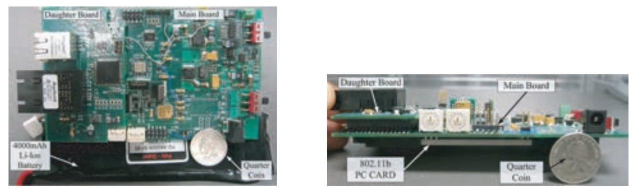
DuraNode: Wireless Networked Sensor for Structural Health Monitoring

Chulsung Park, Qiang Xie, Pai H. Chou
Center for Embedded Computer Systems
University of California, Irvine
Irvine, CA 92697-2625 USA
Email: chulsung@uci.edu

Masanobu Shinozuka
Dept. of CEE
University of California, Irvine
Irvine, CA 92697-2625 USA
Email: shino@uci.edu

***Abstract*— DuraNode is a sensor node for real-time monitoring the health of civil engineering structures such as highway bridges and skyscrapers. It is specially designed to take civil engineers' requirements into account. To meet their requirements DuraNode has a dual-microcontroller architecture sharing a FIFO memory. Evaluation shows that DuraNode has many distinguished features over other sensor nodes such as high power-efficiency, low jitter, and high network performance.**



(a) Top view

(b) Side view

Fig. 1. Photo of DuraNode

I. Introduction

Current structural safety monitoring techniques rely on visual inspection by 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 [1] [3]. 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 [2]. However, they can hardly be used for structural safety monitoring, because of low data rate, short operating lifetime, and low data accuracy. Several deep discussions with civil engineers envision us a new sensor node, especially designed for real-time structural health monitoring application.

In this paper, we first show the requirement specifications from civil engineers. Later sections of this paper will cover the hardware and software architecture of DuraNode. Then, finally we will show the evaluation results and conclusion.

II. Requirements Specification

This section presents the requirements specification for DuraNode. This specification was developed in conjunction with those civil engineers who process the collected data for analysis. We divide the specification into four topics: functional specification, timing, communication interface, and power and energy constraints.

A. Functional Specification

Each DuraNode should be able to sense tri-axial vibration and one-axial angular movement. MEMS-type sensors are preferred because of their small form factor, low prices, and low power consumption. Signals from these sensors are to be sampled at a minimum of 10-bit resolution.Also, each node should transmit the collected data over a high speed, wired or wireless link. In fact, multiple links should be included for fault tolerance reasons.

B. Timing

DuraNode's hardware and software should be designed with main considerations for timing issues: synchronization, jitter, and data latency.

Precise time *synchronization* among sensor nodes is crucial for the post-analysis of the data, because the civil engineers are interested in knowing how the impact at a certain spot of a structure propagates. Also, they want to monitor different parts of a given structure simultaneously for structural analysis.

Jitter is the deviation from a precise, fixed time distance in between consecutive samples. Ideally, this sampling interval should be constant, though in practice it is almost impossible to make it constant. Nevertheless, minimizing jitter is crucial for this application, because the our civil engineering collaborators compute FFT with collected data in order to perform for frequency-domain analysis.

Data latency is the time it takes for sampled data to travel through the instrument and communication links to appear in the host computer or data logger. Civil engineers usually prefer to look into the data collected from a structure immediately or with minimum delay.

C. Communication Interface

Most of research groups in the sensor network community focus on the wireless communication interface. In practice, however, having a wired interface as well as a wireless interface can be desirable. For

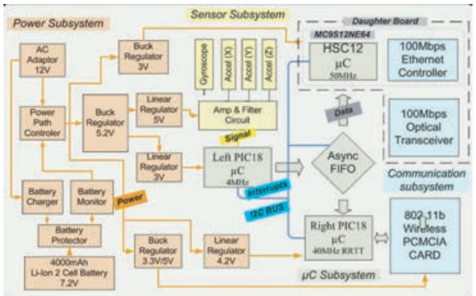
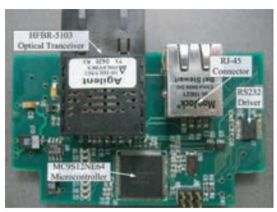


