 SDHM, vol.5, no.4, pp.295-310, 2009

# Development of a Portable Integrated Wireless Sensor Module for Structural Damage Monitoring

**Ramana M. Pidaparti[1], Ashwin Belle[2] and Ju Wang[3]**

**Abstract:** This paper presents the development of a portable integrated wireless sensor module with video camera and ultrasound capabilities to monitor and investigate corrosion damage "in" structures. There are many studies in the literature on structural health monitoring with various sensors systems. However, very few of them utilize low power devices with reliable wireless communication capability to support data-intensive sensing which is a critical issue for practical applications. In this study, we developed a wireless sensor module with video camera capabilities and integrated it with a damage analysis module to investigate the damage of a structure. The module provides an open interface design which allows different physical sensors to be plugged into the existing software and hardware stack. It's high speed flexible networking layer allows stand-alone as well as networked sensing. The preliminary results indicate that the developed system can be scaled up to monitor structural damage in infrastructural systems.

## 1 Introduction

Degradation of metallic structures due to its operating environment is a major factor affecting the structural integrity, public safety and economy of industries around the world. Structures made from metals and their alloys are being used as structural/load bearing members in many areas including infrastructure, mechanical, aerospace, and petroleum industries. During operation, these structures are subjected to a variety of damage mechanisms including metal corrosion, cracks, and fatigue, among others. Structural durability of an operating/aging structure is directly related to the material and structural performance and related parameters, and hence the safety of operation.

[1] Department of Mechanical Engineering, Virginia Commonwealth University, Richmond, Virginia 23284
[2] Department of Computer Science, Virginia Commonwealth University, Richmond,Virginia 23284
[3] Department of Mathematics and Computer Science, Virginia State University, Petersburg, Virginia 23806

Structural health monitoring (SHM) is a process to detect, monitor and assess damage in structures in real time. The importance of SHM is increasing due to natural disasters and environmental effects impacting the structural integrity of structures. In the past decade, there have been many accidents in civil infrastructures due to structural damage. The recent failures in infrastructural systems (Minnesota bridge collapse, pipeline failures in Alaska and others, see Fig. 1) have brought national attention to the problem of structural damage detection and monitoring. As evidenced by the above situations as well as in other applications, it is possible for severe degradation in infrastructure systems to remain undetected until a catastrophic failure occurs. In order to avoid such failures, various SHM and Non Destructive Evaluation systems (eddy current inspection systems, enhanced visual inspection system or stereographic system, acoustic emission, and others) have been used to detect the cracks/damage in aging structures and materials Finlayson et al (2000); Rong-Sheng (2004); Wilson and Hagemaier (1999); McAdam et al (2005); Maalej et al (2004); Reda Taha et al (2006). Non-destructive evaluation (NDE) procedures involve establishing a correlation between measured properties and quantitative information about anomalies. For example, Eddy current NDE involves measurement of impedance and correlating it with the damage (crack, or change in microstructure) producing it. There is a growing demand for improving existing NDE techniques to achieve maximum confidence and reliable results with minimum damage.

Figure 1: Recent failures resulting from corrosion damage in bridges and pipelines (from USA Today)

The SHM system includes both hardware and software and can be cost effective using the approach of condition-based maintenance [Worden and Dulieu-Barton (2004)]. SHM systems are built around the concepts of embedded sensors Wang, Mbonisi and Liu (2007), networked sensing systems Akyildiz et al (2002) and intelligent sensing algorithms Shehata and Rizkalla (1999). With the recent progress in sensing and computing and wireless communication technologies Wang and Liu

(2010), sophisticated computational modeling can be performed in the SHM sensor systems that was not imaginable in the past. The new generation of SHM systems will be even more powerful with added smart sensing capability.

Wireless sensing network and communication systems are being used to monitor several structural systems, see for example Refs. Lynch (2005); Marscarenas et al (2007) and Whelan and Janoyan (2009). Smart sensing technologies that incorporate wireless sensor networks in SHM using small integrated sensor and processor systems have been reviewed by Lynch and Loh Lynch and Loh (2006). Energy efficiency has become an important design consideration for wireless communication systems. A poorly designed network protocol can easily drain the battery and shorten the lifespan of sensor devices. For wireless sensor networks, an energy efficient protocol design can be implemented at the transporting layer Luo et al (2003); Wu, Chan and Mukherjee (2000), MAC layer Wu (2002); Guha and Khuller (1998); Ye, Heidemann and Estrin (2002) and the network layer Wu (2002); Guha and Khuller (1998). Transmitting data through wireless transceiver presents several issues dealing with limited bandwidth, possibility of dropping data packets and coordination of decentralized hardware, among others. Even though, there is a great deal of literature focusing on structural health monitoring with various sensors systems, very few studies have employed low power devices with reliable wireless communication capability to support data-intensive sensing, which is a critical issue for practical applications. In this study, we developed a wireless sensor module with video camera capabilities and integrated it a with damage analysis module to investigate the damage of a structure. The module provide an open interface design which allows different physical sensors to be plugged into the existing software and hardware stack. Its high speed flexible networking layer allows stand-alone as well as networked sensing.

