An Autonomous Time Synchronization Sensor Device Using a Chip Scale Atomic Clock for Earthquake Observation and Structural Health Monitoring

Narito Kurata
Faculty of Industrial Technology
Tsukuba University of Technology
Tsukuba City, Ibaraki, Japan
e-mail: kurata@home.email.ne.jp

Abstract - **This article describes the research and development directed toward an autonomous time-synchronized sensor device equipped with a chip scale atomic clock (CSAC) that records highly accurate time information. The R & D project presented herein aims to achieve earthquake observation to prepare for disasters and structural health monitoring to improve the efficiency of maintenance and management of buildings and civil engineering structures. For these reasons, it is necessary to install sensors in a wide area at a high density and to measure the data with accurately synchronized time information. It is recommended that the sensor device itself maintains accurate time information without relying on the network or a Global Positioning System (GPS) signal. Therefore, in this study, a sensor device that autonomously maintains accurate time information using an ultra-high precision, ultra-low power consuming, and ultra-small (and therefore, loadable on a board) atomic clock, known as CSAC, was developed. In this article, first, the concepts of autonomous time synchronization and CSACs are described, and the mechanism for assigning ultra-high precision time information to the sensor data by using a CSAC is explained. Next, the performance of the improved sensor device is demonstrated and the results of the vibration table test, which was conducted to examine the performance, are presented.**

Keywords-Time Synchronization; Chip Scale Atomic Clock; Earthquake Observation; Structural Health Monitoring; MEMS

I. INTRODUCTION

Previously, a sensor based on wireless sensor networks and microelectromechanical systems (MEMS) was developed for structural health monitoring and applied to a high-rise building as an Internet of Things (IoT) device [1]-[3]. In the corresponding research, the sensor device was installed at a high density inside the building, and a method to accurately detect the stability of the building and the damage caused to it after an earthquake, was demonstrated. However, in order to compare and analyze the data measured by several sensors, they must be time-synchronized [4]-[6]. In this work, time synchronization was achieved by transmitting and receiving wireless packets among the sensors [3]. Although a wireless sensor network enables time synchronization among the sensors installed inside a single building, it is not capable of achieving the same in multiple buildings, large-scale structures such as a bridge, or a wide urban space. Alternatively, a global positioning system (GPS) is available for outdoors; however, it cannot be used underground or in tunnels. To obtain measured data from any sensor installed anywhere using time synchronization, it is desirable that each sensor maintains accurate time information autonomously without relying on the networks or GPS signals. Therefore, by employing a chip scale atomic clock (CSAC), which is an ultra-high precision clock with considerably less delay than quartz oscillators [7]-[9], a sensor device that records accurate time information autonomously was developed [10][11].

In Section III, the concepts of autonomous time synchronization and CSACs are described, and a mechanism to assign ultra-high precision time information to sensor data using a CSAC is presented.

In Section IV, the sensor device, which was developed as a prototype, and the improvements made to the sensor are explained in detail.

In Section V, the construction of an autonomous time synchronization sensing system with the sensor device is discussed.

In Section VI, a vibration table test is performed for the improved sensor device, which is equipped with a MEMS acceleration sensor, and its amplitude performance is examined based on a comparison with the results obtained by a comparative servo-type acceleration sensor. Multiple sensor devices are installed on the vibration table and allowed to vibrate simultaneously in order to confirm that time synchronization is realized among the sensors within 0.001 s for a 100 Hz measurement sampling. In addition, the output of one displacement sensor is branched in order to connect to eight improved sensor devices via external analog sensor input interfaces, and a test is conducted to prove that the measured results are in agreement.

Furthermore, to apply this technology for earthquake observation, the logic for detecting the occurrence of an earthquake according to a set threshold and saving only the data of the earthquake event is presented. Its function is illustrated using a vibration table test.

Based on these test results, the performance of the developed autonomous time-synchronized sensor device is confirmed, and it is shown that this device can be applied for earthquake observation and structural health monitoring.

