The 11th IEEE International Workshop on
Advanced Motion Control
March 21-24, 2010, Nagaoka, Japan

Effective Data Sharing System for Fault Tolerant Structural Health Monitoring System

Yoshinao Matsushiba, Hiroaki Nishi *Member, IEEE*
yoshi@west.sd.keio.ac.jp, west@sd.keio.ac.jp
Department of System Design Engineering, Keio University
3-14-1, Hiyoshi, Kouhoku-ku, Yokohama-shi, Kanagawa-ken, Japan

Abstract- **Structural Health Monitoring (SHM) system is a promising technology to determine the health condition of a structure and localize its damage. SHM system is widely used, especially in gigantic structures for its strong requirements of safety. Many researches about SHM system have been conducting. However, conventional SHM system did not take account of an accidental collapse caused by earthquake. As a result, there is a possibility that sensor nodes, network links, and a center server cause failures in processing or storing of data gathered in the building. These failures may lose important data that contains useful information for post-analyzing the collapse. The data includes when, where and why the structure is damaged and collapsed. Theses information have a great deal of potential for preventing similar damage or collapse and it will make great contribution to accelerate future structural researches. To solve the problem of data losses in a damage, data sharing system for SHM system is proposed. This system shares data within sensor nodes. The proposed system achieves the following three processes; node search, backup node selection and backup data transfer process. It is important to conduct these processes under the condition of limited resources due to small and not powerful sensor nodes. Backup node selection is an important process of this system. This paper mainly focused on this selection. Round-trip time, a size of free memory space of backup nodes and value of displacement caused by vibration are used for the selection. In this paper, the selection method based on displacement was checked. An experiment was conducted by using practical sensor nodes and acceleration data. From the result of this experiment, proposed system could share data by using selection method based on displacement.**

I. INTRODUCTION

Currently, sensor network technology has been remarkably developed and becoming more prevalent. Small sensor node of sensor network system becomes to integrate multiple sensors in it, and it is controlled by tiny high-performance microprocessor. This powerful sensor node is connected by using wired/wireless networks each other and organizes complex and highly functional sensor network system. Sensor network is exploiting many kinds of applications in order to seize the real-time or non-real-time information for providing useful summarized information for us. Sensor networks are now indispensable for our society.

SHM (Structural Health Monitoring) system [1] is a typical application of sensor network system. The system monitors structural vibration caused by earthquake, detects structural damage and predicts performance and lifecycle of the structure. SHM system is used in an infrastructure, such as bridges and buildings etc [2]. The SHM system mainly uses acceleration sensor nodes in order to obtain the information of acceleration data. It is better to distribute acceleration sensor nodes in each floors of target structure. Most of SHM systems gather the information into a center server from these distributed sensor nodes. After gathering sampled data, system user calculates barometer such as natural frequency of the structure based on sampled acceleration data. It enables to detect a damage of the structure and also enables to predict its performance. SHM system is a promising technique to determine the condition of target structure.

Most of existing SHM system uses wired network for data acquisition to collect vibration data of the target structure. Recently, SHM system, using wireless sensor network, is researched and used due to system installability [3]. Wired sensor network system, however, can supply electric power to sensor nodes and it is superior in the reliability of communication. Additionally, in a wired sensor network system, complicated routing protocol for maintaining Ad-Hoc network is not necessary, which is expensive to install and manage. This protocol sometimes wastes larger bandwidth and it will become significant weakness of the total network performance. While collapsing, network configuration is dynamically changed. In Ad-Hoc network, the network system will exchange many packets for maintaining Ad-Hoc network. It will reduce the sufficient network throughput required for backup. When selecting weird or wireless sensor network for a system installation, the application of SHM system should be considered.

