LOW COST BRIDGE SEISMIC MONITORING APPLYING USED SMART PHONES AND CLOUD SERVER

J. Dang¹, A. Shrestha¹, X. Wang², S. Matsunaga³, P. J. Chun⁴ and S. Asamoto¹

ABSTRACT

In this study, a bridge seismic response monitoring system was developed based on smart phones and cloud server. Smart phones with built-in batteries, processor units, and a variety of MEMS, can offer promising hardware and software environments which can be used in Structural Health Monitoring System. Instead of building an independent network server, Cloud server is used in this study to compose a low cost smart sensor network for easy data upload and access. With all these features, a decentralized and self-governing smart phone based SHM framework was developed, which can be installed easily onsite. A long-term field application test of this system has been carried out in the Takamatsu Bridge, Japan. First, a measurement system including a group of smart phones has been established successfully. The system is then connected to cloud server for real-time data acquisition. A few seismic acceleration response records of Takamatsu Bridge were captured. Dynamic properties extracted from smart-device-based system are very similar to those of high-quality-sensor-based system.

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Template for Paper submission to the Eleventh U.S. National Conference on Earthquake Engineering

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ABSTRACT

This template illustrates the format that must be used in the preparation of papers for the Eleventh U.S. National Conference on Earthquake Engineering. Text and headings should be in 12-point type. Included in this template are examples of headings, equation format, references, and other typographical features likely to be encountered in technical papers. The abstract can be shorter than the originally submitted abstract. Maximum paper length is 11 pages, including the cover page. The cover page is in a format required by Google Scholars for proper indexing. A good abstract should be an informative summary of the most important results. It should not be a summary of subjects covered. It should avoid expressions such as “is discussed” and “is described.” It should not include references, figures, or tables. The abstract is of utmost importance, because it is the most widely read portion of a manuscript.

Introduction

The Infrastructure Health Report issued by Japan Society of Civil Engineers assessed Japan’s bridge infrastructure with an index of D (means that deterioration is obvious in many facilities, requiring repairs and reinforcements) 2016 \cite{1}. Reports from the National Highway Maintenance Budget (2005) indicates that a total of £1.44 billion is needed to rehabilitate existing road and bridges infrastructure system \cite{2}. National budget priorities do not allow for this high level of investment. Thus, many existing infrastructures need to be serving with deficient. Determining prioritization of the maintenance, repair, and replacement of this infrastructure requires inspection, a process that can be costly and prone to error. In case of large-scale infrastructure systems such as bridges, diverse dynamic loads, including traffic, wind and earthquakes can aggravate the

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condition of the structures. Structure Health Monitoring (SHM) can provide a useful diagnostics tool for ensuring integrity and safety, detecting damage and evaluating performance deterioration of civil infrastructures [3-5].

After the 2011 Great East Japan Earthquake and 2016 Kumamoto Earthquake, bridge seismic response monitoring has been realized as one of the most emergent issues for earthquake resilience of urban areas. The Micro Electro Mechanical System (MEMS) based measurement has been applied to SHM systems for bridge, such as wireless sensor [Spencer et al. 2004] [6], or dense earthquake and SHM system such as Community Seismic Network (CSN) (Clayton et al. 2015) [7]. However, in general, these system, that combines accelerometers, data log, hard disk, computer, power supply, modem and network connection, is often high cost and difficult for wide application in structures.

Meanwhile, having significant computational power, large memory resources, built-in batteries, processor units, and a variety of MEMS, modern smart phones can offer a promising hardware and software environment that can be used as SHM components. Several researchers (Yu et al 2012 [8], Dashti et al 2011 [9], Morgenthal and Hopfner 2012 [10,11], Naito et al. 2013 [12], Reilly et al 2013 [13], Feng et al 2015 [14], Han et al 2014 [15], Shrestha et al 2015 [16]), studied the measurement and monitoring ability of smart phones through laboratory and field tests and confirmed the potential usage of smart phones in the health monitoring of civil infrastructures. However, the performance of Smart phones as structural measurement and monitoring device has not been verified before its practice in real structural monitoring or seismic response recording. Also, reliability of using smart phones for long-term monitoring with stable and easy data transport has not yet been clarified.

Therefore, this study attempts to illustrate the effectiveness of the proposed approach in more detail by utilizing the advanced embedded processing capabilities of smart phones for structure monitoring applications. In this study, the implementation feasibility of long-term bridge health monitoring technique using smart phones has been investigated through, a real field application test of the measurement system applied to long-term seismic-response and environment-vibration measurement of the Takamatsu bridge. Measurement system including a group of smart phones has been established successfully on the bridge and the system is connected to cloud server for real-time data acquisition. The feasibility of the system for long term monitoring is then evaluated based on stable and continuous measurement and data transfer. The field measurement results based on the few seismic acceleration response recorded on Takamatsu bridge show that the dynamic properties extracted from smart-device-based system is very similar to those of high-quality-sensor-based system.