II. STATE OF THE ART

The time synchronization function is essential for sensor devices used in earthquake observation and structural health monitoring. In this research, a prototype sensor module that autonomously maintains accurate time information by applying an ultra-high precision clock, CSAC, was made to improve practical applications. Even if a huge number of sensors are installed, if accurate time information can be autonomously assigned to the measurement data of each sensor, time synchronization of the data of the sensors can be established just only by collecting data with arbitrary means and rearranging the data based on the time information.

For time synchronization sensing, many studies such as Global Positioning System (GPS) using radio clocks and satellites, and Network Time Protocol (NTP) [5] for achieving time synchronization on the Internet have been conducted so far. Some studies have realized highly accurate time synchronization with a simple mechanism by utilizing the characteristics of wireless sensor networks with small propagation delays. For example, various time synchronization protocols such as Reference Broadcast Synchronization (RBS), Timing-sync Protocol for Sensor Networks (TPSN), and Flooding Time Synchronization Protocol (FTSP) have been studied [4][8][12]-[14]. However, although these time synchronization techniques are still used today, as described in the Introduction, they are not ideal for sensor devices used in earthquake observation and structural health monitoring. As shown in this research, if each sensor gives accurate time information autonomously to the measurement data, even if a huge number of sensors are installed in an arbitrary environment, it is possible to create data groups with secured time synchronization and use them for comparison and analysis.

III. AUTONOMOUS TIME SYNCHRONIZATION AND CSACS

In order to obtain a collection of sensor data with stable time synchronization, even when GPS signals are not available, wireless data transmission is unstable, or there is no wired network connection, the most idealistic condition is that each sensor maintains accurate time information autonomously. If accurate time information (time stamp) can be provided to the data measured by each sensor, a collection of sensor data with time synchronization can be obtained. Therefore, in this study, a CSAC with a high-precision time-keeping performance and considerably less delay than quartz oscillators was used [7]-[9] to develop a sensor that can autonomously maintain accurate time information.

Figure 1. Chip Scale Atomic Clock (CSAC).

TABLE I. CSAC SPECIFICATIONS

Model	SA.45s
RF output	10 MHz
1 PPS output	Rise/fall time: < 10 ns Pulse width: 100 µs
Power consumption	< 120 mW
Outside dimensions (mm)	40 × 35 × 12
Frequency accuracy	$\pm 5 \times 10^{-11}$
Aging	$< 9 \times 10^{-10}$/month

TABLE II. VARIOUS CLOCKS AND OSCILLATORS

	Cesium atomic clock	Rubidium atomic clock	CSAC	Quartz oscillator
Time until it has a 1-s delay	50,000 years	1,000 years	1,000 years	1 day
Size	0.1 m^3	1,000 cm^3	1 cm^3	10 mm^3
Power consumption	50 W	Several tens of W	30 mW	10 µW

A CSAC is a clock that realizes ultra-high precision time measurement of several tens of picoseconds (5×10^{-11} s) with low power consumption. Owing to its ultra-small size, it can also be loaded on a board (see Figure 1, Table I and II). The development of CSACs began with the support of the Defense Advanced Research Projects Agency (DARPA) in the United States in 2001, and commercial products were launched in 2011. Its applications include countermeasures for disturbance of GPS positioning caused by jammed signals, high-precision positioning for smartphones and other devices, and incorporation in cloud servers. Owing to its increasing popularity, further reduction in price and a smaller unit design are expected. By installing a CSAC in each sensor device and loading a mechanism to assign highly accurate time stamps to the sampling data, a group of sensor data with autonomously secured time synchronization can be obtained. To collect the measured data with accurate time stamps, any technology, such as 3G, Wi-Fi, or Ethernet can be used.

IV. DEVELOPMENT AND IMPROVEMENT OF SENSOR DEVICE EQUIPPED WITH CSAC

A sensor device usually consists of the following: CPU for controlling the measurement, sensor, filter, analog-to-digital (A/D) converter, storage, and network interface. A crystal oscillator is used as the CPU. If a CSAC is installed in it and used for measurement, then a time delay will occur while correcting the CPU, because the timing accuracy of the CSAC is very high. Therefore, in order to directly assign the timing information provided by the CSAC to the data measured by a sensor using hardware, a mechanism equipped with a dedicated integrated circuit, field-programmable gate array (FPGA), was developed and a prototype of the sensor device was produced [10][11]. Since an FPGA is programmable, a logic for earthquake detection using the measured data can be incorporated, by assigning it the time measurement information provided by the CSAC.

