Source*: Proceedings of the MCEER Mitigation of Earthquake Disaster by Advanced Technologies (MEDAT-2) Workshop,* Las Vegas, NV, USA, November 30-31, 2000.

The Development of a Wireless Modular Health Monitoring System for Civil Structures

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Abstract

Current structural monitoring systems employ conventional cables to allow sensors to communicate their measurements to a central processing unit. Cabled based sensing systems for structures have high installation costs and leave wires vulnerable to ambient signal noise corruption. To address these disadvantages, a research effort has been initiated towards the development of a wireless modular monitoring system. The developed wireless modular monitoring system (WiMMS) would have lower capital and installation costs as well as ensure more reliability in the communication of sensor measurements. Some key areas of innovations emphasized are the use of a wireless communication system for inter-sensor communication, the utilization of micro-electro mechanical sensing elements, and the use of a microprocessor for advanced damage detection methods.

Introduction

There exists a need for a rational and economical method of monitoring the performance of civil structures over their lifespans. Monitoring systems are currently playing a dominant role in applications such as nonlinear model validation, structural health monitoring and structural control. Current design practice analytically determines a structure's nonlinear response based upon nonlinear models of the key load carrying elements. A monitoring system can provide invaluable insight into the accuracy of these nonlinear models and can assist engineers in refining them. For example, short and long span bridges in California are being instrumented by the California Department of Transportation (Caltran) to monitor the nonlinear response of the bridges during extreme seismic events [1]. Just as important is the need of a rapid assessment of the performance and safety of civil structures. Using a monitoring system to measure structural responses, a damage detection strategy is then employed to diagnose possible short and long-term damage in a structure. Last but not least, in the structural control field, one key component of a control system is an integrated monitoring system that can provide feedback of real time measurements of structural response.

With the rapid advancement of sensing, microprocessor, wireless and other technologies, one of the research challenges is to assess the benefits gained from the application of such technologies in the structural engineering field. Our research efforts have identified wireless communication technology, micro-electro mechanical (MEM) devices, microprocessors and digital signal processors, as key areas of innovation that can be used to develop a novel wireless monitoring system for civil structures.

Traditional Structural Monitoring Systems

The origin of commercially available structural measurement systems is from those regularly used in enclosed, laboratory settings. As a result, the systems are characterized as being of the hub-spoke architecture with accelerometers remotely placed throughout the structure but wired back to a single centralized data acquisition unit.

Among the key problems inherent in these systems are the installation time and cost. From experience, the installation time of a complete measurement system for bridges and buildings, can potentially consume over 75% of the total testing time. Installation labor costs can approach well over 25% of the total system cost. Caltran reported that it costs over $300,000 per toll bridge to install a measurement system comprised of 60 to 90 accelerometers. To isolate the wires from the bridge's harsh environment, a wire conduit is installed at a cost of $10 per linear foot [1]. Within buildings, wires are susceptible to tearing, rodent nibbling and measurement corruption through signal noise.

Wireless Structural Monitoring System

Our primary goal is to change the practice of using extensive cabling and high cost labor as is typical of the traditional monitoring systems to a system of inexpensive wireless embedded systems that can be installed, maintained and operated with ease (see Figure 1).

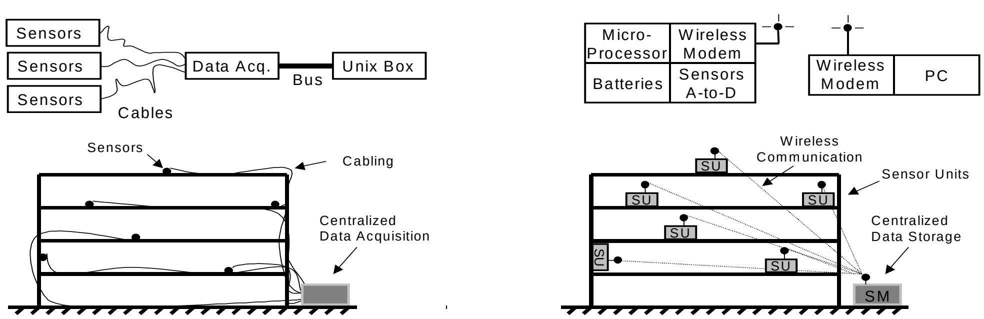

Figure 1 – From Conventional Cabled to Wireless-Embedded Structural Monitoring System

In a previous study, a proof-of-concept system has been fabricated from commercially available components. The system has been successfully used in a full-scale experiment of the Alamosa Canyon Bridge in New Mexico [2]. With the collaboration of researchers at Los Alamos National Laboratory, the units were validated by comparing the wireless sensor's measurements to those of a conventional cabled monitoring system. Installation took well over 2 hours for the cabled monitoring system while the five wireless sensing units took less than a half hour to install. This study has clearly demonstrated the time and cost effectiveness of a wireless monitoring system.