In this paper, we propose a new backup system for SHM system and it supports both wired sensor network and wireless sensor network. Many researches about SHM system are conducted. One of researches focused on developing algorithms for damage detection and localization [4]. In another research, time synchronization for wired sensor network was conducted [5]. Additionally, some researches only focus on SHM system with wireless sensor network. These existing systems, however, did not take account of an accidental collapse. In the accidental collapse, there are possibilities that sensor network nodes are broken and terminate their operation. Network connection between sensor nodes and a center server also has a possibility to be broken and go offline. If sensor nodes are damaged, important sampled data will be lost. Most of all sensor network system gathers sampled data into a center server. If the center server is located in the same site of the target sensor network, there is a possibility that the server is broken down at the same time when the sensor network is damaged. In addition, if the center server is located in remote, the connection between a sensor network and a center server will be easy to go offline. These failures cause loss of sampled data. The data acquired by SHM system becomes more important when the structure is actually collapsed by natural disasters, especially earthquake in Japan. The data includes when, where, and why the structure is damaged and collapsed. Theses information is useful to prevent structures from a damage or collapse caused by similar accidents. It will make great contribution to future structural design or study. SHM system must detect and localize damages by using acquired data. Though many collapse experiments by using miniature have been conducted in laboratory environment, real collapse data of natural disaster are recorded only a few times and are very valuable. It is important to prevent from the loss of these real sampled data.

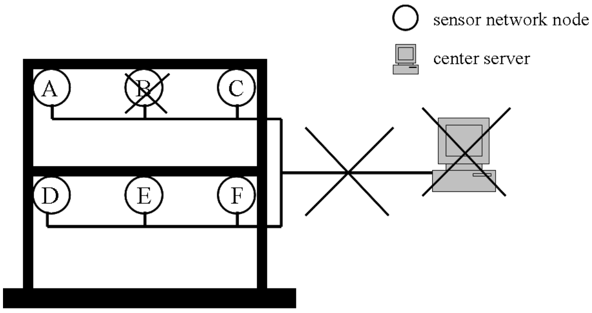

Figure.1 Breakdown of conventional SHM system

In this paper, system for preventing loss of sampled data is proposed and the detail of this system is described. Related works are shown in section II. Next, the architecture of this proposed system is shown in section III. Then, an experiment and result are shown in section IV. Finally, this paper is concluded in section V.

II. Related Work

In [3] and [6], performance of a multi-hop wireless data acquisition system for SHM system, called Wisden, is discussed and evaluated. [7] proposes an open software architecture design approach for the implementation of SHM system with wireless sensor nodes. In this paper, a library is designed and it helps to design common computation functions or subtasks of SHM analysis. [4] and [8] propose a holistic approach to SHM system that features a decentralized computing architecture based on the characteristics of a practical damage localization algorithm. The proposed system in this paper was compared with typical centralized architecture and showed that proposed system reduces its latency by 64.8% and energy consumption by 69.5% in its comparison. [9] discusses data transfer protocol based on clock synchronization in bridge structure with wireless sensor. These researches are conducted by using a SHM system with wireless sensor network. In contrast, there are some researches about SHM with wired sensor network. [5] introduces a time synchronization system for wired smart sensor networks for a structural health monitoring of gigantic structures. The proposed system in this paper theoretically proves the accuracy is up to 34 ns in its jitter of sensors by adjusting the time according to the wire length, and experimentally showed the jitter of 190 m separation is within 25 ns.

In these broad researches, SHM system considering loss of sampled data in a collapse has not been considered.

III. Proposed System

To prevent the loss of sampled data, sensor nodes have to exchange information each other before a breakdown of sensor nodes, a center sever and links. Namely, sharing data with sensor nodes is indispensable. For the sensor network system, it is difficult to implement a complex data sharing algorithm because of its limited or energy critical processing power and network bandwidth. A simple, effective and safe data sharing application is indispensable for preventing the loss of sample data for exchanging sampled data among sensor nodes.

In the proposed system, all sensor nodes are categorized into two types of node by their function. One is a sender node that has original sampled data to be shared, which should be prevented from data loss. The other is a backup node that is regarded as an appropriate node to receive the original data. In most of existing SHM system, sensor nodes constantly monitor acceleration data of target structure. When the value of sampled data exceeds a threshold, SHM system regards that an earthquake attacks and starts capturing acceleration data and send the data to its center server. Proposed system needs to set another threshold for a beginning of backup. A sensor node that exceeds this second threshold will become a sender node. The sender node selects backup nodes and sends data to them periodically. Fig.2 shows the image of proposed system. In this figure, circles and arrows stand for sensor nodes and paths of data transfer, respectively.