Overview of Takamatsu Bridge

The Takamatsu bridge, as shown in Fig. 1 was built in 1982 at Miyazaki, Japan. It is a PC box continued girder bridge with 7 spans, 444 m in length and a pile basement. The bridge has BP bearing at abutments and pin bearing at the pier part and with a Gilber hinge at 3rd and 5th span. This bridge connects two parts of the city separated by Oyodo river and maintaining the road transportation function as a key for resilience of this area. Instrumentation of this bridge offers opportunities to study and understand dynamic and long-term behaviors. It will be of great interest
to monitor and evaluate the long-term structural performance of such bridges under not only seismic but also service loads. Especially, long term seismic monitoring can be a useful way to check its functionality and damage of risk under earthquakes.

**Measurement Application Development**

Measurement Application program for smart phones was developed, which interacts with hardware and operating system features to make the built-in MEMS sensor components available and are responsible for acquiring data, analyzing data, storing data, and transferring useful data to the cloud. In this study, measurement application was developed based on the Objective-C programming language in the integrated development environment Xcode. Dropbox sync API (Dropbox developer, 2014 [17]) is imported to the app to build connection with data-restoring cloud server. Using this API, the app can read, create, and modify files and implement the changes on the server.

As depicted in Fig. 2, this measurement system consisting of independent smart phone can be installed at different locations of a bridge and measure data independently. Moreover, when all the devices are connected to a common network with the ability to communicate with each other, then a robust measurement system for whole bridge can be established. In this way, real-time record data from all the terminals can be obtained. Also, with real-time processing of the record data via the computational capability of smart phones, faster diagnose of the structure can be generated in the form of damage index report or emergency warning alarm output, especially during the case of earthquakes.

![Figure 1. Longitudinal section of Takamatsu bridge, Miyazaki](image1)

![Figure 2. Measurement System Overview Using Smart phones](image2)
Long-Term Field Measurement and Validation Tests

Overview of Field Measurement
Field experiment is conducted to verify the proposed method. For this purpose, Takamatsu bridge as described in previous section is selected. To measure accuracy, the identified system from smart phones is compared with the high precision accelerometer sensor results as a reference solution. To measure the dynamic response of the bridge model, the bridge has been instrumented with four smart phones (iPhone 5s labelled as 1, 1a, 2 and 3) inside of the box girder at three different locations, two directly over the pier, one at the 1/4th span between two piers and one at the midway between the two piers as shown in Fig. 3. High precision seismometer sensors (Hakusan Industrial SU501) [18] at the respective locations had already been installed after the 2016 Kumamoto earthquake, thus giving measurements from both the smart phones and high precision sensors. The smart phones are fixed via double-sided adhesive tape. Data is transmitted wirelessly to the cloud server by setting up Wi-Fi connection via router to each smart phone terminals. Power supply and internet connection was established by mobilizing already installed power source and LAN service inside of the box girder. The reference coordinate of smart phones for measuring vibration response is shown in Fig. 3. Table 1. summarizes the basic properties of smart phone and high precision accelerometer sensor used in the field measurement.

Sensor System and Specifications
The reference-measurement systems, as shown in Fig. 3, consists of three high-quality servo-acceleration sensor and four other widely used smart phones (iPhone 5s). The MEMS accelerometers inside of smart phones can sample stably at a maximum frequency of 100 Hz (corresponding to a Nyquist frequency of 50 Hz). This sampling frequency is generally considered sufficient for most engineering applications, including ground-shaking or structural-response measurement.

Long-term Monitoring Record Overview
After installation, 24 hours continuous measurement from all smart phones are being performed and recorded data can be monitored in real-time. Since the start of measurement i.e. from 7th month of last year, recordings of two smart phones at location 1 (iPhone 5s_01 and iPhone 5s_1a) were interrupted due to power issues. However, we can observe a continuous, non-interrupted measurement from two other smart phones at location 2 and 3 (iPhone 5s_02 and iPhone 5s_03) as depicted by connected lines in data volume information chart in Fig. 4. This continuous and stable data measurement justifies the applicability of smart phones for long-term vibration monitoring applications.

Sampling Frequency Deviation and Error Correction
Fig. 5 shows the example record of sampling rate for iPhone 5s set to 100 Hz. Over the entire measurement, sampling frequency measured by iPhone 5s at location 1 is observed to be around 96.25 Hz. This error in sampling frequency is random and is different in different smart phones. However, there are several numerical methods, such as data resampling or use of the real sampling time, to correct this error. In this study, data resampling to a common target rate of 100 Hz is performed by interpolating from the raw data. Unification to a common target rate, ensures that all interpolated samples in each data window will be equidistantly separated in time.
Figure 3. Installation of Smart phones on Takamatsu Bridge

