Performance Evaluation of An Autonomous Time-synchronized Sensing System with A Camera Sensor

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

Abstract - **The maintenance of aging civil infrastructure, such as bridges, highways, and buildings, has become a critical social issue in Japan. Proper maintenance requires regular and highly accurate inspections; however, these inspections still rely heavily on human visual observation, which is costly. To improve efficiency, automated sensing systems are increasingly needed. Moreover, following large-scale disasters such as earthquakes and tsunamis, rapid evacuation and rescue operations must be carried out. For this purpose, it is essential to quickly and accurately evaluate structural integrity and damage using sensing systems. To address these challenges, research and development have been conducted on an autonomous time-synchronized sensing system that assigns highly precise time information to measurement data, enabling synchronized acquisition and analysis across multiple sensors. As an initial step, a sensor device was developed that realizes autonomous time-synchronized sensing using a high-precision digital accelerometer. Subsequently, a heterogeneous digital sensing platform was prototyped, allowing simultaneous connection of both a digital accelerometer and a camera sensor. In this system, accelerometer data and camera images are assigned unified timestamps synchronized with absolute time at the instant of acquisition. This enables synchronized measurement of vibration and imagery. The timestamping mechanism relies on the accuracy of a Chip-Scale Atomic Clock (CSAC) mounted on the device. Experimental evaluation confirmed that the prototype system achieves the desired performance. This paper describes the details of the time synchronization mechanism using a CSAC and presents detailed experimental results regarding its performance.**

Keywords-Time Synchronization; Chip Scale Atomic Clock; Earthquake Observation; Structural Health Monitoring; Micro Electro Mechanical Systems; Camera Sensor

I. INTRODUCTION

Civil infrastructure such as bridges, highways, and high-rise buildings deteriorates with time, and automation of inspection for their maintenance and management has become an important social issue. In Japan, which is prone to earthquakes and other disasters, rapid post-disaster detection of structural damage and evaluation of its extent are required. Automated inspections and damage detection require data collection using sensing systems. To analyze data measured by multiple sensors and evaluate structural integrity, time synchronization among sensors is essential. Without synchronized data, cross-sensor and time-series analyses that use phase information cannot be performed. Time synchronization methods have traditionally been implemented using dedicated wiring, wired networks, or wireless networks. However, wired synchronization imposes significant restrictions on sensor placement, whereas wireless synchronization is applicable only where wireless communication between sensors is possible. In either case, wide-area deployment is infeasible. Conversely, if sensors installed at arbitrary locations can autonomously maintain accurate time information, this issue can be overcome. The Global Positioning System (GPS) is effective for outdoor synchronization but is unusable indoors, underground, beneath bridges, or in tunnels. To overcome this limitation, a sensor device capable of autonomously maintaining precise time information was developed using a chip-scale atomic clock (CSAC) [1][2][3][7], an ultra-high-precision clock [4][8][9]. For earthquake observation, logic was implemented to detect earthquakes and record seismic event data, and its functionality was validated using shaking-table experiments. The developed sensor device was also deployed in actual buildings and bridges for earthquake observation and structural health monitoring [4]. However, the device initially employed a MEMS accelerometer, which struggled to measure minute vibrations accurately and remained susceptible to analog-signal noise contamination. Therefore, the accelerometer was replaced with a digital type, eliminating the risk of noise [5]. A camera sensor was also integrated, and a heterogeneous digital sensing platform was prototyped [6]. A previous paper described the design and construction of the autonomous time-synchronized sensing system based on prior research and development, including a mechanism to append ultra-precise time information to sensor data using the CSAC [1]. In this paper, the details of the time synchronization mechanism using the CSAC and experimental results on the time-synchronization performance of the developed sensing system are presented. Section II reviews existing time synchronization methods, their limitations, and the achievements of the proposed digital sensing platform. Section III describes the overview of the developed sensor device and the time synchronization mechanism using the CSAC. Section IV provides details of the performance verification experiments on synchronizing the camera sensor and external input sensors. Finally, Section V presents the conclusions and future work.

