SENSORS AND STRUCTURES

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ABSTRACT

Sustainability of urban systems is dependent on quantitative information of their conditions, such as level of deterioration and level of safety, in major structures, and sensors are key devices for acquiring such essential information. In addition, it requires modern technology to extract only the relevant information from the enormous amount of data gathered by the sensors. In this paper, a structural health monitoring system is presented which has been developed and studied in our laboratory for several years. The system consists of a smart sensor network for data acquisition, and a database server for data storage and management together with diagnosis and prognosis applications. This paper aims to introduce the concept of the aforementioned system and the related technologies. Other sensors and networks, however, can be extended to more novel roles for civil engineering applications, such as detecting and recording the histories of environmental conditions. Among many potential applications, we are particularly interested in using robots as moving sensors to gather information in living spaces. The information obtained by robotic sensors is used to record life phases of the living spaces as “genes”, to transform the environment and its “genes”, and to pass on selected information to future “generations” of living spaces. We call this concept “biofication of living spaces”, and we are working to develop the concept as well as the generation of such “genes”.

KEYWORDS

Sensors, structural health monitoring, biofication, genes, prognosis, sustainability
INTRODUCTION

With increasing awareness of urban sustainability, the interests in accurate evaluation of structural health have increased. Structural health monitoring (SHM) technologies which capture the current status of structure quickly, and estimate the health quantitatively is improving gradually, and the number of real structures implemented with SHM technologies is increasing.

For the purpose of structural health monitoring, damage indices that are strongly correlated to the structural damages must be identified precisely. Many studies have been conducted in this area as presented in Doebling et al. (1996). The conventional damage indices such as modal frequencies, mode shapes, curvature mode shapes and modal flexibilities are considered not accurate enough for local and quantitative damage detection. When damage occurs in some layers of the building due to, say, a large earthquake, the stiffness will be reduced. In this case, the story stiffness may be a good index. There are some studies, such as the method for online estimation of the stiffness matrix using extended Kalman filter such as Loh & Tou (1997). The accuracy of these methods highly depends on the noise level contained in the data. Recently, our research group proposed several new methods to overcome the problems as presented in Qian & Mita (2007), Zheng & Mita (2007). Examples for bridges in Hong Kong are found in Ko and Ni (2005).

However, the information obtained from SHM has not ever been shared effectively, because the information is only valid for individual structures. In fact, a structural evaluation index has not been established despite of the progress of SHM technologies. As the demand from a community in which homeowners want to know about the health information of their own houses is growing, we need a system that can collect and store the data from structures as well as to analyze and disclose the data to consumers. Moreover, such a system can be extended to gather information from living spaces. Using these data, the living spaces can react and evolve quickly and inherit the acquired characteristics to the next generations. We call this concept “biofication of living spaces”.

In our laboratory, the sensing platform called SHM system has been developed, which can evaluate the soundness of structures using SHM technologies and networks explained in Mita et al. (2006). This system consists of three components, i) database (data bank with management functions), ii) smart sensor network (data acquisition function), and iii) MATLAB web server (data analysis and disclosure functions). In previous research, the usefulness of analyzing and publishing the data on the web was demonstrated though the challenges in data management remained to be resolved, for examples, data were only managed by a layered directory while they data were collected by hand. In this paper, we
present a new sensing platform which integrates sensor networks, database and data model for automatic data acquisition with sensors. The sensor network is composed of smart sensors which incorporate a micro network terminal called SUZAKU-V (Ishikawa & Mita (2006)), and are implemented with TCP/IP based application. Besides, after a server gets information from a sensor node, it processes the information and inserts Meta data of the sensor node to a data table in the database. Then, a benchmark testing is carried out, in such a way as to evaluate the proposed sensor system. To have better performance, the cell-based network topology is employed. This network consists of a number of sensor units called “cells”, and has a hierarchic structure. A limited number of sensors called “root nodes” are used to collect the data, and to connect to the server. Therefore, a cell-based network is established which is highly effective to reduce the workload of the server, and to eliminate data lack in the database.

The work presented here was conducted by staff members at the Mita Laboratory of the Keio University, and the paper presents key findings on recent advances in sensors and structural health monitoring systems as reported by Mita et al. (2006, 2007).

