Journal of Physics: Conference
Series

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To cite this article: Gokhan Kilic 2024 *J. Phys.: Conf. Ser.* **2647** 252007

Wireless Sensor Network-Based Systems for Monitoring a Lifting Bridge

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Abstract. Assessing the health and condition of structures like bridges involves frequently using structural health monitoring (SHM). In the past, wire sensors had to be installed on bridge structures as part of the SHM process so that data could be collected and sent to a data gathering unit there. However, this study suggests switching out the conventional wire sensors with wireless ones to create a Bridge Health Monitoring System (BHMS) that is affordable, practical, and simple to install. A software translation program attached to the monitoring server is used by each wireless sensor. In a GSM LAN (Global System for Mobile Communications) environment, this monitoring server system has the ability to link and interact with other similar systems of that type. The evaluation approach provided by the BHMS is thorough, secure, and portable.

1. Introduction

With the key role bridges play in a society's economic and environmental wellbeing, it is of the utmost importance to ensure their continued integrity. There exist many thousands of bridges and the nature of the construction of these structures varies, depending on such parameters as location and their initial perceived purpose. The structural integrity of a bridge is compromised on a daily basis from many directions, including flooding, certain weather conditions, the natural ageing process and traffic loads. However, the scarcity of knowledge in relation to the effects of traffic loads on bridge structures is in part due to the difficulties involved in synchronizing the monitoring of both the bridge dynamics and a moving vehicle.

A clear sign of degeneration in a bridge structure is the appearance of cracks. Not all cracks are obvious from visual inspection, as some may be internal (e.g. related to water ingress) and others may be occur below the ground, but all can conceivably weaken bridge decks and supports, potentially to the point of collapse. A vigorous health monitoring and assessment plan must therefore be considered to be of the utmost importance for bridge owners, in terms of avoiding the disruption caused by an inoperative bridge, the high cost of bridge repairs and potential human safety issues.

There are various techniques of bridge inspection available, such as initial inspection, routine inspection, detailed inspection and structural assessment, with both destructive and non-destructive testing (NDT) methods being commonly used. However, with increasingly complex bridges being constructed, improved systems of assessment and monitoring are imperative because traditional methods are not adequate enough for this purpose.

We turn now to examine some of the typical systems of bridge assessment currently available to bridge engineers. The IBIS-S interferometric radar system offers an advanced NDT method of assessment which can accurately (up to a hundredth of a millimeter) measure the dynamic or static displacement and vibration of bridge (and other) structures. The system is capable of monitoring these structural movements [1] insofar as vertical bending movements dominate torsional movements. The interferometric sensor module transmits, receives and operates electromagnetic waves based on the precept of electromagnetic conflict between controlled waves.

It should be noted that obstructions located between the radar and reflectors will lead to inaccurate data collection by IBIS S. In addition, structural defects will not register on the system. Whilst the system clearly has the capacity to monitor the structural behavior of a bridge under load, it must be used in combination with other testing methods in order to offer full structural health assessment [2] can provide further information in this regard.

Another NDT technique commonly used within the field of bridge engineering is the quick and economical accelerometer method. There are many designs of accelerometer available, with various capability ranges in terms of measurement, range and resolution, the choice of which should depend on the ultimate use to which the system will be put, and the particular structure it will be monitoring [3]. Accelerometers have the capacity to be integrated with handheld data collectors for permanent mount and routed applications [4]. The accelerometer method of assessment enables bridge engineers to analyses and determine resolution time histories of acceleration and, according to [5], the system has useful application in analyzing the displacement and stress levels a bridge structure comes under. It can detect and measure vibrations caused by objects such as hanger cables, pylons and stiffening trusses. It is also widely used within the industry to evaluate load capacity and is especially useful for testing on reinforced concrete bridges. The system can detect the presence of cracks, monitor beam behavior and follow dynamic interactions between vehicle and bridge upon that vehicle passing over the structure [6]. By assimilating the collected acceleration data, knowledge can be gained on the deflection and rotation of the structure in question.

First, the system has advantages; however, there are three points that need consideration. Although installation of accelerometers is a straightforward procedure, caution should be exercised in the actual placing of the accelerometers, since the effect of dynamic interaction in the presence of existing cracks needs to be analyzed. In addition, a large amount of power is required to transmit the mass of information from the main station by cellular modem [7]. Finally, resolution can be problematic for the accelerometer method of assessment as, due to resistive noise, their suitability is limited to low and medium frequencies.