II. State of the Art

Research on time synchronization in sensing systems has been extensive, including the use of Global Navigation Satellite System (GNSS) signals via satellites [12] and the Network Time Protocol (NTP) [10] for synchronization on the Internet. Other studies have explored synchronization in wireless sensor networks, leveraging low propagation delay. For example, protocols such as Reference Broadcast Synchronization [13], Timing-sync Protocol for Sensor Networks [14], and the Flooding Time Synchronization Protocol [11] have been proposed. While wireless-based methods are convenient, they cannot guarantee reliable communication. In particular, during disasters such as earthquakes, wireless communication may be disrupted, rendering time-synchronized sensing and data analysis infeasible. The IEEE 1588 Precision Time Protocol (PTP) achieves high-accuracy synchronization indoors by using Ethernet cables as transmission paths in general Local Area Networks (LANs). PTP can provide synchronization accuracy within 1 microsecond. However, maintaining stable accuracy is difficult due to fluctuations in packet delays and packet losses caused by congestion. Furthermore, because synchronization relies on packet switching compensation, the number of devices that can be connected to the master is limited, and wide-area deployment is impractical.

When GPS signals are unavailable, wireless connections unstable, and wired networks inaccessible, it is desirable for sensors to autonomously maintain precise absolute time information. If each sensor can append accurate timestamps to its measured data, autonomous time-synchronized data collection becomes possible. To realize this, a sensor device was developed using a CSAC [2][3][7]. CSAC provides ultra-high-accuracy time measurement (on the order of tens of picoseconds, 5×10^{-11} s) while being sufficiently compact for board mounting. Development began in 2001 with support from DARPA, and consumer versions were released in 2011 [9]. CSACs are expected to be further miniaturized and reduced in cost as their applications expand, including GPS interference countermeasures, high-precision positioning in GPS-denied environments, integration into smartphones, and advanced disaster monitoring. Compared with quartz oscillators, NTP, or GPS-based timekeeping, CSACs reduce errors by 4 - 8 orders of magnitude. By equipping each sensor device with a CSAC and implementing timestamping mechanisms, synchronized data collection can be achieved even when GPS is inaccessible, wireless connections are unstable, and wired networks are unavailable. Previous developments incorporated an analog MEMS accelerometer and allowed connection of arbitrary analog sensors through an external interface. However, the limited accuracy of MEMS accelerometers and the noise susceptibility of analog signals led to the development of a fully digital platform. Specifically, a digital accelerometer was integrated to allow high-sensitivity measurements without noise, while a camera sensor was supported. Both digital outputs were precisely timestamped using the CSAC. The resulting synchronized data can be applied to civil infrastructure inspection and structural health monitoring.

III. Developed Autonomous Time-synchronized Sensing System and Time Synchronization Mechanism

As shown in Figure 1, the developed sensor device consists of an oscillator and a Field-Programmable Gate Array (FPGA) that synchronize GPS time (GPST) with the CSAC, supply stable reference signals, and maintain absolute time; a sensor section with a digital accelerometer and analog input interface; a signal processing board with a CPU; and a camera. The oscillator and FPGA provide a high-precision 10 MHz reference clock and a 1 pulse-per-second (PPS) signal. The FPGA generates timestamps and trigger signals for data acquisition. The sensor section comprises a digital accelerometer and an external analog input interface, allowing the connection of arbitrary analog sensors. The digital accelerometer outputs data in response to trigger signals via UART. Signals from external analog sensors are converted by A/D converters and output as 16-bit serial values. The camera sensor captures images in response to trigger signals and outputs RGB data. Data are stored on solid-state drives (SSDs), with separate SSDs for sensor and camera data to optimize access speed. Data can be retrieved, deleted, or viewed via network connections. Network options include wired LAN and Wi-Fi.