**STRUCTURAL HEALTH MONITORING SYSTEM**

![Diagram of structural health monitoring system]

The typical process for structural health monitoring systems is depicted in Figure 1. The data from sensors are collected in the form of electrical signals in most cases. The signals are correlated with physical sources. However, most sensor signals are contaminated with noises, such as those from unwanted physical sources and electrical noises. The noise components should be cleaned, and accurate data should be obtained during cleansing curation. The system identification process estimates system models that correlate input
and output signals. From the identified models, features that have strong correlation with damage and deterioration are extracted to be used in diagnosis and prognosis. In the last process, pattern recognition tools such as support vector machines (SVM) and neural networks are frequently used.

The outline of the MATLAB-based health monitoring system that we have been developing is depicted in Figure 2. The data obtained at a building are automatically transmitted to the server through the internet when the monitored responses are requested to be transferred. The conditions to trigger the transfer and the other configurations of the system can be set in advance in the form of a database for each sensor. Thus, the users of this system do not need to configure the sensors for each building. Only when it is necessary, the set up conditions can be changed through the server using an easy-to-use user interface. The system architecture of this prototype structural health monitoring system is presented in Figure 3. Typical user interface of the prototype system is shown in Figure 4. As the database for the server, a relational database, PostgreSQL, was adopted. The user interfaces were coded using “Hyper-text Pre-processor” (php) to make the system flexible. The data needed for analyses are selected using a php interface and submitted for analyses by MATLAB web servers.

Figure 2: Prototype structural health monitoring system using smart sensors.

Figure 3: System architecture of prototype structural health monitoring system.
SMART SENSOR NETWORK

We have recently developed a smart sensor unit to be used in the smart sensor network with an automatic configuration mechanism. The smart sensor unit communicates readily with the server to configure the sensor unit automatically. The most important components of the system are i) a smart sensor unit, ii) a data model, and iii) a user data management. The mechanism of the proposed sensor network to achieve automatic configuration is described as follows:

- A smart sensor unit with a brain communicates with other sensors as well as the server.
- All specifications associated with the smart sensor unit are stored in the sensor memory, so that once the network is connected all the necessary data are automatically fed to the server.
- All meta-data including the sensor configuration are stored in the database. The raw data are linked to the meta-data models so that easy and fast data selection is possible.
- Easy-to-use user interfaces are developed using php, and the configuration of the sensor network can be also conducted through this user interface.

The details of the system are briefly explained below.

**Smart Sensor Unit**

The smart sensor unit is shown in Figure 5.
It consists of three boards: i) a micro-network terminal SUZAKU-V board, ii) a power supply board, and iii) a sensor board with an A/C converter. The physical dimension of this unit including the sensor case is 5 cm (H) × 8 cm (W) × 10 cm (L). Although any sensor can be installed into this unit, a servo-accelerometer is used for the prototype system, and the accelerometer can measure in three orthogonal directions simultaneously.

**Data Model**

The database selected for the prototype system is PostgreSQL which is relational type database. The meta-data are used for searching a particular data needed for analyses. Thus, the structure for storing the meta-data affects the speed of the search. In addition, any improper relating between tables will make the update of the data very difficult and less flexible. Thus we adopt a star-shape data model as depicted in Figure 6.

A table describing information of a smart sensor unit called Table ‘Sensor-Info’ is located in the center of all tables. All meta-data are connected through this table using keys. Table ‘Str-Info’ contains structural information while Tale ‘Accelerometer-Info’, Table ‘A/Ddevice-Info’ and Table ‘Suzaku-device-Info’ contain information of an accelerometer, an A/D converter, and a SUZAKU-V, respectively. In addition, files containing measured acceleration data are linked to Table ‘Acc-data’. Table ‘Sens-sync-data’ contains synchronization information for all the sensors while Table ‘Channel-Info’ has detailed information on the configurations of the sensors. Tables ‘UserProfile’ and ‘RoleProfile’ have information of a system manager and of a user, respectively.
In Figure 7, a diagram for communication between the sensors and the server is presented. The TCP/IP in the server-client structure is used as a protocol for this system. Three programs run on a smart sensor unit (or a client): i) a ‘receiver’ program receiving messages from the server, ii) a ‘sensor-read’ program controlling the A/D converter unit, and iii) a ‘measure’ program sending data to the server. The server program receives the data from the smart sensor units (clients), and then stores all the data into the database.
The server program takes care of both data communication and database management at the same time. The measured data from the sensors are sent to the server as text-format data together with associated meta-data. When the server receives the measurement data, the following processes are executed by the server program:

- The original data are divided into four files which are measured data in the x, y, z directions, and the time synchronization data.
- The meta-data in the original text data are inserted into the database.
- The notice of completion is sent.

