DuraNode: wireless-networked sensing system for structural safety monitoring

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ABSTRACT

DuraNode is a sensing system designed for structural monitoring. It can detect the damage of structural members, provide crucial intelligence information of structural integrity and activate emergency response mechanism in the initial stages of a disaster. The sensor encompasses three *MEMS*-type accelerometers (SD-1221) and Wi-Fi (802.11b) communication adapter. It operates on solar power and rechargeable battery making it last for long term service without battery replacement. DuraNodes can be deployed in the form of a dense wireless network to enable seamless acquisition of structural intelligence in a complex structural system. A preliminary data acquisition and signal display module with graphic user interface (GUI) has been developed for connection of access points in ad-hoc networking. To validate the performance of DuraNode in structural monitoring applications, experiments were conducted on measuring vibration of a Pedestrian bridge in UC, Irvine, and a two-column bridge bent specimen with a Shake-table test in University of Neveda, Reno. Results were compared with that from conventional wired sensors and showed that DuraNode is cost-effective for carrying out robust sensing functions in the structural safety monitoring missions.

1. INTRODUCTION

The objective of this study is to develop a sensing system with visualization tools for monitoring the nation's important infrastructures and essential building structures. Fundamental studies indicate that the structural health monitoring technology can be used effectively to reduce the extent of natural or man-made disasters[2,5]. This research focuses on the application of emerging *micro-electro-mechanical-system* (*MEMS*) and wireless technology for the use of structural health monitoring and evaluation of structural integrity and safety. This paper specifically reports on the progress in the development of the sensing system and its preliminary validations on the basis of bridge structural monitoring experiments.

Current structural safety monitoring techniques rely on visual inspection by the field engineers, and using cabled sensors in order to perform more detailed analysis. Although traditional sensing systems have proved useful in the sense that engineers can gather data, they have significant drawbacks. The major drawback is that sensor devices need cables to be connected to the central data acquisition unit. In worst case, this cable lies on one end of the structure to the other. These cables can easily extend to thousands of meters in length, in order to gather safety data of complex structural systems such as long bridges and skyscrapers in response to dynamic load. Each bridge monitoring exercise is costly and time-consuming, making it a very inefficient process. In other cases, cables are pre-buried deep inside the structure of the bridge to minimize future testing costs. This may reduce the costs each time the bridge is tested; however, burying the intricate pattern of cables inside the structure becomes an additional task to the contractors and design engineers. Thus, it is debatable whether the cost is significantly reduced. Once the buried cables become damaged by forces or degraded due to the chemical reactions with the concrete material, it becomes extremely difficult to replace them.

A number of wireless nodes have been built by other research institutes and some private sectors[4,5,6]. However, they can hardly be used for structural safety monitoring, because of low data rate, short transmission distance, and short

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Nondestructive Detection and Measurement for Homeland Security III, edited by
A. A. Diaz, A. E. Aktan, H. F. Wu, S. R. Doctor, Y. Bar-Cohen, Proceedings of SPIE
Vol. 5769 (SPIE, Bellingham, WA, 2005) · 0277-786X/05/$15 · doi: 10.1117/12.601534

operating lifetime. As the name suggests, DuraNode is designed to be long lasting: it should operate for months, if not years, without any maintenance. With a limited battery capacity, to achieve long operation lifetime, DuraNode should have the ability to harvest energy from the environment using a solar panel and a wind generator.

DuraNode has a set of unique features. In addition to supporting standard dynamic voltage/frequency scaling and subsystem shutdown, DuraNode uses a novel multi-regulator topology: it maximizes the energy efficiency of the regulators by matching the dynamic range of the corresponding power consumers, while at the same it provides digital/analog separation for noise reduction. The firmware architecture by default supports deterministic, time-triggered operation and communication; it also includes hardware support for event-triggered operation as an alternative paradigm. The combination of these features makes DuraNode not only durable for extended operations, but more importantly the use of tried-and-true, industrial-strength WLAN interface is expected to keep DuraNode transmit data reliably even in a noisy environment.