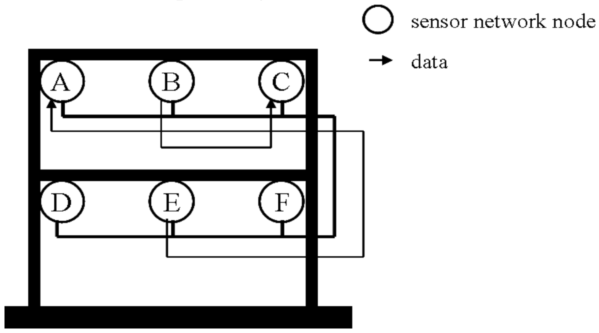

Figure.2 Image of proposed backup system

The proposed system achieves following three processes in order to backup data. These processes should be simple because of limited recourse of sensor nodes.

- *Node detection*: At first, all sender nodes have to seize all other active sensor nodes in the same sensor network by using node searching function because these nodes can be a candidate of backup node. PING (Packet InterNet Groper) protocol with broadcasting option is a simple solution for the node searching function.
- *Backup node selection*: Proposed system uses the information of node detection for selecting the candidates of backup nodes. For selecting, the information of round-trip time, available memory size, and displacement of the target structure are used for attaining robustness. At first, PING protocol includes this time information between a sender node of PING and its receiver nodes. Secondly, before sending backup data, it is necessary to check memory space of the candidates whether they have enough memory space for storing backup data. At last, information of displacement caused by a vibration is used to select the candidates. A sensor node that has bigger displacement is comparatively more dangerous than others and is appropriate to be regarded that the sensor node is easy to be broken down by the vibration.
- *Backup data transfer*: The sender node sends backup data to backup nodes by using TCP/IP (Transmission Control Protocol / Internet Protocol) socket communication.

Proposed node detection process and backup node process are important parts of proposed system. In this paper, the detail of these functions is described.

A. Node detection

In proposed data backup system, the sender node detects the candidates of backup node to send backup data beforehand. In this selection, the location of nodes is important information. GPS (Global Positioning System) is one of the technologies for localization. However, GPS cannot be used directly because of reflection or attenuation in an indoor environment. Moreover, it is expensive to install GPS module in each sensor nodes. Namely, another method for measuring location information is required. PING protocol with broadcasting operation is a simple solution for the node detection process. In PING protocol, Sender nodes send ICMP (Internet Control Message Protocol) echo request message to another sensor nodes within sensor network with broadcasting option. Active sensor nodes, which received the ICMP request message, reply ICMP reply message to the sender nodes. The sender node regards the nodes whose ICMP reply message is reachable as a candidate of backup node.

The use of PING protocol has some merits. When a sender node sends data to a backup node, both nodes can avoid paying high communication costs because PING protocol is a lower layer protocol in OSI model and it prevents to use complex higher layer protocol which consumes processing power. Moreover, the sender node can recognize both the backup nodes existence and communication delay between the sender node and the backup node simultaneously. The communication distance between the sender node and the backup node can be obtained by using this round-trip time of a PING packet. This is described in the next subsection.

B. Backup node selection

After Node detection process, proposed system conducts Backup node selection process. In backup node selection state, the following process are achieved in order; selection method based on round-trip time, selection method based on memory utilization of backup node, and selection method based on displacement.

- *Selection method based on round-trip time*

When selecting a candidate of backup node, the locations of the candidate is an important factor. If a backup node is close to the sender node, there is a possibility that the backup node and the sender node are broken and damaged simultaneously when a disaster comes. In this case, the possibility of perfect data loss becomes higher because both sender node and backup node may be broken at the same time. If the backup node is away from the sender node, the possibility of network connection loss between them will be increased.

The delay of PING protocol contains the information of the distance. In proposed system, PING protocol is used instead of GPS for obtaining location information and node availability at the same time.

