FINAL REPORT FOR AWARD # 0928095

Georgia Tech Research Corp
Adaptive Mobile Sensor Networks for Structural Health Monitoring

Participant Individuals:

CoPrincipal Investigator(s) : Kok-Meng Lee
Graduate student(s) : Dapeng Zhu; Jiajie Guo

Participants' Detail

Partner Organizations:

Activities and findings:

Research and Education Activities:

Through this project, Prof. Yang Wang and Prof. Kok-Meng Lee's teams at the Georgia Institute of Technology have developed miniature robots as mobile sensor carriers for inspecting steel bridges. With magnet wheels, the tetherless robot climbs on steel structures. The robot can automatically attach sensors to bridge members for measuring vibration. Multiple robots form a mobile sensor network that provides more detailed measurement.

Advanced transmissibility function techniques are proposed for identifying potential structural weaknesses of the bridge, using the mobile sensor data. Further laboratory experiments with a four-story shear building model are conducted. It is demonstrated that the mobile sensors can provide high-precision data that allows accurate damage detection on the structure.

In addition, field deployment of the mobile sensors at a steel bridge on Georgia Tech campus has been performed. Four mobile sensors are demonstrated to be traveling on the bridge frame members, and record bridge vibration data. Modal analysis is successfully conducted to the mobile sensor data. The analysis result is then utilized to update a finite element model of the bridge.

Findings:

1. Theoretical advancement has been made on transmissibility function for structural damage. It is analytically proved that transmissibility function can serve as a reliable indicator for minor structural damage.
2. Large-displacement analysis using multiple shooting method to the compliant flexible beam provides accurate matching with experimental measurements.

3. Experiments with a four-story shear building model using the mobile sensors are conducted. The experimental data supports the analytical derivation on transmissibility function.

4. Field deployment of multiple mobile sensors showcases the advantage for structural health monitoring. The mobile sensors navigate to different sections of a structure and measure structural vibrations at high spatial resolution.

Training and Development:

This highly interdisciplinary project involves background in civil engineering, mechanical engineering, and electrical engineering. Interdisciplinary research experience is provided to those who worked on the project. Regular meetings and discussion, as well as presentation opportunities, have been organized.

Outreach Activities:

(1) In Summer 2009, the Smart Structural Systems Laboratory led PI Dr. Wang hosted the five week stay of Ms. Heui-Yung Do, a high school senior from Corcord Academy, Condor, MA (Figure 20). The effort is part of an outreach residential program organized by Laurus Educational Consulting and the School of Civil and Environmental Engineering (CEE) at Georgia Tech. It provides prospective college students with hands-on research experience in engineering. Formal progress meetings and a final presentation are scheduled for the students to regularly report their progresses throughout the internship.

(2) Through the Center for Education Integrating Science, Mathematics, and Computing (CEISMC) at Georgia Tech, the PI and one graduate student on this project were involved in an one-day outreach activities to K-12 students on November 18, 2009. We demonstrated the wireless sensing devices on a laboratory structure to four groups (about ten people each group) of African American high-school students from local Atlanta communities.

(3) Through the Technology, Engineering, and Computing (TEC) Camp sponsored by Women in Engineering Program at Georgia Tech, Dr. Wang's lab provided hands-on lab tours for 2 groups of 15 high-school female students from local Atlanta communities on June 18, 2010.

(4) On January 4 & 5, 2011, the research team on this project provided live demo of mobile sensor application for 2 groups of 20 visitors attending the 2011 NSF CMMI Engineering Research and Innovation Conference.

Journal Publications:

Zhu, D., Yi, X., Wang, Y., Lee, K.-M. and Guo, J., "A mobile sensing system for structural health monitoring: design and validation", *Smart Materials and Structures*, vol. 19, (2010), p. 055011., "10.1088/0964-1726/19/5/055011 " Published

Guo, J., Lee, K. M., Zhu, D., Yi, X. & Wang, Y., "Large-deformation analysis and experimental validation of a flexure-based mobile sensor node", *Mechatronics, IEEE/ASME Transactions on*, vol. , (2011), p. ., "10.1109/TMECH.2011.2107579 " Accepted

J. Guo, K. M. Lee, D. Zhu, X. Yi, and Y. Wang, "Wireless mobile sensor network for system identification of a space frame bridge", *Mechatronics, IEEE/ASME Transactions on*, vol. , (2012), p. ., " " Accepted

D. Zhu, Y. Wang, and J. Brownjohn, "Vibration testing of a steel girder bridge using cabled and wireless sensors", *Frontiers of Architecture and Civil Engineering in China*, vol. 5, (2011), p. 249., " " Published

Book(s) of other one-time publications(s):

Lee, K.-M., Wang, Y., Zhu, D., Guo, J. and Yi, X., "Flexure-based mechatronic mobile sensors for structure damage detection" , bibl. Stanford, CA, USA, September 9 - 11, 2009, (2009). *Conference proeedings* Published
of Collection: , "Proceedings of the 7th International Workshop on Structural Health Monitoring"

Guo, J., Lee, K.-M., Zhu, D. and Wang, Y., "A flexonic magnetic car for ferro-structural health monitoring" , bibl. Hollywood, CA, USA, October 12-14, 2009, (2009). *Conference* Published
of Collection: , "Proceedings of 2009 ASME Dynamic Systems and Control Conference"

