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Wireless Smart Sensor Network System Using SmartBridge Sensor Nodes for Structural Health Monitoring of Existing Concrete Bridges

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Abstract. There are over 8000 bridges in the Philippines today according to the Department of Public Works and Highways (DPWH). Currently, visual inspection is the most common practice in monitoring the structural integrity of bridges. However, visual inspections have proven to be insufficient in determining the actual health or condition of a bridge. Structural Health Monitoring (SHM) aims to give, in real-time, a diagnosis of the actual condition of the bridge. In this study, SmartBridge Sensor Nodes were installed on an existing concrete bridge with American Association of State Highway and Transportation Officials (AASHTO) Type IV Girders to gather vibration of the elements of the bridge. Also, standards on the effective installation of SmartBridge Sensor Nodes, such as location and orientation was determined. Acceleration readings from the sensor were then uploaded to a server, wherein they are monitored against certain thresholds, from which, the health of the bridge will be derived. Final output will be a portal or webpage wherein the information, health, and acceleration readings of the bridge will be available for viewing. With levels of access set for different types of users, the main users will have access to download data and reports. Data transmission and webpage access are available online, making the SHM system wireless.

1. Introduction

Deterioration of civil infrastructure systems, such as bridges, buildings, and pipelines, is a complex, yet common problem. Currently, visual inspection is the most common practice used in monitoring the structural integrity of bridges. Visual inspections are highly variable, lack resolution, and fail to detect damage unless it is visible. Thus, structurally substandard, and even dangerous bridges may be left undiscovered, potentially placing the public at risk. Structural Health Monitoring (SHM), is used to combine all the inspection methods performed on a bridge. Alongside visual inspections, some systems include a sensor monitoring system to measure the response of a bridge (e.g. acceleration, displacement). Other SHM systems are using different techniques for structural health monitoring. However, in the Philippines, due to high-cost of instrumentation devices, large installation costs (e.g. wiring), or high maintenance costs, engineers and maintenance managers are limited to visual inspection. Introduced in the SHM system in this study is a sensor of considerably low price and efficiently programmed and built to read acceleration in real-time. The SmartBridge Sensor Nodes will be used in the detection of vibration of a concrete bridge. The changes to structural properties of a bridge caused by damage will change the way the bridge responds to ambient motions. For example, corrosion of steel members of a steel bridge results in a reduction in the cross-sectional area of those
steel members, which then would lead to a reduction in the stiffness or other structural properties. It is crucial to inspect the bridge periodically and to assess its condition and evaluate its integrity.

1.1. Objectives

This study addresses the following: a) To develop a Wireless Smart Sensor Network (WSSN) System for SHM of an existing concrete bridge; and b) To develop a portal or webpage, wherein authorized users may input visual inspection data, download sensor data, and check the health of the bridge.

1.2. Significance

In compliment with visual inspection, SHM would be the best way to monitor the health of a bridge. SHM provides a way to continuously capture structural response and assess structural condition in real-time. SHM can also be utilized to characterize actual loading, which enables engineers to predict the response of a structure to certain extreme loading conditions. SHM can also be used in forensic engineering, wherein data collected and stored by the sensors during natural hazards or man-made disasters, can be analysed and used to determine the cause of damage. Overall, SHM has an advantage compared to the traditional visual inspection in terms of monitoring and assessment of structural health in real-time. In addition, having a wireless or “smart” structure monitoring system, would mean that data gathered by the sensors installed on site would be easily accessible to engineers, maintenance managers, and other government offices that may have researches concerned with acceleration readings on a bridge.

2. Sensor Technology

The most common sensors used in SHM Systems are accelerometers and strain gauges. SHM systems monitors the health and behavior of a bridge, by embedding sensors during the construction of the bridge. Theoretically, embedded sensors are designed to gather data continuously throughout the lifespan of the bridge. Wired accelerometers are the most commonly used sensors in SHM Systems to monitor the structural health status and behavior of a bridge. Magalhaes et al. executed monitoring on a long span arch bridge in Portugal. After installing 12 wired accelerometers that were placed of equal spacing on the deck, they determined the first 12 mode shapes using Frequency Domain Decomposition (FDD) Method. These mode shapes, along with modal frequencies, were used to develop a numerical model to be utilized for the generation of events wherein damages are present [1]. However, one major disadvantage of these type of sensors is the wiring system that links all these sensors to a central server. Cabling numerous sensors is labor-intensive, and requires planning beforehand to avoid complications. Also, all wired sensors require a connection to a power supply [2].

