A User-Centric Approach to the Design of Structural Health Monitoring Systems

J. Kuckartz[a, *], P. Collier [a,b]

[a] Department of Infrastructure Engineering, The University of Melbourne, Victoria 3010, Australia
[b] Cooperative Research Centre for Spatial Information, Carlton, Victoria, 3053, Australia
j.kuckartz@student.unimelb.edu, p.collier@unimelb.edu.au

KEY WORDS: Structural monitoring, user-centric, design, objectives, multi-disciplinary

ABSTRACT:

The design of a structural health monitoring system is mainly governed by the information required by civil and structural engineers. With more structures being constructed incorporating long-term monitoring systems and being managed by owners or engineering firms, a shift of the design concept from an engineering approach to a user-centric approach is recommended. A literature review of existing structural health monitoring concepts reveals some progress in this direction but highlights that most system designs focus on hardware architecture and technical capabilities.

This paper reviews existing structural monitoring systems and the objectives of structural monitoring in general and proposes an interdisciplinary design process with a user-centric focus for structural monitoring systems of the future.

1. INTRODUCTION

Monitoring a structure allows us to see what is happening to it over time. Structures might appear static to the casual observer, but the forces of wind, temperature, vertical load and seismicity affect their shape, size and location. Such changes are collectively referred to as *deformation*. Deformation of a structure can produce long-term damage and may ultimately lead to structural failure.

Structural health monitoring systems (SHMSs) are capable of tracking deformation through results drawn from various sensors, such as accelerometers. A SHMS is sometimes installed to allow the validation of design assumptions. This is important for civil engineers wishing to improve construction practices, overall structural performance and serviceability.

SHMSs are starting to be used by building managers and owners as a decision support tool. Such individuals are typically less knowledgeable than professionally trained engineers in regard to their understanding of structural principles and the implications of detected movements. The design of new monitoring systems needs to take this reality into account. It is for this reason that a *user-centric* approach in the design of SHMS is proposed in this paper.

2. OBJECTIVES OF MONITORING

2.1 General objectives

A SHMS can be developed to obtain comprehensive knowledge of the performance of a structure, which knowledge can then be used to assess safety, durability and serviceability. A SHMS can also be used to validate design assumptions and design loads, it can provide a basis for decision making on issues of maintenance and management and it can give indications of structural deterioration and performance degradation. A SHMS should also provide data to help in the development of future design scenarios. For these purposes, environmental conditions and geometrical states such as stress and deformation, as well as mechanical behaviour of the key components of the structure, should be monitored. This should be done in real-time as well as storing the data off site for post-processing and further analysis. An alarm system should be present to warn of abnormal behaviour or pending failure. The monitoring system should be able to statically and dynamically identify structural anomalies. The data from the SHMS should be accessible to all parties with a professional interest in the structure and its performance (Sumitro, 2001).

2.2 Visions of SHMS

Aktan et al., 1998 were amongst the first to introduce objectives for and components of an intelligent monitoring system. One of the main components identified is the communication interface. This interface does not only include the sensor network which measures structural response and environmental loads, but also includes the human interaction required for understanding sensor data. The inclusion of the human interaction allows for experience learning and decision making, such as issuing alerts or identifying the need for repairs.

Before a SHMS can provide information such as structural condition, health and capacity, a complete understanding of the mechanisms affecting structural performance needs to be present. This includes the structure's state parameters (stress, strain, displacement, stiffness), performance parameters (functionality, serviceability, safety, life-cycle), the loading environment, defects, deterioration and damage mechanisms, load-resisting mechanisms and the ability to measure indices for condition and damage.

* Corresponding author.

For comparison and structural understanding, quantifiable metrics for reliability and health are recommended and a generalized theory can be developed (Aktan et al., 2000a, Pines and Aktan, 2002). Both metrics and a generalized theory can be developed when a sufficient amount of monitoring results are present. These results flow out of many long-term monitoring applications, but non-destructive evaluation and controlled testing also provide some of the required information.