The mechanism of time synchronization in this system is described below. As shown in Fig. 2, the devices are divided into a master and slaves. First, the CSAC (Chip-Scale Atomic Clock) of the master device is synchronized to GPS. The master device connects to a GPS antenna and feeds the 1 PPS signal output from the GPS module into the CSAC. Through the built-in synchronization function of the CSAC, both the 1 PPS and 10 MHz signals generated by the CSAC are aligned with the GPS. Depending on GPS reception conditions, the time offset between the GPS and CSAC 1 PPS signals remains within 50 ns. If synchronization is performed too frequently, short-term fluctuations of the GPS signal dominate and the holdover performance deteriorates. Therefore, in this system, synchronization is carried out at intervals of 1000 seconds. The slave devices receive the 1 PPS signal from the master's CSAC and synchronize in the same manner. Since the 1 PPS signal generated by the master's CSAC is more stable than the GPS itself, the time offset with respect to the master device remains within 10 ns. Through this process, the CSAC effectively functions as a GPS-equivalent time source, and the CSACs of both the master and slave devices achieve high-precision synchronization.

By operating with a clock synchronized at high accuracy using the CSAC, sensor devices can maintain absolute time information (timestamps). As shown in Fig. 3, the master device first acquires absolute time information from the GPS module in the format defined by the National Marine Electronics Association (NMEA), which is a standard for data exchange between GPS and marine-related equipment. The master then transfers this time information to the Real-Time Clock (RTC) implemented in the FPGA and starts the seconds count using the 1 PPS signal from the CSAC, already synchronized to GPS. As a result, the count starts at the timing of the 1 PPS signal, the timestamp is aligned with the 1 PPS, and the clock advances based on the 10 MHz signal from the CSAC. The slave devices obtain the time information from the master via NTP or manual configuration, set it in their CPU clock, and forward it to the FPGA. From this point onward, they operate in the same manner as the master device.

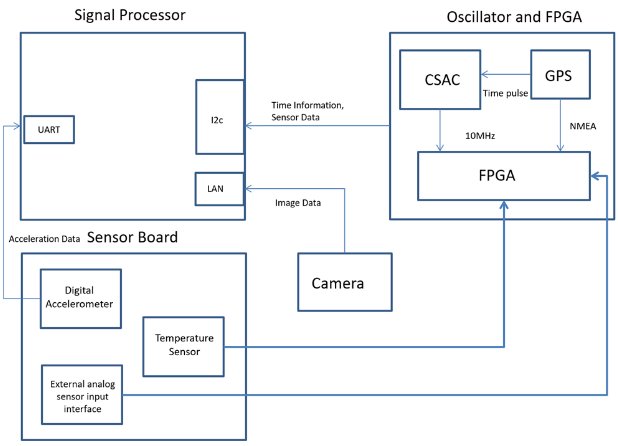

Figure 1. System configuration.

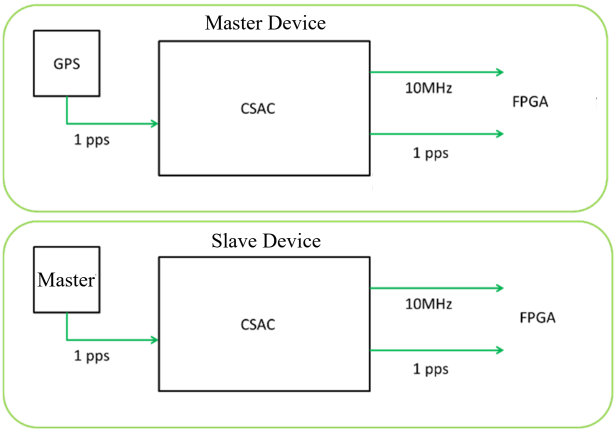

Figure 2. Synchronization of clock.

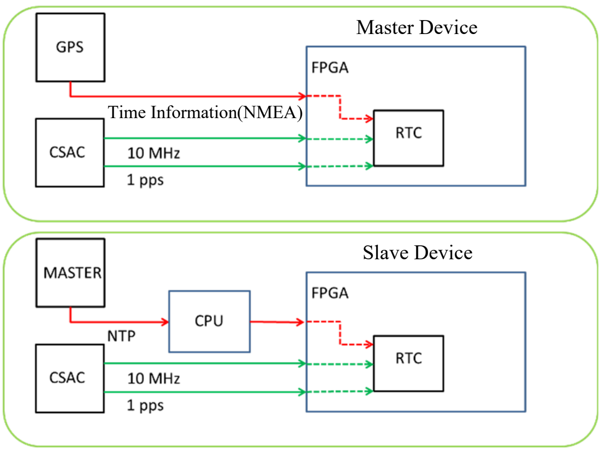

Figure 3. Synchronization of time information(time stamp).