In Sections 2 and 3 below, we provide a brief summary of the system architecture as well as details of the hardware/software aspect of the implemented sensor module. The on board corrosion and damage analysis module is discussed in Section 4. Finally we provide a demonstration of the implemented system in section 5.

## 2 Integrated Wireless Sensor System

The architecture of the integrated smart sensor system consists of three basic components: sensor (JPEG video camera); a PDA device, embedded wireless sensor board, and a handheld device as shown in Fig. 2. The workflow of the system has three processing stages. The first stage is the *Capture* stage. Here we developed an embedded wireless camera sensor [Worden and Dulieu-Barton (2004); Wang, Mbonisi and Liu (2007)] which can be placed in remote areas of a structure (aircraft or bridge) and operated wirelessly to capture and send back images of the damage surfaces that need to be analyzed. The second stage is the *Analysis* stage where the captured images are routed to a server station wirelessly and further processed by damage analysis software to detect and quantify damage. Based on the resulting quantified damage assessment, a decision can be made about the necessary actions to be taken. The third stage involves relaying key *Analyzed Information* to a maintenance technician on the field. This is accompolished with a wireless transmission of the data from the server station to a handheld computing device such as a PDA which has customized software showing easily interpretable data, images and information regarding required actions to be performed.

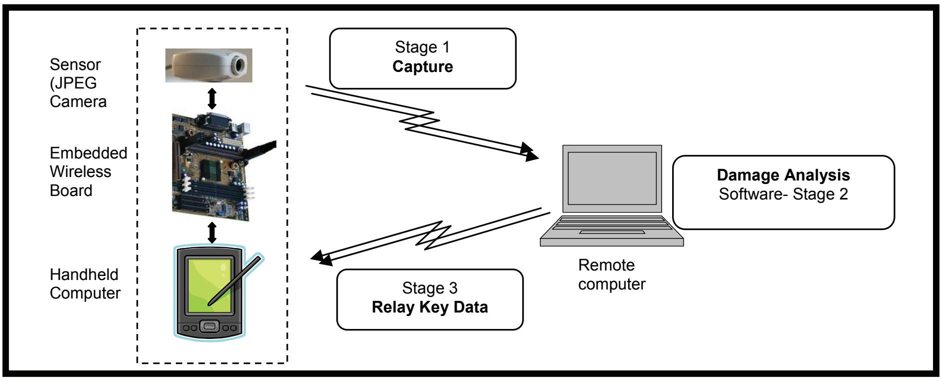



Figure 2: An overview of the system architecture of the portable integrated wireless sensor module for damage monitoring

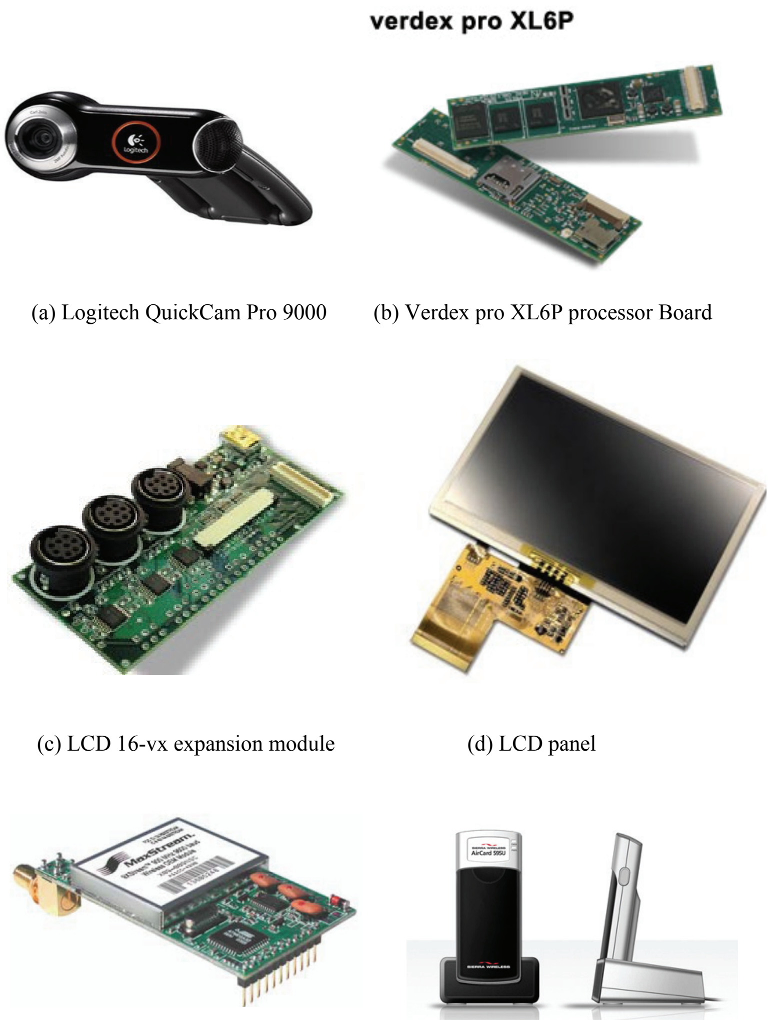
## 3 Development of Wireless Sensor Module