Farrar and Lieven, 2007 mention that identifying the presence and quantifying the extent of damage is a critical component of structural health monitoring. A damage prognosis takes the current and historical states of a structure and predicts its remaining useful life. An existing SHMS capable of damage prognosis is currently still far from reality. One of the main issues is the lack of historical data and knowledge of structural responses, in particular damage mitigation.

Wenzel, 2009 suggests that a SHMS is an integrated decision support system, mainly focused on the users and the availability of data. Such a SHMS may contain a display embedded in a GIS environment reporting the status of the structure. The status report includes a rating based on structural condition assessments and therefore reflects the present condition of the structure. To reach this user-friendly report, a SHMS needs to have the following components: (1) a database with web interface, (2) permanent and mobile monitoring units, (3) data handling, transfer and cleaning routines, (4) a knowledge and history base for statistical comparison, (5) a database on dynamic simulation including automatic model update routines, (6) a case based reasoning system to compute the proposals for decision making and (7) interfaces to existing structural databases, relevant codes and standards.

2.3 Summary of objectives

In structural health monitoring, the monitoring aspect itself is only a subset of all objectives. This becomes clear when those objectives are portrayed graphically as in figure 1. The system objectives are divided into five categories, where the left hand side of each category represent the subcategories. The right hand side show the examples and results of each corresponding category.

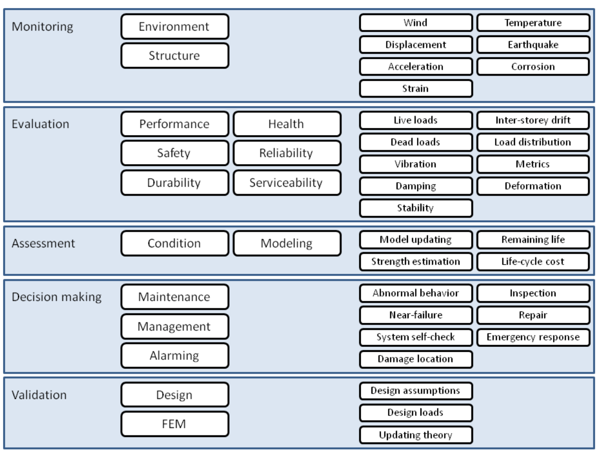

Figure 1. Objectives of a structural health monitoring system

Most of the effort in the design of a new SHMS will go towards the monitoring aspect, which is where the raw data is gathered. Without this data, the subsequent objectives can never be pursued. Evaluation of this data by calculating structural parameters is the most important function of a SHMS.

Civil and structural engineers often consider the evaluation results sufficient and compare the structural parameters with finite element models (FEM) to see if the structure is within the design tolerances. A complete SHMS however continues in assessing the condition of the structure by creating a structural model given the evaluation results. The condition of the structure, which includes damage assessment, can in some cases show enough reason to issue alerts or maintenance requests. This decision making process does contain human involvement, but up to this point all the objectives of a SHMS can be performed in an automated fashion in or near real-time.

The objective of validation is achieved after long-term monitoring or by using historical data. Although this can be done separately from an on-site SHMS and might only be needed once or twice during a structure's lifetime, it should not be omitted as an objective for the design of a SHMS.

The objectives identified above were originally developed for bridge monitoring systems (Aktan et al., 1998, Aktan et al., 2000a, Sumitro, 2001, Pines and Aktan, 2002, Farrar and Lieven, 2007, Wenzel, 2009) but are sufficiently generic to be applied to high-rise buildings, towers and other civil engineering structures as required.

The objectives of a SHMS can also be displayed in a flowchart of processes, as suggested by Zong et al., 2002. Figure 2 represents such a flowchart. Excitation is the only input of the system, acting on the structure (top left). Together with the sensors and data acquisition, these blocks represent the monitoring aspect. The processing and evaluation following data acquisition generate the parameters required to continue the assessment. It is possible that after evaluation, thresholds are set for certain parameters and these can form the basis for issuing an alarm. Often model updating and simulations are needed to generate a complete overview of a structure's condition. Based on the condition of the structure, again alarms can be issued but more advanced decisions like maintenance can now be made. Finally with these results, feedback to update theories and designs can be also be extracted.

