A Time Alignment Method for Multiple Sensing Systems with GNSS Timing and IMUs with Frame-Sync Input

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***Abstract*—In this paper, we propose a method to align time stamps for sensed data among multiple data logging devices. In the method, we use the timing signals from the global navigation satellite systems (GNSS) and inertial measurement units (IMU) that have a frame-synchronous-input. The frame synchronous input is an external input, and its value will be attached to sensed data as the timing label bit. In most of the data logging method, the timestamp is generated and attached to the data by its data logging device. However, the timestamps contain a clock jitter about 100 ppm or more due to the internal clock inferior quality in a low-cost devices. It is difficult to sample data continuously time interval being fixed and to attach timestamps with high reliability. Therefore, we estimate the actual sampling timing of sensed data measured by IMUs using the timing signals from a GNSS module. Our key idea is to utilize the fact that actual sensors' internal oscillator is slightly out of alignment with the precise clock, which can be provided by the navigation satellites. We applied the proposed method to 1 kHz sampling data obtained from a commercially available sensing module of several dollars equipped with a quartz crystal. We have confirmed that the proposed method improves the precision of such sampling timing from around 350 microseconds to 150 microseconds.**

***Index Terms*—Sensing systems, Sampling time estimation, Synchronization, GNSS timing, Signal processing**

I. INTRODUCTION

In order to collect a lot of sensing data accurately for cyber-physical systems, fundamental design and development of inexpensive sensing units and its verification of data processing are crucial. Such a sensing unit often includes a commercially available MEMS inertial motion sensor module and a satellite positioning module. Sensed data usually have timestamps attached by a data logging device when each of the data measured. A timestamp generated by a low-cost data logging device and inertial measurement units (IMU) contains a clock jitter about 100 ppm or more due to the internal clock inferior quality. For this reason, it is also difficult to measure data continuously with accurate time. Some of IMUs have an external timing input as the trigger of sampling, some of IMUs have an external input as the timing label attached to sensed data, and the other IMUs have no such external inputs. The first type of external input can be used to synchronize other sensors with high precision. In the second type of IMUs, the value of the external input signal will be attached to sensed data as the timing label bit. In this case, an expected amount of timing error of the second type is half of the sampling rate because the bit does not denote the exact timing of each sample. In this paper, we target the second type of IMUs as sensors, and we propose a method to align timestamps for sensed data among multiple data logging devices. In the method, we use the timing signals from the global navigation satellite systems (GNSS), and IMUs that have a frame synchronous input as an external input. We estimate the actual measurement time of sensed data of IMUs using the timing signal from GNSS module, which provides the accurate timing aligned with the atomic clock in the navigation satellites as the external input. Our key idea is to utilize the fact that the actual sensors' internal oscillator is slightly out of alignment with the precise clock, which can be provided by the navigation satellites. Through an experiment with a commercially available sensing module and GNSS module, we show the effectiveness of the proposed method.

II. RELATED WORK

Time synchronization methods for sensing data have been studied actively for a long time. The most common method for aligning the system time in the data logging device is the Network Time Protocol (NTP). The fundamental of NTP is to provide accurate time, including packet turn around time from the time server. NTP synchronized time accuracy is milliseconds order. There is also a time synchronization protocol standardized by IEEE1588v2 called Precision Time Protocol (PTP). This method is similar to NTP, but PTP implements hardware-level align logic. NTP generates timestamp at the application layer, but PTP generates at the physical layer. PTP, therefore, removes software delay and improves timing accuracy to microseconds order. Motion sensing units require sub-millisecond order accuracy because of the sampling interval in milliseconds. However, the realization of device time synchronization with higher accuracy than sub-milliseconds by these methods is not optimal for low-cost sensing units, considering the cost and range of use.

GNSS positioning data is the most cost-effective method to obtain accurate time. GNSS positioning information includes nanoseconds of accurate global time. This is because GNSS positioning requires it for meter accuracy positioning. In other words, even any low-cost GNSS positioning device has an accurate time. GNSS module generally has an output function of rectangular waves called a *timing pulse*, which synchronized UTC. The following studies use the time accuracy and period accuracy of the timing pulse output from the GNSS module. Ding et al. and Li et al. designed dedicated hardware that generates a clock that is completely synchronized with GNSS time information [1] [2]. By using this circuit, we realized data sampling that can integrate multiple sensor data with nanosecond accuracy. For a software implementation, Matsubara et al. corrected the Tick phase, Tick period, and time of the real-time OS using 1 Hz and high-frequency timing pulses [3]. Kurata also studied a technique to keep the GNSS clock inside the terminal using a chip-scale atomic clock as a technique that does not build a dedicated circuit [4]. However, they are not suitable for low-cost embedded sensing devices because they require processing power for each unit.

