Wireless Sensor Network for Structural Health Monitoring using System-on-Chip with Android Smartphone

Won-Jae Yi, Spenser Gilliland and Jafar Saniie

Department of Electrical and Computer Engineering

Illinois Institute of Technology, Chicago IL, USA

***Abstract*— Critical structures such as aircrafts, bridges, dams and buildings require periodic inspections to ensure safe operation. Reliable inspection of structures can be achieved by combining ultrasound non-destructive testing techniques with other sensors (for example, temperature sensor and accelerometers). In this study, we show that adapting wireless embedded systems to the task of structural health monitoring improves inspection productivity, increases mobility, and allows the aggregation of critical data to enhance inspection accuracy. To achieve this objective, we developed a customized system based on Reconfigurable Ultrasonic System-on-chip Hardware (RUSH) platform. RUSH collects and analyzes ultrasonic data to detect structural flaws such as cracks, voids, or fatigue. The collected data is then transferred through a Bluetooth transceiver to an Android smartphone referred to as Mobile Sensor Data Collector (MSDC), where the data is instantly displayed and forwarded to a central server for expert review over the Internet.**

I. Introduction

Civil structures require constant and periodic inspections to maintain their safety and solidity. While there are numerous methods that can be applied to structural health monitoring, most inspections are performed using non-destructive examination (NDE). NDE examinations evaluate the sustainability of a structure without damaging the structure for testing. Widely used NDE methods include ultrasonic testing, radiographic, and eddy current [1]. NDE using ultrasound is accomplished by transmitting ultrasonic pulses to a region of interest and recording the reflected backscattered echoes. In the measured signal, two dominant echoes exist when the ultrasonic wavelet enters and exits the material under test. Any additional echoes found between these two dominant echoes are indications of possible flaws in the material [2]. A more in depth structural health monitoring can be achieved by using sensors such as accelerometers for detecting movements and vibrations of the structure [3], temperature sensors to determine temperature distribution within the structure [4], and acoustic emission sensors for detecting and locating embedded structural defects [5].

Recently, a major technological transformation has occurred with the advent of smartphones. Smartphones are equipped with wireless adapters including Bluetooth for Personal Area Network (PAN) formation, Wi-Fi and mobile baseband connections to access the Wide Area Network (WAN). The smartphone users are free from the limitations of a traditional wired network, and they can remain connected continuously regardless of the mobility. Smartphones, like many other computer based systems, include a powerful RISC processor to govern the system operation efficiently and provide user accessibility and computational capability in real-time.

In this paper, we improve the productivity and mobility, and aggregate critical data for structural health monitoring by the integration of the two customized systems, Reconfigurable Ultrasonic System-on-chip Hardware (RUSH) [5] and Mobile Sensor Data Collector (MSDC) [6]. RUSH platform is a customized system, specifically designed for processing ultrasonic signals and data acquired using multiple sensors on a Field Programmable Gate Array (FPGA). MSDC transforms a standard Android smartphone into a real-time data collection, data display, and data forwarding device. MSDC captures sensor data using Bluetooth and forwards acquired data via the global Internet. The sensor data used in this study includes ultrasonic signals, accelerometer and temperature to demonstrate the system's functional capabilities.

II. System Design

Figure 1 shows an overview of the system design for a wireless sensor network for structural health monitoring using RUSH with MSDC. RUSH uses a Xilinx Zynq 7020 FPGA which embeds a dual-core Cortex-A9 ARM processor at a maximum CPU clock of 1 GHz and 1.5 DMIPS (Dhrystone MIPS)/MHz per core. The embedded processors operate under the ARMv7-A instruction set with SIMD (single instruction, multiple data) NEON media processing engine for single precision floating point operations [7,8]. Also, the integration of high-speed peripherals into the FPGA firmware can boost the performance of the processing system. An Analog Devices AD9467 ADC development board which contains a 16 bit 250 MSPS ADC is used within the RUSH system for ultrasonic data acquisition [9]. For comprehensive structural health monitoring, other sensors such as temperature sensor, accelerometers, and vibration sensor are also used.