Fig. 2. Top-level Block Diagram of DuraNode

(a) Main board top view

(b) Bottom view



(c) Daughter board

Fig. 3. Main board and Daughter board of DuraNode

instance, for the building monitoring application, chances are a local area network (LAN) may exist already. Instead of constructing a new network dedicated to monitoring, it may be possible to utilizing the existing network. Having multiple communication interfaces makes a sensor node more robust against network failures of any kind. There, DuraNode should be able to utilize the pre-installed network and provide a smooth transition between communication interfaces.

D. Power and Energy Constraints

Civil engineers want to use DuraNode to monitoring several different sites including bridges, buildings, and underground pipelines. The available power sources differ depending on the specific deployment site. Therefore, it is desirable for DuraNode to be able to use different kinds of power sources: a battery, an AC adapter, and one or more renewable power sources. Also, the power system of DuraNode should be designed in a manner that archives high power-efficiency.

III. Hardware Design

Fig. 1 shows the picture of DuraNode's hardware. It consists of two boards: *main board* and *daughter board*. The main board itself can be used as a wireless sensor node, and we call this stand-alone operating mode *wireless mode*. As shown in Fig. 3(a) and (b), the single board has everything a wireless sensor node may need, including microcontrollers, sensors, and a wireless communication

	Frequency	Voltage	Current(Act./Idle)	Tasks
Left PIC (PIC18F8680)	4 MHz	3 V	2mA / 18μA	Sampling and Buffering
Right PIC (PIC18F8680)	40 MHz	4.3 V	34mA / 32μA	Wireless Comm.
MC9S12NE64	50 MHz	3 V	65mA / 200μ A	Wired Comm.
CY7C	N/A	5V	60mA / 8mA	N/A
DS1284	32.768KHz	5V	2mA	N/A
Total			Max. 163mA	

TABLE I
SPECIFICATIONS OF DEVICES IN MICROCONTROLLER SUBSYSTEM

	Max. Bit Rate	Current Consumption	Range
802.11b	11Mbps	@5V TX: 278mA RX: 182mA IDLE: 71mA	Max. 500m
Fast Ethernet	100Mbps	@3V 264mA	N/A
Optical	100Mbps	@5V 50mA	Max. 2Km

TABLE II
BIT RATE, CURRENT CONSUMPTION, AND RANGE OF EACH COMMUNICATION INTERFACE

interface. On the other hand, the daughter board, as shown in Fig. 3(c), has only a microcontroller but two wired communication interfaces, namely Fast (10/100 Mbps) Ethernet and Optical. With the daughter board plugged in, DuraNode can send data through the wired communication interface in *wired mode*. In addition, it can also use both wired and wireless interfaces in *dual mode*. As shown Fig. 2, DuraNode consists of four subsystems: Microcontroller, Communication, Power, and Sensor.

A. Microcontroller Subsystem

As shown in gray color in Fig. 2, the microcontroller subsystem consists of *three* low-power microcontrollers (two PIC18F8680s [4] and one MC9S12NE64 [5]), one asynchronous first-in first-out (FIFO) memory (CY7C Series), and one real-time clock (DS1284). The PIC18F8680 is an 8-bit microcontroller from Microchip with 3.3KB of RAM, 64KB flash memory, and an 8-channel 10-bit A/D converter. The MC9S12NE64 is a Freescale HSC12-based 16-bit microcontoller, which has an integrated Fast Ethernet MAC/PHY controller, 8KB RAM, and 64KB flash memory. DuraNode uses a 28-pin PLCC socket for the FIFO memory, instead of soldering it directly onto the PCB. This enables us to adjust the size of the FIFO memory according the required data latency and power management scheme. The memory size is selectable among 8KB, 16KB, 32KB, and 64KB. The RTC is used for time synchronization with a resolution of 1ms.