Table I summarizes the specifications of the camera sensor, the Baumer VCXG-02C, a compact, low-power, high-speed Gigabit Ethernet camera [6]. It features excellent performance in low-light conditions, supports external trigger input, and includes a retransmission buffer for stable data transfer. Its global shutter mechanism enables accurate timestamping of images by capturing entire frames simultaneously, avoiding temporal distortions associated with rolling shutters.

TABLE I. SPECIFICATIONS OF CAMERA SENSOR

Model	Baumer VCXG-02C
Active Array Size	640 x 480
Sensor	CMOS ON Semiconductor : PYTHON 300
Pixel Size	4.8 μm x 4.8 μm
Shutter	Global Shutter
Power Supply	12-24 VDC/2.6W
Image Formats	BayerRG / RGB / BGR / Mono
Frame Rate(fps)	401(640 x 480)
Exposure Control	20μsec ～ 1sec
Operation Mode	Trigger/Free Run
Size(mm)	29 × 29 × 49
Weight(g)	120
Interface	GigabitEthernet (1000BASE) / FastEthernet (100BASE)

IV. TIME SYNCHRONIZATION PERFORMANCE TEST BETWEEN CAMERA SENSOR AND EXTERNAL ANALOG INPUT SENSOR

In this section, the synchronization performance between the camera sensor and external analog input sensors is evaluated in detail. The purpose of the experiments is to verify whether both sensing modalities, despite differing in sampling characteristics and data acquisition timing, can be assigned unified timestamps that accurately represent the same physical phenomenon. As shown in Figure 4, three developed sensor boards were mounted on a vibration testing apparatus, together with a specially designed LED visualization board. The vibration table was driven by a sine wave excitation signal, which was simultaneously fed into the external analog input interface of the sensor boards and the FPGA controlling the LED board. The FPGA controlled the LED lighting pattern in real time, based on the amplitude of the input sine wave. This setup ensured that the LED illumination served as a visual representation of the vibration waveform, allowing direct comparison with the analog sensor data and camera images. The excitation waveform was a 1 Hz sine wave. Since the timestamps of the camera images and analog sensor measurements were synchronized using the CSAC, comparing the LED images captured by the camera with the vibration waveforms measured by the analog sensor enabled direct evaluation of timestamp accuracy and potential delays.

The camera sensor was configured to operate in external trigger mode. The image acquisition process followed the sequence: trigger input (shutter) → exposure → data readout. The timestamps were appended when the CPU acquired the complete image frame. As a result, a small inherent delay occurred depending on the exposure duration. For these experiments, the camera was configured to capture frames every 20 ms, while the analog sensor was sampled every 1 ms. This setup allowed verification of synchronization within a resolution of 20 ms.

To visualize the sinusoidal input signal, the LED board, shown in Figure 6, consisted of 50 LEDs (25 green and 25 red). A single sine wave cycle was divided into 50 segments, with LEDs arranged in a circular pattern and illuminated sequentially in a counterclockwise direction. This arrangement enabled a rotating light pattern corresponding to the instantaneous phase of the sine wave. The mapping of input voltage to LED illumination was pre-calibrated using approximately 20 sampled sine waves, ensuring that LED lighting accurately represented the vibration amplitude.

Initial experiments used a synthesized 1 Hz sine wave to validate the system. Camera images of the LEDs confirmed that transitions occurred in accordance with the expected waveform progression. As shown in Figures 9 and 10, the LED positions captured by the camera corresponded to the positive and negative peaks of the sine wave. The analog sensor data recorded in parallel are shown in Figure 11. Comparison with the analog sensor waveforms indicated a delay of approximately 2 ms between the two measurement modalities, which is well within the 20 ms threshold. This confirmed that synchronized timestamping between the camera and analog sensor was functioning as intended.