2. REQUIREMENTS SPECIFICATION

The requirements specification of the DuraNode is provided by civil engineers who process the sampled data for structural analysis. Their specification is then translated into system design parameters, and they include timing, energy constraints, and wireless interface

2.1 Functional Specification

Each DuraNode should contain three accelerometers for sensing vibrations in the *x, y,* and *z* axes. *MEMS*-type sensors are preferred, because they have smaller form factor and consumes less power than other types of sensors[1,9]. The vibration along each axis should be sampled at 10-bit or higher resolution and be tagged with a time stamp or a sequence number. Each node should transmit the sampled data over a wireless link to the central data acquisition unit in the laboratory. It should also be possible for a researcher in the laboratory to query the status of each node, upload new configurations, and perform calibration remotely. To enable *real-time* monitoring, DuraNode should support a *time-triggered* operation mode as well as an *event-triggered* mode in which data is transmitted only when it exceeds a certain threshold.

2.2 Timing

Timing specification includes the sampling rate, data latency, and sampling jitter. The normal sampling rate is 200 Hz, but it should be configurable up to 1 KHz. The data latency refers to the delay between the time when the sample is taken and the time when it is ready to be processed back in the laboratory. The normal latency is less than 30 seconds. The sampling jitter means the time variation in sampling periods. To accurately convert data from time domain to frequency domain, minimizing the sampling jitter is a must. The sampling jitter should be less than 100 microseconds at 1 KHz sampling rate.

2.3 Energy Constraints

DuraNode must be able to sustain at least one year without any maintenance such as replacing the battery. At the same time, because of the time-triggered requirement, it does not have the luxury of sleeping most of the time. Therefore, DuraNode should have the ability to harvest energy from the environment using a solar panel or a wind power generator. However, these ambient sources of power are not always available. The battery's capacity should be large enough to supply power to a DuraNode for a week.

2.4 Wireless Interface

The data rate, distance between nodes, and the air bandwidth constrain the choice of a wireless interface. The payload is 6bytes×200sps=1200bytes/s=9.6Kbps (vibration data of three axes + a time stamp). For point-to-point communication, this is well within the range of serial port speeds, even with header overhead. However, the air bandwidth is shared among nodes, and thus it is desirable to keep the utilization low to allow retransmission and communication scheduling.

The range distance is 5–200 meters. Together, these requirements rule out those low power radios such as the ISM-band radio used in the MICA2 and other low power sensors: they have an advertised range of 50 meters, even though in practice it may be much shorter. Furthermore, the effective data rate is about 7 Kbps according to our actual measurements. This leaves the choice of *BlueTooth* and 802.11b as the current viable commercial options. The 802.11b WLAN is currently the most widely available interface, due to its higher data rate and lower energy per bit than *BlueTooth*, and the availability of drivers.

3. HARDWARE DESIGN

Fig. 1 shows the top-level block diagram of DuraNode. DuraNode consists of five subsystems: Microcontollers, Sensor circuitry, 802.11b WLAN, Power circuitry and External sensor interface. Figures 2 and 3 show the photos of the DuraNode. The dimension is 137mm (W) x 87mm (D) x 17mm (H). All components are located on the top layer of the PCB and the 802.11b WLAN card is on the bottom layer. This section describes the design details of DuraNode.

3.1. Microcontrollers

DuraNode has two low-power microcontrollers. This unique architecture enables DuraNode to sample data at a precise, constant rate and increases the network performance. The one microcontroller is dedicated to sampling the output of the accelerometers at a constant rate. The other microcontroller controls an 802.11b WLAN card and handles communication-related tasks such as forwarding incoming data packets to the next hop as well as sending out local data samples. These two microcontrollers communicate with each other using *Serial Peripheral Interface (SPI)*. In designs with only one microcontroller, it must do sampling and networking tasks simultaneously. In that case, it must use a higher performance microcontroller, which not only consumes more power but also costs more.