From Figure 2, it can be seen that the sensor device consists of a main control unit, sensor unit, and wireless communication unit. The main board is equipped with a CSAC, FPGA, GPS, CPU, storage, and network interface. The main control unit controls the measurement made by the sensor while generating time stamps based on the ultra-high precision timing information given by the CSAC. The measured data is stored in the storage and then transmitted to the network via Ethernet or wireless communication. The measured data to be saved is of two types: data to be measured on a steady basis and data of extracted events such as earthquakes. To handle data of the latter type, the logic to detect the beginning and end of an earthquake is incorporated in the FPGA, and data of only the earthquake events are promptly transmitted to the network after the earthquake. For initialization and adjustment of time information, it is equipped with a GPS. The sensor unit obtains measurements based on the commands given by the main control unit. The sensor unit is equipped with tri-axial MEMS acceleration sensor, external analog sensor input interface, temperature sensor, anti-aliasing filter, and A/D converter.

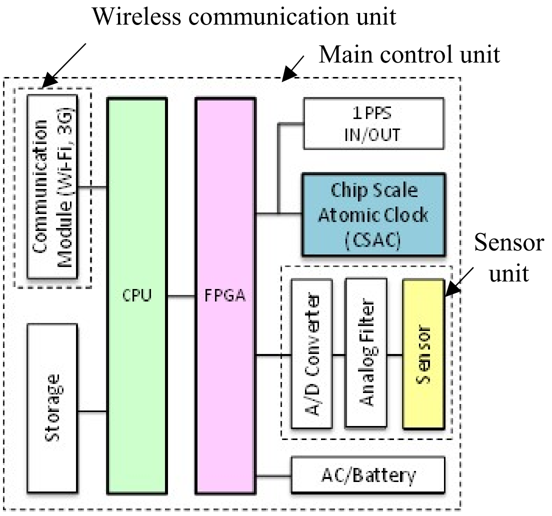

Figure 2. Design of Sensor Device Equipped with CSAC.

TABLE III. SPECIFICATIONS OF MEMS ACCELERATION SENSOR

Model	LIS344ALH
Measurement direction	3
Maximum acceleration (± G)	2
Outside dimensions (mm)	4 × 4 × 1.5
Consumption current (mA)	0.68
Stand-by power consumption (μA)	1
Detection sensitivity	660 mV/G ± 5%
Noise characteristics	50 μG/√Hz
Operating temperature (°C)	-40 - +85

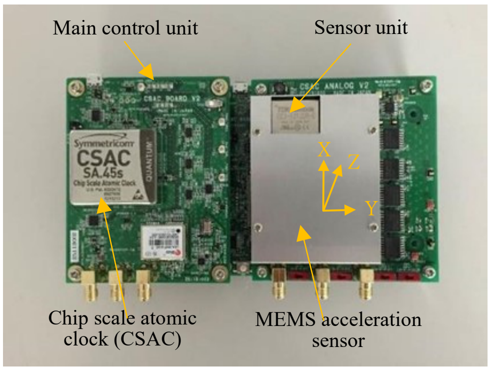

Figure 3. Improved Sensor Module with CSAC.

Table III shows the specifications of the mounted tri-axial MEMS acceleration sensor. The wireless communication unit enables data collection using a wireless system and allows selectable use of either a general wireless LAN (Wi-Fi) or 3G. The basic performance of the prototype of the developed sensor device was examined [10][11].