The wireless sensor module consists of a sensor component, a processing module, user interface boards, and communication modules which are detailed below.

### *3.1 Sensor Component*

The sensor component involves capturing an image of the damage surface on the structure with a Logitech QuickCam Pro 9000 as shown in Fig. 3(a). This webcam is a high resolution webcam providing both video stream and static images with a 2 mega pixel resolution. The camera can capture images with a frame rate of up to 30 frames per second. It is a well designed highly compact image capture device.

Although it is primarily designed to work with desktop computers, there are certain open source drivers available that will integrate this webcam with linux based em-




(a) Logitech QuickCam Pro 9000

(b) Verdex pro XL6P processor Board

(c) LCD 16-vx expansion module

(d) LCD panel

(e) 900MHz wireless modem

(f) AirCard® 595U USB CDMA modem.

Figure 3: Wireless sensor module components

bedded devices. The camera driver must be modified and ported to work with the customized Linux operating system running on top of the target Gumstix platform (see next section). The driver also had to be integrated onto the arm architecture. We used the BitBake OpenEmbedded cross compiler and an open source UVC driver was cross compiled to work on the Gumstix platform.

To provide easy integration of other imagery sensors, a well defined sensory software architecture must be implemented to act as a uniform docking station and provide data stream for upper layer softwares. After careful consideration, the V4L framework (also known as the Video4Linux framework) was selected. The V4L framework is a video capture application programming interface for Linux which already supports several USB webcams, TV tuners, and other devices. Video4Linux is closely integrated with the Linux kernel. The modified framework can interface with general imagery sensors and provide a standard accessing port for sensor inquiry, reading and control. For example, the framework allow us to capture images and store them on the local memory.

### *3.2 Local Processing*

All control and local processing was completed with a Gumstix embedded computer running a fully functional, Linux operating system. Each Gumstix motherboard is packed with the power and performance of much larger SBCs (Single Board Computers), making Gumstix motherboards practical as the brains of the network management appliances, handheld devices, industrial monitors, robotics and much more.

Gumstix motherboards come in two active product lines; the smaller than a gum stick, Overo™ series based on Texas Instrument OMAP® 3503 and gum stick size verdex pro using Marvell® PXA270 with XScale™. For this project the Verdex pro (Fig. 3b) with the Marvell chipset seemed ideal and was chosen as the primary processing module. Verdex pro motherboard offers on-board storage with microSD and flexibility by way of adding two expansion boards: one on each side of the motherboard.

With the on-board memory slot and optional 10/100 and wifi connectivity, the verdex pro motherboard becomes the core component inside demanding mobile, remote and engineering devices. Our prototype device was expanded with a 2GB micro SD Card. The Linux Image has been built onto the SD card for easy booting and expansion. The implemented Linux kernel is the 2.6.21 version. The device was setup such that the booting can directly take place from the SD card.

The physical connections between the Gumstix computer and the external sensors and the user interface are provided by a console expansion board. The extension board driver has a touch resistive LCD panel as a local display device (see Fig. 3c). The touch screen adds a level of sophistication as well as usability to the overall system. The expansion board comes with three RS-232 ports on miniDIN8 connectors, thus allowing several I/O interaction capabilities. It also hosts a USB mini-B connector with USB Host signals. The board also provides GPIO lines and an I2C port, allowing connection to various kinds of peripheral devices to the system.

Communication with the embedded computer is provided by a communication expansion board with standard networking interfaces such as LAN and Wifi. Such facilities allows the device to be remotely debugged and managed and in case of system errors, to be fixed without retrieving the physical device.

### *3.3 Software Development Cycle with the Sensor Module*

It is to be noted that the Gumstix is of the ARM architecture. So each operation and the Linux image itself must be cross compiled onto the arm architecture before being flashed onto the Gumstix board. The basic development environment consists of a Linux Desktop computer running Ubuntu 7.10. This desktop hosts all the source codes trees for the customized embedded Linux operating system, the image sensory framework, the remote communication driver, the image processing algorithms and the cross compilation tools.