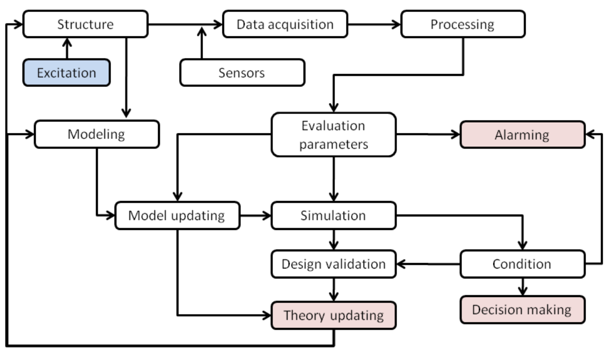

Figure 2. Processes needed to achieve the objectives of a full structural health monitoring system (modified but based on Zong et al., 2002)

3. DESIGNING A SHMS

3.1 Defining the need

Before creating a monitoring system, the need for one is to be established. In some cases the structure under consideration is not very susceptible to damage, in other cases, monitoring is deemed too expensive. It is practically impossible to implement a structural monitoring system on every structure, therefore cases where structural monitoring is most essential need to be identified. Moss and Matthews, 1997 identified several circumstances where a monitoring system might be useful. The following identifies cases for installing a short-term monitoring system:

- Structures affected by external works
- Structures being demolished
- Structures being modified

The same authors also identified long-term monitoring cases and suggested the following:

- Structures subject to long-term movement or degradation of materials
- Structures used in the improvement of future designs based on experience
- Structures used for fatigue assessment
- Structures used with novel systems of construction

Brownjohn, 2007, adds the following cases for long-term monitoring:

- Structures being assessed for post-earthquake structural integrity
- Structures requiring extensive maintenance
- The move towards a performance-based design philosophy

The lists above discuss short-term and long-term needs but the items are very similar. The following compounded list of cases for the need of a SHMS is therefore proposed:

1. Structures affected by temporary impacts (such as modification, demolition, works on nearby structures)
2. Structures subject to potentially damaging environmental impacts
3. Structures used in a research and development setting
4. Structures requiring extensive maintenance
5. Structures that pose a particular risk to life or property

The first case above focuses on temporary monitoring systems, which can be installed when a structure is being modified, demolished or affected by nearby works. A SHMS can be installed on the structure to monitor impacts, but can be removed when the work is finished and it has been shown that there are no significant or lasting structural consequences.

The second case considers the impact of environmental forces such as seismic, wind and thermal loading and it is suggested that a long-term monitoring system is required. This category also contains the installation of a new monitoring system to assess structural change after major seismic or wind events occurred.

When a new construction technique or new materials are used, or a structure is monitored for use in a design feedback loop, the third case applies. SHMSs in this category can be of interest for structural validation and to test or prove new theories and techniques.

The fourth case focuses on cases where a SHMS is financially more viable for maintenance than human inspection. Certain structures, especially long bridges, have a large maintenance cost when visual inspection alone is used. As an example, the Brooklyn Bridge in New York, USA is inspected every two years, which takes 3 months to finish and costs 1 million US dollar. An added disadvantage is that the average condition ratings from visual inspection were incorrect to an amount of 56% with a 95% probability (Aktan et al., 2000a).

Finally, the fifth case focuses on structures which are high risk. Such structures include nuclear installations and dams, which on failure affect a large amount of people. For these structures codes and guidelines are commonly present.

For each of these cases different users can be involved in the design of a SHMS. Civil engineers and engineering firms are involved in every case, with the interest of knowing that a structure is safe whatever happens to it. For the second and fourth case however, owners want to make sure the structure is undamaged and safe for use. The users of the third case include universities and research institutes, interested in design validation and theory development.