In improving the sensor technology, studies such as the vibration monitoring experiment executed by Yu et. al. utilized wireless sensor technology, and compared it to wired sensors [3]. While, Hoult et al. used three wireless inclinometers and three wireless displacement transducers of a bridge in the United Kingdom, Ferriby Bridge, to assess the potential of WSSN for use in bridge management [4]. Wireless sensors are portable, and its reusability gives it a great advantage over wired sensors. Wireless sensors may also provide flexibility and reduce the number of required sensors compared to when using wired sensors, as they can be installed instantly or with ease, and removed in a shorter amount of time. Due to the easy installation and reinstallation of wireless sensors, a lot of tests can be done at other parts or sections of the same bridge. In conclusion, wireless sensors are more economical and effective when implemented to perform the structural health monitoring of a bridge. Due to the wireless feature, the sensors need to have batteries as power source. Thus, a disadvantage of this system is having a power supply that is limited, since batteries run out and needs to be replaced periodically. However, with advantages such as reusability and ease of installation, wireless sensors are clearly currently the best, reliable, and cost-effective option for sensors to use in a SHM system.

Numerous other SHM strategies needs a lot of sensors to be installed in the structure. With this, the SHM strategy shall be scalable, depending on the number of sensors. Scalability refers to the ability to...
add number of sensors in a certain network while maintaining manageable increases in cost and preserving efficiency of data collection [5].

The SmartBridge Sensor Node used in this study, is an accelerometer taking advantage of the wireless technology. It meets the minimum requirement for accelerometers set by the local standards as indicated in Section 105.2 of the National Structural Code of the Philippines 2010 [6] and Section 102 of the National Building Code of the Philippines, otherwise known as P.D. 1096. The specifications were also approved by the DPWH as part of the Guidelines and Implementing Rules on Earthquake Recording Instrumentation for Buildings [7] of the National Building Code. Note that the SmartBridge Sensor node can be modified to satisfy other requirements or codes in other countries. The SmartBridge Sensor Node stores acceleration readings in the x, y, and z directions, with a sensitivity range of 2g to 16g and natural frequency of 100Hz. The recording ability complies with the minimum requirement of 100 samples per second, and has a memory card built-in with a 32GB storage capacity. Its power supply comes from an AC source, but in the event of a power outage, the sensor has a battery which can power the device for at least 8 hours. Data are stored in each individual sensor and then uploaded to a central server via the internet. Figure 1 below shows the IP67 Polycarbonate enclosure of the sensor, in compliance with the required specifications for weather-proofing purposes.

![Figure 1. Sensor Casing.](image1)

Due to the AC and battery power source, SHM systems which utilizes the SmartBridge Sensor nodes are better for continuous SHM than periodic SHM.

### 3. SHM System

For this study, the SmartBridgeSensor Nodes were installed on an existing concrete bridge with American Association of State Highway and Transportation Officials (AASHTO) Type IV Girders. The bridge is a reinforced concrete bridge built in the 1960's and became operational in the year 1963. Its length is about 410 meters, linking Pandacan and Paco, Manila. It is shown in Figure 2.

![Figure 2. Padre Jacinto Zamora Bridge.](image2)

Sensors will be placed on the concrete girders and columns of the bridge. As shown in Figure 2, the bridge was installed with four (4) AASHTO Type IV Girders. The sensors were placed on the interior face of the interior girders as shown in Figure 3.
SmartBridge Sensor Nodes for this study were installed with stainless steel bracings for theft-proofing purposes. Considering a single span of the bridge, the interior girder was installed with three (3) sensors: one at the mid-span of the girder, and two sensors, each at a distance of 2H from the support. Wherein H is the overall height of the AASHTO Type IV Girder. Sensors were installed at 2H from the support since it is the location wherein the girder is expected to undergo flexural yielding and is also the location with the highest shear. The sensor is placed between the structural supports (the theoretical weakest point) for a worst-case measurement. There are two major sensor configurations for wired and wireless accelerometer that were commonly used in most of the SHM projects. Firstly, it is very common to place the accelerometers near the mid-span, where highest vibration responses are likely to occur. This configuration is ideal to obtain the modal frequencies of the structure. The sensor configuration should be defined based on the project's interest. If mode shapes are required, the sensor should be equally distributed on the girder of interest. On other hand, if modal frequencies are the only interest, mid-span where highest vibration responses are likely to occur will be the ideal location to place the sensor. (Teng, 2012). For sensor placement on the piers, all shall be installed at the mid height, wherein, maximum deflection occurs, as shown in Figure 4. Inelastic Time History Analyses, these analyses predict that the maximum column demand moments occur at approximately mid-height of concrete structures. In addition, the structural model of the bridge yielded the highest value for deflections at the mid-height of the columns.