Methods that use the GNSS time information similarly to estimate and correct the sampling time of the sampled data also have been studied. These methods target low-cost modules, and they are the direction of the method proposed in this paper.

Torii et al. [5] and Koo et al. [6] use the timing pulse, which known output time and calculate sampling time from the time difference between a coming timing pulse and sampled sensor data. In the methods, the internal local time of a logging unit uses for time difference measurement. Koo et al. corrected the sampling time using this method and then shaped the data by resampling [6]. They use a oven-controlled crystal oscillator [7] with 10 ns jitter for sampling clock. The accuracy of the synchronization was verified by observing the fluctuation of the standing wave with four wireless sensors and four wired sensors with an accelerometer. As a result, the data of the wireless sensor agreed with the data obtained by wire, and the error of the phase angle of the cross-spectrum density of the obtained waveform was also less than 0.1%. A problem of their method is a transition delay time of the interrupt process started by the timing pulse. For instance, the interrupt process has to wait until serial data transportation is done in the case of a single-core microcontroller. The delay negatively effects to estimated timestamp.

We estimate the sampling time using timing pulses in the same way. Unlike the previous research [6], the method shown in Section V does not use the time difference of the local time of logging device from the rise of the timing pulse to a sampling. Also, we estimate the maximum error of the estimated sampling timestamps.

III. PRELIMINARY EVALUATION OF TIME ACCURACY OF CURRENT GNSS MODULE

The accuracy of the timing pulse generated by a GNSS module is important to estimate time using it in our proposed method. In this section, we show the verification results of the jitter and delay of the timing pulse between several GNSS modules.

TABLE I
SPECIFICATION OF TIMING INFORMATION OF GNSS MODULES

Module No.	Chip	Timing Pulse Jitter (ns)	Time-mark Resolution (ns)
(1) (2) (3)	u-blox NEO-M8T	± 11	21
(4)	u-blox ZED-F9P	non-public	non-public

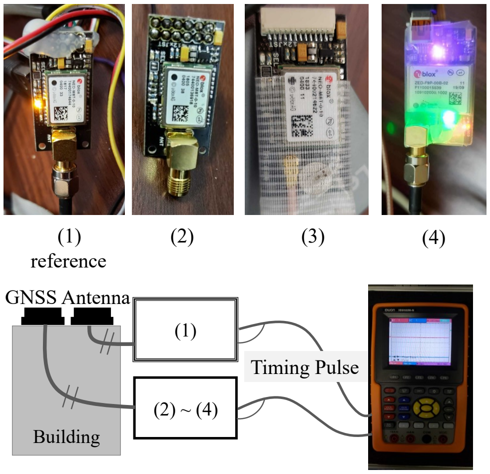
(1) reference
(2)
(3)
(4)

Fig. 1. Validation modules and validation setup

We incorporate a low-cost GNSS timing module with a chip made by u-blox into the sensing unit and collect the sensing data whose sampling time can be estimated. Generally, the time synchronization accuracy inside a GNSS timing chip is within 20 ns. However, the timing pulse output from the chip has a propagation delay due to the electrical impedance of the circuit and cable before it is brought to the external module.

The GNSS module provides not only position information but also accurate timing information. The navigation satellites always keep accurate time by the atomic clock, and GNSS signals align with the clock. By synchronizing the virtual clocks in a GNSS receiver and each navigation satellite clock, it is possible to measure the time until the signal generated from the satellite reaches the receiver. Position and Receiver Clock error calculate simultaneous equations using virtual clocks value. A receiver's time accuracy is maintained by to fix the virtual clocks and recalculate the internal clock error.

The specification of timing information of GNSS receiver chips used in this verification are shown in Table I. The modules used in the verification are the following products from Eltehs GNSS OEM Store [8].