3.2 Components and structure evaluation

Design of a SHMS starts with choosing the objectives as mentioned in section 2, but not all of these objectives need to be addressed. A discussion with the end-user is of utmost importance as their input will help determine the exact objectives, outputs and additional requirements.

The use of monitoring systems should be considered during the design phase of a structure, as the design will highlight critical structural sections. This ensures that the monitoring system infrastructure and components can be installed without modification to the design and that they are optimally located. Attempts to install monitoring equipment post-construction inevitably impose limitations on the capabilities and effectiveness of the system.

The design of the SHMS can be divided into the following components (Brownjohn, 2007):

1. Sensors
2. Data storage
3. Data transmission
4. Database management
5. Data mining (for feature extraction)
6. Load/effect model development
7. Heuristics (learning from past experiences)
8. Decision making
9. Reporting

Although Brownjohn, 2007 only lists the first 8 components, the last component is added for the benefit of the user. This is also the only component which interfaces the SHMS with the end-user, and until recently (Wenzel, 2009) has commonly been omitted.

3.3 Hardware and limitations

Having determined the need for a SHMS, their objectives and components, the system design process enters a more detailed and hardware-related phase. It is useful to identify the risks, uncertainties and opportunities the structure poses (Inaudi et al., 2010). The risk and uncertainty analysis will list a structure's weak points such as joints, locations with heavy loads, the existence of corrosion-prone material and the performance of construction material. It also includes the possible events which can affect the structure, such as weather and earthquakes. The opportunity analysis on the other hand allows for validating a structure's design by comparing the instrumentation result with finite element models and research into the use of new materials or construction techniques.

The results of these analyses allow the identification of measurable structural parameters and observed responses. This will pave the way for the selection of appropriate sensors and their location for installation in the structure. Together with the installation of sensors, a communication system for transmission of the data needs to be selected.

In the hardware-related design process, several key problems and limitations must be considered (Brownjohn, 2007).
(1) A cost-benefit analysis is required to show the benefits of the system. This analysis needs to not only cover the costs of equipment purchase and installation, but also operation and maintenance costs.
(2) The selected sensors should be appropriate for the requirements of monitoring and they should be installed at key locations in such a way that sufficient information can be routinely gathered.
(3) Data overload can result from having too many sensors or sampling the sensors too frequently.
(4) The communication links should be capable of handling the data speed required. The data links may be wired or wireless.
(5) Environmental factors and noise can downgrade measurement results at the sensor-level but also through the data transmission hardware. This should be minimised or compensated for in such a way that data remains fit for purpose.
(6) Data handling, conversion into information and subsequent presentation are all important to support robust and consistent decision making.

Limitations in monitoring technology and sensor systems combined with the complexity of modern structures, make it difficult to monitor every location continuously and in real-time. This limitation is mostly due to the cost of sensors but also to the point-wise nature of how sensors measure. With ever faster sensors, measurements can be performed in real-time but a complete structural view is only possible by using and integrating all of the gathered data.

The limitations in sensor overload, data overload and data mining can be overcome by selecting the appropriate location of the sensor, frequency of data sampling and time of data evaluation (Aktan et al., 1998). The data components for a SHMS with respect to time, frequency and space are shown in figure 3. In this graph one can select the appropriate time, frequency and space of a specific monitoring parameter.