Despite the successes of the above two methods of inspection, recent technological progressions have seen much growth in the popularity of the Wireless Sensor Network (WSN) method of inspection, partly due to its mobility, ease of use and low level maintenance. In addition, it is reality inexpensive and quick to install the system on major structures. WSN offers a highly accurate means of collecting data in relation to dynamic and static displacement monitoring from various locations on the bridge structure. In addition, [8,9] describe the system’s suitability for the remote measurement of structural displacements under such loads as micro-tremors, traffic and wind. Major bridges to have had the WSN installed include the Alamosa Canyon Bridge in New Mexico, Geumdang Bridge in South Korea, WuYuan Bridge in China, and Voigt Bridge in California [3]. Research by [10] provides additional information on WSN in relation to bridge assessment.

The number of sensors in a complete WSN system can range from a few to many thousands. There is flexibility in terms of placement and reorganization of the sensors in order to offer the particular formation required [11]. A small number of sensors will be placed strategically in order to gain information for system operatives on environmental parameters. A fully networked system requires an information gathering system, transmission system, processing system, analysis system, system control and feedback [12]. Individual wireless sensors interact and transmit data either to the data acquisition hardware or via neighboring sensors.

Despite its benefits to the world of bridge engineering, there are restrictions to the use WSN in terms of its detection of damage, limitations in the range and speed of data communication, and the fact that radio wave reflection and absorption can arise in the presence of concrete and steel. In addition, there is a necessity for wireless models and computer compatibility.

2. Design and Methodology-

2.1. Site Description

HMS Chatham Bridge is located in Chatham, Kent and was constructed in 1996 (Fig. 1) [13].

Figure 1. Location of the HMS Chatham Bridge [13].

In 1994 St Marys Island Lifting Bridge (see Fig. 2) project involved the removal of an existing bridge structure and construction of a new access bridge to St Marys (Fig. 3) and its approach embankments [13].

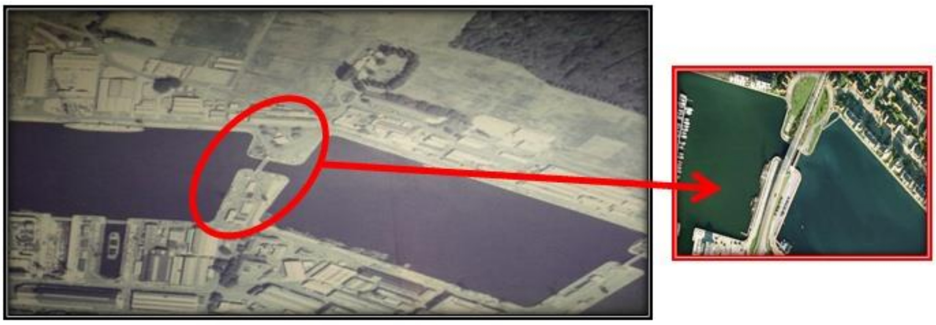

Figure 2. The St Marys Island Bridge previous (left) and recent view (right) [13]

The bridge consists of two concrete approach spans and a single leaf lifting bridge centre span. The carriageway measures 6.75m. In addition, a footpath/cycle path on the west side of the bridge measures 3.0m and a footpath on the east side measures 1.8m. Two internal piers connect to pile caps, which in turn are supported by bored piles.

On 10 June 2012, the author conducted a visual inspection of HMS Chatham Bridge, which revealed no obvious structural defects. The conditions on the day were bright and dry and a temperature of 16 ˚C was recorded.

Figure 3. HMS Chatham Bridge [14]

2.2. WSN for Bridge and Vehicle Monitoring

Whilst the WSN method of inspection provides reliable data within the context of SHM, the large volume of data gathered during an inspection of a bridge structure can lead to certain constraints in terms of resources [15].

WSN works by collecting and assessing data from a structure in relation to its behaviour under static or dynamic loading. This information is collected at an individual node before being processed centrally. This method of inspection is economical, includes the necessary technological requirements for the processing of data, and is simple to install [10, 11, 12].

In order to ascertain the load bearing capacity of a bridge, it is necessary to conduct vehicle loading tests, using a vehicle of a specific known weight, to evaluate the quasi-static response of the structure in such areas as neutral axis locations and load shedding paths. Since the bridge must remain out of commission for the duration of the test, it is not practical to carry out continuous monitoring, and so inspection needs to be conducted on a periodic basis [16].

