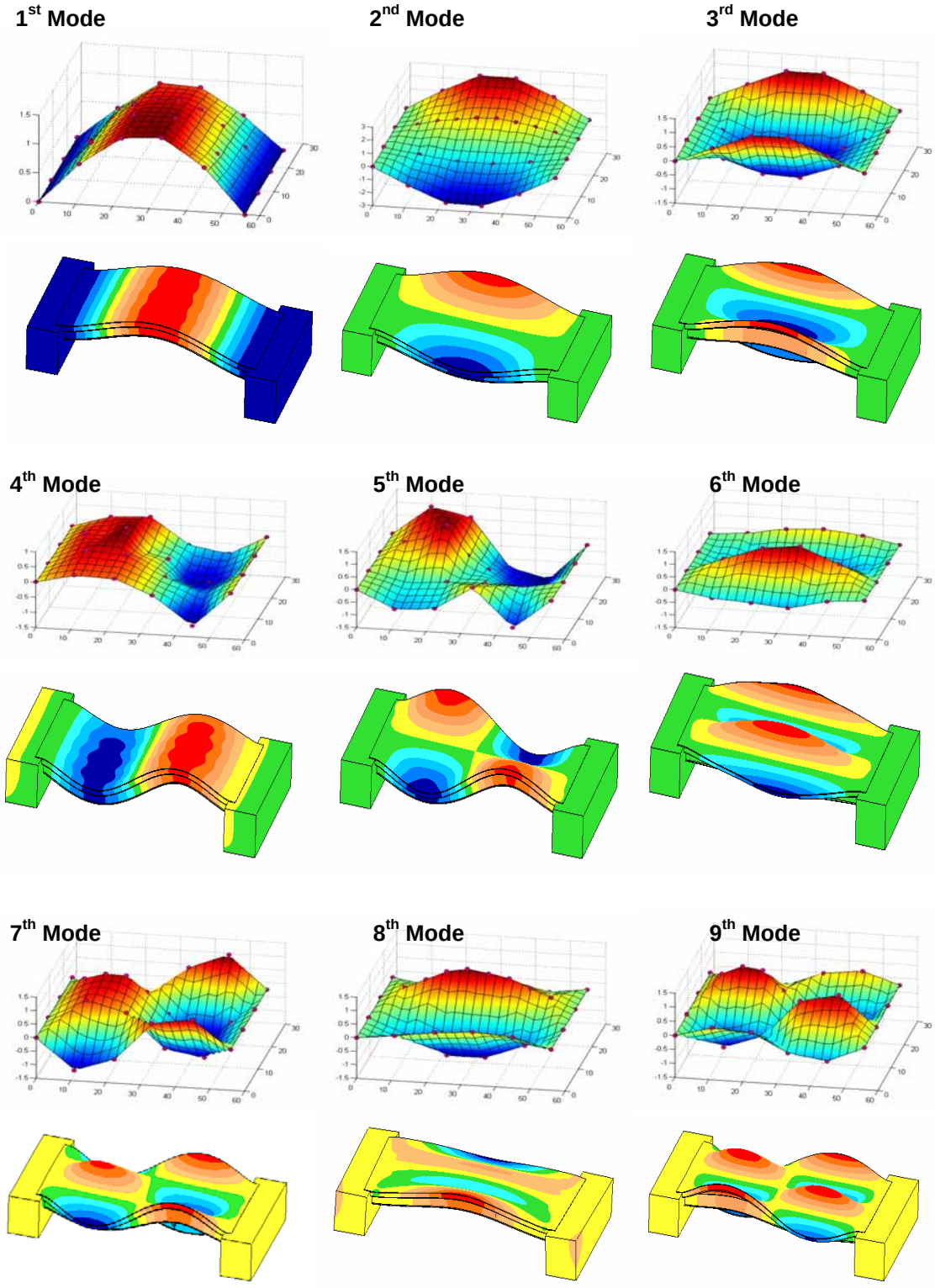

Figure 8. Experimental mode shapes generated through system identification compared with numerically determined mode shapes from finite element analysis

CONCLUSIONS

A multi-functional wireless bridge monitoring system has been developed for concurrent deployment of a wide variety of sensors typical instrumentation of civil infrastructure. These nodes provide an economic, low-maintenance solution for both small and large scale investigations with flexible signal conditioning enabling application to a number of tasks including structural health management and homeland security monitoring. Furthermore, extensive laboratory and field testing and development has been performed to produce a reliable radio transmission protocol capable of sustaining a large number of nodes with high data throughput in real-time. Field deployments using MEMS accelerometers and strain transducers have verified the performance of the wireless acquisition system. The deployments demonstrated the ability of the system to capture natural frequencies, construct clear modes shapes, and measure small amplitude strain responses.

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