Time Control and Experimental Verification of IoT based Structural Seismic Monitoring

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Abstract

Great earthquakes such as the 1995 Kobe Earthquake or 2011 Great East Japan Earthquake caused large casualties and severe and long-term economic impact to the society. In the events of such disasters, real-time information collection and correct decision making are significantly important for mitigate the disaster and increase the resilience of urban area. Emergency inspection is compulsory for conducting the post-earthquake assessment, but it is difficult to perform considering the complex situation in the aftermath of an earthquake. It may compromise the health and safety of inspectors when they are approaching to some potentially damaged structures and carry out the inspection when strong after shock are occurring frequently. Besides, the time cost in this method is very high from the inspection to the report generation, and eventually to the decision making.

Though structural health monitoring (SHM) system can provide valuable service status information of structures, only a very limited important bridges and buildings have the SHM system installed. Due to the high cost of this system, it is almost impossible to deploy it for normal bridges in dense. The IoT sensing based structural seismic monitoring (SSM) system is becoming much lower in cost than conventional SHM system, but with some space to improve in accuracy, sampling rates and functions.

The physical size of IoT sensing based SSM system is much smaller as well, showing the advantage when it comes to installation. In addition, the power consumption is also lower for IoT sensing based SSM system, which makes the long-term monitoring easier to realize. As for data-processing, AI-based solutions derived from massive volume of monitoring data provide valuable engineering parameters for fast decision making. A low-cost, high-accuracy, long-term and real-time acceleration monitoring system was proposed in this study. The measurement unit consists of a M.EMS accelerometer and a single-board computer. The measurement system was developed by Python to handle data acquisition, data storage, and data transfer in the real time.

However, IoT sensing is orienting to low frequent measurement with low accuracy demands, it is generally difficult to make sure the quality of data in sampling rate, and the time gap between two recorded files may be large when the sampling number per file is increasing. To solve the time control issue for IoT based low cost SSM, three time-control tricks were proposed to stable the sampling rate and shorten the time gap between files with limited processing power.

Feasibility and measurement accuracy were verified through shaking table tests conducted in laboratory environment. The experiment results show satisfactory agreements between the reference sensor and the IoT sensor in both time and frequency domains.

Keywords: IoT Sensing, Structural Seismic Monitoring, MEMS, Time Control, Shake Table Tests

1. Introduction

Earthquakes, as large as the 1995 Kobe Earthquake or 2011 Great East Japan Earthquake, commonly impact broad area and cause severe and long-term economic loss. As one of important way to improve the resilience of seismic prone area, real-time seismic monitoring and information collection system can fasten the decision-making progress and mitigate the secondary disaster [1-3].

Emergency inspection is compulsory for conducting the post-earthquake assessment [4], but it is difficult to perform considering the complex situation in the aftermath of an earthquake. It may compromise the health and safety of inspectors when they are approaching to some potentially damaged structures and carry out the inspection when strong after shock are occurring frequently. Besides, the time cost in this method is very high from the inspection to the report generation, and eventually to the decision making.

Bridges perform as key infrastructures to recover emergency logistics function for conducting evacuation and rescue [5], to monitor the response of bridges during earthquake is valuable. Though structural health monitoring (SHM) system can provide valuable service status information of structures, only a very limited important bridges and buildings have the SHM system installed. Due to the high cost of this system, it is almost impossible to deploy it for normal bridges in dense.

The IoT sensing based structural seismic monitoring (SSM) system is becoming much lower in cost than conventional SHM system [6], but with some space to improve in accuracy, sampling rates and functions [7]. The physical size of IoT sensing based SSM system is much smaller as well, showing the advantage when it comes to installation such as using Smartphone as sensor unit [7, 8]. In addition, the power consumption is also lower for IoT sensing based SSM system, which makes the long-term monitoring easier to realize [9, 10]. As for data-processing, AI-based solutions derived from massive volume of monitoring data provide valuable engineering parameters for fast decision making [11-13]. A low-cost, high-accuracy, long-term and real-time acceleration monitoring system was proposed in this study. The measurement unit consists of a MEMS accelerometer and a single-board computer. The measurement system was developed by Python to handle data acquisition, data storage, and data transfer in the real time.

However, IoT sensing is orienting to low frequent measurement with low accuracy demands [14], it is generally difficult to make sure the quality of data in sampling rate, and the time gap between two recorded files may be large when the sampling number per file is increasing. To solve the time control issue for IoT based low cost SSM, three time-control tricks were proposed to stable the sampling rate and shorten the time gap between files with limited processing power.

In this study, A low-cost, high-accuracy, long-term and real-time acceleration monitoring system was proposed. Feasibility and measurement accuracy were verified through shaking table tests conducted in laboratory environment. The experiment results show satisfactory agreements between the reference sensor and the IoT sensor in both time and frequency domains. A prototype has been installed in a research building to detect seismic events for long term. Two earthquakes happened recently can be recognized by monitoring data, though the seismic intensity in the region where the prototype was deployed were both low according to the Japan Meteorological Agency (JMA) seismic intensity scale.

2. IoT sensing unit for structural seismic monitoring

The basic way of IoT sensing is to mount a single board computer such as Raspberry Pi or Arduino with some MEMS sensors through GPIO (General-purpose input/output) pins. Many open sources are available from internet to help user programming the computer to read data from the sensor. As the opposite of becoming powerful gradually, this kind of single board computer also consuming quite a bit of electric power. Unless the wireless sensor, it is better to supply the device with stable power connection and battery as UPS (Uninterruptible Power Supply). The normal mobile battery for smartphones can be conveniently used as the power supply for Raspberry Pi or Arduino. To use it safely a protection case may necessary. For vibration monitoring outdoor (e.g., bridge seismic monitoring), a water and dust prove case can protect the sensor unit to be used for long time. A prototype IoT sensing unit are shown in the following figure.