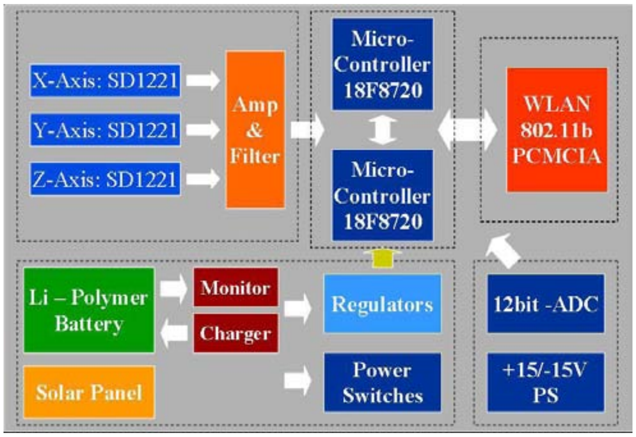


Fig. 1 Top-level block diagram of DuraNode

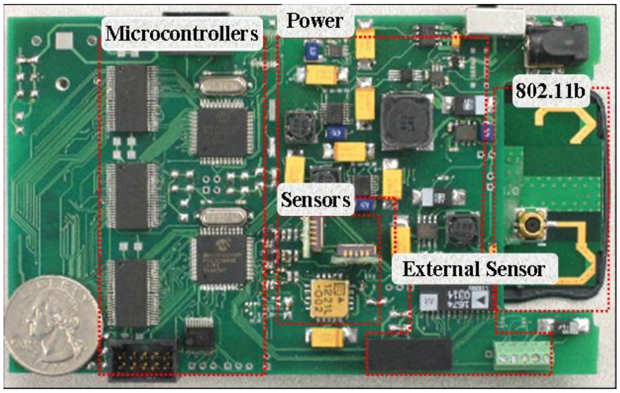


Fig. 2 Top view of DuraNode with a quarter coin

Fig. 3 Bottom view of DuraNode

The microcontroller is the PIC18F8720. It has 64 Kbytes of flash program memory, 3328 bytes of on-chip SRAM, an EEPROM of 1 Kbytes and 8 channels of 10-bit ADCs. It consumes 15mA at 4.2 V and 25 MHz.

3.2 Sensor Circuitry

As shown in Fig. 4 (a), the sensor circuitry consists of *MEMS*-type sensors and signal conditioning circuitry. Three MEMS-type SD-1221 accelerometers are installed for sensing vibrations in the *x*, *y*, and *z* axes. SD-1221's measurement range is from -2g to 2g and its frequency response is from DC to 400Hz. This sensor produces two analog output voltages whose range is from 0.5 V to 4.5 V. A low-noise operational amplifier (LMV751M5) takes these two voltages and outputs the difference. We can also calibrate the output signal's span and offset by a potentiometer.

3.3 801.11b WLAN

DuraNode use 802.11b WLAN as a wireless communication channel. Its bandwidth and coverage is up to 11Mbps and 100 meters (outdoor, 1Mbps), respectively[8]. It consumes about 1W maximum.

