Structural health monitoring and diagnosis of civil structures using mechatronics-based methodology and technology

In 1997 noted futurist Paul Saffo wrote that the next decade, which we now call the “noughties” (2000-2010), would be heralded as the “age of the sensor” and in particular that ubiquitous, low cost, high performance sensors linked to silicon chips (computation) would be the next great technology revolution [1]. In particular, he noted that such sensors and computation hooked together would add sensory organs to our networks and products, and that we would become increasingly interlinked by these actions. It was clear that he was not alone in this idea of an increasingly sensed and interconnected world. In my mind, they simply said that mechatronics-based methodology and technology would reshape our world.

Today, the idea that all new powerful tools, enabled by new waves of more powerful sensors, of all types, and increasingly power computational resources, has reshaped our lives is pretty well accepted. However, to my mind, this revolution is not nearly so short as many have intimated. Succinctly, we are at the beginning rather than the end. How, specifically? Well, in essence, there are three classes of increasingly ubiquitous sensing: **1**) **smart, active** products and systems like advanced aircraft that act deliberately on these sensor inputs; **2**) **passive, mobile** monitoring that we carry around such as that found in cell phones that “check your presence in” at a certain location on Facebook; and **3**) **fixed monitoring** and surveillance in buildings, infrastructure and cities. This last area is the topic of this section, and is an one that has mostly been reflected by its “dark side” post 9/11. This section will talk more about some of the positive gains to be made by these technologies in quietly assessing and maintaining the health, integrity and quality of the buildings, infrastructure and lifelines that we use so ubiquitously that we often dramatically under-estimate their impact on our lives.

Structural health monitoring or SHM is a broad term defined as is the process of comparing the current state of a structure’s condition relative to a baseline or expected state to detect the existence, location, and degree of likely damage after a damaging input, such as an earthquake. SHM can simplify and improve typical visual or localized experimental approaches, as it does not require subjective visual inspection of the structure [2]. Finally, it is equally applicable to buildings, critical infrastructure like bridges or tunnels or waterworks, and is a topic that has always been considered difficult [3].

Most efforts to date in this field have focused on structures in seismic zones and assessing damage after a major event, and in particular on computational methods to assess damage (eg [3-11]). Many current vibration-based SHM methods, particularly for large civil structures, are based on modal parameter damage detection in both the time series and frequency domain [2, 12]. Current modal methods are more applicable to steel-frame and bridge structures where vibration response is more linear [4, 12] and several assume one has data from the undamaged state [8], which is increasingly possible with advanced sensor technologies.

In addition, SHM must be identify localized damage, be robust in the presence of noise and evaluate structural health rapidly or in real-time [4, 5]. All of these characteristics are ones that can increasingly be met by emerging, improved sensor technologies that are more distributed, low cost and easily used in volume, and/or integrate computation directly with measurement.

Most existing methods that could potentially provide real-time SHM are modal or frequency based methods. These methods typically only use accelerometers as sensors and rely on the change in natural frequencies to detect damage [5, 10, 13]. However, a change in a frequency doesn’t necessarily represent damage, particularly with highly non-linear responses [14, 15]. Significant changes in story stiffness are often required as well, which would normally cause clearly visible damage [15]. Equally, [13, 16] identified changes in structural stiffness in real-time using a Least Mean Squared (LMS)-based adaptive filtering approach in real-time. However, this method requires measurement of velocity and displacement, which has often been considered impractical in many realistic cases due to excessive sensor requirements.

Recently there have been significant advances in Global Positioning System (GPS) displacement monitoring technology for large structures [15-20]. Displacements can be measured with 1-3 mm accuracy for rates of up to 3-4 Hz, which include the modal frequencies of the rigid structure [16], and for 1 Hz, measurement errors have been stated as less than 12% [9]. The use of GPS opens up new opportunities in real-time structural health monitoring [15]. Equally, there are increasing advances in a wide range of displacement sensing technologies (eg [21-26]) that will enable further improvements in our ability to accurately identify and locate damage.

However, monitoring structural damage is just the beginning. Buildings increasingly have the ability to monitor all their functions, such as climate and energy usage. Integrated together these present other forms of monitoring to improve lifecycle and services in these buildings, as well as making them more economic and cost effective. Even that is not the end of the age of the (fixed) sensor. Networking lets us integrate buildings and regions into wider area monitoring and leads eventually, with other systems, towards what some are now calling “smart cities” where data from buildings, power grids, traffic and much more are integrated into an entire interconnected, some might dare say optimised, organism.

Thus, the next, “next age” is always around the corner. Increasingly the use of sensors to monitor, improve performance, and aid decision making, whether human or automated, is seen as an avenue to achieve significant social and economic benefits. More succinctly, our ability to sense our environment has always let us assess and monitor what is around us, with silicon and other advanced sensors and computation this ability is being dramatically enhanced via mechatronics-based methods and technologies.

REFERENCES:

[1] P. Saffo, "Sensors: the next wave of innovation," *Commun. ACM,* vol. 40, pp. 92-97, 1997.

[2] J. E. Doherty, "Non-destructive evaluation," in *Handbook on Experimental Mechanics*, A. S. Kobayashi, Ed., 1 ed Englewood Cliffs, NJ: Prentice-Hall, Inc., 1987.

[3] H. Sohn, C. R. Farrar, F. M. Hemez, D. D. Shunk, D. W. Stinemates, B. R. Nadler, and J. J. Czarnecki, "A Review of Structural Health Monitoring Literature: 1996-2001," Los Alamos National Laboratory LA-13976-MS, 2004.

[4] J. G. Chase, K. L. Hwang, L. R. Barroso, and J. B. Mander, "A simple LMS-based approach to the structural health monitoring benchmark problem," *Earthquake Engineering & Structural Dynamics,* vol. 34, pp. 575-594, May 2005.