Although the Gumstix has a prebuilt image ready to go out of the box, a new image had to be built for the more sophisticated needs of the system under development. Hence the newer Linux image was built with the target application in mind. The newer image has the GUI (Graphics User Interfacing) interfacing rather than just a command line interaction setup. The newer image also supports the touch screen feedback, thereby enhancing the user interaction in a more effective manner.

Due to the enhancements in the new image, the actual size of the image was found to be considerably larger than the standard pre built image. Thus a MicroSD card of size 2GB was installed to expand the memory space so as to accommodate the larger sized Linux image.The 2GB SD card was divided into two partitions and the second partition occupies the majority of the storage space and is formatted to the EXT2 type file system. This partition will host the root file system of the Linux OS.

### *3.4 Wireless Communication Modules*

In additional to the WIFI interface, two more wireless technologies were built in our design to boost the communication capability. For short range inter-sensor communication, the Zigbee interface was chosen due to its ease of operation, scalability and power. But due to its shortcoming such as its short range and lesser reliability, it was decided that a different wireless protocol would be necessary to be implemented for long range communication to connect between sensor devices and a remote computer. Therefore, the CDMA protocol was chosen. In this design frame we incorporated a commercially available wireless data card by Sprint. This wireless data card functions on the CDMA technology and can be used in all places where the CDMA network reception is available.

The AirCard 595U USB modem (see Fig. 3d) can either plug directly into any USB port, or can be connected via the included docking cradle. The AirCard supports wireless data transfer at max speeds of 3.1 Mbs downlink and 1.8 Mbps uplink, It has the EV-DO Rev A networks High performance internal antenna with increased improvements in data speed, signal acquisition and retention. It supports Dual-band, 800 and 1900 MHz, with built-in GPS antenna.

When communication infrastructure is not available, an auxiliary long range Xtrem wireless modem (Fig. 3d) is used as a back up. The Xtreams are designed for long range data communications and are capable of up to 7 miles line-of-sight range with a 2.1 dBm dipole antenna. Ranges of up to 20 miles can be achieved with high gain antennas. Power output is 100mW. The receiver sensitivity is -110 dBm for the 9600 bps model and -107 dbm for the 19200 model. The modem operates in the 902-928 MHz frequency range using a spread spectrum frequency hopping wide band FM modulator. This range is divided into 25 channels with 7 hopping sequences.

The whole assembly of the Gumstix computer including the Linux image and the LCD screen is presented in Figure 4.

## 4 Damage Analysis Module

After the image of the structural damage is captured, the image is processed for damage analysis. Image analysis-based techniques are being developed for the identification and quantification of structural corrosion damage based on several sensor techniques (ultrasound, acoustic imaging, infrared imaging, eddy current imaging, impedance imaging and X-ray radiography). The overall process of identification of structurally corroded regions from sensor images is shown in Figure 5. The process essentially involves two stages: first, classification of various regions in the image as corroded or uncorroded, and second, prediction of the material loss of the corroded regions using neural networks. The classification process involves segmenting the image into various regions. Multi-resolution wavelet analysis is performed on the sensor images to obtain a set of wavelet coefficients as feature vectors. These features were used for the identification of the damaged regions