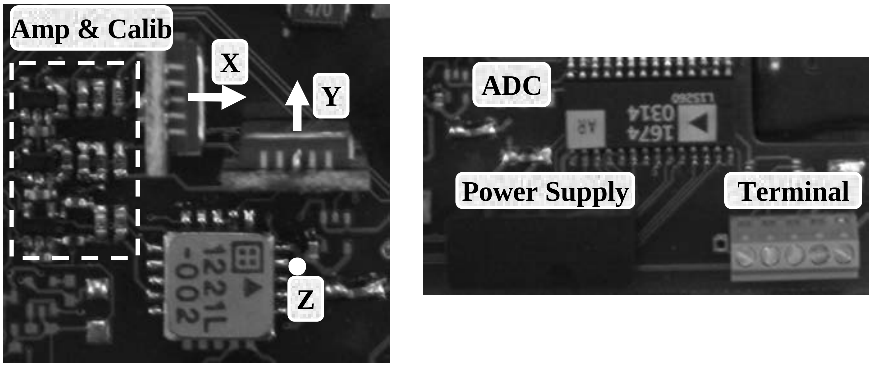
3.4 Power Circuitry

The purposes of the power circuitry are to manage three sources of power, the solar, wind and rechargeable battery, provide battery charging and monitoring, and supply the power to microcontrollers, sensors, and 802.11b WLAN card. The solar and wind power goes through the step-down switching regulator, whose output is split between the battery charger and the power switch. The power switch will choose between solar, wind, and 4000mAh Li-Polymer battery depending on their availability.

The output of the power switch is distributed over four high-efficiency switching regulators. Each switching regulator supplies power to two microcontrollers, sensor circuitry and the 802.11b WLAN card. We use separate regulators for several reasons. First, it allows us to do power management for these different subsystems separately, including complete shutdown of each subsystem. Second, keeping the power supply separate between the digital and sensing subsystems will minimize noise in the data. Third, because each subsystem consumes power at a level quite different from each other, it is much more power-efficient to use a different regulator with the highest conversion efficiency at power consumption level of each subsystem.

3.5 Interface Circuitry for external sensors

Fig 4 (b) shows an interface to take other types of sensors such as AS-3257 from Tokyo Sokusin Inc. and FBA-11 from Kinemetrics Inc. With this interface, DuraNode can be used as a *wireless data transmitter*. It consists of a 12-bit ADC (A/D Converter-AD1672), a power supply, and electrical terminals. The ADC has various ranges of input voltages (+/- 5V, +/-10V, 0V – 10V, 0V – 20V) which enable DuraNode to interface with a wide variety of sensing devices. The power supply provides two different voltage levels (+/- 15V, +/-12V) and 40mA of current maximum.



(a) Three SD-1221 Accelerometers (b) Interface for External Sensing Device

Fig. 4 Snapshot of Sensor Circuitry and Interface for External Sensing Device

4. SOFTWARE DESIGN

Fig. 5 shows the block diagram of the software architecture. The bottom layer consists of the hardware components, including the WLAN card, sensors, microcontroller, regulators, and battery monitor. The software layers can be divided into firmware and application software.

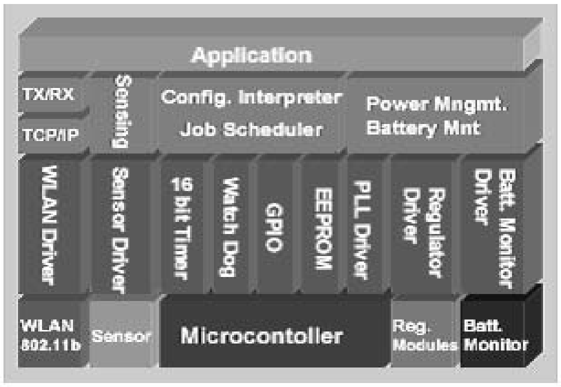


Fig. 5 Block Diagram of Software Design

4.1 Firmware

The firmware is software stored in flash memory and is executed when the device powers up. The firmware is further divided into device drivers at the low level and a service layer above.

Just above the hardware layer are the device drivers, which are the low level software routines called by the PIC microcontroller to control the hardware devices. In addition to hardware components external to the PIC, the PIC also has a number of built-in devices, including a 16-bit timer, a watchdog timer, general purpose I/O pins (GPIO), on-chip EEPROM, and phase-lock loop (PLL). Each of these is also accessed via a driver routine.

The service layer is built on top of the device drivers and provides system-level services to the application software above it. These services include communication, sensing, configuration, job scheduling, and power management. For communication, we have ported a TCP/IP protocol stack on top of the WLAN driver so that the application software can send/receive data and commands over the Internet. The sensing service provides a uniform programming interface so that the data sampling can be performed uniformly without concerns for whether the ADC or PWM decoding should be used. The configuration interpreter and job scheduling service use the built-in timer, watchdog timer, GPIO, and EEPROM to support both event-driven and time-driven job scheduling. Finally, the power management service runs alongside the job scheduler to optimize energy usage.