2.3. Monitoring Strategy of HMS Chatham Bridge

Following the visual inspection carried out on HMS Chatham Bridge on 10 June 2012, WSN testing was conducted the following day. Conditions were broadly similar, i.e. bright and dry with a temperature of 16 ˚C. As already explained, structures undergoing this method of inspection are required to be closed to all traffic.

The inspection involved the driving of an 8 tonne vehicle across the bridge 16 times, simultaneous to the electronic acquisition of data. The speed of the vehicle was strictly limited to 25 miles per hour to ensure that the test could be reproduced (see Fig. 4).

Figure 4. The vehicle passing the bridge during data acquisition [14]

Approximate crossing durations are listed in Table 1.

TABLE 1. MOVING VEHICLE CROSSING DURATIONS (SECONDS)

Crossing	**Time (second)**
1	6.16
2	6.53
3	6.43
4	6.17
5	6.25
6	6.28
7	6.57
8	6.53
9	6.12
10	6.23
11	6.54
12	6.29
13	6.35
14	6.29
15	6.10
16	6.48
Average	6.33

2.4. Development of Software

The particular node used for the inspection on HMS Chatham Bridge was an Oracle SunSPOT wireless sensor node, as shown in Fig. 5.

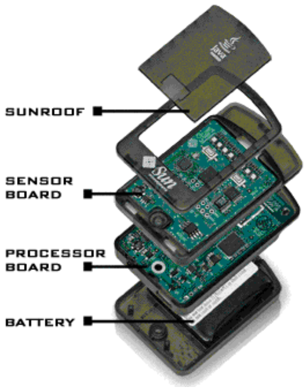

Figure 5. Oracle SunSPOT wireless sensor [14]

The system (see Fig. 5) requires a base station (connected to a laptop) and eight SunSPOT sensor nodes located 10m apart. Each node is designed to communication with its neighbouring node. Specifications of the WSN system for both the hardware and software used from the litreture shown in Table 2 [15].

Table 2. The hardware specifications and software versions used to evaluate the algorithms [15].

Name	Alix	Back-End
RAM	256 MB	512 MB
CPU	Geode (TM) Integrated	AMD Athlon (tm) 64 3000+
CPU Speed	500 MHz	2 GHz
Java version	1.6.0u21	1.6.0u21
Application container	Tomcat 6.0.18	Glassfish 2.1.1
Reasoner	Pellet 2.2.2	none
Metamodel service	none	Joseki 3.4.1

Fig. 6 demonstrates how this works in principle – sensor 5 transmits its own data, along with the data received from sensor 4, to sensor 6, and so on. Ultimately, sensor 8 transmits a full set of data to the base station for analysis by Global System for Mobile Applications (GSMA) software.

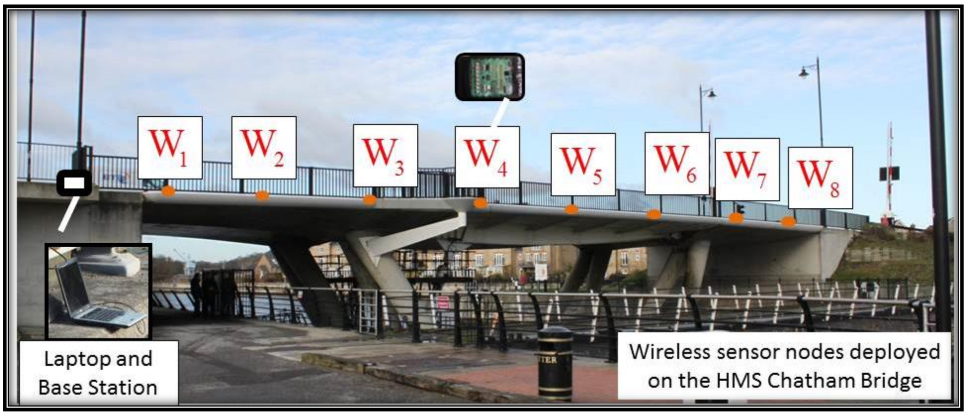

Figure 6. Diagram of the system [14]

The Oracle SunSPOT wireless sensor node is controlled by Java embedded software and needs no operating system [17]. The main processor used in this research is an Atmel AT91RM9200 system on a chip, which is based on an ARM (Acorn Reduced instruction set computer Machine) processor, which has 512 K of RAM and 4 MB of flash memory. The design of the sensor communication board is based on the IEEE 802.15.4 radio over the 2.4 GHz frequency band [18].