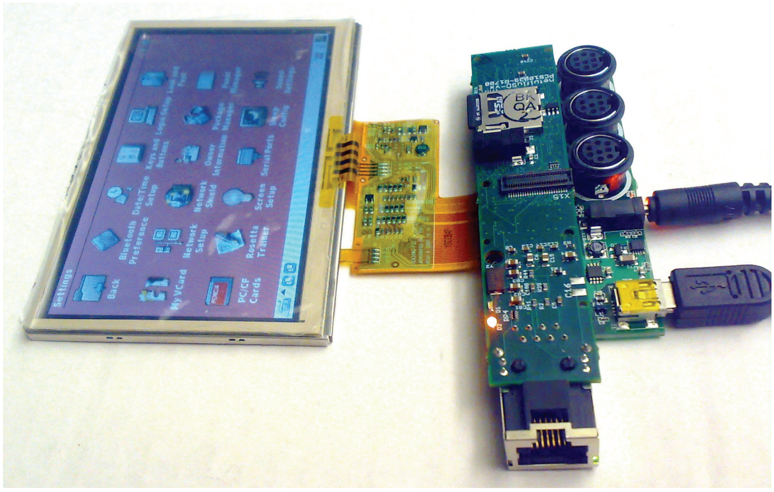


Figure 4: Completed wireless sensor module and Gumstix setup

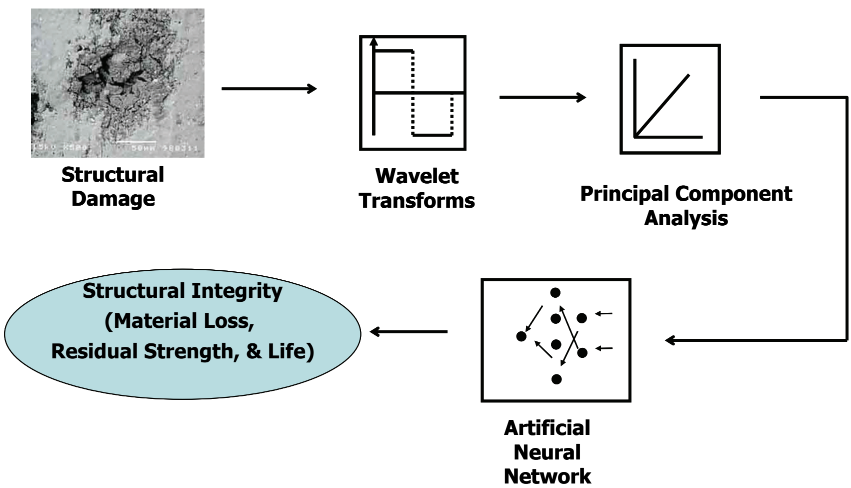



Figure 5: An overview of damage analysis module

on the sensor images using clustering techniques. Each of the segments on the segmented image corresponds to a damaged region or an undamaged region and results of segmentation algorithms were developed. Once the damaged segments are identified, first-order and second-order features are extracted from each identified segment. Neural networks are capable of realizing a variety of non-linear relationships of considerable complexity and are effectively used in this study. A back-propagation neural network is then used to quantify the damage. The quantification of damage is based on the extent of material loss. Further results on material loss prediction and the quantification algorithms can be found in Pidaparti (2007, 2006).

In order to demonstrate the validity of the present approach for corrosion damage assessment, an engineered corrosion panel imaged using Eddy current sensor technique is used. Figure 6 shows the original panel along with the assessment results of corroded panel using the approach presented earlier. Assessments of the severity of structural damage are based on factors such as the quantitative value of the damage, the area where it occurred and other peripheral information. Severity of damage is estimated through a learning and prediction model that is based on artificial neural networks (NN) and fuzzy logic. The developed models learn to predict various properties such as fatigue life, material property, and residual strength. An example of NN prediction of the residual strength and fatigue life for a corroded panel is shown in Fig. 7. The results obtained from the developed damage analysis models are in good agreement with the experimental data. The results obtained demonstrate the value of damage analysis methods for the analysis and prediction of structural degradation at any instant in time during the structural health monitoring process.

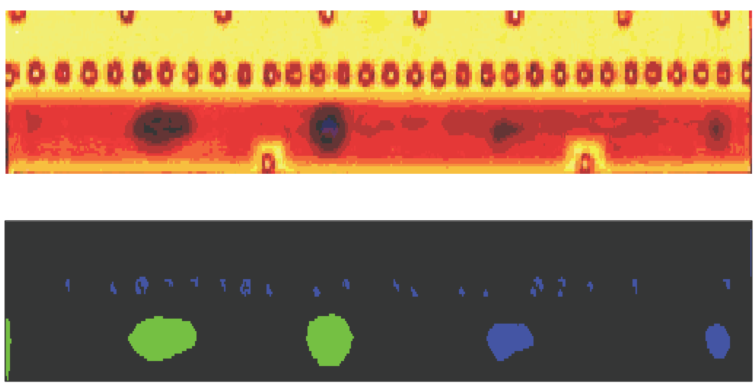


Figure 6: The original corrosion damage panel (left). Image right damaged panel are the assessment obtained from the proposed techniques. The color index shows the material loss as, Black: 0%; Blue: 0% - 5%; Green: 5% - 10%; Yellow: 10% - 15%; Magenta: 15% - 20%; and Red: 20% - 25%.

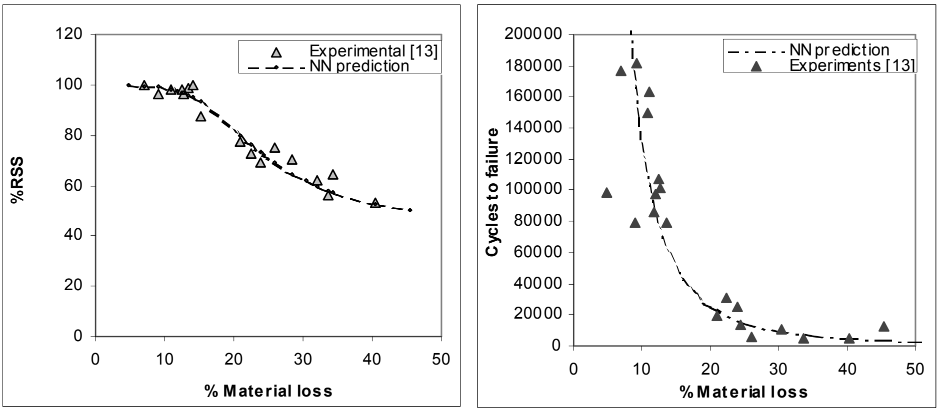



Figure 7: Neural Network Model for Residual Strength and Fatigue Life Prediction given a Material Loss due to Corrosion

## 5 Demonstration Experiments

We primarily focused on the latency and throughput of the long range communication capability when infrastructure is not available. Our implemented communication protocol is optimized for the long range, low density deployment which is typical in a remote monitoring system. Such properties results in a more smart retransmission design and relatively simple upper layer functionality. Figure 8 shows the layered communication stack governing the device communication. In the following experiment the sensor device is programmed in transmit mode, and the remote server is used in receiving mode.