4.2 Power Management Service

The power management service controls the energy usage in the system. The management is divided into the energy source manager and energy consumer manager. The energy source manager is responsible for coordinating the use of energy from the solar panel, wind turbine, and the Li-ion battery pack. The energy source manager checks the battery level by querying the current-accumulation based battery monitor chip and measures the output voltages of the solar panel and wind turbine, which are closely related to environmental situation. Base on these parameters, it decides which source supplies power to DuraNode. It decides whether to enable battery charging based on the charge state of the battery and the profile of expected energy availability. If the battery is well above the charging threshold and there is plenty of solar power available, then it will not enable charging as a way to prevent premature aging of the battery.

The energy consumer manager is responsible for controlling all devices that pertain to energy consumption, and they include both the devices and the regulators that directly consume energy. Some modules such as the WLAN card may have built-in power management as part of the protocol. The power consumer manager therefore need not actively manage them for the most part, but other devices may not have such capabilities. The general mechanism for dynamic power management is to turn on and off the regulator to a whole subsystem during extended idle intervals so that they do not consume power. However, the microcontroller itself requires a separate strategy for power management. The main strategies are dynamic voltage scaling (DVS) and interrupts. DVS is a widely used technique for reducing both power and energy in processor-based systems. The PIC can change its clock to operate from 10MHz to 40MHz by calling the PLL driver. Running at a lower clock rate enables reduction of the voltage via a call to the regulator driver, and as a result it consumes less energy per instruction. During extended idle intervals, it may be desirable to execute the idle instruction, which cuts the power consumption from a few mW down to less than one μW.

It is also possible to put the microcontroller to sleep in order to further reduce power consumption. However, another device must be kept on to wake it up. While it is possible to keep the WLAN card on and interrupt the microcontroller on receiving a packet, doing so is not considered productive because the stand-by power consumed by the WLAN card is one to two orders of magnitude greater than that of the microcontroller. Instead, either a timer interrupt or a threshold detector would be a better choice for generating this wake-up interrupt. Event-triggered model is used in conjunction with a threshold detector to generate this interrupt.

4.3 Data Acquisition and Display System

Application software can be loaded to run on top of the firmware architecture described above. Currently, DuraNode runs only the simplest application software, which calls the job scheduler to sample the accelerometers periodically via sensing service calls. In the future, the application software may perform additional computations that include some local data processing, compression, and localized data aggregation by coordinating with neighboring sensor nodes. The Data Acquisition and Display System (DADS) consist of three parts, the acquisition unit, the data processing unit and the graphical user interface (GUI), as shown in the Fig. 6.

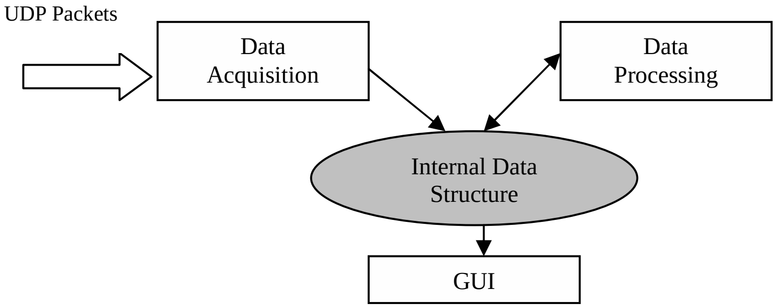


Fig. 6 Scheme of Data Acquisition and Display System

In the scheme of DADS, each DuraNode acts as a “server”, and the acqusition untit as a “client” opens a socket connection to each DuraNode over User Datagram Protocol (UDP). After it receives UDP packets from a DuraNode, the acquisition unit unpacks the packets and converts them into the corresponding acceleration data. These data will be stored in the DADS' internal data structure, which is a hash table including the identification of DuraNode, the timestamps, and the acceleration data. The GUI obtains acceleration data from the internal data structure, and displays as a time-history graph. The Data Processing unit also obtains acceleration data and performs FFT transformation on those data. After processing, the FFT data will be displayed in the GUI showing the frequency domain information. The entire DADS is implemented in Python. Python is an interpreted, object-oriented programming language. Python is portable: it runs on many OS platforms, such as Windows, Mac OS, and Linux. By implementing in Python, the entire DADS code only takes 100Kbyte of disk space, and it is highly portable to different OS platforms.