1) InCase PIN series NEO-M8T TIME & RAW receiver board
2) InCase PIN series NEO-M8T TIME & RAW receiver board
3) InCase series NEO-M8T TIME & RAW receiver board
4) ZED-F9P RTK GNSS receiver board with SMA Base or Rover

In this verification, we observed the difference in pulse output timing and the fluctuation range of the timing. Figure 1 shows the experimental equipment configuration. We prepared two GNSS antennas (u-blox ANN-MB-00) connected by a

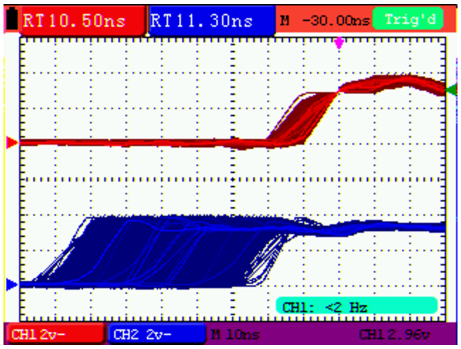

Fig. 2. A jitter measurement result of timing pulse using an oscillo scope

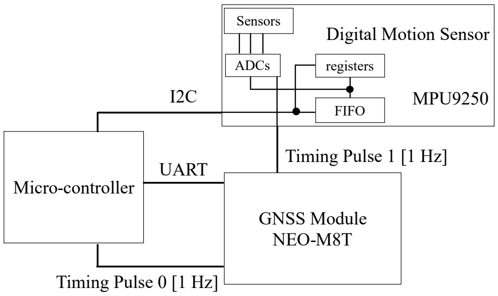

Fig. 3. An example of sensing unit

20-meter cable, and it installed on the roof of a building in an open sky environment. An open sky environment means no obstructions to hindrance satellite signal propagation like buildings around the antenna.

The GNSS modules output the timing pulse on 1 Hz, called 1PPS, and it rises at every .0 seconds (Top of Second). We observed their waveform using a 2-channel digital oscilloscope (HDS1022M-N) with a sample rate of 100 million samples per second. Trigger edge sets the rising edge of the reference timing module (module 1 in Fig. 1).

Figure 2 shows a one of results. It was measured for about 20 hours for each compare device. In this figure, the signal waveform shadow indicates the longtime signal observation. From the CH1 waveform, it took about 20 ns to rise, and compare between CH1 and CH2 waveform, the maximum difference of rising time of the pulse between modules was about 80 ns. Therefore, if calibration is performed, the difference in pulse rise time between different modules can be reduced to about ±40 ns.

For other companies' products, it has been investigated that there is an error in the rise timing from several tens of nanoseconds to several hundreds of nanoseconds [6] [9].

IV. TARGET LOW-COST SENSING SYSTEM WITH TIME SYNCHRONIZATION MECHANISM

The minimum information required for the proposed sampling time estimate method is timing information of constant cycle and GNSS time information. In this section, we explain the construction of the sensing system that can attach timing information to sensing data.

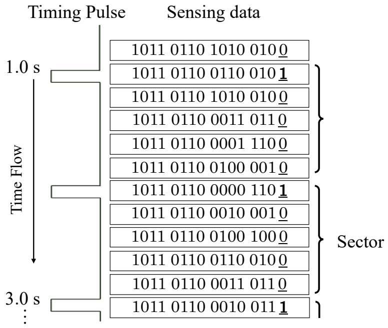

Fig. 4. Timing pulses and sampling data
(Timing pulse interval W = 1 [sec])

Figure 3 shows our sensing system of a prototype. The system consists of a GNSS receiver, a 9-axis motion sensor, and a micro-controller. The system's cost includes about $10 for a sensor, $100 for a set of GNSS receiving equipment (module and antenna), and $20 for a micro-controller.

The motion sensor, Invensense MPU9250, we used has a frame synchronous input. The value of the frame synchronous input is attached at the least significant bit of the optional axis x, y, or z data as the synchronization bit. It embeds signal value 0 or 1 from the external input by sampling mechanism (Fig. 4). The timing pulse pf a GNSS module is connected to the synchronous input of a motion sensor in order to relate sensing data with the GNSS time. Also, a GNSS module was connected to the microcontroller via serial communication in order to obtain global time information and positioning results for grasping and estimating the sampling time. When the positioning interval is 1 Hz, positioning information is received after the 1 PPS timing pulse rises. It is necessary to associate the synchronization bit in the motion sensor data with the output time of the timing pulse. Therefore, the system also records the internal timer value when the timing pulse input rises.