The prototype of the developed sensor device was improved in the following ways, with the aim of achieving increased functionality and practical usability:

a) Generation of three channels for serving as an external analog sensor input interface
b) Addition of a 24-bit A/D converter
c) Reinforcement of FPGA
d) Separation of the wireless communication unit and adoption of a commercially available motherboard (Raspberry Pi 2 Model B)
e) Loading of the IEEE 1588-based time synchronization function

By including the 24-bit A/D converter and using three channels as the external analog sensor input interface, a sensor that requires a wide dynamic range, such as a servo-type acceleration sensor, can be connected. Furthermore, by joining three units of a strain or displacement sensor, the sensor device can be used as a data logger. In addition, with the wireless communication unit and the use of commercially available Raspberry Pi, the system is capable of responding to a new wireless communication system quickly. Finally, by equipping the interface based on the IEEE 1588 standard for time synchronization of networks, the measurement timing can be initialized among the sensor devices for synchronization. Figure 3 shows the improved sensor device that was produced.

V. FORMULATION OF AN AUTONOMOUS TIME SYNCHRONIZATION SENSING SYSTEM

Herein, the construction of an autonomous time synchronization sensing system with the sensor device described in Section III is discussed. To construct the sensing system composed of multiple sensors using the CSAC equipped sensor devices, it is necessary to prepare one device as the master, define absolute time information on it, and synchronize the other devices as slaves. The main control unit of each sensor device is armed with an I/O connector for 1 Pulse Per Second (PPS) signals of the CSAC. By using this, the master device outputs 1 PPS signals to each slave device to synchronize them, and adjusts the clock phase of the CSAC of the slave devices. Although a CSAC has a high time-keeping accuracy, it is necessary to define the absolute time information separately, because it originally has no such information. At the time of initial setting, the GPS module installed in the main control unit is used. The data is transmitted from the master device to the slave devices based on the IEEE 1588 method. Once all the sensor devices have been initially synchronized, they will autonomously retain the high-precision time information, and they only need to be set at arbitrary places for data collection. As mentioned previously, since accurate time stamps are recorded for the measured data, the data can be collected via any system including Ethernet, Wi-Fi, and 3G. Furthermore, even in places where GPS signals are not available and wireless or wired networks cannot be prepared, the data can be measured and collected. Therefore, this system can be used for mobile measurement or as a portable sensing system.

Figure 4 shows the configuration of the autonomous time synchronization sensing system. The sensor devices, which are individually equipped with the acceleration sensor board containing the MEMS acceleration sensor, can be freely combined with the other sensor devices having displacement sensors or strain sensors via external sensor boards.

VI. BASIC PERFORMANCE TEST OF IMPROVED SENSOR DEVICE

a) *Vibration table test with built-in MEMS acceleration sensor*

To check the basic performance of the improved sensor device proposed in Section III, a vibration table test was conducted. During the vibration table test, measurements were made with the built-in MEMS acceleration sensor in each sensor device.

The purpose was to check the measurement performance of the MEMS acceleration sensor and the time synchronization performance of the sensor device. As shown in Figure 5, four sensor devices were fixed on the vibrating table, the same vibration was applied towards one horizontal direction, and the measured results were compared. In the test, a swept sine wave of 0.1 to 2 Hz and 2 to 10 Hz was applied as the input wave, as shown in Figure 6. The measurement sampling frequency of the sensor device was set as 100 Hz in this case.

A vibration was applied along the Y direction of the sensor devices and measurements were made with the sensor devices and a comparative servo-type acceleration sensor. Figure 7 shows the calculated results of the Fourier amplitude spectral ratio for the acceleration waveforms measured with the four sensor devices and the servo acceleration sensor (for control). Compared to that of the servo acceleration sensor, the amplitudes of the four sensor devices were flat in the frequency bands of 0.1 to 2 Hz and 2 to 10 Hz, and the MEMS acceleration sensors loaded on the sensor devices showed a good performance for the components in the Y direction. Figure 8 shows the calculated results of the Fourier phase spectrum ratio of the acceleration measurement waveforms of the three (slave) devices with one sensor device on the vibration table as the master. If there is no phase delay among the sensor devices and time synchronization is secured, the Fourier phase spectrum ratio should be close to zero in all the frequency bands. In Figure8, a phase delay within 0.001 s is plotted with a dotted line. This indicates that the time synchronization realized among the sensor devices was within 0.001 s.