Further experiments were conducted using the vibration table to replicate realistic conditions. As shown in Figure 5, the three sensor boards were rigidly mounted to the vibration platform. The excitation signal was simultaneously applied to the analog input interface of the sensor boards and to the LED control FPGA. Camera images obtained during vibration are presented in Figures 12 and 13, corresponding to the maximum and minimum points of the sinusoidal vibration cycle. The analog sensor data recorded in parallel are presented in Figure 14.

From Figures 12–14, the maximum value of the analog sensor waveform occurred at 268 ms, while the corresponding maximum indicated by the LED pattern in the camera images was observed at 260 ms. This corresponds to an offset of 8 ms. Similarly, the minimum value of the analog waveform occurred at 773 ms, while the LED-based minimum occurred at 760 ms, corresponding to an offset of 13 ms. Both offset values fall within the 20 ms resolution limit imposed by the camera's frame interval. Thus, the results confirm that synchronization accuracy between the camera images and analog sensor data was maintained.

The detailed experimental validation demonstrated that the developed autonomous sensing system, employing a CSAC for timestamp generation, successfully achieved synchronization between heterogeneous sensor modalities—specifically, the camera sensor and external analog sensors. Although small offsets of several milliseconds were observed due to the camera's exposure and frame acquisition process, these offsets were consistently within the 20 ms limit, thereby confirming the effectiveness of the proposed system.

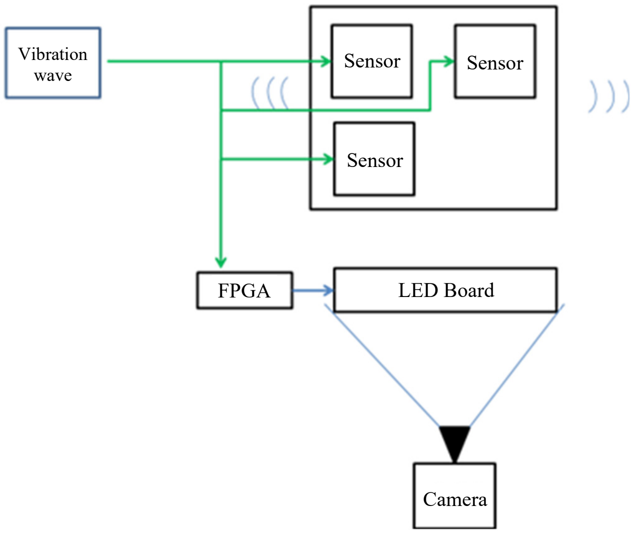

Figure 4. Block diagram of vibration wave time synchronization verification test system.

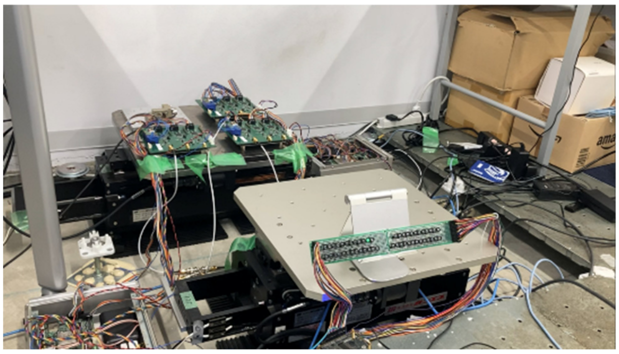

Figure 5. Vibration wave time synchronization verification test system.

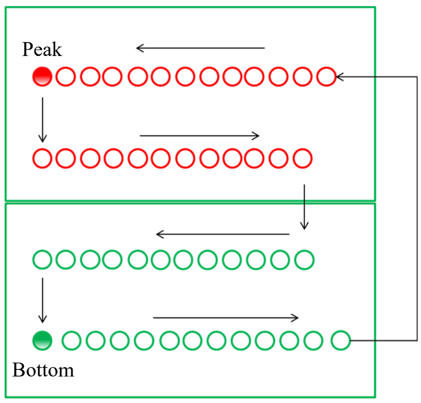

Figure 6. LED board diagram.