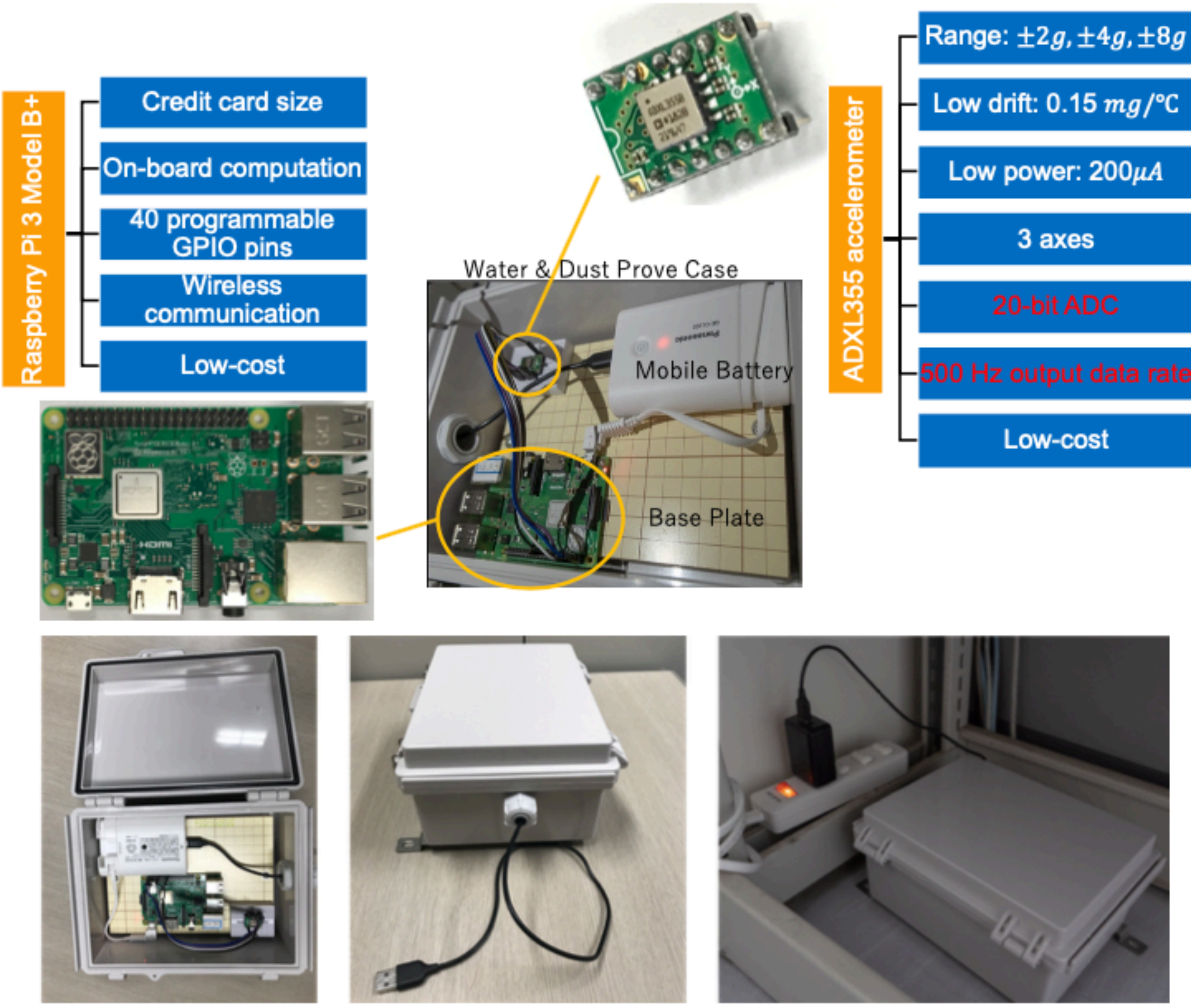


Fig. 1 – A prototype IoT sensing unit

After fetched the data from the sensor time to time, it is also important to safe the data properly, not only on the on-board storage (SD card etc.), but also to the cloud server. The basic framework and data flow, showing in the next figure, is including:

Level 1: Requiring and fetching data from sensor, in accurate time which is going to be discussed in later chapters.

Level 2: Collecting data and time stamp to build sensing record in temporary memory of single-board computer.

Level 3: Saving data safely to local and cloud path.

In this study, as the cloud storage both Dropbox and NAS(Network Attached Storage) are used to save the records. For Dropbox, the Dropbox Uploader, an open sourced script from github, was used to send record to the Dropbox cloud folder. And the SAMBA, an VPN (Virtual Private Network) protocol, was use to connect the single board computer and the NAS.