Fig. 7 shows the screenshot when the GUI is running. The upper part of the GUI shows the layout of the DuraNodes, where each node could be filled with a different color representing its current status, such as working, or sleeping. The example here shows two DuraNodes working currently. The user can select one DuraNode by clicking on its icon, and the information of that node will be shown in the other part of the GUI. The middle part of the GUI is the time-domain window. It shows the time-history of three axes (*x*, y amd *z*) of the selected DuraNode. The bottom part is the frequency-domain window, which shows the frequency domain information after running FFT. When running the DADS, the user first click the "start" button on the top, and this will start the data acquisition unit. The data is collected and stored into the internal data structure. In the mean time, the GUI reads data from it and display it as time-history information in the graph. After running for some time, the user can run FFT by clicking the "FFT" button on the top, this will start the data processing unit. The data processing unit performs FFT over the collected data and display the FFT result in the frequency-domain window.

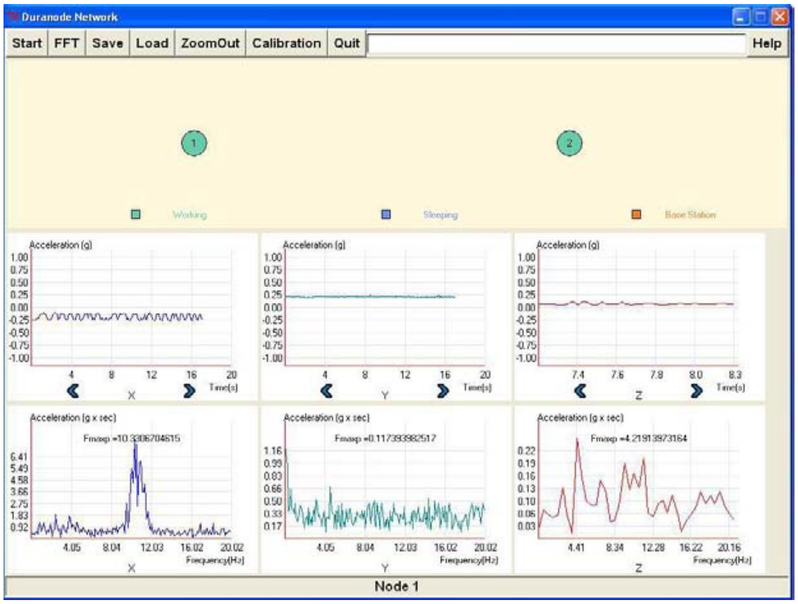


Fig. 7 Snapshot of DADS' Graphic User Interface

5. FIELD EXPERIMENT

The DuraNode sensing system has been validated with tests on bridge vibration monitoring for two times: the Pedestrian bridge located on the East Peltason Drive at the University of California, Irvine, and the shake-table test for a bridge bent specimen in the lab of the University of Nevada, Reno.

5.1 Experiment of a Pedestrian Bridge at UCI

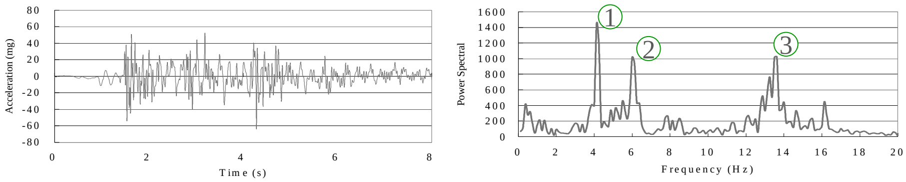
A pedestrian bridge located on the East Peltason Drive in the University of California, Irvine has been tested. This bridge is a steel truss bridge, approximately 30m long and 3.0m wide. Concrete decks are apparent on the structure as well as steel tubular elements for the truss. The bridge was subjected to an excitation load simulated on the middle span.