Round-trip time of PING does not stand for the correct distance. The round-trip time contains communication load and does not consider the straight-line distance. In proposed system, the sender node sends data to multiple backup nodes for enhancing reliability of the selection method. Additionally, proposed system can attain both high-throughput and reliable backup by using multiple backup nodes. When the sender node selects a sensor node of shorter round-trip time as a backup node, high-throughput backup can be attained. When a sender node selects a sensor node of longer round-trip time as a backup node, reliable backup can be attain. This means there is a trade-off between throughput and reliability. Proposed system sends backup data to the node of both shorter round-trip time and longer round-trip time simultaneously.

- *Selection method based on memory utilization of backup node*

In proposed system, it is necessary to consider memory resource for a stable backup. For example, if many backup data transfers concentrate in a specific backup node, there is a possibility that the amount of memory space in the backup node is exhausted. Thus, proposed system has to avoid concentration of load by using distributed selection methods.

Generally, sensor node has a sensor device, CPU and A/D converter. Additionally, RAM and flash memory are implemented on CPU. A simple configuration diagram of sensor node is shown in fig.3.

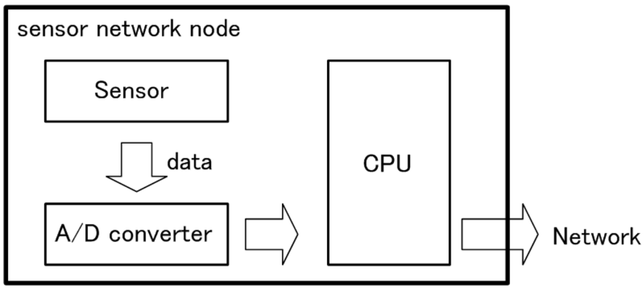

Figure.3 Simple configuration diagram of a sensor node

In proposed system, backup data is stored at flash memory. Additionally, when sensor nodes have USB interface, backup data can be stored at USB flash memory module. Most of small sensor nodes do not have USB interface. These sensor nodes cannot store a large amount of data created by long term capturing. In small sensor nodes, storing at on-chip flash memory is suitable for temporary backup. If the USB flash memory is available for storing, it is suitable for long term backup because it can store large size data. In proposed system, backup timing is dynamically changed according to the size of memory space or its implemented style.

A sender node sends backup request message to candidates of backup node. Next, the candidates, which received the request message, check the memory space for backup data. Candidates that have enough space to store backup data allow the sender node to send backup data and send a grant message of backup request. If the sender node does not receive any grant messages, it sends the request message to another candidate of backup node.

- *Selection method based on displacement*

There is a possibility that a sensor node, selected as a backup node, is broken by accidental collapse. This failure will bring loss of both original measured data and backup data. Therefore, it is necessary to select more safe backup nodes. In proposed system, Backup node selection process also uses the value of displacement, which is generated by a vibration of target structure. Displacement of target structure can be an indicator for predicting damage. A place or area where displacement is larger is regarded as a dangerous area [10]. When displacement of a candidate of a backup node is larger than that of a sender node, the sender node does not send sampled data to the candidate and shifts the selection process to other candidates.

Displacement can be calculated by using integration of acceleration data. In most of existing SHM system, sampled acceleration data is converted from time domain to frequency domain data by using FFT (Fast Fourier Transform) at center server for calculating displacement. After that, low-pass filter is used to correct error. Then, integration is conducted in frequency domain. In proposed system, however, it is difficult to use this integration method. Computing resource of sensor nodes is not enough for this calculation. For solving this problem, proposed system conducts integration by low-pass filter with moving average in time domain at each sensor nodes. There is a tradeoff between simple calculation and more accurate displacement value. This integration is enough for proposed system to predict the safety of the sensor node.

Sensor nodes are constantly monitoring acceleration of target structure and the nodes sample acceleration data of earthquake. When integration is conducted, the acceleration data of earthquake is used for the calculation. Zero as initial-value is set for the integration.

IV. Experiment & Result

In [11] and [12], performance of backup node selection method based on round-trip time and memory utilization was accomplished. In this paper, performance and reliability of backup node selection method based on displacement were confirmed. In this experiment, proposed method was implemented on two practical sensor nodes called KNIVES terminal.