V. SAMPLING TIME ESTIMATE METHOD

In this section, we show a sampling time estimation method of sensing data using GNSS timing information. A key idea of this method is to identify the most aligned sampling data to the timing pulse generated by a GNSS module. In our method, We estimate the accurate actual sampling time of sensed data by attached accurate GNSS timing trigger as the synchronization bit of the sensed data.

A. Relationship between timing pulse and sampling data

For the proposed method, we assume the following conditions. First, GNSS timing pulses are output with an accuracy of less than 100 nanoseconds. Second, the sampling clock frequency of the sensing module is stable, and it does not change within a certain time because the part of our estimation method assigns a timestamp to data proportionally.

The sensed data with the frame synchronous bit can be divided into the data groups depending on the interval of the

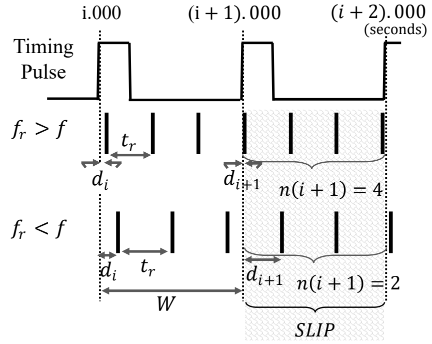

Fig. 5. An example of sampling data

frame synchronous bit. The divide time interval depends on an output interval (W) of the timing pulse. In this paper, a data group of every W second is called a "sector" (Fig. 4).

When we count samples in each group, these include sectors of ± 1 of the expected number usually. As an example, Fig. 5 shows the data when sampling at 3 Hz, the sampling frequency $f = 3$. In this example, the timing pulse interval assumed to be 1 second, and it means sectors are divided every 1 second. The $n(i)$ denotes the number of sampled data in Sector i. The $n(i)$ is usually equal to f. The $n(i+1)$ in Fig. 5, is the sector that the number of samples is different from the expected number f. In this paper, such sectors are called *slip*.

We can get the following two things from the sectors. First, We can estimate the actual sampling frequency (f_r).

$$f_r = \frac{n(i) + n(i+1) + \cdots + n(i+y)}{W \cdot (y+1)} \tag{1}$$

In this paper, We use the f_r' as the number of sampling per optional time interval (W).

$${f_r}' = \frac{n(i) + n(i+1) + \cdots + n(i+y)}{(y+1)} \tag{2}$$

Second, If we focus on the first sample in each sector, we can estimate the sampling time roughly. The following equations express each element in Fig. 5. In this paper, d_i means the time difference between the rising time of timing pulse i (T_{P_i}) and the sampled time of data that measured immediately after the pulse. Equation 3 shows the time range of it. In addition, f' means the expected number of samples ($\lceil {f_r}' - 0.5 \rceil$), ${t_r}'$ means sampling interval ($1/{f_r}'$), and W means timing pulse interval. Equation 4 shows relationship between them.

$$0 \leq d_i < {t_r}' \tag{3}$$

$$d_i + {t_r}' \cdot W \cdot (f' - 1) + {t_r}' \cdot W - d_{i+1} = W \tag{4}$$

We focus on d_i between the first slip to the next slip, d_i changes regularly. The following equation expresses the actual sampling time changes regularly.

$$d_i - d_{i+1} = W - {t_r}' \cdot W \cdot f' \tag{5}$$

In the $f_r > f$ case, d_i decrease monotonic within a block because $d_i - d_{i+1} > 0$. On the other, in the $f_r < f$ case, d_i increase monotonic within a block because $d_i - d_{i+1} < 0$.

Furthermore, the number of samples in each sector is determined by the following condition.

$$n(i) = \begin{cases} f' + 1 \ ({f_r}' > f' \text{ and } d_i < W - ({t_r}' \cdot W \cdot f')) \\ f' - 1 \ ({f_r}' < f' \text{ and } d_i > W - ({t_r}' \cdot W \cdot (f' - 1))) \\ f' \ \text{(otherwise)} \end{cases} \tag{6}$$

B. Sampling time estimation using timing pulses

In the previous section, we showed the actual sampling frequency could be estimated, and the first sample of each sector changes regularly. In this section, we explain the method to estimate the actual sampling time of each sampling data based on them.