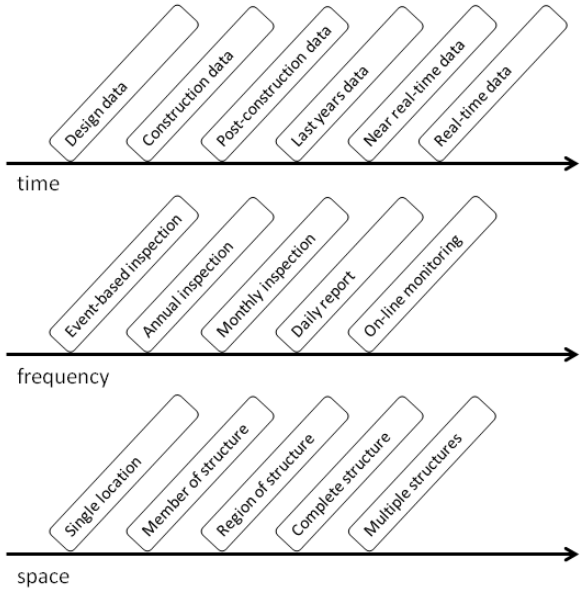

Figure 3. Time, frequency and space considerations for the design and evaluation of structural health monitoring data

3.4 Multi-disciplinary

The complete design process of a SHMS can be summarized by following these steps:

1. Identify the need for monitoring
2. Set the objectives of the monitoring system
3. Undertake risk, uncertainty and opportunity analysis
4. Identify parameters and response requirements
5. Select appropriate sensors
6. Select sensor location and communication system
7. Install system and calibrate
8. Acquire data, process, manage and report
9. Assess data
10. Decide on the need for remedial action

The design process covers several traditional study fields, such as civil engineering, electrical engineering and computer science. Figure 4 represents the interdisciplinary design process as a flowchart. In combination with the 10 steps of the design process, this flowchart addresses all aspects of the design of a SHMS.

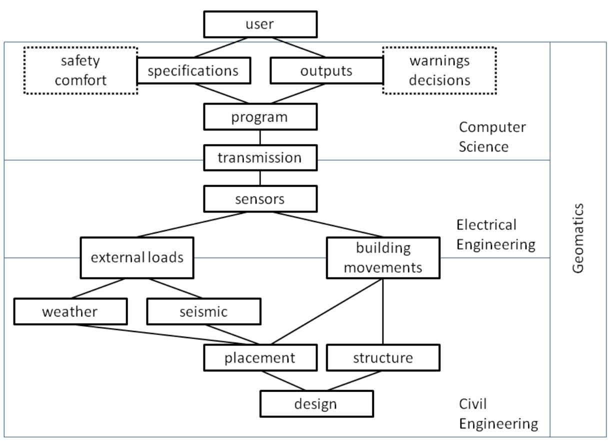

Figure 4. Fields involved in the design of a structural health monitoring system

A bottom-up or a top-down approach for the design of a SHMS is possible. In either case, the specifications and outputs are determined by the user, which can be a civil engineer, owner, manager, research institute or university. Given these specifications and outputs the SHMS is designed to provide the required results. At the bottom of the flowchart are the structure and its design, which determine correct sensor placement.

The user first identifies the need for monitoring by checking the four cases listed in section 3.1. Second, the user will set the objectives for the SHMS (section 2.3). The user then analyses risks, uncertainties and opportunities for the structure (section 3.3) before identifying the required structural parameters for output and selecting the sensors which are able to provide these. The location of the sensors for installation then follows and a communication system needs to be selected. This allows for the installation of the SHMS on the structure and measurement can begin. All that is left is data acquisition, management, assessment and reporting.

4. SHMS ARCHITECTURE

4.1 Early architectures

The use of monitoring systems on bridges is a recent development (Sun et al., 2009) and each bridge has a different SHMS architecture. One of the earlier architecture representations was presented for the Commodore Barry Bridge, Philadelphia, USA (Aktan et al., 2000b). The architecture presented contained several local data acquisition systems (DAQs), a fibre network for LAN and a local LAN server. Real-time data access was possible by the use of a web browser.

Many bridges, due to their size, have several DAQs reading sensor data, and each of the DAQs is connected to a local server. Although placement of the sensors, DAQs and local server are often represented in architecture diagrams, any SHMS architecture, not only for bridges, can be represented by a simple 4-block diagram as shown in figure 5.