To conduct this experiment, two KNIVES terminals for emulating a sender node and a backup node were used. Before the sender node sends data stored in its memory to the backup node, the sender node compares max value of displacement of both nodes. The sender node detects whether an area including a candidate of backup node is safe or not. When the sender node judges it is safe, the sender node sends data to the backup node.

In this experiment, a sampled acceleration data beforehand is used. This data is captured by using experimental model structure (Fig.5). In a grant message of backup request from sender node, displacement data and free memory size are piggybacked.

A. *KNIVES terminal*

KNIVES terminal [13] is a sensor network system for environmental measurement. Several KNIVES terminals are under operating in some practical sites. It has universal I/O interfaces; analog I/O, digital I/O, 1-wire interface, and I2C. Additionally, KNIVES terminal uses two-coin size tiny Linux module (Fig.4). In this module, ARM-9 microprocessor, 32MB SDRAM memory and 8MB flash memory are implemented. These specs are enough for this proposed SHM system. KNIVES terminal can be used for emulation. In this experiment, external USB flash memory was used for storing backup data.

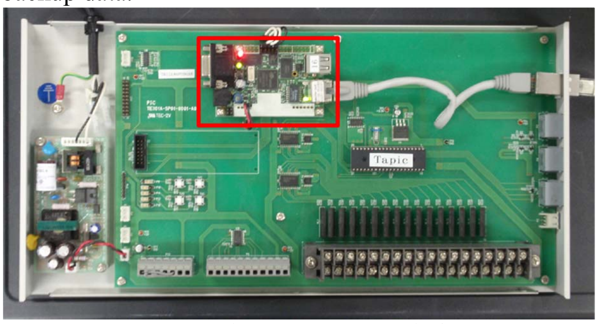

Figure.4 KNIVES terminal

B. Acceleration data

In this emulation, acceleration data sampled from a vibration experiment with an experimental steel structure was used. Fig.5 shows the steel structure. This steel structure is 155 cm long.

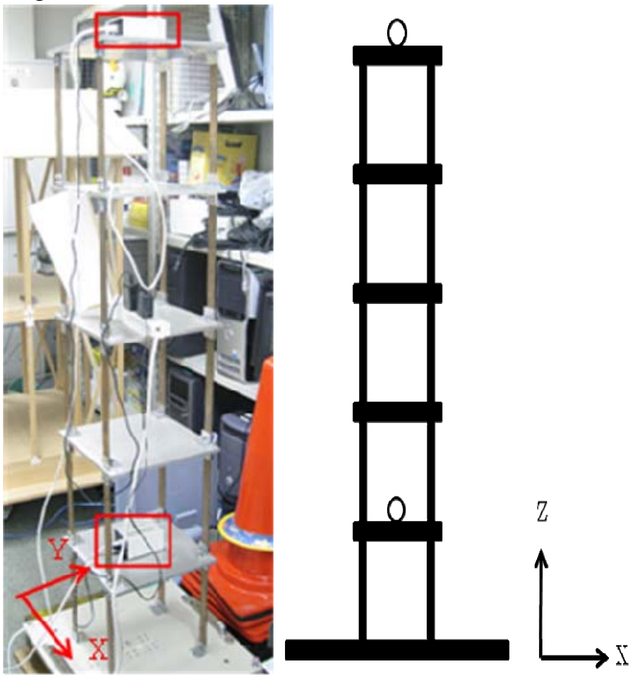

Figure.5 Experimental structure

Two MEMS 3D acceleration sensor nodes were implemented on second floor and sixth floor of the structure. These sensors are connected to a server by using wired network and have a tiny Linux module. After making an impact with a hummer, these sensor nodes sampled acceleration data for three minutes at 0.01[s] intervals.

For checking a relationship between displacement and dangerous area of the structure, the acceleration data were processed by using band pass filter after gathered. Table 1 shows value of displacement of each floor. "Date" in this table is observational day. In data number one and two, steel columns of fourth floor were replaced with thinner steel columns for conducting experiment of weak structure. Additionally, steel columns of third and fourth floor in data number three and four were replaced with thinner steel columns.

