Multi-scale Smart Sensing for Monitoring Civil Infrastructure

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Work currently being conducted under the NSF award entitled "Multi-scale Smart Sensing for Monitoring Civil Infrastructure" at the University of Illinois at Urbana-Champaign involves the development of a wireless smart sensor which can be used in a sensor network to quickly and accurately assess structural condition. Structural health monitoring (SHM) is a rapidly growing area of research in the field of Civil Engineering. Smart sensors incorporate wireless communication ability and on-board computational capacity and memory. These features allow a network of such smart sensors to aggregate and process data thus providing only pertinent information on the condition of a structure in almost real-time. Prof. Tomonori Nagayama at University of Tokyo has spent several years working with smart sensors for SHM applications and has pioneered efforts to use the Imote2 (a wireless sensor platform developed by Intel) for structural monitoring and damage detection. Jennifer Rice, a Ph.D. student from the University of Illinois traveled to the Bridge and Structures Laboratory at the University of Tokyo to work with Prof. Nagayama as well as Prof. Yozo Fujino, an expert in long span bridges. The goal of the research conducted at the University of Tokyo was to allow Jennifer to learn more about both the hardware and software involved in developing a wireless sensor network for SHM applications. In particular, she became familiar with the coding required to realize reliable communication within a network, synchronized sensing, system identification, and damage detection. She also received guidance on the design of a new multi-scale sensor board for SHM that interfaces with the Imote2. In addition, she and Prof. Nagayama set goals for future collaboration to accomplish multi-hop communication in a smart sensor network. Jennifer was also able to meet with industry leaders in Japan to discuss SHM practices, particularly in relation to seismic loading. She was an active member of her host laboratory, participating in meetings and giving research presentations. She participated in a number of technical site visits to various state-of-the art structures throughout Japan thus allowing her to see many parts of the country. In summary, the experience that Jennifer gained while in Japan will further the research being conducted at UIUC on smart sensors by allowing her to draw upon the experience of her collaborators at the University of Tokyo. In turn, Jennifer can pass on her knowledge to her colleagues in the U.S. where there is increasing realization of the necessity for effective monitoring of civil infrastructure.

INTRODUCTION

The institution awarded the original NSF grant is the University of Illinois at Urbana-Champaign (UIUC). The work currently being carried out under the NSF award is in the application of wireless sensors for structural health monitoring. This work encompasses many areas of structural health monitoring and is inherently interdisciplinary in nature. Research is being conducted in the development of damage detection algorithms suited to implementation on a wireless sensor network (WSN), as well as the development of the wireless sensor nodes and necessary software. In addition, work is being done in numerical simulation of damage and damage localization and then extended to a laboratory size test structure. Finally, preparation is being made to implement a full-scale WSN on a historic structure. This sensor network will have the ability to detect changes in the structural condition.

Jennifer Rice, a Ph.D. candidate in Civil and Environmental Engineering at the University of Illinois, traveled to and conducted research at the Bridge and Structures Laboratory at the University of Tokyo from March 29, 2007 to July 2, 2007. This trip also included 10 days in China to participate in a major conference in the area of structural health monitoring.

Jennifer's research is focused on the use of the Imote2, a wireless sensor developed by Intel, for structural health monitoring (SHM) applications. The Imote2 provides the wireless sensor platform, i.e. the radio, processor and memory as well as a flexible interface for various types of sensors. Although there is a commercially available accelerometer sensor board to interface with the imote2, it is not specifically designed for SHM applications and lacks the necessary resolution required for such applications. In addition, it has been suggested that by combining strain measurements with acceleration measurements, better assessment of the structural condition can be obtained. For these reasons, Jennifer has developed a high resolution accelerometer board to interface with the imote2. This board will be further expanded to incorporate strain measurement capability as well as digital light, temperature and humidity sensors. In addition to the design of the sensor board, the user must implement their desired algorithms on the sensors in terms of communication protocols, sensing tasks and data aggregation and processing. This requires knowledge of the operating system implemented on the Imote2s as well as the specific programming language used to execute the necessary tasks (NesC).

One of the researchers leading the efforts in the application of wireless sensors for structural health monitoring is Prof. Tomonori Nagayama at the University of Tokyo. He has pioneered work with the Imote2. He has also conducted extensive evaluation of previous wireless sensor platforms, such as the Mica mote, for which he also developed a strain sensor board. Prof. Nagayama has developed all the necessary NesC code to realize a successful SHM system in a laboratory environment, including reliable communication, synchronized sensing and the hierarchical damage detection algorithms.

It became clear that working with Prof. Nagayama at the University of Tokyo would greatly benefit the work being conducted at the University of Illinois with the Imote2 for SHM applications. Guidance in the area of programming the Imote2s was required as well as collaboration on the requirements for the sensing capabilities of the sensor board to interface with the Imote2. Japan was also an appealing country in which to explore the potential for state-of-the-art sensor networks for structural monitoring because it has traditionally been more open to cutting edge structural control and monitoring systems.

This is, in large part, due to the frequent occurrence of seismic events that pose a threat to civil infrastructure.