### *5.1 Transmit Mode*

When serial data is received from the UART to the modem's buffer, it will attempt to enter into Transmit mode. At this point, the modem will initiate an RF connection with another modem. Serial data in the modem's buffer is grouped into RF packets of up to 2KB and is transmitted until the buffer is empty. The *RF Initializer* is sent when a new connection is established. It contains channel information for the receiving modems. This includes the hopping pattern. When sending multiple packets, the initializer is only sent at the beginning of the first packet.

The *Header* contains the network addressing information. This is used to filter incoming data. The modem checks for matching hopping channel, vendor identification number and destination address. If these criteria are not met, the packet is discarded. The Cyclic Redundancy Check is used to provide error checking, and a

16bit-CRC is computed and sent at the end of every RF packet.

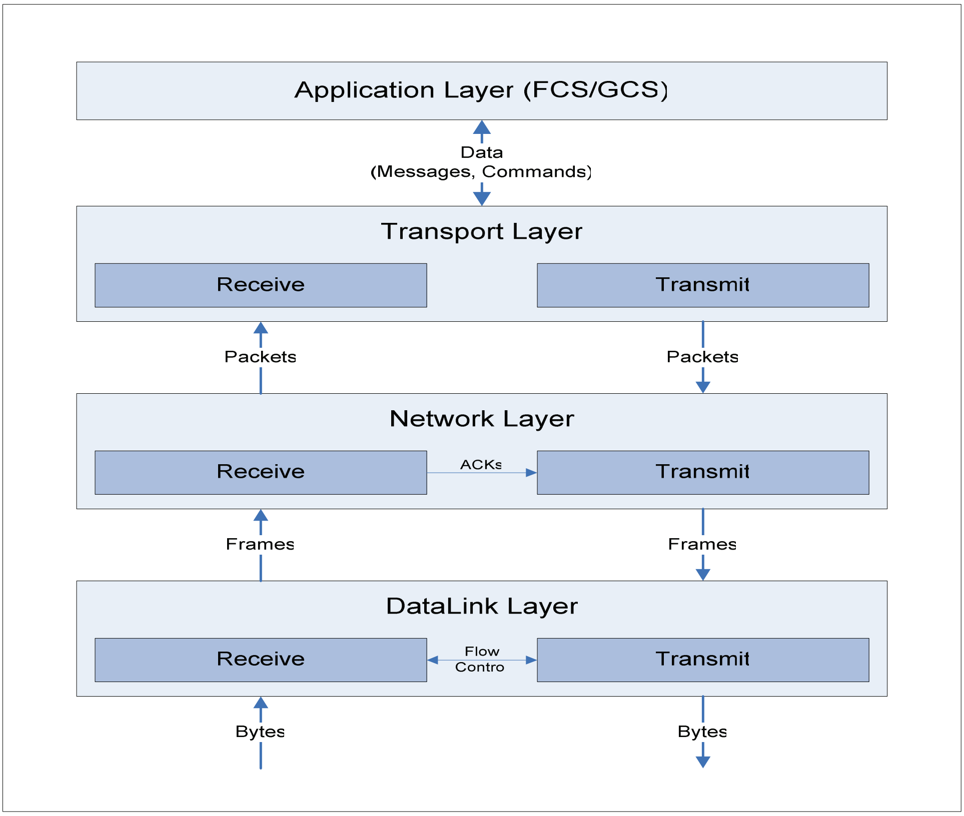



Figure 8: Protocol stack

### *5.2 Receive mode*

The modem will enter the Receive mode from the idle mode when it detects RF data. Once a complete packet is received, the modem will perform a CRC and verify the addressing information in the header. If CRC is valid and network address information match, the packet will placed in the data output buffer.