Using these components, we implemented a dual-microcontroller architecture. This architecture is unique to sensor nodes designs and enables us to achieve design goals including low-power, low jitter, and high network performance. The physical architecture, as shown in Fig. 2, consists of three microcontrollers sharing a FIFO memory, an I2C bus, and interrupt signals for inter-processor communication. We can optimize power consumption in this architecture by first assigning tasks to the microcontrollers and then scale the microcontrollers' clock frequencies and supply voltages based on the timing constraints and the complexity of assigned tasks.

B. Communication Subsystem

The communication subsystem, colored sky-blue in Fig. 2, consists of an 802.11b wireless PC card (MA401), a Fast Ethernet controller (MC9S12NE64), and an optical transceiver (HFBR-5103). The bit

	Current	Power	Regulator Chosen
Left PIC	@3V 2mA	6mW	LT1761ES-3(Linear)
Right PIC	@4.3V 34mA	146mW	LT1761ES-5(Linear)
FIFO Memory	@5V 54mA	270mW	LT1761ES-5(Linear)
Sensor Subsystem	@5V 44mA	220mW	LT1761ES-5(Linear)
802.11b	@5V 278mA	1390mW (tx)	MAX1672(Buck)
miscellaneous	@3V 12mA	36mW	
Total(Wireless)		2068mW	
MC9S12NE64(HSC12) (Ethernet)	@3V 65mA @3V 264mA	195mW 792mW	MAX1672(Buck)
Optical TX/RX	@5V 50mA	250mW	LT1761ES-5(Linear)

TABLE III
POWER CONSUMPTION LEVELS AND SELECTED REGULATORS

Fig. 4. Screenshot of GUI: Receving data from three nodes.

rate, power consumption, and range of each communication interface are summarized in Table II. Having multiple communication interfaces is very useful, especially for indoors deployment. LAN is available in most of buildings, and sometimes an optical network is also available especially along utility conduits. With the wired interface, DuraNode can easily tap into a pre-installed network instead of having to set up its own wireless network. For outdoors deployment, we can unplug the daughter board to save the power consumed by the wired interfaces. Also, DuraNode supports the soft transition between a wired and wireless interface. When the micrcocontroller detects the sudden failure of the current communication interface, it automatically switches to the other interface within 10 microseconds.

C. Power Subsystem

The power subsystem, colored orange in Fig. 2, consists of a set of regulators, a power path controller, battery-management ICs, and two power sources: a Li-Ion battery and an AC adapter.

In designing the power system of battery-powered devices, the crucial issue is how to design the regulator topology, because it directly affects the overall power efficiency of the system. The inputs to designing the regulator topology can be each subsystem's supply voltages, current consumption levels, expected battery lifetime, and so on. Table III shows those of DuraNode. Based on this table, we designed DuraNode's regulator topology shown in Fig. 2. DuraNode has two switching regulators and four linear regulators, which are combined in a manner that maximize the conversion efficiency and minimize the cost and space. We used switching regulators for power-hungry subsystems such as 802.11b and Fast Ethernet, and for the rest of subsystems we used a two-stage conversion scheme. In this scheme, the switching regulator first converts a battery's output voltage (7.4V) into an intermediate voltage level (5.2V) and the linear regulators of each subsystem finally converts the intermediate voltage into the appropriate voltage level. We chose the LTC1742 and MAX1672 switching regulators, both of which show over 90% conversion efficiency at the current consumption levels of the corresponding subsystems. Also, we chose the LT1761 series linear regulators for their low voltage dropout.

DuraNode has a two-cell 4000mAh Li-Ion battery which nominal output voltage and rated current are 7.4V and 4A, respectively. To protect and manage this battery, we use a battery protector (UCC3911), battery charger (LTC1732), and battery monitor (DS2438).

The power subsystem is able to take two different power sources: a battery and an AC adapter. The AC adapter, when available, powers the entire system while charging the battery also. In case that the AC power source suddenly fails, the power path controller makes a smooth and quick transition from the AC power source to the battery.