With the sensors installed, acceleration readings are continuously monitored and transmitted to a central server through the internet. The Theoretical Framework is shown in Figure 5.
The SHM System designed is accessible through a portal or a webpage wherein data acquired is shown through a graph or a table, depending on the user. For the SmartBridge System, there are levels of access for the portal or the webpage, namely: a) Level I – Public access; b) Level II - Technical Staff; and c) Level III - Admin User.

Public access requires no account sign up for access, however, the page will only show basic information about the bridge, its maintenance managing party, and overall health of the bridge. For the data viewing and access to editing reports, the Level II access are included but not limited to the Maintenance Engineers that handles the visual inspection of the bridge. Level III access on the other hand are for the Maintenance Managers, Researchers, Administrators, and other Government Officials that may download and utilize data. Level III access allows the user to download visual inspection reports and data.

The Visual Inspection and Threshold Value generation are not included in this study. Visual Inspection Reports shall come from the Maintenance Engineers, whose frequency of inspections will be dependent upon the health of the bridge, as assessed by the SHM System. In the event of an acceleration reading reaching a certain threshold, the system triggers an alert and sends an e-mail notification to the Maintenance Managers that has authority over the bridge.

4. Results

With the installation procedures set, one span of the bridge would have a total of five (5) sensors installed. These sensors in one span is called a cluster. The configuration indicates that each SmartBridge Sensor Node has the ability to connect to the internet in order to transmit data to the central server, ready for remote access by the authorized users. The SHM System designed in this study would capture the actual acceleration readings on the bridge in real-time, and compare these readings to thresholds set through the structural analysis of the bridge.

The SHM System webpage or portal shall be designed to contain at least, but not limited to the following: Bridge Profile, Editable Inspection Report, Acceleration Graph, Downloadable Data, Levels of Access, and Alert/Notification System.

Structural Health Monitoring of Bridges is one of the interests in civil engineering that is quickly improving due to the fact that calamities such as earthquakes may damage lifeline structures such as a bridge. One of the most common SHM Methods of bridges revolves around the idea that structural damage in a structure is related to the modal properties and vibration of a structure. A Wireless Smart Sensor Network was installed on an existing Concrete Bridge with AASHTO Type IV Girder, and threshold values for each of the axes were used as limits for a Single Threshold Based SHM System. The SmartBridge Sensor Node was installed and utilized in this study to record acceleration responses in specific parts of the existing concrete bridge. Through Continuous SHM, each acceleration response is then monitored against the set thresholds values in g. A simple integration and double integration algorithm was used in order to derive velocity response and displacement response respectively. As part of the Portal/Webpage wherein continuous monitoring is done, the users of Level III access are able to receive a notification in the event of a threshold breach. Attached along with the notification e-mail and SMS, is a set of data recorded 20 seconds before and 30 seconds after the threshold breach. With this, the Level III users may react accordingly, such as being able to send inspectors in the particular portion of the bridge, wherein the threshold breach occurred. Due to the continuous aspect of the recording of acceleration responses, researchers may also find the gathered data in this study to be beneficial.

Using a different SHM method for the data gathered by the SmartBridge Sensor Nodes can also be used for further studies. Through Statistical Analysis, the normal vibration of the bridge can be determined through the use of data in which the structure is in normal condition. This normal vibration of the bridge can then be compared to the vibration of the bridge after the event of a threshold breach. In summary, the ambient or normal vibration of the bridge after an excitation can be compared to the normal vibration of the bridge before the excitation in order to determine if the response of the bridge has changed, hence determining a possible structural damage.
5. References