RESEARCH ACTIVITIES AND ACCOMPLISHMENTS OF THE INTERNATIONAL COOPERATION

The ultimate purpose of the work being carried out under the current NSF award is to realize a fully integrated, full-scale implementation of a wireless sensor network employing multi-scale smart sensors. Prior to the research conducted at the University of Tokyo, a network of Imote2s with generic accelerometer boards was successfully deployed on a laboratory-scale structure at UIUC. This network was capable of detecting damage in the laboratory setting where only limited communication ranges were required and other variables could be carefully controlled.

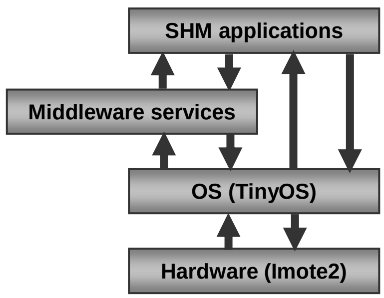

FIGURE 1. WIRELESS SENSORS: FROM HARDWARE TO APPLICATION.

Figure 1 illustrates the way in which a wireless sensor platform, such as the Imote2, is utilized to implement the desired applications. In the case of this research, the applications are those employed for structural health monitoring, such as sensing, system identification, and damage detection. The Imote2 employs TinyOS as its operating system. The code implemented on the operating system can directly interact with the applications but often times other services are required to bridge the gap between the hardware and the applications. These services, known as middleware services, are independent of the applications but are required to successfully execute the network tasks. The middleware services utilized for the SHM network include: time synchronization, model-based data aggregation, reliable communication, and synchronized sensing and were originally created by Prof. Nagayama while during his Ph.D. research at UIUC.

In order to move beyond the laboratory environment to a full-scale structure, several capabilities must be added to the network in order to have a robust SHM system. These changes include the implementation of multi-hop communication protocols and the integration of a new multi-scale sensor board. Prior to adding these services, it is important for the researchers at UIUC to understand the currently available middleware services and SHM applications. This is was the primary motivation for international research.

The research conducted at the University of Tokyo had four primary purposes. The first, and most important to the success of the NSF awarded project, was to learn and understand the NesC code implemented in TinyOS that makes up the middleware services and SHM applications that have been successfully implemented. Other goals included receiving guidance on improvements for the newly designed, high-resolution accelerometer board, the development of a software driver for the multi-scale sensor board, and finally, gaining a broadened understanding of how Japanese engineers and researchers view the expanding field of structural health monitoring employing wireless sensors.

For the three months Jennifer spent in Tokyo, she worked in the Bridge and Structures Laboratory on the Hongo campus of the University of Tokyo. She met almost daily with Prof. Nagayama as she worked towards understanding the intricacies of his code and testing the applications on the Imote2. These efforts began with learning NesC, the programming language utilized by TinyOS. From there, she went through each application, from sensing to communication to data aggregation. These efforts resulted a thorough understanding of how to write applications and middleware services for the Imote2. This knowledge provides the necessary foundation for work to be done upon returning to UIUC.

Prof. Nagayama and Jennifer collaborated to refine the performance targets for her high-resolution accelerometer board design. They established the baseline sensitivity required to measure ambient vibration in both building structures and bridges and set goals for the design based on these values. She was able to troubleshoot some problems with preliminary revisions of the sensor board and work towards the development of the necessary hardware drivers that link the sensor board with the processor on the Imote2. This work resulted in a final, successful design of the accelerometer board and a working driver. The revised sensor board is shown in Figure 2.

In addition to her close interaction with Prof. Nagayama, Jennifer also participated in weekly research meetings attended by all members of the Bridge and Structures Laboratories. The presentations and discussions in these meetings focused on the topics of structural health monitoring and damage detection, as well as general topics in bridge engineering and testing. Jennifer presented her work to the laboratory members on several occasions and was able to receive valuable feedback on her research

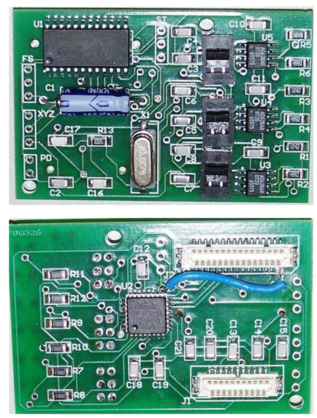

FIGURE 2. ACCELEROMETER BOARD TOP SIDE (ABOVE) AND BOTTOM SIDE (BELOW).

BROADER IMPACTS OF THE INTERNATIONAL TRAVEL

While in Japan, Jennifer presented her work to the participants of the 39th Joint Panel Meeting on Wind & Seismic Effects of the U.S.-Japan Cooperative Program in Natural Resources (UJNR). These meetings were attended by leading researchers and policy-makers from both countries in the fields of wind engineering, seismic engineering and disaster mitigation. Her work and the work being conducted at UIUC in the area of civil infrastructure monitoring were very well received. Participants from both nations see the need for more effective SHM practices and many potential collaborative relationships were formed. Jennifer gained a broadened perspective on potential applications of SHM technology and how these technologies are viewed by Japanese engineers. As a part of her involvement in these panel meetings, Jennifer participated in several technical site visits throughout Japan and had exposure to many unique Japanese cultural experiences. Figure 3 highlights some of these activities.