The bridge was excited accordingly and generated vibrations measured using three different sensing devices: ADXL202, SD1221, and PCB 393C.

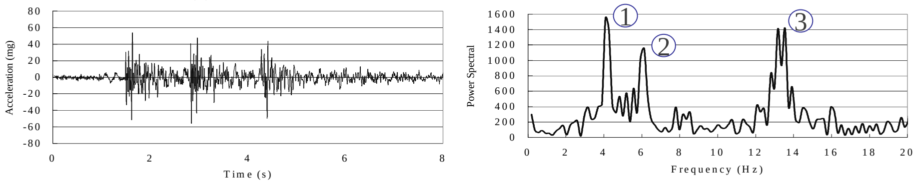
As shown in Fig. 8, the sensing devices ADXL, SD and PCB were positioned in the middle of the bridge and close to one side. That to place the devices in the middle of the span was for measuring the maximum vertical excited displacement and acceleration. The primary interest in this experiment was to investigate the movement in vertical (up and down) and transverse directions, and the torsional response was not intentionally recorded in this study. However, torsional movement, caused by wind forces was observed from the data.

Fig. 8 The Pedestrian Bridge

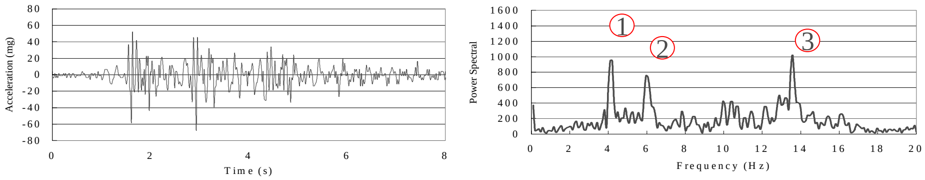
Fig. 9 shows time-domain plots of the vibration data collected from PCB, SD and ADXL. The GUI, which runs on a notebook computer, can display these samples in time and frequency domain, from 0Hz to 60Hz. Results collected from MEMS-type ADXL and SD accelerometers are compared against the high precision instrument, PCB. The results match well within a small margin of error. Based on the original detailed blueprints from the bridge design company, a computer model of the bridge was created using SAP-2000 to perform dynamic analysis. The material properties and structural dimensions details were retrieved from the blueprints and had been verified in SAP-2000 numerical test. The specifications and boundary conditions were inspected using the 3-D frame FEM model. The first two modal frequencies evaluated from the SAP-2000 agree with the observed frequencies from the ADXL, SD and PCB sensing device with a small margin of error.



(a) PCB; Mode 1: 4.12 Hz, Mode 2: 6.00 Hz, Mode 3: 13.63 Hz



(b) SD-1221; Mode 1: 4.08 Hz, Mode 2: 6.12 Hz, Mode 3: 13.17 Hz



(c) ADXL-202E; Mode 1: 4.20 Hz, Mode 2: 5.96 Hz, Mode 3: 13.57 Hz

Fig. 9 Measurement from PCB, SD and ADXL Sensing Devices

5.2 Experiment of a Bridge Specimen at UNR

This experiment was conducted in the lab of the University of Nevada, Reno, on December 7-8th, 2004. A flared two-column reinforced concrete bent specimen was employed for a shake-table test, as shown in Fig. 10. This experiment was to investigate vibration mechanism of the system, sequentially at different damage levels, with the introduced strong motions. During the test, the ground motion record at Sylmar station in 1994 California Northridge Earthquake was used, and scaled with factors, for the driving signal of the shake-table to simulate strong motions. An ambient signal measured from the Jamboree Bridge, Irvine, CA was also used, and amplified by 50 times, for the shake-table's ambient input before and after each drive of the strong motions. The experiment was successful, and the transverse direction measurement of the bent was observed and analyzed to identify the system characteristics.