3. Results

As explained, by initiating deck deflection tests utilising both a loaded and unloaded bridge deck, it is possible to compare results in order to understand the behaviour of the structure under dynamic, live and static loads.

The WSN method of assessment is ideal for testing of this nature, since the wireless sensor nodes are powered by battery and can be recharged by connecting to a laptop. With this particular test necessitating many sets of 16 vehicle crossings, this recharging facility was of key importance. A further solution involved simply powering down the nodes when not in use. Schematic view on measurement system of transmission is further demonstrated in Fig. 7.

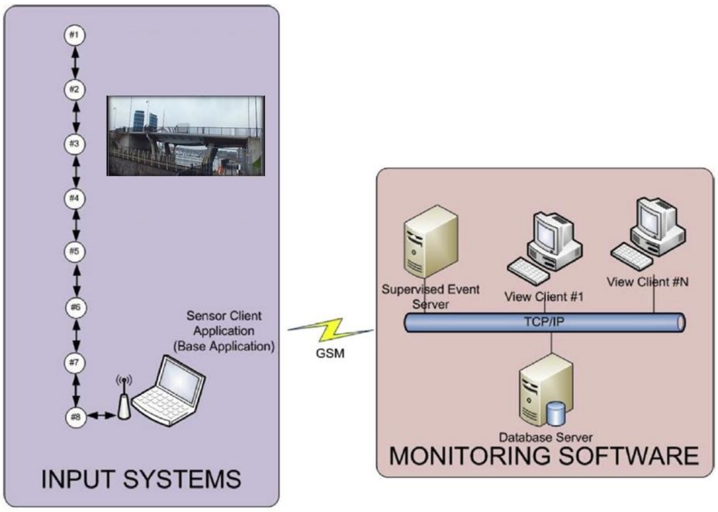

Figure 7. Schematic view on measurement system

The deflection time history (Frequency/Hz – Time) taken from the initial four crossings of the vehicle can be viewed in Fig. 8. This diagram demonstrates that there are four district points on the bridge deck where heightened deflection occurs. These results are considered highly reliable because the timing of the survey was recorded and the vehicle location on the bridge at any specific time was visual recorded.