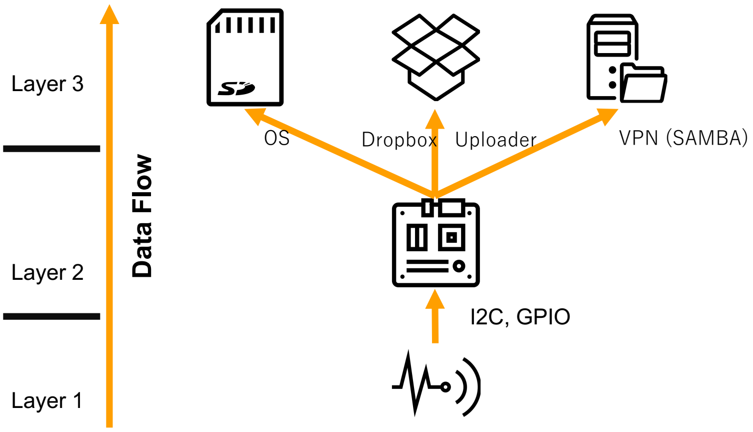


Fig. 2 – Basic framework and data flow

3. Time Control for IoT sensing

As the limitation of the computing speed, using IoT sensing may normally difficult to get a stable and accurate time stamp of each data. Commonly, seismometers and microtremor sensing system will use portable GPS to acquire satellite time. This may need to setting GPS on opened place to get the satellite connection. However, long term monitoring inside building may difficult to set those GPS connections. As alternate way NTP (Network Time Protocol) is more convenient and also quite accurate.

Another issue is that the inside CPU of computer such as Raspberry Pi may not good enough to control the interrupt latency in an ignorable level. Randomness of sampling interval are very common. To overcome this, a few methods are used here to help to control the time.

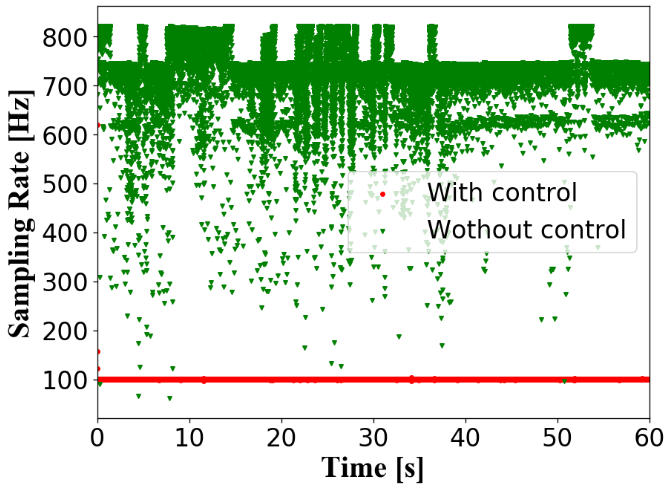


Fig. 3 – Improvement of sampling rate be interrupt latency control

A straightforward way for SSM was acquiring data from the accelerometer and waiting for a time interval dt (=0.01 second for sampling rate f=100Hz) to interrupt and get another, without any control mechanism. Static tests were conducted to investigate the sampling rate stability, the program was executed repeatedly with leaving the devices on a desk to measure just the ambient vibration. The result is shown in the following figure by the green dots, where the vertical axis is the actual sampling rate (Hz) and the horizontal axis is the time. It can be seen that there is great variance, due to the unstable interrupt by the CPU.

However, it is also can be seen that in the most of times, sampling rate is higher than the targeted sampling rate 100 Hz. This implies that the sampling should be wait for more time. Thus, it is very natural to solve the issue by put the program sleeping in small time interval and check the time until the scheduled sampling time from the start time. Here it is important to use the scheduled time, not the time from the last sampling, to prevent the cumulation of small time different. The flowchart of this progress is plotted in the figure 4 and this control method resulted very stable sampling rate as shown in figure 3.

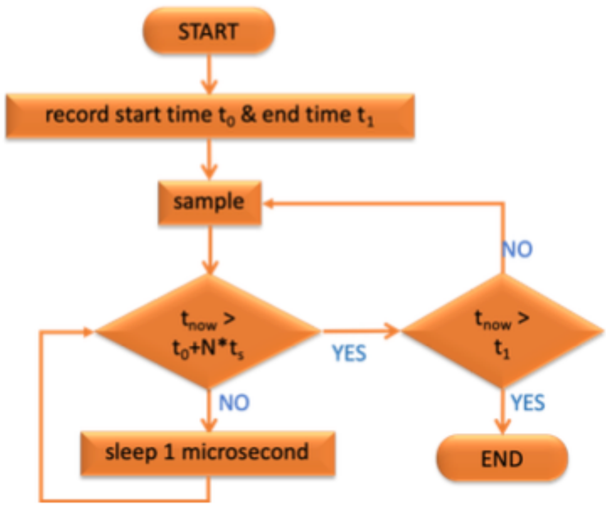


Fig. 4 – Interrupt latency control

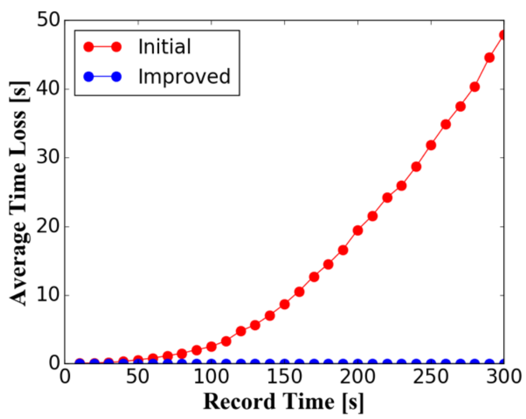


Fig. 5 – Improvement of time loss by recording writing latency control

When a group of data was recorded in the memory, it is necessary to same them to file time by time. The recording time for one file can be, each 1 second, 1 minute, sometime 5 minutes. However, to process the mission of writing data from memory to file in the recording device, send them to internet serve would cost latency, and data between file to file will be lost, as at that time interval the CPU is too busy to process the mission of recording to fetch any data from sensor. The time loss will be increased when the recording time become long as can be seen in the following figure.