D. Sensor Subsystem

The sensor subsystem, colored yellow in Fig. 2, consists of three accelerometers (SD1221) [6], one gyroscope (ADXRS300), and amplifier and filter circuitry. Three SD1221s are used to monitor tri-axial vibration. The SD1221 is a low-noise integrated accelerometer whose input acceleration range is from -2g to $+2$g. Also, its frequency response range is 0 – 400 Hz. Two differential analog output signals (0.5 to 4.5V) of the SD1221 first go to the low-noise operational amplifier (LMV751), which converts these signals into a signal-ended one. Then, the signal flows through an RC filter and feeds the AD converter of the left microcontroller.

IV. SOFTWARE DESIGN

This section presents the software side of DuraNode. We first discuss firmware running on the microcontrollers. Then, we describe the our Graphical User Interface (GUI) program running on the host computer.

A. Firmware

As described in the previous section, DuraNode has three microcontrollers. Each microcontroller needs a different version of the firmware. The Left PIC has the relatively simple firmware architecture, which basically consists of hardware drivers, a power management unit, and a battery monitor. On the top, an application program performs data sampling, writing data into FIFO memory, and communication with other microcontrollers. The power management unit keeps monitoring power sources and manages the power modes of each subsystem according to the power management policy. The Right PIC and MC9S12NE64 share almost the same overall firmware architecture. The only difference is that each contains a different driver for its communication interface: 802.11b or Ethernet. The application program reads out data and transmits data through the communication interfaces when it detects the FIFO-memory-full interrupt signal.

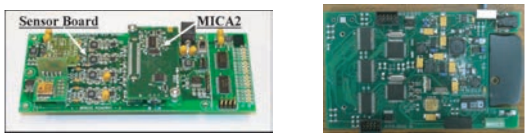
B. Graphic User Interface

The Graphical User Interface (GUI) program consists of three parts: the data acquisition unit, data processing unit, and the real time display unit. Fig. **??** shows the screen shot of the GUI.

The acquisition unit of the GUI opens a communication link to each sensor node. It initiates communication and receives data packets over the User Datagram Protocol (UDP) from each sensor node. The received UDP packets are unpacked and converted to the corresponding acceleration data.

V. EVALUATION

For evaluation, we first compare DuraNode with the widely used Mica2 mote platform, as well as with our previous versions of DuraNode. Then, we analyze power conversion efficiency of the



(a) MICA2-based Sensor Node

(b) First Prototype of DuraNode

Fig. 5. Existing Sensor Nodes for Structural Health Monitoring

	InfraNode	MICA2-Based	First Prototype
Sensors	3 x Accel. (SD1221) 1 x Gyroscope	3 x Accel. (SD1221)	3 x Accel. (SD1221)
μC	Dual 40MHz 8-bit 4MHz 8-bit	Single 8MHz 8-bit	Dual 2 x 20MHz 8-bit
Radio	802.11b 11Mbps	CC1000 38.4Kbps	802.11b 11Mbps
Wired Comm. hline Shared Memory	YES 8K,16K,32K,64K Asynch. FIFO	No None	No None
Battery	4000mAh Li-Ion two-cell 7.2V AC Adapter	two AA type 3V AC Adapter	2000mAh Li-Poly one-cell 3.6V Solar Panel

TABLE IV
COMPARISONS OF SENSOR NODES FOR STRUCTURAL MONITORING

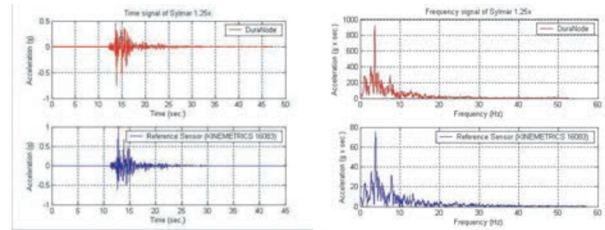
power subsystem. Finally, we show our field experimental results comparing with a conventional sensing device that collects data precisely but costs substantially more.