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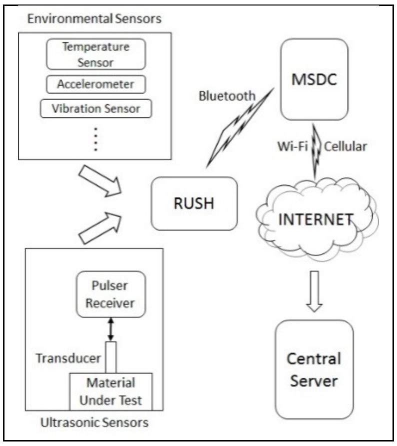

Figure 1. System overview

For this study, we integrated a USB Bluetooth transceiver with RUSH to add communication ability for transferring data to MSDC. With this arrangement, current health status of the structure can be identified by the user-end and displayed on the smartphone's screen in real-time. Figure 2 illustrates the customized RUSH platform configured for ultrasonic testing with an external ADC board, as well as a USB Bluetooth transceiver.

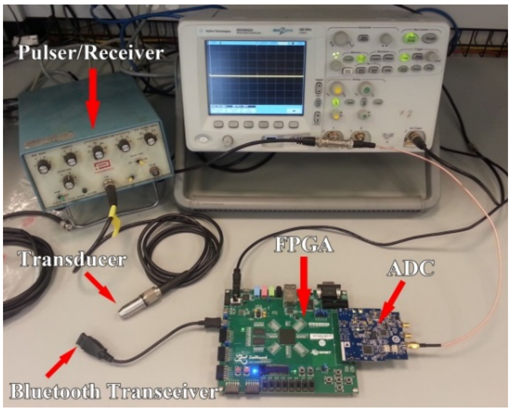

Figure 2. RUSH ultrasonic testing setup

Specifically for finding flaws using ultrasonic NDE, a signal processing technique called Split Spectrum Processing (SSP) is implemented to reduce scattering echoes which are significant source of noise [10]. In ultrasonic NDE, scattering echoes are due to material's microstructure and follow a Rayleigh scattering pattern. By splitting the broadband signal into multiple narrow band signals, statistical methods can be used to filter the Rayleigh scattering from the original signal. Steps 2 to 4 of Figure 3 describe the procedure of how the SSP decomposes a broadband source into multiple sub-band signals.

The external Bluetooth transceiver, with theoretical maximum throughput of 2.1-3.0 Mbit/s [11], is the bridge between RUSH and MSDC. MSDC, which can be deployed on any standard Android smartphone, is equipped with multiple wireless accessibilities including the Bluetooth transceiver, Wi-Fi and mobile baseband for Internet access (see Figure 4).

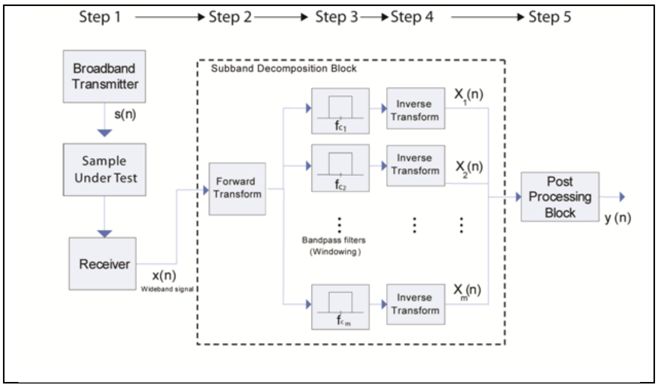

Figure 3. Split Spectrum Processing algorithm

For this study, the MSDC application is implemented on a Samsung Galaxy S III (SGH-T999) with no hardware modifications. This device is equipped with a powerful Qualcomm MSM8960 dual-core 1.5 GHz RISC-based processor, running Android 4.1.2 operating system, 2 GB of system memory, and offers wireless communications using a standard Bluetooth 4.0 transceiver and an 802.11 a/b/g/n Wi-Fi adapter [12].

MSDC is designed to receive ultrasonic signal, accelerometer and temperature sensor data from RUSH via the Bluetooth connection. Then, it performs two important roles; displaying the data on the smartphone screen for users and streaming the data instantly to the central server in real-time. The central server represents a remote accessible location for experts to analyze the received data for monitoring the physical condition of the structure. A Java server application is developed for this study to demonstrate the server behavior. This server application is designed to display and save incoming data from MSDC over the Internet.