Here two methods were used to overcome this time delay. First, in each time interval, after fetch data from sensor, there are quit a time left to write the data to file. By appending a new data line to the record file in each time interval, the time to write whole recorded data lines was separated and hide to small time interval. In practice, it is very effective when sampling rate is 100 Hz. Secondly, using crontab to schedule another program to handle the file uploading in another CPU thread, and the sensing program can let the current CPU thread to focus on sampling and writing to file, as can be seen in Fig.6. Thus, time loss is small as can be seen in the following figure.

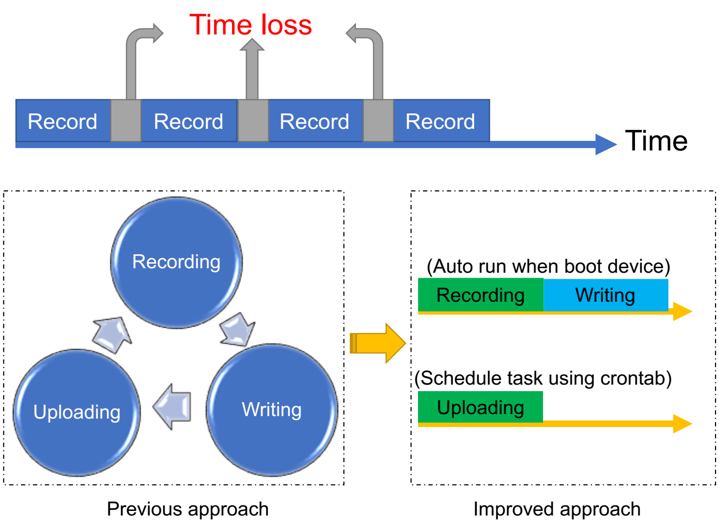


Fig. 6 – Record writing latency and control

4. Performance verification by shake table tests

The shaking table tests were carried out to investigate the performance of ADXL355 accelerometer under different frequencies and amplitudes. The specification of the ADXL355 is described in chapter 2.1. The reference sensor used in this study is a high-quality servo velocity seismometer VSE-15-D.

A uniaxial shake table (APS-113) was used to simulate sinusoidal motion with different frequencies and amplitudes. The sinusoidal signal was generated by WF-1974 function generator with different frequencies and then amplified by SVA-ST-30 power amplifier. The layout of specimens on the shaking table and the reference data acquisition unit is shown in Fig.7.

To investigate the capability of the IoT sensing unit to capture structural seismic response vibration, sinusoidal excitation with frequencies from 0.1 to 10.0 Hz and amplitudes from 1 to 100 gal were implemented, as shown in Table 1. For every case in the tests, the time taken of measurement was assured that there were enough cycles of sinusoidal waves. The sinusoidal motion recorded by IoT sensing with that recorded by the reference sensor were compared in terms of time domain and frequency domain of acceleration time history records. Peak amplitudes in same frequency from the fourier amplitude spectrum are compared between the IoT sensing unit with the reference sensor. The amplitude ratio, which is the amplitude of IoT with ADXL355 sensor devided by those of reference, of each experiements are shown in the Fig.8

It can be seen from Fig 8. That in the range of 0.2 to 10 Hz, the IoT sensing unit recorded data are agree with the reference data basically. In the case of mall amplitude such as loading with amplitude of 1 Gal the amplitude ratio is variating relatively large. This is because the noise from MEMS.

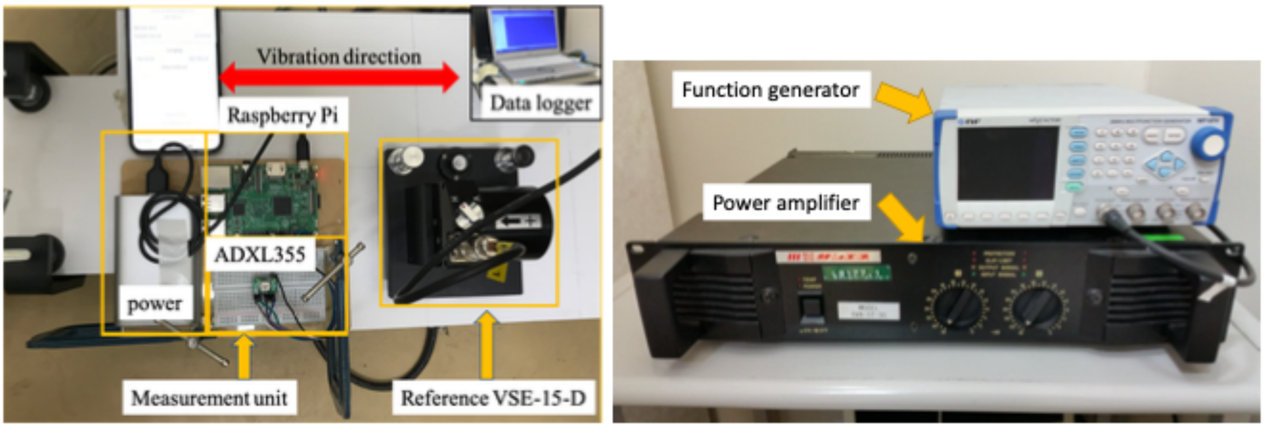


Fig. 7 – Setup of shaking table tests

Table 1– Frequency and Amplitude combination of shaking table tests

Freq. / Amp.	0.1Hz	0.2Hz	0.5Hz	1.0Hz	2.0Hz	5.0Hz	10.0Hz
1 Gal	◎	◎	◎	◎	◎	◎	◎
5 Gal	◎	◎	◎	◎	◎	◎	◎
10 Gal	◎	◎	◎	◎	◎	◎	◎
50 Gal	×	◎	◎	◎	◎	◎	◎
100 Gal	×	×	×	◎	◎	◎	◎