These programs were run in a PC server and also in the smart sensor units. The OS is Red hat Enterprise Linux ES (Version 4) while the database used here is PostgreSQL 8.1.5. In the prototype system, acceleration measurements are initiated with user input. As this system uses only a limited number of ports, smart sensor units can be installed within most computer firewalls.

SENSOR NETWORK ARCHITECTURE AND TIME SYNCHRONIZATION

The developed sensor nodes can be networked in any form. However, to reduce traffic in the network, the cell-based network topology was employed. As the smart sensor unit transfers data in a digital form, rather than in an analog form, time synchronization is
not automatically guaranteed. We need a typical accuracy within a few micro seconds to ensure correct time steps for system identification up to 1 kHz sampling data. A unique time synchronization mechanism implemented in our smart sensor network is explained below.

**Cell-based Sensor Network Architecture**

Sensor networks can be wired or wireless. In this study, a wired network is employed as the network should be able to work for more than 10 years which is considered to be the minimum practical life span of buildings structures. Thus, it would be reasonable to assume power supply is not an issue for wired sensor networks.

The concept of the cell-based sensor network topology is illustrated in Figure 8. Each cell uses a hub to be connected to an upper level cell, i.e. a “mother” sensor node, or several “child” sensor nodes. The ports of the child sensor nodes are connected to not only other child sensor nodes but also to the lower level cells, and the hubs reduce the number of cables.

In the sensor network, the sensors and the servers communicate to each other using TCP/IP or UDP/IP. Hubs in this network are modified so that the time synchronization mechanism can be embedded. The time synchronization is very important when smart sensors are used because the sensors have their own time sources. Rendered data from sensors become meaningless without proper time synchronization. A synchronization signal is generated from the root cell, and propagates to the lower level cells. When connections between the root cell and the lower cells become off line, the mother sensor nodes continue to generate their own synchronization signals which propagate to the lower level cells.

![Figure 8: Cell-based network topology to reduce the data traffic](image-url)
**Time Synchronization**

The Global Positioning System (GPS), operated by the National Institute of Standards and Technology, is used widely for synchronizing reference time. Its precision is 200ns. However, it requires highly sophisticated hardware. In addition, we have to have a line-of-sight with GPS satellites. Most of the sensors will be installed in buildings so that GPS may not be applicable.

The Network Time Protocol (NTP) [5] is a protocol for synchronizing time of computer systems over a packet-switched data network. It can synchronize the time of computer systems to resist the effects of variant latency. NTP uses Marzullo’s algorithm with the UTC time scale, and performs important features such as leap seconds. NTP can achieve an accuracy of at least 200 microseconds in local area networks under ideal conditions. Unfortunately, this accuracy is not sufficient for our application.

Thus, we decide to develop our own time synchronization mechanism. The sensor network in this implementation uses 2 pairs of unused lines (4-5 pair line and 7-8 pair line) in the category 5 cable, and hubs and cables are slightly modified. Modifications are easy, requiring only the circuit patterns being cut, and the lines being re-connected. The ports of the hubs can be modified to be able to connect to the common network. Synchronization signals are transmitted in the RS-485 form. Each mother node can deal with up to 32 child sensor nodes. Details of the cable connections in the modified hub are presented in Figure 9.

![Figure 9: Typical cable connections at modified hub](image)

The mechanism for synchronization is explained below.

- Synchronization signals are transmitted from a 7-8 pair line on a child sensor node
port of an upper level cell to a 7-8 pair line on a synchronization port of a lower level cell.

- The 7-8 pair line on the synchronization port is connected to a 7-8 pair line on a mother sensor node port.
- The 7-8 pair line on the mother sensor node port in the hub is connected to a 7-8 pair line on a mother sensor node.
- The mother sensor node is synchronized by using received synchronization signals.
- The mother sensor node generates new synchronization signals.
- The new synchronization signals are transmitted from a 4-5 pair line on the mother sensor node.
- The 4-5 pair line of the mother sensor node is connected to a 4-5 pair line of the mother sensor node port in the hub.
- The 4-5 pair line on the mother sensor node port in the hub is connected to a 7-8 pair lines of child sensor node ports in the hub.
- The 7-8 pair line on the child sensor node port in the hub is connected to a 7-8 pair line on a child sensor node, and a 7-8 pair line on a synchronization port in a lower level cell.
- The child sensor node is synchronized by using received new synchronization signals.