From table 1, displacement of sixth floor is bigger than displacement of second floor at every observational day. This table shows that displacement of target structure can be regarded as a barometer of predicting damage. These displacements were calculated by using acceleration data of x-axis acceleration sensor (Fig. 5).

Table 1 Value of displacement

Data number	Date	Floor	Maximum displacement [cm]
1	12.08.2008	2F	0.12
		6F	0.59
2	12.09.2008	2F	0.16
		6F	0.77
3	12.13.2008	2F	0.17
		6F	1.03
4	12.14.2008	2F	0.13
		6F	0.76

C. Result

Two KNIVES terminals as a sender node and a backup node were used and these terminals calculate displacement by using acceleration data described in the above section. Firstly, the sender node and backup node calculates displacement of second floor and sixth floor, respectively. Accordingly, the area of sender node can be regarded as safe area. The sender node gives a judgment that there is a possibility of collapse and it is required to send a backup data based on the displacement. When a backup is required, memory usage of the backup node is checked. In this experiment, the data is stored at USB flash memory of backup node. The inverted experiment in their installed floor is also conducted. Table 2 shows result of this experiment.

"Before" in this table means memory usage of backup node before comparison of each displacement. Additionally, "After" means its memory usage after the selection. In every case, memory usage is increased when the sender node of sixth floor send the data to the backup node of second floor. In short, the sender node considered that the backup node was implemented on safe area and sent own acceleration data to the safe backup node. In contrast, the memory usage was not changed when the sender node and backup node were installed on second floor and sixth floor, respectively. Namely, the sender node considered that displacement of backup node was bigger than the own displacement, and the area of the backup node was danger.

From table1 and table 2, the sender node could be considered to judge condition of structure correctly by using the proposed selection method. Performance and reliability of backup node selection method based on displacement was proved.

In this paper, real computation time of proposed system also was checked. The time was shown table 3. Average time of the sender node and the backup node were 0.86[s] and 1.07[s]. This result means that the processing load is light enough for sensor nodes. Additionally, the proposed system can conduct before a structure collapses. Structure collapse within about three[s].

Table 2 Result of the experiment

Data number	Date	Node	Used data	Memory usage of backup node[Kbyte]	
				Before	After
1	12.08.2008	Sender node	2F	200512	200512
		Backup node	6F		
		Sender node	6F	200512	200576
		Backup node	2F		
2	12.09.2008	Sender node	2F	200512	200512
		Backup node	6F		
		Sender node	6F	200512	200576
		Backup node	2F		
3	12.13.2008	Sender node	2F	200512	200512
		Backup node	6F		
		Sender node	6F	200512	200576
		Backup node	2F		
4	12.14.2008	Sender node	2F	200512	200512
		Backup node	6F		
		Sender node	6F	200512	200576
		Backup node	2F		

Table 3 Computation time of sender node and backup node

Data number	Date	Computation time[s]	
		Sender node	Backup node
1	12.08.2008	1.36	0.67
2	12.09.2008	0.63	1.33
3	12.13.2008	0.77	1.20
4	12.14.2008	0.69	1.09

V. Conclusion & Future works

In this paper, the effective data sharing system for SHM system that prevents the data failures or loss is proposed. This system shares data within sensor nodes. Proposed system consists of three processes; node search, backup node selection and backup data transfer. In this paper, proposed selection method based on displacement was evaluated. The experiment was conducted by using practical sensor nodes called KNIVES terminal and measured acceleration data. From result of this experiment, performance and reliability of the proposed selection method were proved. Proposed system could share data by using selection method based on displacement.

In this paper, acceleration data of only second floor and sixth floor was used for this experiment. As future works, we are planning to conduct an experiment to install sensor nodes in an experimental steel structure at every stories. In this experiment, we can evaluate proposed system by using acceleration data of each stories. Additionally, we will use total of absolute value of acceleration data to update our proposed system. It means proposed system can detect dangerous area more accurately by using total of absolute value of acceleration data [14].