Table 1. Reference sensor and smart phone properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Sensor Maker</th>
<th>Sensor Model</th>
<th>Sensor Type</th>
<th>Sensitivity</th>
<th>Resolution</th>
<th>Acceleration Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>Hakusan Corporation</td>
<td>SU501</td>
<td>Servo accelerometer</td>
<td>0.0006 gal</td>
<td>±4g</td>
<td>±2g/±4g</td>
</tr>
<tr>
<td>iPhone 5s</td>
<td>Bosch Sensortech</td>
<td>BMA220</td>
<td>MEMS</td>
<td>15.6 mg</td>
<td>2.0 gal</td>
<td>±8g/±16g</td>
</tr>
</tbody>
</table>

Figure 4. Data volume chart for long-term (24 hrs) measurement
Sensor Fault Detection and Recovery Technique

The record data was checked for any discrepancies during long-term measurement by observing a one month measured data at location 2. As observed in Fig. 6, two main types of sensor faults are found in long-term measurement of Takamatsu Bridge using smart phones: 1) drift faults and 2) spike faults which accounts for 1.30% and 15.48% of total measured data respectively. A number of factors, including heavy multitasking and I/O loading on smart phones, may lead to unstable measured signals.

A preliminary two-stage strategy can be used to address this concern on measurement from smart phones. First, a fault sensitive feature is proposed based on histogram feature of the recorded measurements. Then, mean value and data fitting technique is applied to recover the identified faults. As seen from Fig. 7, histogram plot of a good data generally follows normal distribution, while for a channel of faulty response data, histogram plot is irregularly shaped. For correction of faulty response data, the original data vector was cut into group of time blocks into small data windows. Mean values of each time window was calculated and a smooth fitting line was obtained by polynomial function. The corrected data was then obtained by subtracting the error signal with mean signal through all points in time domain as shown in Fig. 7. This recovery method should work whether the original data has a drift or not, therefore, this strategy will not negatively affect the results, even if there are some false positive cases in sensor fault detection.

Figure 5. Variation in sampling frequency measured by iPhone 5s

Figure 6. Different sensor faults observed during long-term measurement using smart phones
Earthquake Response Observation at the Bridge

With 24 hours of continuous environment-vibration measurement, the smart phones recorded 4 earthquake events from the date of installation. The epicentre, distribution of Peak Ground Acceleration (PGA) and other important details of those 4 earthquakes are shown in Fig. 8. From the peak acceleration contour map in Fig. 8, it can be seen that the average PGA near the bridge location is around 10 gal which means that all the 4 earthquakes recorded in this location were small in amplitude.

Figure 8. Epicenter of 4 different recorded earthquakes (K-NET & KiK-net NIED)

Among the 4 recorded earthquake events, acceleration waveform along bridge axis for 017/03/02 earthquake at 3 different locations is shown in Fig. 9. Acceleration records of the servo-acceleration sensors (SU501 by Hakusan Industrial) were taken for the purpose of comparing the
waveforms and Fourier spectrum of the simultaneous records with the record of smart phones. Though it is difficult to compare the waveforms of these two systems in time domain due to high noise level, it can be seen that acceleration measurements from smart phone showed high agreement with that of reference system as depicted in Fig. 9(c). Similarly, Fast Fourier Transform (FFT) which is one of the commonly used technique to identify dynamic properties of structures in the frequency domain was applied. The fundamental natural frequency of the bridge is identified by the peak picking method i.e. by selecting the frequency corresponding to the first peak. The ratio of identified natural frequency of bridge between smart phone and high precision sensor (reference) for different earthquakes and at different locations are summarized in Fig. 10. This ratio for all different records is near unity, means that measurements of smart phone agree well with the measurements of reference accelerometers in terms of frequency identification with a maximum error of around 2.0%. These results justifies the reliability of using smart phones for real field applications. Moreover, for further analytical purposes in future, the system shall also be tested to see if it can produce valuable modal-identification results for SHM.

Figure 9. Time History and Frequency Domain comparison for 017/03/02 Earthquake at 3
Conclusion

In general, smart-device-based system naturally possess the three prerequisites of a vibration measurement system, i.e. sensors, data transfer, and GPS information (location and time). By using smart phones for vibration sensing and seismic monitoring, the proposed technique can offer a dense array of strong-ground-motion and structural-response system that will facilitate studies leading to an improved understanding of the dynamic behavior and potential for damage to structures.

Different from the state-of-the-art conventional SHM methods that requires expensive sensors and data acquisition components, the proposed method enables dynamic characteristics of structures to be derived with consumer-grade device like smart phones without the need of intensive instrumentation. To validate the proposed method, response of Takamatsu bridge during some of the recorded earthquakes using smart phones together was compared with the reference accelerometer. Results show that proposed method has potential to identify the natural frequency with reasonable levels of accuracy. This study thus emphasizes greater potential of smart phones for civil infrastructure monitoring and health assessment in a rapid, remote, automated, and quantified framework. Robust implementation in smart phone-based SHM can radically influence the future advancements in smart, sustainable, and resilient infrastructures.

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References