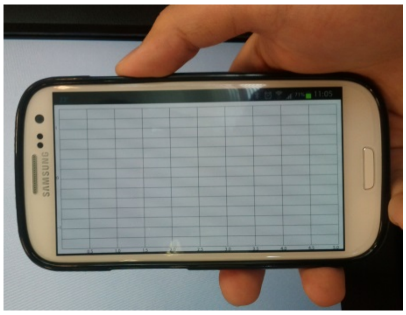

Figure 4. MSDC for sensor data display and communication using Android smartphone

III. Experimental Results

As part of this study, we have explored three different types of sensor data acquisition to demonstrate the system functional and communication capabilities of the RUSH platform and MSDC system. Sensor data is sent to MSDC from RUSH using the Bluetooth transceivers. Then, MSDC displays the received data on the screen and streams the data to the central server in real-time.

A. SSP Data Acquisition

The SSP algorithm was implemented on the RUSH platform using the ultrasonic data acquired from the ultrasonic pulser/receiver through the ADC extension board. The 2048 sample data (see Figure 5) were analyzed using four sub-band channels. Figure 5 displays the signals of four sub-band channels and the output result on the MSDC screen. Sub-band channel 1 frequency band covers 0 to 4 MHz, channel 2 covers 0.5 to 5.9 MHz, channel 3 covers 1 to 5.8 MHz, and channel 4 covers 1.5 to 5.9 MHz. In this figure, the flaw can be identified at about 1700th sample across all four sub-band signals and also the output result. The computation time for SSP was approximately 0.1 second. This implies that ten measured signal can be processed by the combination of RUSH and MSDC in one second which is highly practical for routine structural health monitoring.

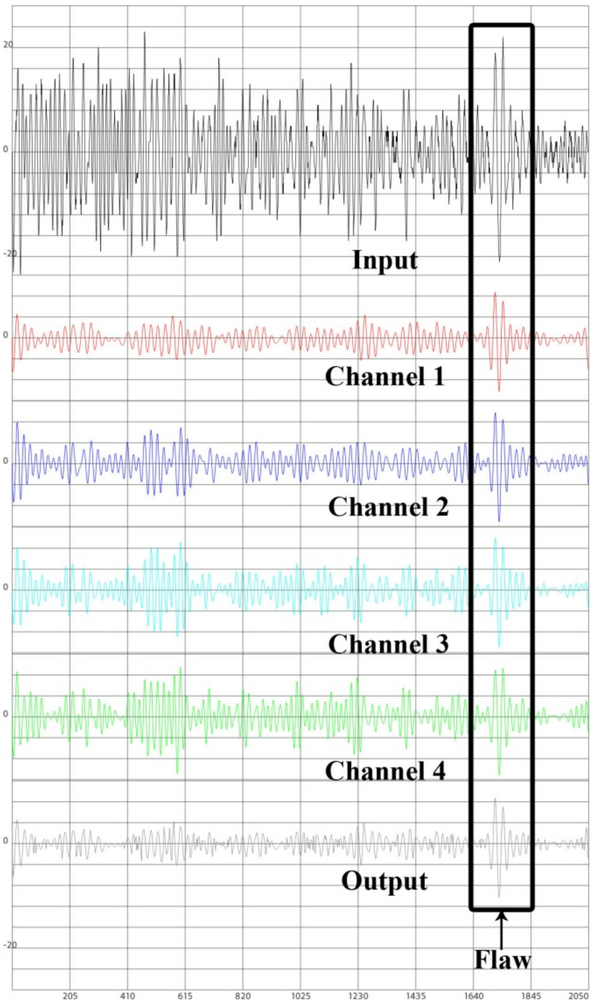

Figure 5. Real-time SSP sub-bands and output results displayed on the MSDC screen (Black rectangle indicates the flaw)

After the analyzed SSP data is displayed on the MSDC screen, the system transmits all received data to the central server through the Internet via Wi-Fi or the mobile baseband connection. All sub-band signals and the output result are sent to the central server where these data are stored and displayed on the server, as shown in Figure 6.