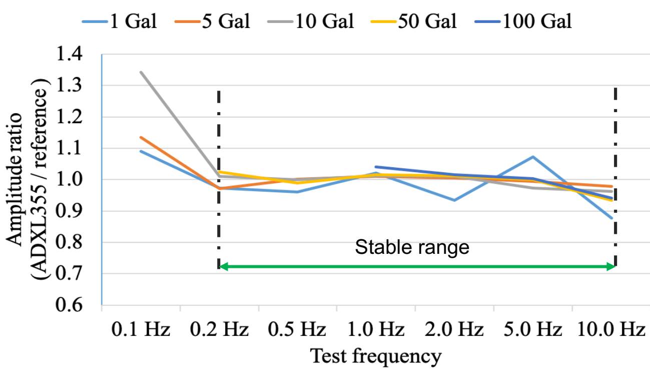
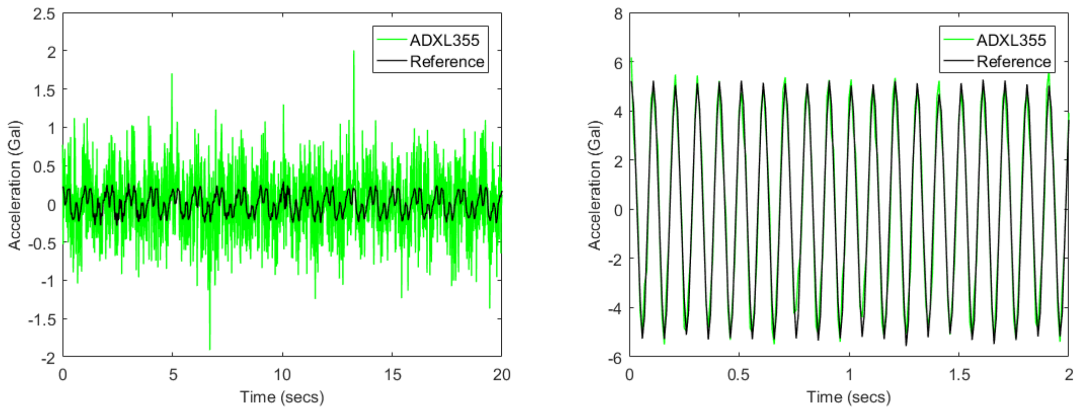
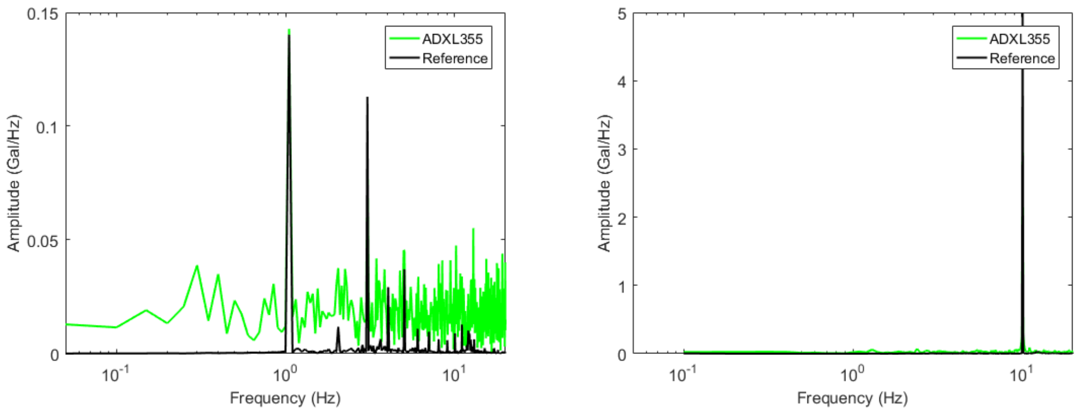


Fig. 8 – Results of shaking table tests



(a) Waveform at f = 1.0 Hz, A=1 Gal (b) Waveform at f = 10.0 Hz, A=5 Gal



(c) Spectrum at f = 1.0 Hz, A=1 Gal (d) Spectrum at f = 10.0 Hz, A=5 Gal

Fig. 9 – Waveform and Fourier amplitude spectrum of shaking table tests

Part of the shaking table test results was represented in Fig.9. Test 1 with frequency at 1Hz and amplitude 1gal shown in Fig.9 (a) the wave form comparing, and (c) Fourier Amplitude Spectrum. Test 2 with 10Hz and 5gal shaking shown in Fig.9 (b), (d). It can be seen that shaking with small amplitude like 1 gal, the noise will cover most of the real shake waveform. When the wave amplitude is lager than 5 gal, the noise seems small enough to be ignored. The component amplitude in frequency domain of noise seems distributing evenly from low to high frequency. And still, the predominant component, from Fig.9(c), in small amplitude shaking, can be recognized easily from spectrum and the amplitude is quit agree with the reference sensor's record.

5. Application of SSM System

To investigate the feasibility and effectiveness of applying the proposed SSM system for long-term structural seismic response monitoring, the prototype was installed on the 8th floor of a 10-story reinforced-concrete-frame building in Saitama University in 2019 June as shown in the following figure.

There were 4 earthquakes observed from the deployed prototype since the system was installed:

(a) M 6.7 Yamagata Offshore Earthquake on June 18th in 2019

(b) M 5.5 earthquake in Chiba Prefecture on June 24th in 2019

(c) M 6.6 earthquake in Mie Prefecture on July 28th in 2019

(d) M 6.2 earthquake in Fukushima offshore on August 4th 2019.