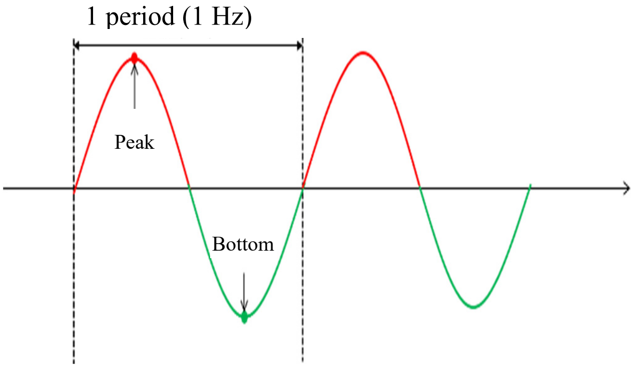

Figure 7. Waveform and LED.

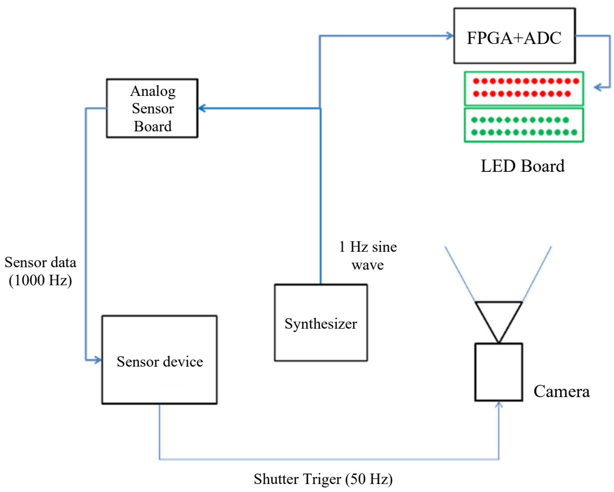

Figure 8. Synthesizer-based measurement system.

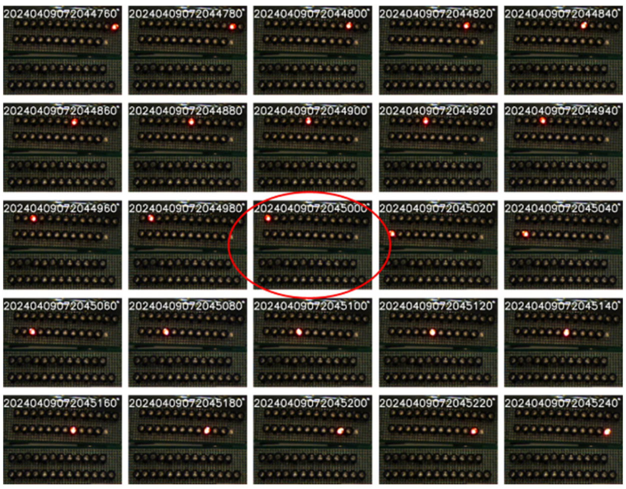

Figure 9. Image of an LED (first half of the sine wave).

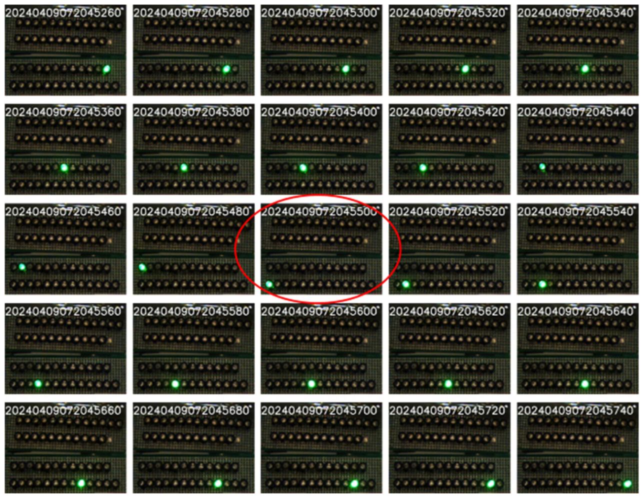

Figure 10. Image of LED (second half of sine wave).