[5] M. Nayyerloo, J. G. Chase, G. A. MacRae, and X. Q. Chen, "LMS-based approach to structural health monitoring of nonlinear hysteretic structures," *Structural Health Monitoring-an International Journal,* vol. 10, pp. 429-444, Jul 2011.

[6] C. E. Hann, I. Singh-Levett, B. L. Deam, J. B. Mander, and J. G. Chase, "Real-Time System Identification of a Nonlinear Four-Story Steel Frame Structure-Application to Structural Health Monitoring," *Sensors Journal, IEEE,* vol. 9, pp. 1339-1346, 2009.

[7] B. Nigbor, H. Gavin, G. MacRae, G. Rodgers, M. Nayyerloo, J. Chase, S. Gutschmidt, and C. Granger, "Earthquake Response and Structural Health Monitoring of Christchurch Women's Hospital Following the Canterbury and Christchurch Earthquakes," presented at the 15th World Congress on Earthquake Engineering (15WCEE), Lisbon, Portugal, 2012

[8] G. Konstantinidis, P. D. Wilcox, and B. W. Drinkwater, "An investigation into the temperature stability of a guided wave structural health monitoring system using permanently attached sensors," *Sensors Journal, IEEE,* vol. 7, pp. 905-912, 2007.
[9] J. N. Yang and S. Lin, "On-line identification of non-linear hysteretic structures using an adaptive tracking technique," *International Journal of Non-Linear Mechanics,* vol. 39, pp. 1481-1491, 2004.
[10] Z. Hou, M. Noori, and R. S. Amand, "Wavelet-based approach for structural damage detection," *Journal of Engineering Mechanics,* vol. 126, pp. 677-683, 2000.
[11] R. Jankowski, "Theoretical and experimental assessment of parameters for the non-linear viscoelastic model of structural pounding," *Journal of Theoretical and Applied Mechanics,* vol. 45, pp. 931-942, 2007.
[12] S. W. Doebling, C. R. Farrar, P. M.B., and S. D.W., "Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: a literature review.," Los Alamos National Laboratory 1996.
[13] J. G. Chase, H. A. Spieth, C. F. Blome, and J. B. Mander, "LMS-based structural health monitoring of a non-linear rocking structure," *Earthquake Engineering & Structural Dynamics,* vol. 34, pp. 909-930, Jul 2005.
[14] S. Li, Y. Suzuki, and M. Noori, "Improvement of parameter estimation for non-linear hysteretic systems with slip by a fast Bayesian bootstrap filter," *International Journal of Non-Linear Mechanics,* vol. 39, pp. 1435-1445, 2004.
[15] A. G. Chassiakos, S. F. Masri, A. W. Smyth, and T. K. Caughey, "On-Line Identification of Hysteretic Systems," *Journal of Applied Mechanics,* vol. 65, pp. 194-203, 1998.
[16] J. G. Chase, V. Begoc, and L. R. Barroso, "Efficient structural health monitoring for a benchmark structure using adaptive RLS filters," *Computers & Structures,* vol. 83, pp. 639-647, 2005.
[17] C. Christopoulos, A. Filiatrault, and B. Folz, "Seismic response of self-centring hysteretic SDOF systems," *Earthquake Engineering & Structural Dynamics,* vol. 31, pp. 1131-1150, 2002.
[18] X. Li, G. D. Peng, C. Rizos, L. Ge, Y. Tamura, and A. Yoshida, "Integration of GPS, accelerometer and optical fibre sensors for structural deformation monitoring," in *the 17th International Technical Meeting of the Satellite Division of the Institute of Navigation ION GNSS*, Long Beach, California 2004, pp. 211-224.
[19] T. Kijewski-Correa, A. Kareem, and M. Kochly, "Experimental Verification and Full-Scale Deployment of Global Positioning Systems to Monitor the Dynamic Response of Tall Buildings," *Journal of Structural Engineering,* vol. 132, pp. 1242-1253, 2006.
[20] X. Li, G. D. Peng, C. Rizos, L. Ge, Y. Tamura, and A. Yoshida, "Integration of GPS, accelerometer and optical fibre sensors for structural deformation monitoring," presented at the 17th International Technical Meeting of the Satellite Division of the Institute of Navigation ION GNSS, 21-24 Sep., Long Beach, California 2004.
[21] C. C. Chang and Y. F. Ji, "Flexible Videogrammetric Technique for Three-Dimensional Structural Vibration Measurement," *Journal of Engineering Mechanics,* vol. 133, pp. 656-664, 2007.
[22] G. Fu and A. G. Moosa, "An Optical Approach to Structural Displacement Measurement and Its Application," *Journal of Engineering Mechanics,* vol. 128, pp. 511-520, 2002.
[23] T. C. Hutchinson, S. R. Chaudhuri, F. Kuester, and S. Auduong, "Light-Based Motion Tracking of Equipment Subjected to Earthquake Motions," *Journal of Computing in Civil Engineering,* vol. 19, pp. 292-303, 2005.
[24] T. C. Hutchinson, F. Kuester, K. U. Doerr, and D. Lim, "Optimal hardware and software design of an image-based system for capturing dynamic movements," *Instrumentation and Measurement, IEEE Transactions on,* vol. 55, pp. 164-175, 2006.
[25] M.-S. Lim and J. Lim, "Visual measurement of pile movements for the foundation work using a high-speed line-scan camera," *Pattern Recognition,* vol. 41, pp. 2025-2033, 2008.
[26] J.-J. Orteu, "3-D computer vision in experimental mechanics," *Optics and Lasers in Engineering,* vol. 47, pp. 282-291, 2009.