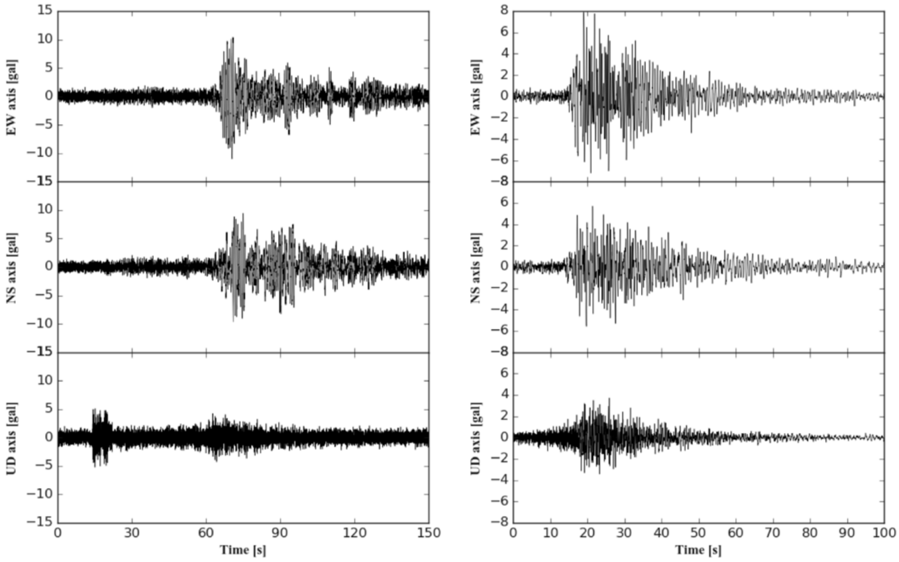
The seismic intensity in the region where the prototype was deployed was low in JMA seismic intensity scale. The records from the nearest observation station (K-NET SIT010) of strong-motion seismograph networks in Japan (K-NET and KiK-net) [19] were collected for comparison with that of the proposed system. The distance between two observation locations is 13 km. The orthogonal tri-axis measurement direction was aligned to East-West (EW), North-South (NS) and Up-Down (UD) direction, the same as the observation station recorded.

Fig. 10 – Deploying the IoT sensing SSM in a 10 Floor Building

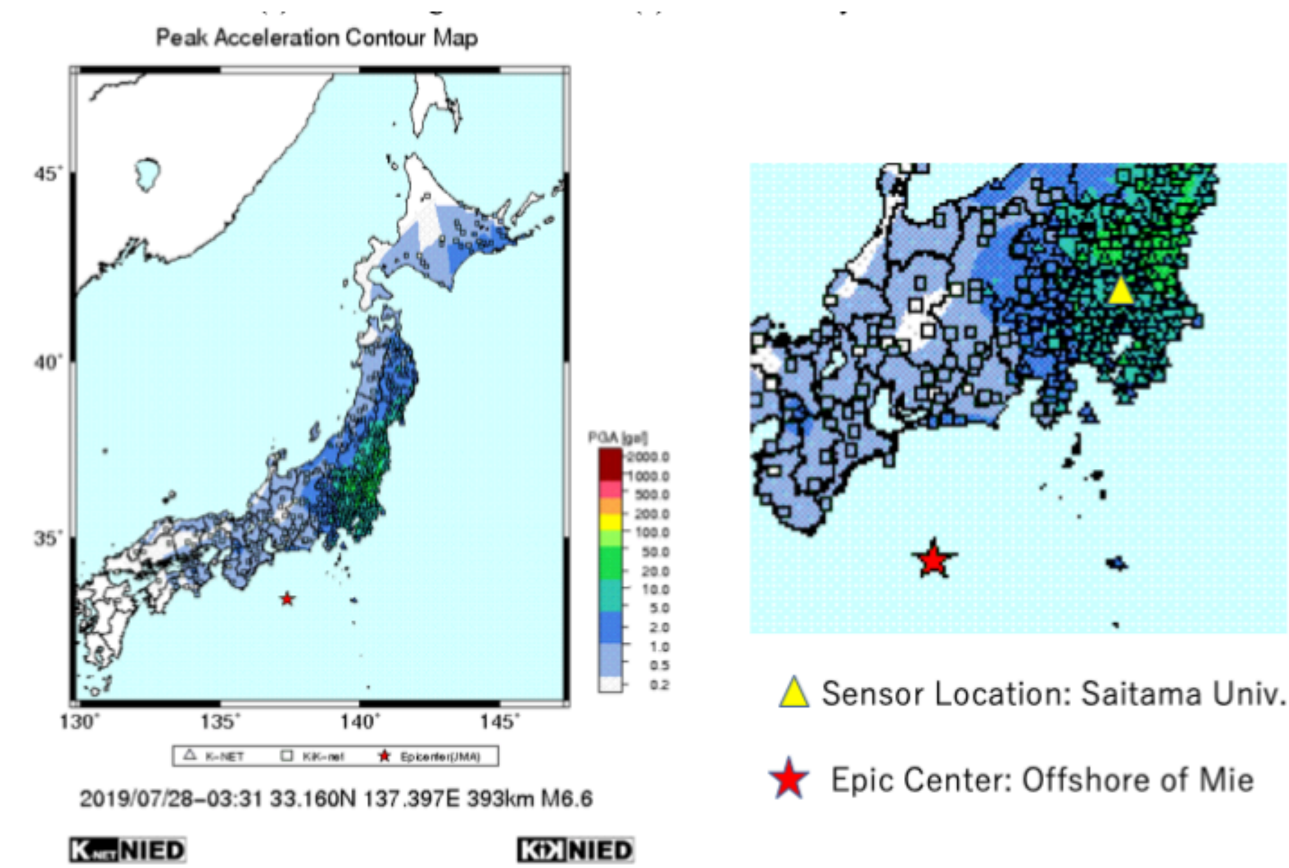
The acceleration waveforms for 3 axes are shown in Fig. 10 for earthquake (c), and the corresponding Fourier amplitude spectrums along EW direction are plotted in Figure 11. The data was extracted from continuous monitoring according to the record time from the observation station and then compared with the record data from the observation station via manually tuning the time axis in the monitoring data.