What should be noted information in sampling data is d_i changes monotonically. By the characteristics, We can find the sample that closest to the ideal sampling timing generated by an atomic clock synchronized with the global time. For instance, we can identify samples nearest to top of second (TOS). We call such samples *Time base point (TBP)*. Samples other than time base point execute linearly computed from TBP using the estimated sampling interval.

The maximum time length of d_i of sampling data that nearest TOS within a certain time range is estimable. The fact that d_i is under t_r is known. Considering Eq. 5, the maximum d_i of the TBP is shown Eq. 7. The N_B indicates the number of sectors in a slip occurrence interval. Thus, if the estimated frequency is correct and the actual sampling frequency does not fluctuate, all samples are given times within that error.

$$d_i < {t_r}'/(W \cdot N_B) \tag{7}$$

The N_B can be represented by $N_B = 1/(f' - {f_r}')$, and substitute it into Eq. 7.

$$d_m < \frac{1/{f_r}'}{W \cdot 1/(|f' - {f_r}'|)}$$

$$d_m < \frac{|f' - {f_r}'|}{W \cdot {f_r}'} \tag{8}$$

A basic concept was shown above. However, that method has some problems. The method notably depends on the actual sampling frequency. One of the problems is the slip will not occur if the sampling frequency is very close to an integer multiple of the ideal sampling frequency. Another problem might be that it will be milliseconds accuracy with low-frequency sampling data.

There are two ways to solve this problem. One is to adjust an output interval of timing pulse. The other is to find other time base points that are shorter than based on TOS.

The GNSS module (u-blox timing module) that we use shown in Sec. IV can change the timing pulse output interval with nanosecond accuracy. Further, the output time of the timing pulse can also be obtained as GNSS time information (GPS week, time of week) with nanosecond accuracy. Equation 8 shows that the time estimation accuracy depends on the sampling frequency and the sample division time (w). From

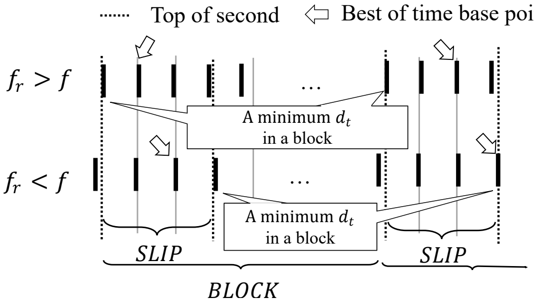

Fig. 6. An example of time base point
($f = 3$, $W = 1$, $|f - f_r| < 0.5$)

those reasons, we think it is possible to adjust the slip interval and to improve estimate time accuracy.

In addition to the previous improve method, we show a method to specify the sample closest to the ideal sampling timing among the other samples in the sector used for time base point. We find it from the sector that exists time base point based on TOS. The ideal sampling points that are the condition for finding are .00, .25, .50, and .75 seconds for a sampling rate of 4 Hz, for example. An example of a sample closest to the ideal sampling time estimated by the newly proposed method is shown in Figure 6. Monotonous variation of timing is used in this determining time base point too. Define the ideal timing as time 0 and focus on the sampling closest to that point. By changing the sample of interest in a time-series order, the actual sampled timing that nearest it also changes monotonously. Therefore, by using d_i and amount that varies, the time assignment accuracy can be improved compared to the method presented first. For that purpose, it is necessary to observe the change of the slip interval, and long time data sampling is required.

VI. EVALUATION OF THE PROPOSED METHOD

By measuring the vibrations of the speakers with two independent motion sensors. We conducted two experiments to evaluate a previous method and our proposed method. In this experiment, in order to confirm the accuracy of the estimated sampling time, we prepared a sensor that can be sampled according to the external synchronization signal and used it as comparison data. Figure 7 shows a experimental configuration. MPU9250 have an external input as the timing label attached to sensed data, and ADXL355 has an external timing input as the trigger of sampling. The microcontroller in the sensing unit used a single-core processor device that operates at a clock of 84 MHz, and data recorded using a serially-connected computer to reduce the effect on sensing.