Figure 5. General structural health monitoring system platform architecture

In this diagram sensor data is gathered by one or more acquisition stations, at the location of the structure. A local station, often a computer system, gathers the data from one or more acquisition stations and stores it on-site in a database or file system. A communication channel is present for a user to access the local station and therefore the data. The lines between sensors, acquisition station and local station also represent communication channels and these generally include a one-way direction of either wired or wireless data transmission. Systems implementing this general architecture are the SHMS from the Korea Highway Corporation (Yun et al., 2003), Hong Kong Bridges (Wong, 2007), 3DeMoN (Manetti et al., 2008), VCDECIS (Wenzel, 2009), Canton Tower (Ni and Zhou, 2010) and SmartSync (Kwon et al., 2010).

4.2 Modularity

The installation of a SHMS on the Commodore Barry Bridge was a demonstration project and is therefore a one-off system. The SHMS operated by the Korea Highway Corporation however is installed on at least three bridges and operated from a single location (Yun et al., 2003). Several long-span bridges in Hong Kong and several other locations in China use a single, modular system (Wong, 2007). Due to this modularity these SHMSs are ready to be implemented on other structures.

A seven-tier, modular system is proposed for use in future SHMS designs, as shown in figure 6. This system is based on the design by Wong, 2007, but adds the "User Interface System" to accommodate for off-site end-users. Wong does discuss a data access interface in two modules, but does not discuss the generation of reports or providing information to the end-user as a separate module in the design of a SHMS.

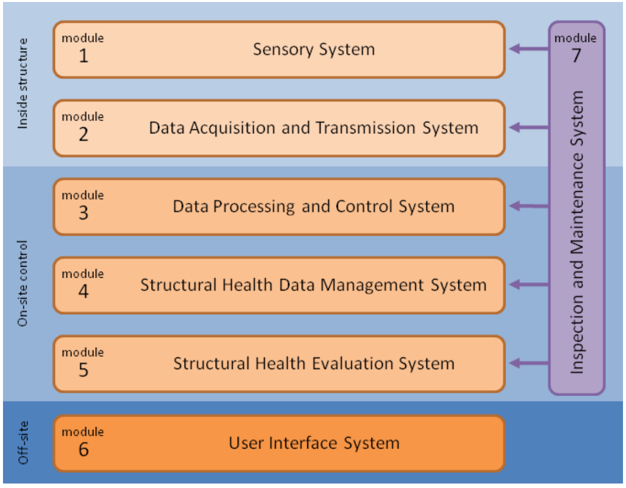

Figure 6. Structural health monitoring system modules (modified but based on Ni and Zhou, 2010)

In Figure 6, the order of the modules is different to that described by Wong, due to the order in which the data is being processed. In summary, module 1 gathers the data and module 2 allows for acquisition and transmission to the local computer systems. The computer systems are divided into module 3, which stores data and calculates structural parameters, module 4, which interfaces with the stored database and manages metadata and module 5, which calculates the structure's health by modelling and comparison. Both modules 4 and 5 therefore have a database system, where module 4 contains the raw data and module 5 the calculated and modelled data. Module 7 is a portable toolbox and laptop to inspect and maintain the hardware of the SHMS.

The User Interface System (module 6) is the newly proposed module. Its contents depend on how the system interfaces with the user and can consist of a web server to interface with both module 4 and 5 by showing the end-user structural data. If direct-to-user data transmission is unwanted, this module accounts for the processing needed to generate periodic reports for the structure.

Because of its modularity, its proven implementation for several Hong Kong bridges and the detail provided by Wong, 2007, the Hong Kong SHMS has been implemented on the Canton Tower

(Ni and Zhou, 2010). This shows that the system architecture is independent of the structure. With addition of the User Interface System it covers all objectives listed in section 2 and it is therefore proposed that this architecture be used for future SHMS designs.