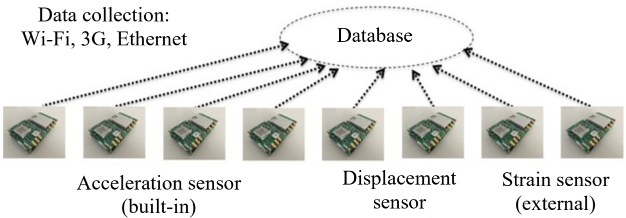

Figure 4. Configuration of Autonomous Time Synchronization Sensing System.

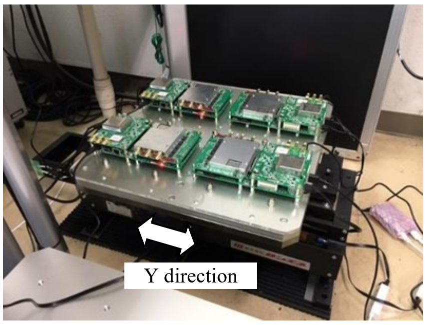

Figure 5. Vibration Table Test in Y Direction.

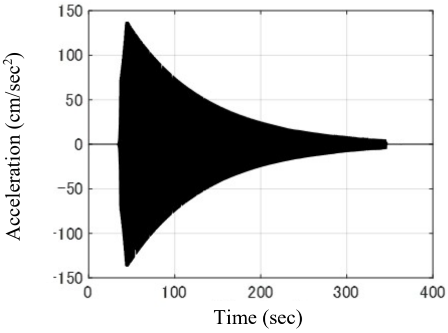

Figure 6. Input Swept Sine Wave (2 to 10 Hz).

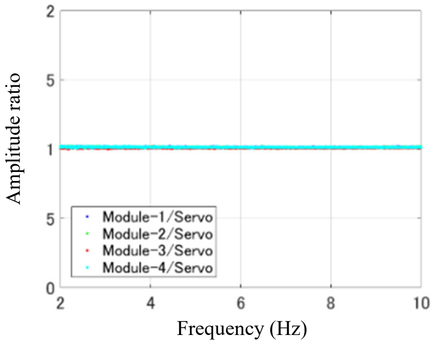

Figure 7. Spectrum Ratios of Fourier Amplitudes of Four Sensor Modules to Servo-Type Acceleration Sensor (Y direction).

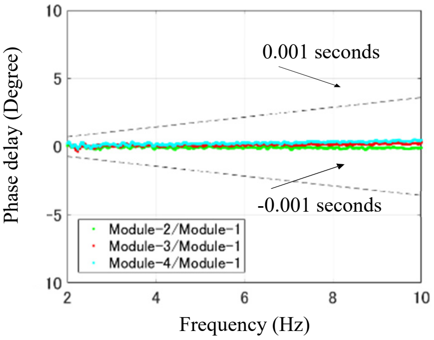

Figure 8. Spectrum Ratios of Fourier phase of Three Slave Modules to Master Module (Y direction)

b) *Displacement measurement test using external analog sensor input interface*

In order to examine the time synchronization performance when using an external analog sensor input interface, a test was performed using a displacement gauge. As shown in Figure 9, the voltage output of one displacement gauge was branched and given as input to the eight sensor devices equipped with an external sensor board. In the test, the displacement was changed by about 1 cm each time and it was measured using the eight sensor devices. Figure 10 shows the measurement results. The measurement results obtained by the eight sensor devices exactly match each other, indicating that they had correctly synchronized time data.

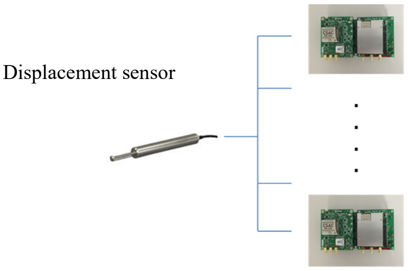

Figure 9. Measurement Test with the Displacement Sensor Connected to the External Analog Sensor Input Interface.