The P wave can be observed by the prototype can be found in the figure in the UD direction, it can be seen that it traveled a long way to show an interesting amplitude in vertical direction in the IoT sensor, though didn't show in the nearby K-Net Omiya Station, as can be seen from the figure. The depth of the epic center depth of this earthquake is about 393 km. The wave hit Tokyo area in lager intensity than Mie and Aich prefecture around the epic center, propagating through deep ground.

As can be seen form Fig.11, the abnormality can be easily observed in the waveforms. According to the records in some earthquakes, the dominant frequency of the structure at the prototype-deployment location is identified as around 1.4 Hz. The measured waveforms can represent the structural seismic response roughly, though the accurate waveform data concerning earthquakes with amplitude smaller than 2 Gal is hidden due to the noise. Only noise can be observed under 2 Gal in the UD direction, showing the limitation of the accuracy of the proposed system. Nevertheless, the proposed system can observe the earthquake at locations where the seismic intensity is as low as 1 in JMA scale. With advancements in the resolution and sensitivity of MEMS accelerometer in the future, the proposed system can be expected to show better performance in structural seismic response monitoring.



(a) IoT Sensing (b) K-NET Ohmiya station record



(c) PGA Distribution and the location of sensor

Fig. 11 – Waveform comparison in the magnitude 6.5 earthquake in Mie Prefecture

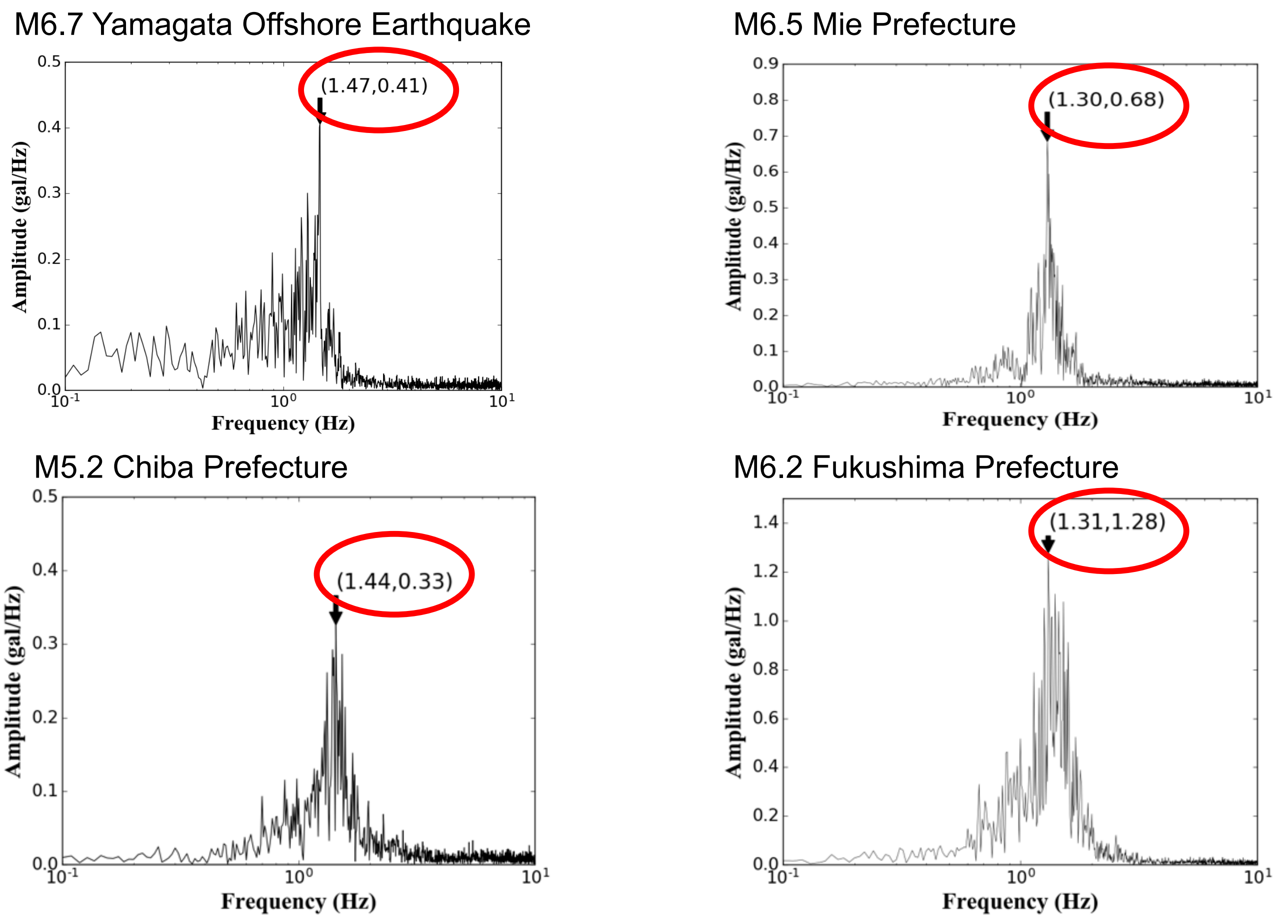


Fig. 12 – Fourier Spectrum of recorded earthquake events

6. Conclusions

In this paper, an IoT sensing based structural seismic monitoring system was proposed. Integrated with the function of data acquisition, data storage, and data transfer, IoT devices considerably reduce the cost of structural seismic monitoring with reasonable perfor-mance. The effectiveness of the proposed system has been verified via shaking table tests and long-term seismic response monitoring at structures. It can be validated through all experiments carried out above, the stable sampling rate at 100 Hz is available, and the de-tectable acceleration level is about 2 Gal in a seismic event. IoT devices make the dense deployment of structural seismic monitoring system possible, and the huge volume of real-time structural seismic response data will enhance the understanding of the structural dy-namic behavior.

7. Acknowledgements

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8. References

[1]Kazuhiko KAWASHIMA (2012): Damage of Bridges Due to the 2011 Great East Japan Earthquake, Journal of Japan Association for Earthquake Engineering, Vol.12, No.4(Special Issue), 2012

[2]Kenji KOSA (2012): Damage Analysis of Bridges Affected by Tsunami Due to Great East Japan Earthquake, Proceedings of the International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake, March 1-4, 2012, Tokyo, Japan

[3]Yoshikazu TAKAHASHI (2012): Damage of rubber bearings and dampers of bridges in 2011 great east japan earthquake, Proceedings of the International Symposium on Engineering Lessons Learned from the 2011 Great East Japan Earthquake, pp. 82-101.

[4]Nikos D. L., Matthew G. K. A. (2011): A critical assessment of metaheuristics for scheduling emergency infrastructure inspections, Swarm and Evolutionary Computation.