Reference

[1] H. Kinawi, MMR. Taha, N.El-Sheimy, “Structural Health Monitoring using the Semantic Wireless: A Novel Application for Wireless Networking,” *the 27th Annual IEEE Conference on Local Computer Networks* (LCN’02), pp.770-778, 2002.

[2] A. Bashart, N. Catbas, M. Shah, “A Framework for Intelligent Sensor Network with Video Camera for Structural Health Monitoring of Briges,” *Third IEEE International Conference on Pervasive Computing and Communications Workshops* (PERCOMW’05), pp.385-389, Mar. 2005.

[3] K. Chintalapudi, J. Paek, N. Kothari, S. Rangwala, R. Govindan, “Embedded Sensing of Structures: A Reality Check,” t*he 11th IEEE International Conference on Embedded and Real-Time Computing Systems and Applications* (RTCSA’05), pp.95-101, Aug. 2005.

[4] G. Hackman, S. Fei, N. Castaneda, L. Chenyang, S. Dyke, “A Holistic Approach to Decentralized Structural Damage Localization Using Wireless Sensor Networks,” *29th IEEE International Real-Time Systems Symposium, 2008,* (RTSS 2008), pp. 35-46, Nov. 30 2008-Dec. 3 2008,

[5] K. Ishikawa, A. Mita, “Time synchronization of a wired sensor network for structural health monitoring,” *Smart Mater Structures,* Vol.17, No.1, 2008,

[6] J. Peak, K. Chintalapudi, R. Govindan, J. Caffrey, S. Masri, “A Wireless Sensor Network for Structural Health Monitoring: Performance and Experience,” *The Second IEEE Workshop on Embedded Networked Sensors, 2005*. EmNetS-ll, pp.1-10, May. 2005,

[7] C. Bo, M. Tomizuka, “OpenSHM: Open Architecture Design of Structural Health Monitoring Software in Wireless Sensor Nodes,” *IEEE/ASME International Conference on Mechtronic and Embedded Systems and Applications* (MESA 2008), pp. 19-24, Oct. 2008.

[8] A. Messina, I. A. Jones, E. J. Williams, “Damage detection and localization using natural frequency changes,” *In Conference on Identification in Engineering Systems, U.K.*, 1996.

[9] L. Fangmin, X. Li, L. Xinhua, W. Xuehong, “Data Transfer Protocol in Bridge Structural Health Monitor System Using Wireless Sensor Network,” *The Sixth World Congress on Intelligent Control and Automation 2006*, (WCICIA 2006), Vol. 1, pp. 5102-5105, 2006.

[10] T. Yamada, J. Komori, M. Noumori, S. Nakaminami, M. Kawashima, T. Takeda, “Development of Non-Touch Measuring System for Relative Story Displacement,” *SUMMARIES OF TECHNICAL PAPERS OF ANNUAL MEETING ARCHITECTURAL INSTITITE OF JAPAN*, Aug. 2009 (in Japanese).

[11] Y. Matsushiba, H. Nishi, “Structural Health Monitoring system considering fault-tolerance,” *sixth IEEE International Conference on Industrial Informatics (INDIN 2008),* pp. 330-335, July. 2008.

[12] Y. Matsushiba, H. Nishi, “Lightweight Data Duplication for Fault Tolerant Structural Health Monitoring System,” *8th IFCA International Conference on Fieldbuses & Networks in Industrial & Embedded Systems* (FeT’ 2009), pp. 255 – 258, May. 2009.

[13] S. Ishida, C. Roesenser, H. Nishi, J. Ichimura, “Discussion of Aspects in Energy Management with Demand Response System KNIVE,” *IEEE Conference on Emerging Technologies and Factory Automation* (ETFA’06), pp.465-468, Sept. 2006.

[14] T. Yanase, S. Ikegaya, M. Nakamura, K. En, K. Yoneyama, “Proposal on Health Monitoring System of a RC Structure for Damage Detection Part3: Trial Manufacturing of Smart VA Sensor Measuring Acceleration Data”, *SUMMARIES OF TECHNICAL PAPERS OF ANNUAL MEETING ARCHITECTURAL INSTITITE OF JAPAN*, Sep. 2006 (in Japanese).