A DuraNode and a conventional acceleration sensing device, Kinemetrics-16083, were both installed on the base of the bent to measure the movement. The DuraNode was proved to be capable of accurately sensing ambient vibration and the strong ground motion. Fig. 11 shows the fast Fourier Transform results from the acceleration time-histories obtained from DuraNode and Kinemetrics were nearly identical in identifying modal frequencies by overlaying two curves.

Fig. 10 Shake-table Test at UNR

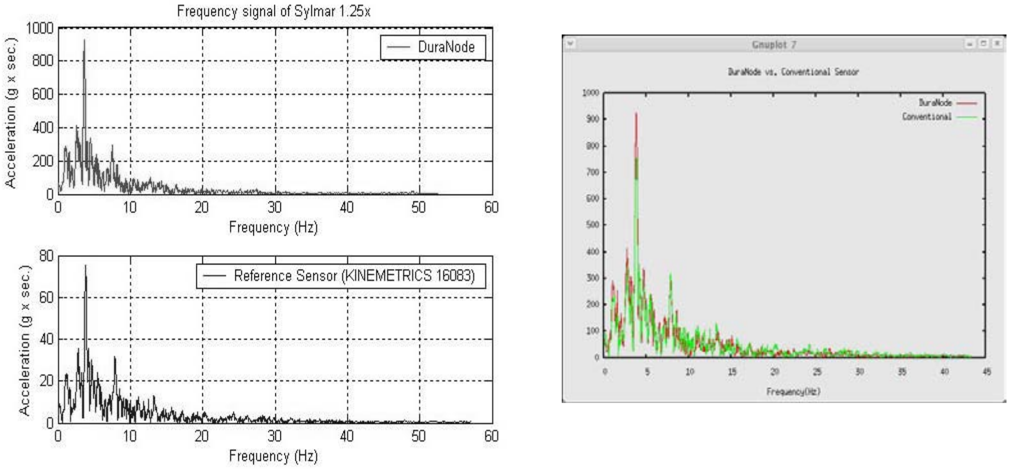


Fig. 11 Frequency Domain Analysis from DuraNode and Kinemetrics-16083

6. CONCLUSIONS AND FUTURE WORK

This paper presents the design and evaluation of a power-aware, wireless sensor node called DuraNode. Its distinguishing features include novel power circuitry for managing not only power consumers but also power producers. Multiple power regulators not only isolate digital, analog, and wireless power supplies and enable their individual dynamic power management, but more importantly are matched to the dynamic range of the power consumers for maximum efficiency. Smart circuitry also controls recharging to maximize battery longevity. The time-triggered sampling, combined with high-speed WLAN interface, enables DuraNode to operate with high reliability and determinism, and we believe such characteristics are essential for the civil engineering application. The node is currently fully operational, and initial results are very promising. Many future enhancements have been planned. We are currently developing algorithms to optimize the trade-offs between buffering, compression, transmission power, and relaying. These features will make DuraNode not only a reliable platform for sensing but also studying of wireless networking.

Development of an IT-based disaster simulation and management system is underway. This system can easily be built on a network of DuraNode for structural health monitoring and interpretation of data for jurisdictions in responding to the unexpected catastrophic events. DuraNode will be deployed to assess the vulnerability of structures and to highlight the “red” spot indicating the prioritized location that need to be cared in emergency moment.

ACKNOWLEDGMENT

This study was done under National Science Foundation Grant EEC9701471 and FHWA Contract: DTFH61-98-C-00094 both through the Multidisciplinary Center for Earthquake Engineering Research. The work was also supported by National Science Foundation Grants CMS-0112665 and CMS-0509018. The authors particularly acknowledge the technical assistance provided by Dr. Maria Feng and Mr. Yanbo Chen at University of California, Irvine for the shake-table test at University of Nevada, Reno to demonstrate the efficacy of DuraNode.

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