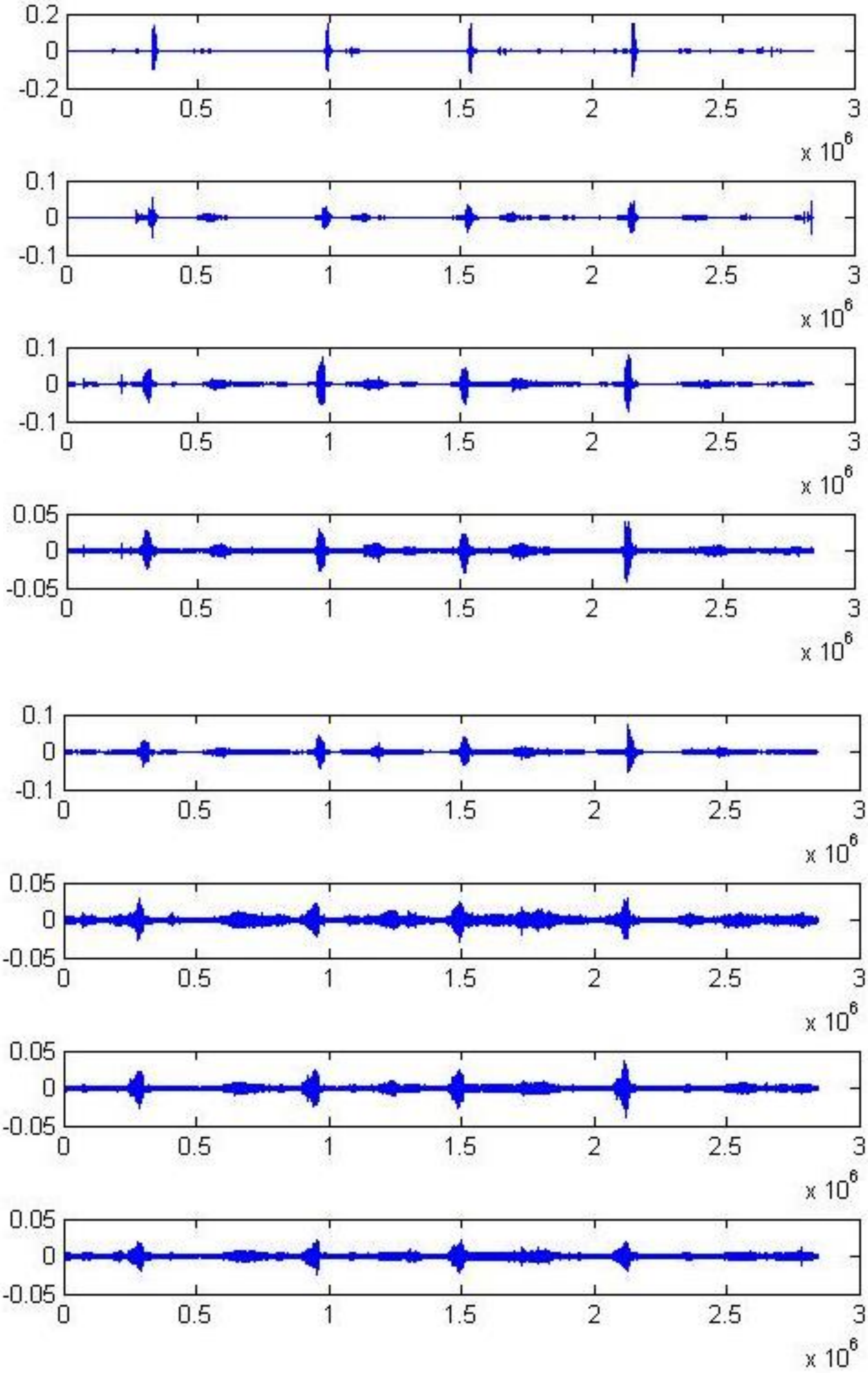

Figure 8. Deflection time history diagram at the WSN node 1-8 (Frequency/Hz – Time)

4. Discussion

In considering the BHMS network presented in this work, the monitoring server is the thin server and clients are the thick clients. The flexibility of the monitoring server allows clients to interact with the relevant hardware, with the monitoring server only distributing messages to relevant clients. It is then for the client to process those received messages.

A crucial benefit of the monitoring server utilised in this BHMS system relates to the fact that all hardware, even if out-of-date, can be linked with the system, so long as there is a compatible software client. There is no requirement for the system's processes to be comprehended by the developer since the client control takes on this function. The software allows for the rapid development of new client applications.

As we have seen, an important consideration of bridge health monitoring is the minimization disruption of to the operation of bridge structures. It is therefore worthwhile installing a permanent sensor system on each structure. Discussions above have outlined the power consumption needs of the system, and therefore the use of solar power would be of great benefit, potentially in terms of a system fully customised for bridge health monitoring. In particular, this is a great potential benefit for developing countries, where poor construction procedures and ineffective maintenance schemes lead to a much more frequent occurrence of bridge collapses than in countries such as the UK [19-23].

5. Conclusions and Future Work

The research presented combines different monitoring systems in a GSM and LAN based environment. Each sensor device is inter-connected to the monitoring server (Fig. 3) by a software translator application. This allows findings to be correlated alongside actual measurements taken from the eight wireless sensor nodes.

The monitoring server has the capacity to present a highly distributed GSM-LAN based system, offering security, flexibility of use and mobility. The software allows a client to transmit messages to the monitoring server, which in turn transmits those messages immediately to other interested clients, thus facilitating the mobility of all clients, as well as improving the GSM-LAN system.

The reliability of communication is the most critical function of the BHMS. By investigating various network environments, reliability can be further enhanced. The workings of the system allow various data pathways to be taken, thus a failed sensor node will not jeopardise the effective functioning of the system. The system discussed in this research transfers all information from all sensor nodes onto sensor node 8, from which the complete data set is transmitted to the base unit (Fig. 7). However, the new topology allows for the transmission of data to the base unit from the various sensor nodes, thus further accelerating the process.

Whilst SunSPOT sensor nodes were implemented in the study on HMS Chatham Bridge, these are unsuitable for long term bridge health monitoring because of their short battery life. Future technological advancements, however, may allow WSN to be combined with a BHMS in which power supply has been optimised. For example, the introduction of solar power as an element of this system could allow a more economical means of bridge assessment in comparison to other methods. This in turn could facilitate an increase in the amount of bridge assessment conducted, leading to increased data collection and, ultimately, to a significant increase in overall knowledge in this area.

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