FIGURE 3. AN ACTIVE VIBRATION ISOLATION SYSTEM IN A TOKYO HIGH-RISE BUILDING (LEFT), THE NEWLY CONSTRUCTED LARGEST STEEL ARCH BRIDGE IN JAPAN (MIDDLE), A TRADITIONAL "IZAKAYA" DINNER WITH THE UJNR PANEL MEETING PARTICIPANTS.

Prior to her visit to Japan, Jennifer took a beginning Japanese language course at UIUC. This class gave her a foundation for continuing to develop her language skills in Tokyo. While at the University of Tokyo, she participated in a Japanese language course offered through the Department of Civil and Environmental Engineering. The Department of Civil Engineering at the University of Tokyo was the first graduate program in Japan to offer Ph.D. degrees to foreign students without the requirement of proficiency in the Japanese language. This has led the department to have a strong international influence which enriches the educational experience for both Japanese and foreign students alike. By participating in the language courses and in the everyday workings of the Bridge and Structures Laboratory, Jennifer interacted with students from all over the world who were in Tokyo to pursue graduate level engineering degrees.

Jennifer plans to continue her career in academia as an educator and a researcher upon the completion of her Ph.D. work. The travel experience that the IREE program has afforded her promotes diversity by giving a female researcher, traditionally a minority in engineering fields, experience which will set her apart as she pursues her career goals. As Jennifer continues her work in engineering research with a more global perspective, she will become a role model for young female researchers with interests in engineering and technology.

DISCUSSION AND SUMMARY

In summary, the supplemental funding that allowed Jennifer to travel to Japan and conduct research at the University of Tokyo has resulted in positive outcomes in research activities, strengthening of collaborative relationships, and overall awareness of international research practices. These positive results have immediate implications but will also reach far into the future for both institutions and the field of structural health monitoring in general.

From a research standpoint, Jennifer has made important strides in her work with the Imote2 as a wireless sensor platform for structural health monitoring. She has brought back to UIUC a strong understanding of how to implement desired functionality on a wireless sensor network through the use the NesC programming and the TinyOS operating system. Equipped with this knowledge, Jennifer can continue to pursue the goals of realizing a fully-integrated, full-scale SHM implementation. In addition, she was able to refine a sensor board design that addresses the needs of SHM applications.

Researchers at UIUC and the University of Tokyo plan to continue collaborative efforts in the future with the goal of implementing new communication protocols on the Imote2. They hope to work together on further development of middleware services and network functionality and test applications for wireless sensor networks. While both universities and the researchers involved will continue to benefit from this collaboration, the ultimate goal is to achieve higher levels of public safety confidence in the global civil infrastructure.

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BRIEF BIOGRAPHIES OF RESEARCHERS

B.F. Spencer, Jr. holds a B.S. in Mechanical Engineering (University of Missouri – Rolla 1981), and M.S. and Ph.D. in Theoretical and Applied Mechanics (University of Illinois at Urbana-Champaign 1983, 1985). He joined the faculty of the department of Civil and Environmental Engineering at the University of Illinois in 2002. Dr. Spencer served as a professor at the University of Notre Dame from 1985-2002. Dr. Spencer has research interests primarily in the areas of stochastic fatigue, stochastic computational mechanics, earthquake engineering, damage detection and health monitoring, and civil engineering applications of smart structures technology. He is currently a member of the executive board of the Asia-Pacific Network of Centers for Research on Smart Structures Technologies (ANCRSST). Dr. Spencer is a member of the American Society of Civil Engineers, the Earthquake Engineering Research Institute, the International Association for Structural Control, and the International Association for Structural Safety and Reliability. He was the founding chair of the Committee on Structural Control and is the past chair of the Committee on Fatigue and fracture Reliability, both in the ASCE Structures Division. He serves as associate editor of Shock and Vibration, is on the editorial board of the Journal of Structural Control, and has served as associate editor for ASCE Journal of Structural Engineering.

Jennifer Rice is pursuing her Ph.D. in Civil Engineering from the University of Illinois at Urbana-Champaign (UIUC). She received her undergraduate degree in Civil Engineering from Texas Tech University in 2003 where she also conducted research in the Wind Science and Engineering Department. Jennifer then came to UIUC to pursue a graduate degree. She completed her Masters degree in 2005 under the supervision of Prof. Doug Foutch. Her Masters research focused on monitoring aluminum highway sign structures for the Illinois Department of Transportation (IDOT). She gained experience in full-scale testing, structural modeling and also examined strategies for vibration mitigation using non-linear passive damping devices. Currently, Jennifer is developing an integrated, multi-scale sensor board to be used with the Imote2 that will facilitate the high resolution and low-noise measurements required for effective structural health monitoring.