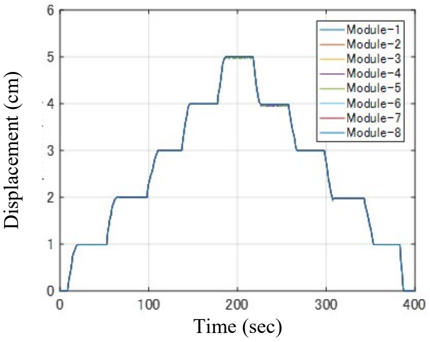

Figure 10. Measurement Test Results with Connected Displacement Sensor

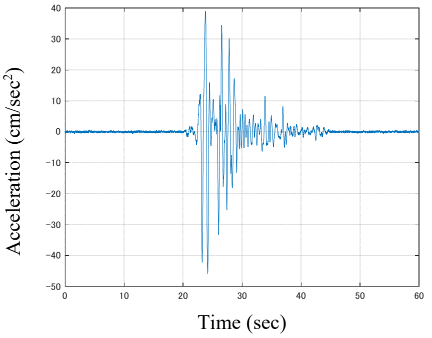

Figure 11. Acceleration of Measurement Results of Earthquake Detection Test

c) *Earthquake detection test*

In order to use the sensor device for earthquake observation, it is necessary to detect the occurrence and end of an earthquake. The developed sensor device realizes earthquake detection by comparing the measured values with the threshold values during sensing. When the occurrence of an earthquake is detected during the sensing operation, it starts saving the measurement data. At this time, immediately after the earthquake occurs, it also saves the data measured for several tens of seconds before the earthquake and the data measured for several tens of seconds immediately after the end of the earthquake, to secure the data of the total event of the earthquake.

In order to check the earthquake detection performance, a test was conducted with a vibration table. An earthquake wave excitation was provided in the Y direction of the sensor devices and the data was measured with a threshold value of 0.5 cm/s^2. The input earthquake wave was the NS direction component of the strong motion record observed at the JMA Kobe during the 1995 Southern Hyogo Prefecture Earthquake. Figure 11 shows the measurement results. It shows that the earthquake detection algorithm was able to first detect the occurrence and end of the earthquake with the set threshold values and then save the measured data.

VII. CONCLUSION

Our research and development efforts for designing an autonomous time synchronization sensor device equipped with a chip scale atomic clock (CSAC), which records and maintains high-precision time information, for earthquake observation and structural health monitoring of buildings and civil engineering structures was reported in this paper. First, the concepts of autonomous time synchronization and CSACs were explained, and the mechanism to assign ultra-precision time information to sensor data using a CSAC was presented. Then, the development of the sensor device as a prototype and the improvements applied to it were described in detail. The improved prototype was used to develop a sensor device for practical application, and a vibration table test was conducted to examine the performance of the improved sensor device.

To apply the device for earthquake observation, the logic to detect the occurrence of an earthquake according to set threshold values and to save the data of only the earthquake event was prepared, and its function was confirmed using the vibration table test. These results demonstrate that the developed autonomous time-synchronization sensor device has good performance and that it can be applied for earthquake observation and structural health monitoring.

One of the future challenges is to consider how to operate the sensing system for measurement purposes, assuming that even CSAC will undergo aging in the long term. In addition, it is not easy to fully utilize the high-precision time-keeping performance of the CSAC device. For example, even with a dedicated built-in FPGA, its clock is just 125 MHz, and it can give time stamps to the measurement data only within a time interval of 8 ns. When the 1 PPS output of CSAC is used to synchronize the sensor devices, a delay occurs due to the length of the cable connecting them. Furthermore, even though it is expected that CSACs will eventually be installed on all computers and smartphones worldwide, at present, only one US company manufactures and sells CSAC products, and therefore, they are very expensive. It can be hoped that more sensor companies will join the market and several products will be actively used in various fields. My future research plan includes detailed verification of the time-keeping performance of a CSAC as an atomic clock and the confirmation of the wireless communication function. In addition, it will be applied for actual earthquake observation, and demonstration tests will be conducted on actual buildings and bridges.