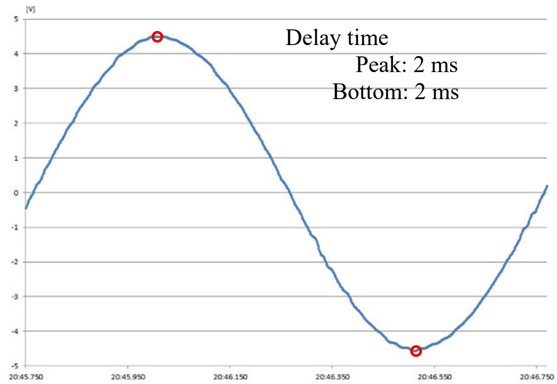

Figure 11. Measurement data using external analog sensor interface

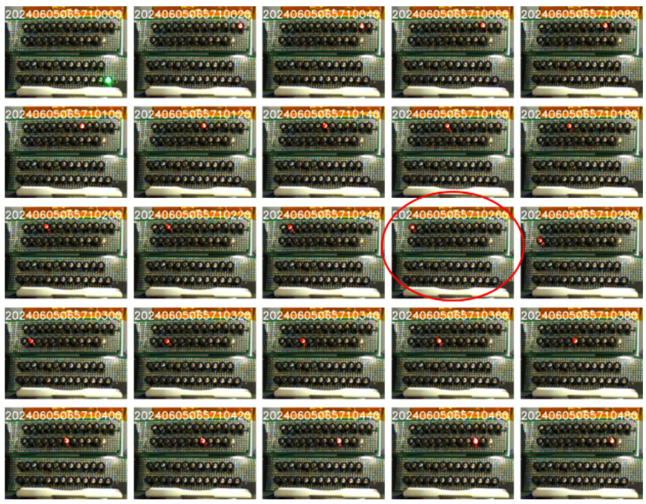

Figure 12. Image of an LED (first half of the sine wave).

 ISBN: ISBNFILL

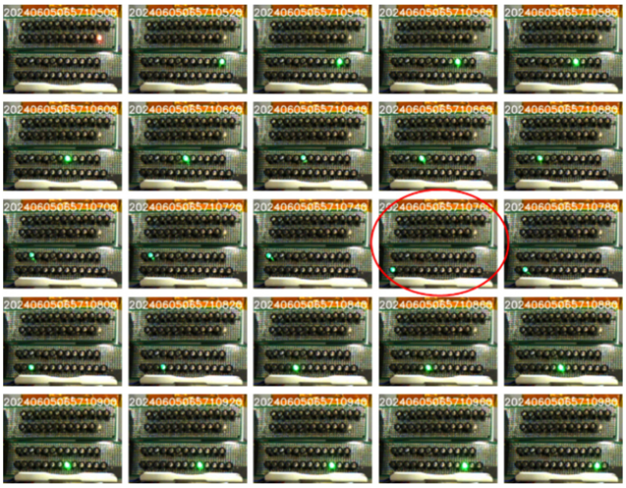

Figure 13. Image of LED (second half of sine wave).

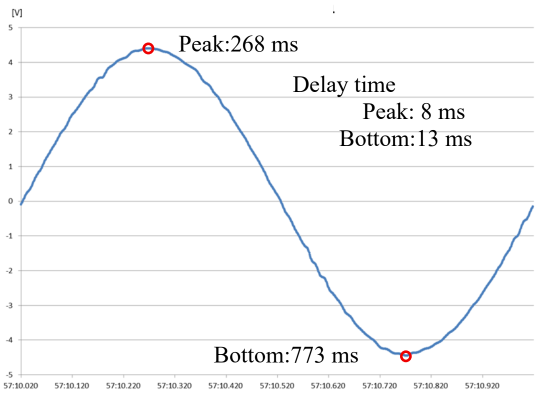

Figure 14. Measurement data using external analog sensor interface.