4.3 User reporting

One of the problems of providing information to the user is the extent of knowledge that is necessary to understand and correctly interpret structural monitoring information. Providing continuous information is possible, but it should be presented in an understandable manner. Additionally, some users might work with multiple structures and an overview of all structures in a similar way is recommended. Wenzel, 2009 suggests using a one-page report with the following information:

1. A photograph of the structure
2. A schematic representation of the monitoring system
3. A graph showing measurement results with relevant thresholds overlaid
4. A window with information the client specifically requested
5. A condition rating based on the measurements
6. An estimate of remaining life capacity

The challenge is to combine all the relevant data of a structure in an informative display, while not overloading the user by providing a multitude of raw data. Raw data itself however should not be avoided; it could be useful for example to check if an exceeded threshold is a single occurrence or a long-term problem.

To combat the extensive knowledge required, a rating system can be used to show a structure's current status. An example of such a rating system is BRIMOS (Wenzel, 2009), but it is only applicable to bridges. A rating system for other structures such as high-rise buildings and towers has not been developed and requires further research (Aktan et al., 2000a, Pines and Aktan, 2002).

Most structural monitoring reports are digital and semi-interactive, to allow for easy comparison and real-time data display. This is the reason a User Interface System commonly employs a web server. The suggested report of Wenzel, 2009 is also semi-interactive, but has the style of a printout. For an example of such a report refer to Wenzel, 2009. Other interfaces, mainly computer displays, are presented by Aktan et al., 2000b for the Commodore Barry Bridge, Yun et al., 2003 for the Korea Highway Corporation, Wong, 2004 for the Tsing Ma Bridge and Kwon et al., 2010 for SmartSync. More research into optimal data presentation for SHMSs is needed, but it is suggested that semi-interactive displays will provide the best solution.

5. CONCLUSION

5.1 Objectives of monitoring

Review of the objectives of structural health monitoring reveals a trend towards a more user-friendly and management-focused system. Five categories of consecutive objectives are proposed: Monitoring, Evaluation, Assessment, Decision making and Validation. A flowchart to obtain these objectives is proposed. The objectives and flowchart are independent of implementation, whether the structural health monitoring system (SHMS) is to be developed for a bridge, tower, high-rise building or other civil engineering structure.

5.2 Design of a monitoring system

The process of designing a SHMS is described and a more general list of needs for SHMS is proposed. This list discerns between the need for a short-term monitoring system, a long-term monitoring system based on structural need, a long or short-term monitoring system based on research and development needs, a long-term monitoring system for maintenance purposes and a long-term monitoring system where life or property risks are involved.

A list of 9 SHMS components is provided. The addition of Reporting to the list of initially 8 components allows interfacing the end-user with the SHMS measurement and calculation results.

A list of 6 hardware-related problems and limitations of creating a SHMS is provided and time, frequency and space considerations are assessed to combat some of the data-related limitations. These considerations, originally created to address post-processing limitations, are modified for use in both the design process and processing situations.

The design process is summarized in 10 steps, where the development of the SHMS hardware only comes after the need for monitoring and objectives of monitoring are established. The interdisciplinary design process with a user-centric focus is laid out in a flowchart. The flowchart shows the need for the involvement of the user in the initial design stage, to address the specifications and outputs required from the SHMS.

5.3 Example systems

It is shown that the hardware architecture of every SHMS can be summarized into a 4-block simple architecture. The four blocks are Sensors, Acquisition stations, Local station and User.

The advanced 6-tier modular structure used for SHMSs on several Hong Kong bridges and Canton Tower is extended with a User Interface System, to account for reporting to managers, owners and other end-users of civil engineering structures. It is suggested that this system be used as a base for future SHMS designs.

Because of the addition of the User Interface System the issue of end-user reports is discussed. It is suggested that semi-interactive displays are most beneficial; however more research is needed into the correct presentation of data according to the user's needs.

REFERENCES

Aktan, A.E., Helmicki, A.J., Hunt, V.J., 1998. Issues in Health Monitoring for Intelligent Infrastructure. *Smart Materials and Structures*, 7(5), pp. 674-692.

Aktan, A.E., Catbas, F.N., Grimmelsman, K.A., Tsikos, C.J., 2000a. Issues in Infrastructure Health Monitoring for Management. *Journal of Engineering Mechanics*, 126(7), pp. 711-724.