ACKNOWLEDGMENT

This research was partially supported by the New Energy and Industrial Technology Development Organization (NEDO) through the Project of Technology for Maintenance, Replacement and Management of Civil Infrastructure, Cross-ministerial Strategic Innovation Promotion Program (SIP). This research was also partially supported by JSPS KAKENHI Grant Number JP16K01283.

REFERENCES

[1] N. Kurata, B. F. Spencer, and M. Ruiz-Sandoval, “Risk Monitoring of Buildings Using Wireless Sensor Network,” Journal of Structural Control and Monitoring, vol. 12, Issue 3-4, pp. 315-327, July-Dec. 2005, doi: 10.1002/stc.73.

[2] N. Kurata, M. Suzuki, S. Saruwatari, and H. Morikawa, “Actual Application of Ubiquitous Structural Monitoring System using Wireless Sensor Networks,” Proc. 14th World Conference on Earthquake Engineering (14WCEE), Beijing, China, Oct. 2008, Paper ID:11-0037, pp. 1-8.

[3] N. Kurata, M. Suzuki, S. Saruwatari, and H. Morikawa, “Application of Ubiquitous Structural Monitoring System by Wireless Sensor Networks to Actual High-rise Building,” Proc. the 5th World Conference on Structural Control and Monitoring (5WCSCM), Tokyo, Japan, July 2010, Paper No. 013, pp. 1-9.

[4] M. Maroti, B. Kusy, G. Simon, and A. Ledeczi, “The Flooding Time Synchronization Protocol,” Proc. the 2nd International Conference on Embedded Networked Sensor Systems (SenSys '04), Baltimore, USA, Nov. 2004, pp. 39-49, ISBN:1-58113-879-2.

[5] D. L. Mills, “Internet time synchronization: the network time protocol,” IEEE Transactions on Communications, vol. 39, Issue 10, pp. 1482-1493, Oct. 1991, doi:10.1109/26.103043.

[6] B. W. Parkinson, and J. J. Spilker Jr. eds, “Global Positioning System: Theory and Applications,” Vol. I & II, American Institute of Aeronautics and Astronautics (AIAA), 1996, ISBN: 978-1-56347-106-3.

[7] S. Knappe, et al., “A microfabricated atomic clock,” Applied Physics Letters, vol. 85, Issue 9, pp. 1460-1462, Aug. 2004, doi:10.1063/1.1787942.

[8] Q. Li, and D. Rus, “Global Clock Synchronization in Sensor Networks,” IEEE Transactions on Computers, vol. 55, Issue 2, pp. 214-226, Jan. 2006, ISSN: 0018-9340.

[9] R. Lutwak, et al., “The Chip-Scale Atomic Clock - Prototype Evaluation,” Proc. the 39th Annual Precise Time and Time Interval (PTTI) Meeting, Long Beach, USA, Nov. 2007, pp. 269-290.

[10] N. Kurata, “Disaster Big Data Infrastructure using Sensing Technology with a Chip Scale Atomic Clock,” World Engineering Conference and Convention (WECC2015), Kyoto, Japan, Dec. 2015, pp. 1-5.

[11] N. Kurata, “Basic Study of Autonomous Time Synchronization Sensing Technology Using Chip Scale Atomic Clock,” Proc. the 16th International Conference on Computing in Civil and Building Engineering (ICCCBE2016), Osaka, Japan, July 2016, pp. 67-74.

[12] J. Elson, L. Girod and D. Estrin, “Fine-Grained Network Time Synchronization using Reference Broadcasts,” Proc. 5th Symposium on Operating Systems Design and Implementation (OSDI’02), Boston, Massachusetts, Dec. 2002, pp. 147-163.

[13] S. Ganeriwal, R. Kumar and M. B. Srivastava, “Timing-sync Protocol for Sensor Networks,” Proc. the 1st international conference on Embedded networked sensor systems (SenSys '03), Los Angeles, California, Nov. 2003, pp. 138-149.

[14] K. Romer, “Time Synchronization in Ad Hoc Networks,” Proc. the 2nd ACM International Symp. on Mobile Ad Hoc Networking & Computing (MobiHoc’01), Long Beach, California, Oct. 2001, pp. 173-182.