Figure 9 showed the latency of unreliable packets that were injected into the transmission of the various-sized reliable packets. Clearly, for both the faster and slower modems, the latency of the packets increases as the packet size increases. The frame size of the reliable packets, however, has little to no effect on the latency of the reliable packets. For the slower modems, again there is a significant issue

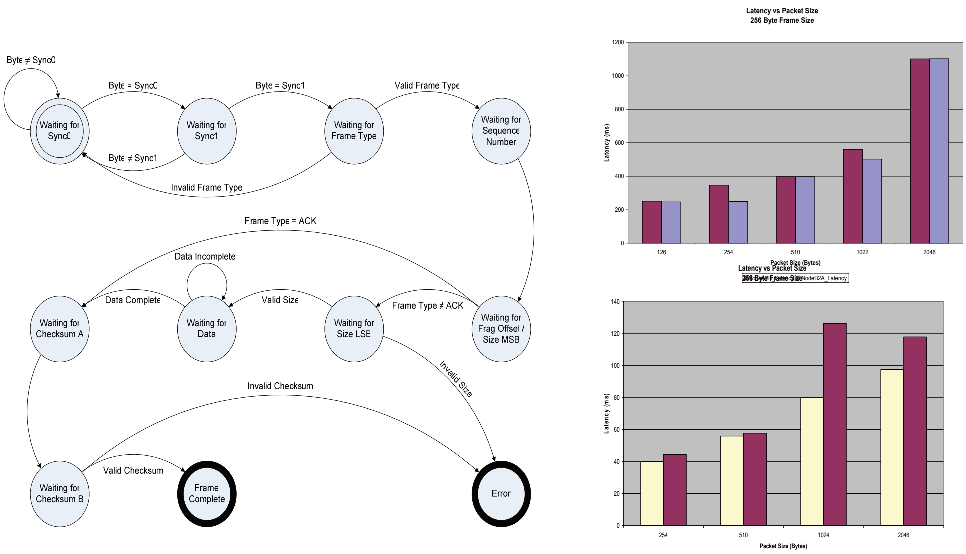



Figure 9: (left) protocol state machine, (right) Link performance under different payload and overhead.

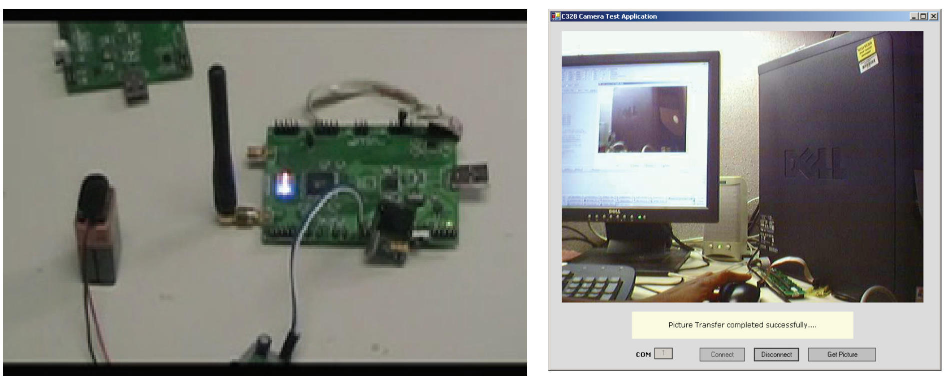



Figure 10: (left) Wireless Image Sensor module in work, (right) Remote desktop server processing captured images.

as the packet size approaches 2KB. The latency doubles between 1KB and 2KB packet sizes for the slower modems. This is likely due to the 2KB internal modem buffer that was mentioned previously. The faster modems are able to transmit the unreliable ping packets in a reasonable amount of time even at that 2KB threshold (approx. 100ms latency). In terms of latency, it would be best to use the smallest packet size possible, but it has too much of an impact on the throughput so that would be a bad trade-off. It is better to sacrifice a little latency for a potentially significant increase in data throughput.

### *5.3 Demonstration*

Figures 10 shows a demonstration setup with one wireless image sensor and the remote server site. The wireless image sensor is powered by a 9-V battery. A CMOS camera is attached to the main sensor module via the industry standard serial interface. The antenna is attached to the left side of the module. The bright LEDs on the module indicate that a good wireless communication link is already established between the sensor module and a remote server.

On the right side, we show a snapshot of the corrosion detection software suite at the remote server. The remote images can be displayed on the screen and processed for corrosion assessment. The software can send control commands to the remote sensor to control the working parameters, such as optical zoom level of the image sensor. This is a preliminary demonstration to make sure all the modules are working together for practical applications.

## 6 Summary and Conclusions

We present a prototype design of a wireless imagery sensor device for infrastructure structural damage monitoring. The underlying hardware and software components are described and its performance is measured. The device allows real time imagery data collection and both local/remote analyzing and diagnosing. Furthermore, its building communication and computing tools make it a flexible platform to test networked co-operative sensing algorithms which will improve accuracy of diagnosis results. Our preliminary data shows that the proposed system represents a blanched computing and communication power for structural damage monitoring applications.

**Acknowledgement:** The first author thanks the National Science Foundation for sponsoring the research through grants CMS-0516665 and DMR-0505039.

## References

**Akyildiz I. F., Su W., Sankarasubramaniam Y., Cayirci E.** (2002): A Survey on Sensor Networks, *IEEE Communications Magazine*.