Aktan, A.E., Catbas, F.N., Pervizpour, M., Kulcu, E., Grimmelsman, K., Barrish, R., Qin, X., 2000b. Real-time Bridge Health-Monitoring for Management. In: *2nd Workshop on Advanced Technologies in Urban Earthquake Disaster Mitigation*, Kyoto, Japan.

Brownjohn, J.M.W., 2007. Structural Health Monitoring of Civil Infrastructure. *Philosophical Transactions of the Royal Society - Series A: Mathematical, Physical and Engineering Sciences*, 365(1851), pp. 589-622.

Farrar, C.R., Lieven, N.A.J., 2007. Damage Prognosis: the Future of Structural Health Monitoring. *Philosophical Transactions of the Royal Society - Series A: Mathematical, Physical and Engineering Sciences*, 365(1851), pp. 623-632.

Inaudi, D. And Cordeau, F. And Figini, A., 2010. Integrated Structural Health Monitoring Systems for Short and Medium Span Bridges. In: *8th International Conference on Short and Medium Span Bridges*, Niagara Falls, Canada.

Kwon, D., Kijewski-Correa, T., Kareem, A., 2010. SmartSync: An Integrated Real-Time Monitoring and SI System for Tall Buildings. In: *2010 Structure Congress*, Orlando, USA, pp. 3175-3185.

Manetti, L., Inaudi, D., Glišiç, B., 2008. 3-DeMoN Monitoring Platform: Examples of Applications in Structural and Geotechnical Monitoring Projects. In: *13th FIG Symposium on Deformation Measurement and Analysis*, Lisbon, Portugal.

Moss, R.M., Matthews, S.L., 1997. In-Service Structural Monitoring: a State-of-the-Art Review. *The Structural Engineer*, 73(2), pp. 23-31.

Ni, Y.Q., Zhou, H.F., 2010. Guangzhou New TV Tower: Integrated Structural Health Monitoring and Vibration Control. In: *2010 Structure Congress*, Orlando, USA, pp. 3155-3164.

Pines, D., Aktan, A.E., 2002. Status of Structural Health Monitoring of Long-span Bridges in the United States. *Progress in Structural Engineering and Materials*, 4(4), pp. 372-380.

Sumitro, S, 2001. Current and Future Trends in Long Span Bridge Health Monitoring System in Japan. In: *Health Monitoring and Management of Civil Infrastructure Systems*, Newport, USA.

Sun, L.M., Sun, Z., Dan, D.H., Zhang, Q.W., Huang, H.W., 2009. Researches and Implementations of Structural Health Monitoring Systems for Long Span Bridges in China. *Doboku Gakkai Ronbunshuu A*, 65(1), pp. 15-29.

Wenzel, H., 2009. *Health Monitoring of Bridges*. John Wiley & Sons, Ltd.

Wong, K.Y., 2004. Instrumentation and Health Monitoring of Cable-Supported Bridges. *Structural Control and Health Monitoring*, 11(2), pp. 91-124.

Wong, K.Y., 2007. Design of a Structural Health Monitoring System for Long-Span Bridges. *Structure & Infrastructure Engineering: Maintenance, Life-Cycle Design & Performance*, 2(3), pp. 169-185.

Yun, C.B., Lee, J.J., Kim, S.K., Kim, J.W., 2003. Recent R&D Activities on Structural Health Monitoring for Civil Infra-Structures in Korea. *KSCE Journal of Civil Engineering*, 7(6), pp. 637-651.

Zong, Z.H., Wang, T.L., Huang, D.Z., Zheng, Z.F., 2002. State-of-the-art Report of Bridge Health Monitoring. *Journal of Fuzhou University (Natural Science)*, 30(2), pp. 127-152.

ACKNOWLEDGEMENTS

This research is supported by the Australian Research Council under a linkage project between the University of Melbourne and the University of New South Wales and industry partners C.R. Kennedy Pty. Ltd., Leica Geosystems and Vekta Pty. Ltd.