Yi, X, Zhu, D., Wang, Y., Guo, J., and Lee, K.-M., "Embedded transmissibility function analysis for damage detection in a mobile sensor network" , bibl. San Diego, CA, March 8, 2010, (2010). *Conference proceeding* Published
of Collection: , "Proceedings of SPIE, Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2010, 7647: 764729"

Zhu, D., Yi, X., Wang, Y., Guo, J. and Lee, K.-M., "Mobile sensor networks: a new approach for structural health monitoring" , bibl. Orlando, FL, USA, May 12 - 15, 2010, (2010). *Conference proceedings* Published
of Collection: , "Proceedings of the 2010 Structures Congress and 19th Analysis and Computation Specialty Conference"

Yi, X., Zhu, D., Wang, Y., Guo, J. and Lee, K.-M., "Transmissibility-function-based structural damage detection with tetherless mobile sensors" , bibl. Philadelphia, PA, USA, July 11 - 15, 2010, (2010). *Conference proceedings* Published
of Collection: , "Proceedings of the Fifth International Conference on Bridge Maintenance, Safety and Management"

Zhu, D., Yi, X., Wang, Y. and Sabra, K., "Structural damage detection through cross correlation analysis of mobile sensing data" , bibl. Tokyo, Japan, July 12 - 14, 2010, (2010). *Conference proceedings* Published
of Collection: , "Proceedings of the 5th World Conference on Structural Control and Monitoring"

Zhu, D., Guo, J., Yi, X., Wang, Y. and Lee, K.-M., "A flexure-based mobile sensing node for the health monitoring of steel structures" , bibl. Atlanta, GA, USA, January 4-7, 2011, (2011). *Conference proceedings* Published
of Collection: , "Proceedings of the 2011 NSF CMMI Research and Innovation Conference"

Zhu, D., Yi, X. and Wang, Y., "Sensitivity analysis of transmissibility functions for structural damage detection" , bibl. San Diego, CA, March 6 - 10, 2011, (2011). *Conference proceedings* Published
of Collection: , "Proceedings of SPIE, Nondestructive Characterization for Composite Materials, Aerospace Engineering, Civil Infrastructure, and Homeland Security V"

Other Specific Products:

Contributions:

Contributions within Discipline:

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 The mobility of a sensing node resolves some most critical challenges
faced by static wireless sensor networks:
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(i) In order to closely monitor a complex large-scale structure, static wireless sensors usually need to be deployed at a very high density. However, the cost and difficulty associated with dense arrays of wireless sensors are still prohibitive for wide deployment in practice. On the other hand, mobile sensor networks offer flexible architectures, which lead to adaptive and high spatial resolutions while using a relatively small number of nodes.

(ii) Limited power supply is one of the largest constraints for wireless sensor networks. This constraint is eliminated in mobile sensor networks, if the mobile sensing nodes can periodically return to a base station for automatic recharging.

(iii) For mobile sensor networks, reduced power constraint means that powerful microprocessors can be adopted to execute more sophisticated damage detection algorithms; it also enables more options for wireless transceivers that offer higher data rate, longer transmission range, and better synchronization accuracy.

Contributions to Other Disciplines:

The flexure-based magnet-wheeled mobile sensing nodes are novel yet practical in maneuvering on the surface of a civil structure built with ferromagnetic materials. The mobile nodes are capable of both sensing and excitation for generating and measuring local vibrations with high signal-to-noise ratios. The research project is generating a comprehensive solution that also includes advanced theoretical formulation for better interpreting sensor data. Proposed mobile sensor network platform offers unique opportunities for validating and improving substructure-based finite-element (FE) model updating and structural damage detection algorithms for large-scale civil structures. With reconfigurable mobile nodes, novel methodologies are developed for FE model updating and damage localization that utilize sensor mobility. The analysis mentioned above can be executed online by the mobile sensing nodes with a high level of embedded intelligence.

Contributions to Education and Human Resources:

The research in wireless and mobile sensors for structural monitoring has attracted a number of undergraduate students at Georgia Tech. The PI is currently involved in an vertically-integrated project that provides research opportunities to students at different undergraduate and graduate levels. Testbed structures include a pedestrian bridge on GT campus and GT football stadium. Students learn structural modeling, instrumentation, and modal analysis from the project.

Conference Proceedings:

Yi, XH;Zhu, DP;Wang, Y;Guo, JJ;Lee, KM, "Embedded transmissibility function analysis for damage detection in a mobile sensor network", Conference on Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2010, MAR 08-11, 2010, SENSORS AND SMART STRUCTURES TECHNOLOGIES FOR CIVIL, MECHANICAL, AND AEROSPACE SYSTEMS 2010, 7647: - 2010

Zhu, DP;Yi, XH;Wang, Y, "Sensitivity Analysis of Transmissibility Functions for Structural Damage Detection", Conference on Nondestructive Characterization for Composite Materials, Aerospace

Engineering, Civil Infrastructure, and Homeland Security, MAR 07-10, 2011, NONDESTRUCTIVE CHARACTERIZATION FOR COMPOSITE MATERIALS, AEROSPACE ENGINEERING, CIVIL INFRASTRUCTURE, AND HOMELAND SECURITY 2011, 7983: - 2011

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