Received Channel & Output Data

channel1	channel2	channel3	channel4	output
-6.31	-4.95	-4.25	-4.42	-4.25
-6.49	-5.95	-5.17	-5.82	-5.17
-6.45	-6.73	-5.9	-6.91	-5.9
-6.18	-7.22	-6.39	-7.57	-6.39
-5.67	-7.36	-6.57	-7.72	-5.67
-4.96	-7.11	-6.39	-7.31	-4.96
-4.06	-6.45	-5.84	-6.35	-4.06
-3.02	-5.41	-4.92	-4.91	-3.02
-1.88	-4.03	-3.67	-3.07	-1.88
-0.7	-2.37	-2.15	-0.97	-0.7

Figure 6. Received real-time SSP results on the central server

B. Accelerometer Data Acquisition

Accelerometers are useful to keep track of structure movements and vibrations, and it is widely used since they are highly sensitive to a broad frequency range [3]. For the movement detection of the structure, 3 axes data (x, y and z axis) were transmitted to MSDC using the Bluetooth transceiver, plotted on the screen, and streamed to the central server in real-time. Figure 7 shows the received data on MSDC from a gently swiveled 3 axes accelerometer. Figure 8 shows the output on the server where the individual 3 axes data is displayed separately.

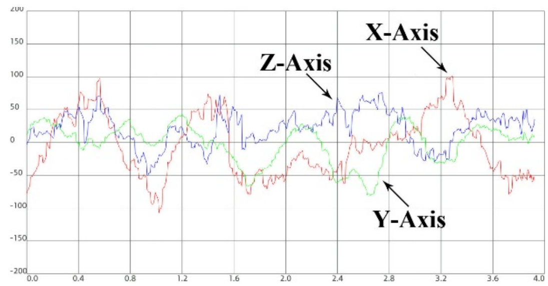

Figure 7. Received real-time accelerometer data on MSDC screen

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Accelerometer 3 axes data -> x: -16    y: 21   z: 28
Accelerometer 3 axes data -> x: -14    y: 20   z: 28
Accelerometer 3 axes data -> x: -10    y: 20   z: 29
Accelerometer 3 axes data -> x: -9     y: 20   z: 29
Accelerometer 3 axes data -> x: 6      y: 15   z: 41
Accelerometer 3 axes data -> x: 7      y: 13   z: 43
Accelerometer 3 axes data -> x: 8      y: 14   z: 44
Accelerometer 3 axes data -> x: 8      y: 16   z: 46
Accelerometer 3 axes data -> x: 9      y: 14   z: 47
Accelerometer 3 axes data -> x: 9      y: 14   z: 46
Accelerometer 3 axes data -> x: 9      y: 13   z: 42
Accelerometer 3 axes data -> x: 11     y: 13   z: 43
Accelerometer 3 axes data -> x: 12     y: 14   z: 43
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Figure 8. Received real-time accelerometer data on the central server

C. Temperature Data Acquisition

Temperature data can be used for various purposes in structural health monitoring. It can be used to determine the surrounding temperature of the structure and the distribution of the temperature within the structure [4].

Similar to the accelerometer experiment, the temperature data was transmitted to MSDC using the Bluetooth transceiver, displayed on the smartphone's screen, and simultaneously sent to the central server. Figure 9 and 10 shows the result of the real-time temperature data received and displayed on MSDC and the server application. In this example, the server application stores and displays timestamps alongside with the received temperature data.

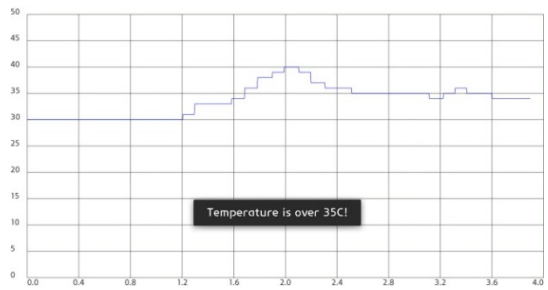

Figure 9. Received real-time temperature data on the MSDC screen

2013/07/30 14:25:50	TEMP: 29C
2013/07/30 14:25:50	TEMP: 31C
2013/07/30 14:25:50	TEMP: 32C
2013/07/30 14:25:51	TEMP: 31C
2013/07/30 14:25:52	TEMP: 30C
2013/07/30 14:25:52	TEMP: 29C
2013/07/30 14:25:55	TEMP: 28C
2013/07/30 14:25:56	TEMP: 29C
2013/07/30 14:25:57	TEMP: 30C
2013/07/30 14:25:57	TEMP: 31C
2013/07/30 14:25:58	TEMP: 32C
2013/07/30 14:25:59	TEMP: 33C
2013/07/30 14:26:00	TEMP: 34C
2013/07/30 14:26:00	TEMP: 35C
2013/07/30 14:26:00	TEMP: 34C
2013/07/30 14:26:01	TEMP: 35C
2013/07/30 14:26:01	TEMP: 36C
2013/07/30 14:26:01	TEMP: 37C