V. Conclusion

In this paper, the mechanism of time synchronization and the details of evaluation experiments for an autonomous sensing system equipped with a CSAC (Chip-Scale Atomic Clock) that provides highly accurate absolute time information were reported. First, the developed autonomous time synchronization sensor device, the synchronization method, and the approach for attaching high-precision absolute timestamps to sensor data using the CSAC were described in detail. A function was implemented to assign identical timestamps to the outputs of the camera sensor, the internal digital accelerometer, and the external analog input interface, and the experimental results for verifying the time synchronization performance of the camera sensor were reported.

Through the outcomes of this study, it was demonstrated that even in environments where GPS signals cannot be received and the installation of dedicated wiring or network infrastructure is infeasible, the sensor device can autonomously maintain absolute time information and ensure the acquisition of time-synchronized measurement data. Such sensor data can be utilized for analyses based on inter-data phase information as well as for time-series analysis. However, accurate time information cannot be permanently preserved by CSACs, as degradation due to aging occurs. Therefore, periodic re-synchronization must be performed, and efficient operational strategies must be considered. Rather than short-term ultra-high-precision synchronization, the development of a new type of CSAC offering moderate accuracy with long-term stability is considered desirable.

In future research and development, the time synchronization performance of this new sensor device will be examined in detail across three channels: the camera sensor, the internal digital accelerometer, and the external analog input sensor.

Acknowledgment

This research was partially supported by JSPS KAKENHI Grant Number JP23K04342.

References

[1] N. Kurata, “Development of An Autonomous Time-synchronized Sensing System Capable of Measuring Acceleration and Images” The Fourteenth International Conference on Sensor Device Technologies and Applications (SENSORDEVICES 2023) IARIA, Sep. 2023, pp.30-37, ISSN: 2308-3514, ISBN: 978-1-68558-091-9.

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

[3] N. Kurata, “An Autonomous Time Synchronization Sensor Device Using a Chip Scale Atomic Clock for Earthquake Observation and Structural Health

[4] Monitoring” The Eighth International Conference on Sensor Device Technologies and Applications (SENSORDEVICES 2017) IARIA, Sep. 2017, pp.31-36, ISSN: 2308-3514, ISBN: 978-1-61208-581-4.

[5] N. Kurata, “Seismic Observation and Structural Health Monitoring of Buildings by Improved Sensor Device Capable of Autonomously Keeping Accurate Time Information,” International Journal on Advances in Systems and Measurements, IARIA, vol 12, no 1&2, pp. 41-50, 2019.

[6] N. Kurata, “Digital Sensing Platform with High Accuracy Time Synchronization Function for Management of Buildings and Cities,” The Tenth International Conference on Sensor Device Technologies and Applications (SENSORDEVICES 2019) IARIA, Oct. 2019, pp. 53-58, ISSN: 2308-3514, ISBN: 978-1-61208-745-0

[7] N. Kurata, “High-precision Time Synchronization Digital Sensing Platform Enabling Connection of a Camera Sensor,” The Twelfth International Conference on Sensor Device Technologies and Applications (SENSORDEVICES 2021) IARIA, Nov. 2021, pp. 98-104, ISSN: 2308-3514, ISBN: 978-1-61208-918-8

[8] 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.

[9] 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.

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

[11] D. Mills, “Internet Time Synchronization: the Network Time Protocol,” IEEE Transactions on Communications, vol. 39, Issue 10, Oct. 1991, pp. 1482-1493, doi:10.1109/26.103043.

[12] 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) ACM, Nov. 2004, pp. 39-49, doi:10.1145/1031495.1031501.

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

[14] 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), Dec. 2002, pp. 147-163, doi:10.1145/844128.844143.

[15] 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) ACM, Nov. 2003, pp. 138-149, doi:10.1145/958491.958508.

[16] K. Romer, “Time Synchronization in Ad Hoc Networks,” Proc. the 2nd ACM International Symp. on Mobile Ad Hoc Networking & Computing (MobiHoc’01) ACM, Oct. 2001, pp. 173-182, doi:10.1145/501436.501440

 ISBN: ISBNFILL