The sensed data observed in this experiment is an acceleration of vibration similar to 100 Hz standing wave waves generated from a 100 Hz pulse signal with a duty ratio of 50 % output from the GNSS timing module. For all sampling data, we calibrate three-axis accelerometer data using the acceleration of gravity before comparing data as preprocess. The target acceleration value after calibration at stationary is 0 on the x-axis and y-axis and -1 on the z-axis.

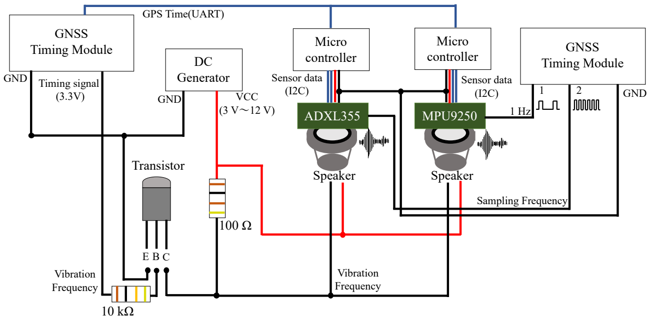

Fig. 7. Experiment configuration

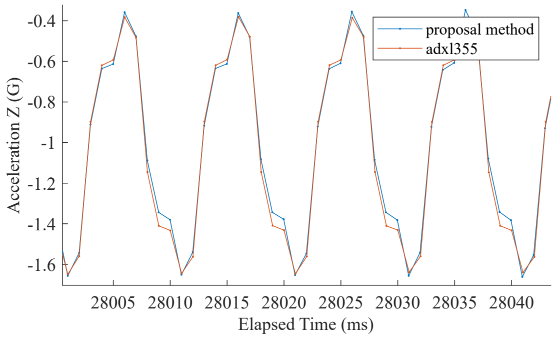

Fig. 8. Time aligned and compare accurate time data

First, to explain the time align method for each data. ADXL355 data was time-stamped using 1 PPS vibration. In just before the experiment, Speaker generated vibration trigged on 1 PPS, and it measured by ADXL355. Global time can be given by recognizing the start point of the vibration that occurs every second as TOS. The data of MPU9250 for the existing method gives timestamp using the relative time between the 1 PPS input time and the sensing time using the internal timer of the microcontroller. The data of MPU9250 for the proposed method uses the most basic method of detecting the sample with the shortest difference time from the TOS as a time base point and gives timestamp to all data based on the calculated estimated sampling interval(t_r). The evaluation point of the time accuracy is the time when the acceleration component of the Z-axis passes -1 while going in the plus direction in the time range of 100 Hz vibration measure. We prepared ten 2-minutes data for each evaluation, and the time differences were aggregated. The following shows verified results for the time estimated accuracy of 1000 Hz sampling and 500 Hz sampling data. Figure 8 shows a result that ADXL355 data and time-aligned data by the proposed method are superposed. It can check by looking waveform match accurate data of ADXL355. Figure 9 shows the number of samples per sector in one of 1000 Hz sampling verified data. In this data, a slip occurs about once every three seconds. Since the slip interval was the same for data with other sampling rates of 1000 Hz, when $W = 1$ and $N_B = 3$ into Eq. 7, an accuracy of about 300 μs can be expected for them. Figure 10 shows the result of time differences at evaluation points of one of the verified data.