[5]Yiping Jiang and Yufei Yuan (2019): Emergency Logistics in a Large-Scale Disaster Context: Achievements and Challenges, Int. J. Environ. Res. Public Health 2019, 16, 779.

[6]Jack W Judy (2001): Microelectromechanical systems (MEMS): fabrication, design and applications, Smart Mater. Struct.10(2001) 1115–1134

[7]Shideh Dashti, Jack Reilly, Jonathan D. Bray, Alex Bayen, Steven Glaser, and Ervasti Mari. (2011): iShake: Using Personal Devices to Deliver Rapid Semi-Qualitative Earthquake Shaking Information, Technical report G10AP00006, Department of Civil and Environmental Engineering, University of California, Berkeley, CA, USA, February 2011.

[8]Shrestha A., Dang J., Wang X. (2017): Development of a smart-device-based vibration-measurement system: Effectiveness examination and application cases to existing structure, Struct Control Health. doi.org/10.1002/stc.2120

[9]J. Dang, A. Shrestha, X. Wang, S. Matsunaga, P. J. Chun, and S. Asamoto (2018): Low cost bridge seismic monitoring applying used smart phones and cloud server, 11th National Conference on Earthquake Engineering, Los Angeles, Proceeding of the 11th National Conference on Earthquake Engineering,11:pp.1-10 201806

[10] B. F. Spencer Jr., Manuel E. Ruiz-Sandoval, and Narito Kurata (2004): Smart sensing technology: opportunities and challenges, Struct. Control Health Monit. 2004; 11:349–368 (DOI: 10.1002/stc.48)

[11] Luyao Wang, Ji Dang, Xin Wang: Pseudo Damage Training for Seismic Fracture Detection Machine, Proceeding of the 8th International Conference on Experimental Vibration Analysis for Civil Engineering Structures, Vol. 8, 2019.

[12] Ashish Shrestha, Ji Dang: Bridge Vibration Status Realization Method Using Deep Learning and Smart Devices, Proceedings of the 9th Symposium on Disaster Mitigation and Resilience of Infrastructures and Lifeline Systems, Vol. 9, pp.35-42, 2019.

[13] Nikesh Maharjan, Ji Dang, Ashish Shrestha: Bridge Damage Recognition From Structural Acceleration Data Using Machine Learning, Proceedings of the 9th Symposium on Disaster Mitigation and Resilience of Infrastructures and Lifeline Systems, Vol.9, pp.64-70, 2019.

[14] Roberto Minerva, Abyi Biru, and Domenico Rotondi: Towards a definition of the Internet of Things (IoT), Technical Report; IEEE Internet of Things: Piscataway, NJ, USA, 2015.

[15] Francesco Lamonaca, Carmelo Scuro, P.F. Sciammarella, D.L. Carnì, R.S. Olivito: Internet of Things for Structural Health Monitoring, 2018 Workshop on Metrology for Industry 4.0 and IoT, 2018.

[16] H. Chang and T. Lin: Real-time structural health monitoring system using Internet of Things and cloud computing, Eleventh U.S. National Conference on Earthquake engineering Integrating Science, 2018.

[17] C. Jr. Arcadius Tokognon, Bin Gao, Gui Yun Tian, Yan Yan: Structural Health Monitoring Framework Based on Internet of Things: A Survey, IEEE Internet Of Things Journal, Vol. 4, No. 3, pp.619-635, 2017.

[18] Raspberry Pi 3 pinout mapping, https://docs.microsoft.com/en-us/windows/iot-core/learn-about-hardware/pinmappings/pinmappingsrpi

[19] National Research Institute for Earth Science and Disaster Resilience, NIED K-NET, KiK-net,National Research Institute for Earth Science and Disaster Resilience, doi:10.17598/NIED.0004, 2019.

[20] Dropbox Uploader, https://github.com/andreafabrizi/Dropbox-Uploader