Thus, the synchronization signals are different between the mother sensor node and the child sensor nodes in the same cell which results in timing jitters between them. The base frequency of the synchronization signals is 250KHz. Using higher frequencies makes time synchronization more accurate, but causes some problems due to the characteristics of high frequency waves. In this implementation, a conservative frequency is used.

The synchronization signals were encoded using modified Manchester encoding as shown in Figure 10. It starts at high for the first 1 ½ cycles, and is followed by an encoded time, a sender ID and other orders. The synchronization signal starts within 0.4ms, and needs 0.27ms to be sent completely. Thus, the measurement starts at 0.67ms after the sensor nodes are connected to the network.

![Figure 10: Signals for time synchronization](image)
**Network Load Test**

Extensive tests have been conducted to gain understanding on the performance of the prototype smart sensor network. Emulation programs were developed to emulate data transmission from each smart sensor unit to the server. Several performance indices such as CPU usage, load average, and free memory amount were measured during the tests. All sensors are assumed to be connected to the server directly.

The maximum number of sensor connections was measured. In the test, the trigger mode was not used, and the duration was not fixed. Instead, the emulated sensors kept sending data to the server. When the data arrive at the server, the server load and time were measured. As a result, the maximum number of connections from sensor units was found to be 5,229. Additionally, free memory space fell gradually and levelled off at 1,500 nodes. Therefore, workable connections were approximately 1,000 from the view point of server load. However, when the data is inserted to the database, some data losses were observed when the number of sensors exceeded 364.

The cell-based network was also employed in the test. It was confirmed that the number of root nodes should be restricted to be smaller than 10 to ensure a good performance. By employing this network structure, the number of sensors can be more than 1,000.

**BIOFICATION OF LIVING SPACES**

Smart sensor network can be an infrastructure for detecting and recording the histories of environmental conditions relevant to buildings beyond structural health monitoring. Among many potential applications, we are particularly interested in using it mounted on robots as moving sensor agents, that we call “sensor agent robots”, to gather information from buildings and residents. The information obtained by the sensor agent robots is used to record life phases of the living spaces as “genes” in the form of DNA, to transform the living spaces and its genes, and to pass on the information to future “generations” of buildings. We call this concept “biofication of living spaces”, and we are working to develop the concept and the generation of such “genes”. The sensor agent robots can work as actuators in many incidents as well. The smart sensor network will be extensively used for this new research field, and the concept is illustrated in Figure 11.

In designing a building, we usually rely on the designer’s knowledge and experience to decide its specifications such as the ceiling heights, the locations of electric outlets, the room layouts and so on. However, it may not satisfy the real needs of the residents. As in
most cases, they do not know what their real needs are, it is truly difficult to know the ideal specifications for the building. Gathering environmental information relevant to how to use the building will change the way of designing of a building from experience-based to data-based design. Thus buildings will evolve much faster and will meet the real needs of their residents. The DNA embedded in a building will be used for converting the recorded environmental information to data needed to design new generations. The data expressed in the form of design drawings will be of another form. Using DNAs of many buildings, we will be able to have variety of buildings without tedious design processes.

Our human body has another important feature called immune system. It is the system to distinguish between my cell and other cells. If harmful other cells are found, the immune system will attach them in many ways. We would like to embed this concept into a building. This system can work as alarm system to detect an intruder into a room. It will detect some unusual incidents such as the damage due to fire, typhoon or earthquake. For a room where an elderly person lives, it will act as a guard for him or her. Thus, the immune system embedded in a building help create a safer, securer and more comfortable spaces for us.

Sensors will play a key role in this new research field. Logging any data of the buildings and the residents will be the sources of evolving the structural systems as well as their smartness.

![Figure 11: Concept of “biofication of living spaces”](image)
CONCLUSIONS

The important roles of sensors for structures are presented. Structural health monitoring is a typical application field of sensors for detecting deterioration and damage online so that immediate retrieval is possible. The system will help saving many lives. The structural health monitoring system reduces maintenance costs and prolongs healthy duration of life for structures. A smart sensor network introduced in this paper will be a good candidate to be used for the system.

As a future application of sensors in a building, a new concept “biofication of building spaces” was presented. This concept provides many technical challenges for us. The biofied building will provide us safer, secure and more comfortable living spaces.

REFERENCES