A wireless communication system provides a “free infrastructure” in that the need for the installation of wires is eradicated and the accommodation of direct communication between sensing units is provided. While a centralized data acquisition system can still be designed using the wireless network, the flexibility of the system allows for a decentralized data acquisition system with sensors transmitting measurements directly to the other system sensors.

A primary innovation is the migration of computational power from the centralized data acquisition system to the sensor units. The computational power that is provided by an advanced microprocessor is harnessed when the wireless sensors are implemented in a structural monitoring system used for such applications as structural health monitoring and structural control. The microprocessor is also utilized to coordinate the functionality of the sensor units such as sampling the sensor’s output, packaging the measurements for transmission, and operating an integrated radio modem for communication.

While accelerometers are used in most structural sensing applications, the sensor units are compatible with any type of analog sensor. In the Stanford prototype, a micro-electro mechanical (MEM) based accelerometer is used. By fabricating micrometer sized mechanical elements upon silicon, revolutionary sensors can be fabricated along with CMOS based circuits all on one chip. The result is accurate and sensitive sensors in form factors and unit costs not previously possible. One example is the high performance planar accelerometers designed and fabricated by Professor Thomas Kenny’s group at Stanford; the accelerometer uses piezoresistive elements along the cantilevering arm of a proof mass for direct acceleration measurements (See Figure 2). By modifying the dimensions of the cantilevering element, desirable sensor characteristics can be attained for structural sensing [3].

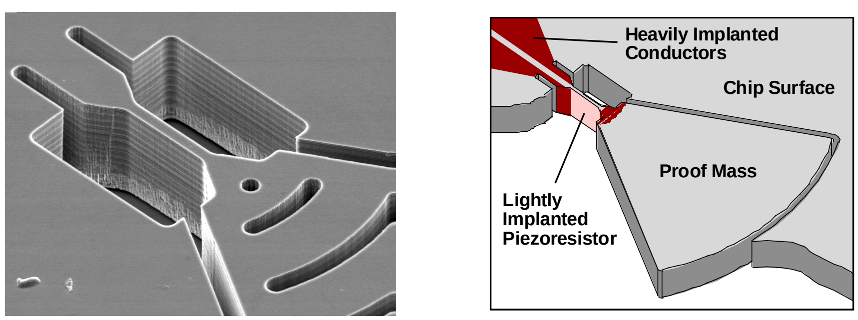

Figure 2 – MEMs Based Piezoresistive Accelerometer

WiMMS Based Structural Monitoring Strategies

Current research efforts are focused on integrating the prototype wireless sensors into a complete structural monitoring system for damage detection. Termed a wireless modular monitoring system (WiMMS), the system will provide rapid and global damage diagnosis. While visual structural inspections would still play a major role in evaluating the safety of structures, the proposed system would serve to assist the inspection teams in prioritizing which structures to consider first and where in them to look.

Structural health monitoring systems utilize a structural sensing system to observe the response of a structure over time at equally spaced intervals. Time and frequency based properties are extracted from these measurements to see their changes over time. Many approaches to health monitoring have been proposed, ranging from those conducted deterministically to those conducted statistically in both the time and frequency domain. Our current research focuses on statistical-based approaches, which can take full advantages of the embedded wireless sensor monitoring system, for rapid damage assessment and global damage diagnosis [4,5].

Conclusion

An embedded wireless sensor monitoring system has been developed. In comparison to its cabled counterparts, the system enjoys the benefit of cheaper and quicker installations as well as superior performance. With computational power pushed forward from the central data acquisition system to the sensor itself, these novel sensors can be integrated with methods for structural health monitoring and damage detection. Rapid and global damage assessment using the sensors is one step towards a modular sensing system for the protection of vital civil structures.

Acknowledgments

This research is partially sponsored by the National Science Foundation under Grant No. CMS-9988909. The authors would like to thank the collaborative support of Drs. Charles Farrar, Scott Doebling and Dr. Hoon Sohn of Los Alamos National Laboratory.

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