**Finlayson, R. D.; Friesel, M. A.; Carlos, M. F.; Miller, R.; Godinez, V.** (2000): Acoustic Emission Structural Health Management Systems (AE-SHMS). *Proceed-*

*ings of SPIE - The International Society for Optical Engineering*, v 3994, pp. 128-137.

**Guha S., Khuller S.** (1998): Approximation Algorithms for Connected Dominating Sets, *Algorithmica*, vol. 20, no. 4, pp. 374-387.

**Luo H., Ramjee R., Sinha P., Li L., Lu S.** (2003): UCAN: A Unified Cellular and Ad-Hoc Network Architecture, in *Proceedings of ACM Mobicom'03*.

**Lynch J. P.** (2005): Design of a Wireless active sensing unit for localized structural health monitoring. *J. Struct. Health Monit.,* 3, 405-423.

**Lynch J. P., Loh K. J.** (2006) A Summary Review of Wireless Sensors and Sensor Networks for structural health monitoring. *J. Shock Vib. Dig*. 38, 91-128.

**Maalej, M., Ahmed, S. F.U., Kuang, K. S.C., Paramasivam, P.** (2004): Fiber Optic Sensing for Monitoring Corrosion-Induced Damage. *Structural Health Monitoring*, 3: 165-176.

**Marathe M. V., Breu H., Hunt H. B. III, Ravi S. S., Rosenkrantz D. J.** (1995): Simple heuristics for unit disk graphs. *Networks*, 25: 5968.

**Marscarenas D. L., Todd M. D., Park G., Farrar C. R.** (2007): Development of an impedance-based wireless sensor node for structural health monitoring, *Smart Mater. Struct.,* 16, 2137-2145.

**McAdam, G., Newman, P.J., McKenzie, I., Davis, C., Hinton, B. R. W.** (2005): Fiber Optic Sensors for Detection of Corrosion within Aircraft. *Structural Health Monitoring*, 4: 47-56.

**Pidaparti Ramana M.** (2006): Aircraft Structural Integrity Assessment through Computational Intelligence Techniques, *Journal of Structural Durability and Health Monitoring,* Vol. 2, No.3, pp. 131-148.

**Pidaparti Ramana M.** (2007): Structural Corrosion Health Assessment through Computational Intelligence Methods, *Journal of Structural Health Monitoring,* Vol. 6, No. 3, pp. 245-259.

**Qayyum A., Viennot L., Laouiti A.** (2002): Multipoint relaying for fooding broadcast messages in mobile wireless networks, in Proceedings of the Hawaii International Conference on System Sciences (HICSS02).

**Reda Taha, M. M., Noureldin, A., Lucero, J. L., Baca, T. J.** (2006): Wavelet Transform for Structural Health Monitoring: A Compendium of Uses and Features. *Structural Health Monitoring*, 5: 267-295.

**Rong-Sheng, G.** (2004): Evaluation of calendar damage of aircraft structures using acoustic emission. *Key Engineering Materials*, v 270-273, No. I, pp. 503-509.

**Shehata E., Rizkalla S.** (1999): Intelligent Sensing for Innovative Bridges, *Journal of Intelligent Material Systems and Structures*, Vol. 10, No. 4, 304-313.

**Wang J., Mbonisi M., Liu J.** (2007): Supporting Video Data in Wireless Sensor Networks, *IEEE International Symposium on Multimedia*.

**Wang J., Liu J.** (2010): Uplink Relaying in Wireless Networks with Out-of-cell Interference Reduction, ACM Journal of Wireless Network, accepted.

**Whelan M. J., Janoyan K. D.** (2009): Design of a Robust, High-rate Wireless Sensor Network for static and dynamic structural monitoring. *Journal of Intelligent Material Systems and Structures*, Vol. 20, No. 5, 849-863.

**Wilson, D. S.; Hagemaier, D. J.** (1999): ABCs of NDT development and adoption for aging aircraft. *Materials Evaluation*, vol. 57, No. 3, pp. 336-346.

**Worden, K., Dulieu-Barton, J. M.** (2004): An Overview of Intelligent Fault Detection in Systems and Structures. *Int. J. Struct. Control Health Monit.*, 12, 85-98.

**Wu X., Chan S.-H., Mukherjee B.** (2000): MADF: A Novel Approach to Add an Adhoc Overlay on a Fixed Cellular Infrastructure, In Proceedings of IEEE WCNC, vol. 2, pages 549-554.

**Wu J.** (2002): Extended Dominating-Set-Based Routing in Ad Hoc Wireless Networks with Unidirectional Links, *IEEE Trans. Parallel and Distributed Systems*, vol. 13, no. 9, pp. 866-881.

**Ye W., Heidemann J., Estrin D.** (2002): An energy-efficient MAC protocol for wireless sensor networks, in Proceedings of the The 21st Annual Joint Conference of the IEEE Computer and Communications Societies.