Figure 10. Received real-time temperature data on the central server

IV. Conclusion

In this paper, we introduced the architecture of wireless sensor network system for structural health monitoring using a customized system-on-chip with a standard Android smartphone. We integrated two systems, RUSH and MSDC, where RUSH is capable of acquiring and processing ultrasonic data, and MSDC is designed to display the sensor data transmitted from RUSH and act as a gateway to the central server to enable data mobility. To illustrate our system, we presented three different types of sensors that can be useful for the structural health monitoring. As an example, we examined a steel block for flaw detection by applying the SSP algorithm to the ultrasonic signal. Acquired data is analyzed on RUSH and transmitted to MSDC using the Bluetooth transceiver. Accelerometer and temperature sensor are also acquired using MSDC. MSDC plots the received sensor data on the screen of the smartphone, and simultaneously transmits to a central server. With this configuration of our customized RUSH and MSDC, we provides a system architecture capable of analyzing and monitoring the health of critical structures robustly and efficiently.

References

[1] NDT Resource Center. (2012) NDT Method Summary. [Online]. Available: http://www.ndt-ed.org/GeneralResources/MethodSummary/MethodSummary/MethodSummary.htm

[2] NDT Resource Center. (2012) Introduction to Ultrasonic Testing. [Online]. Available: http://www.ndt-ed.org/EducationResources/CommunityCollege/Ultrasonics/Introduction/description.htm

[3] Korea Energy Management Corporation. (2009) Vibration- Types and Features of Vibration Measurement Sensors. [Online]. Available: http://www.kemco.or.kr/up_load/blog/%EC%A7%84%EB%8F%99-%EC%A7%84%EB%8F%99%EC%B8%A1%EC%A0%95%EC%84%BC%EC%84%9C%EC%A2%85%EB%A5%98%EB%B0%8F%20%ED%8A%B9%EC%84%B1.pdf

[4] D. Inaudi, B. Glisic, "Distributed Fiber Optic Strain and Temperature Sensing for Structural Health Monitoring," *The Third International Conference on Bridge Maintenance, Safety and Management,* pp. 1-8, Jul. 2006

[5] T.M. Roberts, M. Talebzadeh, "Acoustic emission monitoring of fatigue crack propagation," *Journal of Constructional Steel Research*, vol. 59, no. 6, pp. 695-712, Jun. 2003

[6] S. Gilliland, J. Saniie, S. Aslan, "Linux Based Reconfigurable Platform for High Speed Ultrasonic Imaging," *IEEE 55th International Midwest Symposium on Circuits and Systems*, pp. 486-489, Aug. 2012

[7] W. Yi, W. Jia, J. Saniie, "Mobile Sensor Data Collector using Android Smartphone," *IEEE 55th International Midwest Symposium on Circuits and Systems*, pp. 956-959, Aug. 2012

[8] Xilinx, Zynq-7000 All Programmable SoC Overview DS190 (v1.3), Mar. 2013

[9] Xilinx, Zynq-7000 All Programmable SoC Technical Reference Manual UG585 (v1.5), Mar. 2013

[10] Analog Devices, 16-Bit, 200 MSPS/250 MSPS Analog-to-Digital Converter, AD9467 (Rev. D), Feb. 2013

[11] J. Weber; E. Oruklu; J. Saniie; , "FPGA-based configurable frequency-diverse ultrasonic target-detection system," *IEEE Transactions on Industrial Electronics*, vol. 58, pp. 871–879, Mar. 2011

[12] E. Ferro, F. Potorti, "Bluetooth and Wi-Fi wireless protocols: a survey and a comparison," *IEEE Wireless Communications*, vol. 12, no. 1, pp. 12-26, Feb. 2005

[13] GSMArena. (2012) Samsung Galaxy S III T999. [Online]. Available: http://www.gsmarena.com/samsung_galaxy_s_iii_t999-4804.php