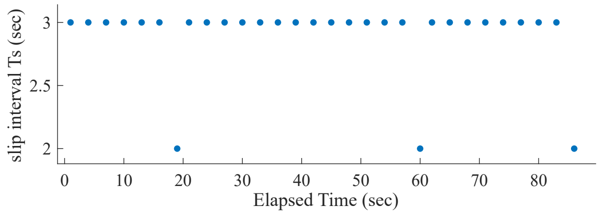

Fig. 9. Slip occurrence time interval of a verification data

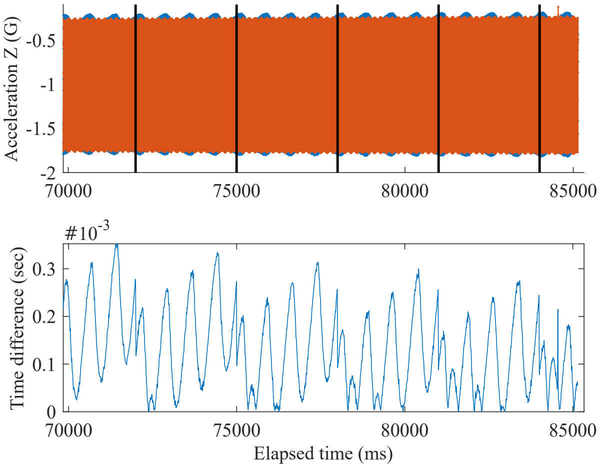

Fig. 10. Time difference of validation point and Time base point

Vertical lines show the time base points. The time difference immediately after the time base points is always less than 300 μs. table II shows statistics of the time difference of 500 Hz sampled and 1000 Hz sampled data. It can be said that the time estimation accuracy of the proposed method is high in sampling over 500 Hz than previous method. However, there is a problem that the estimation time accuracy also decreases in proportion to the decrease in the sampling frequency without the improved method.

VII. CONCLUSION

We have proposed a method to estimate the actual sampling time by processing the timing pulse output from the GNSS positioning module as bit information embedded in the sampling data of the motion sensor. As an evaluation of the time reference, We verified the output accuracy of the timing pulse generated by the GNSS module. We conducted the measurement experiment of the output error of the timing pulse using an oscilloscope for about 20 hours for each of several GNSS modules. As a result, we noticed the jitter was less than 100 nanoseconds.

TABLE II
COMPARISON OF TIME SYNCHRONIZATION ERROR

Method	Sampling frequency(Hz)	Avg.(ms)	Sd.(ms)
Proposal	1000	0.136	0.101
	500	0.267	0.184
[6]	1000	0.354	0.290
	500	0.367	0.284
without any methods	1000	0.5	
	500	1.0	

As a verification of the proposed method of basic logic and comparing a previous method, we measured the vibrational acceleration of a speaker that generates a 100 Hz standing wave. As a result of overlapping accurate sampling data and data that applied the proposed method, It was confirmed that the accuracy was higher than that of the conventional method for data with 500 Hz sampling or higher. However, due to the characteristics of our basic logic, the estimation accuracy is relative to the data sampling frequency, and estimation accuracy is low for data with a low sampling frequency.

Next step, it will be a challenge to realize maintaining estimation accuracy in the microsecond order with any sampling rate by the improved method.

ACKNOWLEDGMENT

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REFERENCES

[1] W.Ding, J.Wang, and Y.Li, “Time synchronization error and clibration in integrated gps/ins system,” *ETRI Journal*, pp. 59–67, 2008.

[2] B. Li, C. Rizos, H. Lee, and H. Lee, “A gps-slaved time synchronization system for hybrid navigation,” *GPS Solution*, vol. 10, pp. 207–217, 2006.

[3] A.Matsubara, M.Yoo, and T.Yokoyama, “A real-time operating system with gnss-based tick synchronization,” *Journal of Information Processing*, pp. 1765–1774, 2016.

[4] N.Kurata, “Fundamental research on autonomous time synchronization sensing system,” in *Proceedings of the 2nd ACM International Symposium on Mogile Ad Hoc Networking & Computing*, 2016, pp. 185–192.

[5] Y.Torii and T.Takahashi, “Development of a precision pitch and stride measurement system for athletes using gps : Investigation of comfortable device mounting position for athletes and improvement of the measurement accuracy,” in *JSME annual Conference on Robotics and Mechatronics*, 2013, pp. 2A2 G02 (1)–2A2 G02 (4).

[6] K. Koo, D. Hester, and S. Kim, “Time synchronization for wireless sensors using low-cost gps module and arduino,” *Frontiers in Built Environment*, vol. 4, no. 82, 2019.

[7] O. Mancini, “Tutorial: Precision frequency generation utilizing ocxo and rubidium atomic standards with applications for commercial, space, military, and challenging environments,” IEEE Long Island Chapter, 2004.

[8] E. SIA. (2018, Dec.) Elthehs gnss oem store. [Online]. Available: ”https://www.gnss.store/”

[9] N. Takamura, *Research Latest GPS & In-door Positionings*. CQ publisher, 2013 (in Japanese), pp. 25–35.