A. Comparison

Many research groups and companies have developed several different kinds of sensor nodes. However, there are still few suitable platforms available, especially for structural health monitoring application. Researchers at UC Berkeley showcased a system based on their Mica2 to monitor the Golden Gate Bridge in San Francisco [7]. As show in Fig. 5(a), it consists of two boards: MICA2 Sensor Node and Sensor Board. However, the Mica2 setup is not adequate for precise and real-time health monitoring because of its very low communication bandwidth (38.4Kbps) and the single slow microcontroller (8MHz, 8-bit) architecture. In addition, Mica2's sensor board needs a separate power source, so that it looks more like two separate hardware boards rather than an fully integrated sensor node like our DuraNode. Our group at UC Irvine has also developed and deployed two previous version of DuraNode (Fig. 5(b)) [3]. Although they share the same design philosophy, the new version of DuraNode has a totally different system architecture that makes it much more power efficient and suitable for structural health monitoring application. More detail comparisons are shown in Table IV.

B. Power Conversion Efficiency

To evaluate the power subsystem of DuraNode's power subsystem, we actually measured power conversion efficiency. The power conversion efficiency is the ratio of the output power to the input power. To measure this, we first programmed our DuraNode to consume maximum power. Then, we supplied 7.4V and measured the current consumption. The current profile looks like a sinusoidal wave, because we used the switching regulator at the front end of the



(a) Time-Domain

(b) Freq.-Domain

Fig. 6. DuraNode field experiment: comparison with Kinometrics'sensor

power subsystem. The RMS value of this current profile is 342mA, and we can calculate the average power by multiplying the value by the supply voltage (7.4V). The average power is 2530mW. Recall that DuraNode's maximum power consumption is 2068mW in wireless mode, according to Table III. Overall, the power conversion efficiency is 82% (2068mW/2530mW).

C. Field Experiment

DuraNode has been validated in a field experiment held in the lab at the University of Nevada, Reno. A flared two-column reinforced concrete bridge specimen was employed for a shake-table test. Our DuraNode and a conventional acceleration sensing device, Kinemetrics-16083, were both installed on the base of the bent to measure the vibration. Fig. 6(a) and (b) show the time-histories, and the FFT results from DuraNode and Kinemetrics' were nearly identical in identifying modal frequencies.

VI. CONCLUSIONS

This paper has presented the design and evaluation of a power-efficient, low-jitter, and high network performance sensor node, called DuraNode. It achieves high power efficiency through vertically integrated techniques. Its distinguishing features include the dual-microcontroller architecture, a shared FIFO memory, and multi-modal operating of communication and power sources. This architecture improves the system performance not only at the system level via enhanced dynamic range, but also at the network level through FIFO sizing for latency/power trade-offs. Also, its power subsystem is carefully design to achieve high conversion efficiency, and evaluation confirmed its actual conversion efficiency to be over 80%.

REFERENCES

[1] Chung, H–C, Enomoto, T. and Shinozuka, M., "MEMS-type accelerometers and wireless communication for structural monitoring", *The 2nd MIT Conferences on Fluid and Solid Mechanics, Cambridge, MA*, June, 2003.

[2] MICA2 Wireless Sensor Node Platform, *http://www.xbow.com*

[3] Chulsung Park, Pai H. Chou, and Masanobu Shinozuka, "DuraNet: Multimodal Sensor Network for Real-Time Structural Health Monitoring", *Proceedings of the Second International Workshop on Advanced Smart Materials and Smart Structures Technology*, Korea, July, 2005.

[4] PIC18F8680 8-bit Microcontroller, *http://ww1.microchip.com/downloads/en /DeviceDoc/30491c.pdf*

[5] MC9S12NE64 16-bit Mircontroller, *http://www.freescale.com/files /microcontrollers /doc/factsheet/MC9S12NE64FS.pdf*

[6] SD1221 3-Axis MEMS Accelerometer *http://silicondesigns.com /Pdf/1221.pdf*

[7] Sukun Kim, *Wireless Sensor Networks for Structural Health Monitoring*, UC Berkeley Master Thesis, 2005.