Remote Monitoring System

Wong Jin Xiang Terence, Department of Electrical and Computer Engineering,
National University of Singapore

***Abstract*—This paper presents a final year project on the design and development of a remote monitoring system for a bridge. Essentially, the system will monitor the health of the bridge based on continuous measurements of physical variables from sensors mounted strategically on the structure, and fuses the available information to yield a decision on the corrective actions to be taken to minimize the possibility of a disaster occurring due to a bridge structural failure. The project is sponsored by *Agilent Technologies* under the *Agilent Engineering Excellence Program*, and it is entirely powered from an instrumentation and control engine which is based on the VEE Pro Graphical Programming software and U2300 Series USB DAQ device. Full details of the working prototype will be furnished in the paper.**

I. Introduction

General structural fatigue is a key factor inducing the occurrences of disasters due to structural failures. Early detection of structural fatigue can arrest the occurrences of such disasters through the use of timely preventive and corrective measures [1]. Symptoms relating to structural fatigue can be effectively inferred from measurements of physical variables relating to stress, strain and/or vibration. These measurements can be obtained through appropriate industrial sensors and instrumentation systems. When such information is transmitted on a regular basis to an intelligence center which diagnoses the health of the structure and takes corrective actions to minimize the risk of a catastrophe from occurring, a structural health monitoring system is essentially in place.

In this paper, a monitoring system will be developed for a bridge which is likely to be remotely located with respect to the monitoring and control center, and personnel. There have been a number of bridges collapsing due to lack of maintenance [2], causing critical damage to the structure. Over the years, bridges have to withstand corrosion and stress fatigue. Another major factor that contributed to fatigue and stress corrosion in bringing down the bridge was the weight of new cars and trucks [3]. Normally when the bridge was designed, the design vehicle loads was of the era at which the bridge was built. No one could foresee that in the many years after the construction of the bridge, traffic loads would more than triple. If these go undetected, the prolong accumulation of these stress margin violations will cause the failure of the entire structure, precipitating a disaster of epic proportions. The collapse of the bridge and loss of vehicles will be costly, but the loss of human lives is beyond measure.

There are three challenges involved in monitoring an extensive and heavily used structure such as the bridge. First, there is an obvious need to have an adequate and extensive arrays of sensors fitted at critical locations on the structure. In many cases, hard wiring of the sensors to a distant control center may not be possible and wireless communication will be necessary. Secondly, an intelligent control center must be present to make quick and sound decision on the health of the structure based on the multiple sources of information coming in on a continuous basis. Finally, any corrective actions necessary for an extensive structure as a bridge will typically require the immediate mobilization of huge number of personnel who can be located anywhere at the time of alert. An efficient and robust notification system must form a part of such a remote monitoring system. .

The entire real-time system is designed and built based on Agilent's USB Data Acquisition (DAQ) system [4] and VEE Pro control platform [5]. In the subsequent sections, the bridge model, the overall structure of the remote monitoring system and its constituent components will be elaborated in this paper. Realistic scenarios will be enacted and presented to show the responsiveness of the system to failing symptoms manifesting.

II. Overview of Remote Monitoring System

An overview of the *Remote Monitoring System* is shown in Fig. 1. The overall system comprises of several key components.

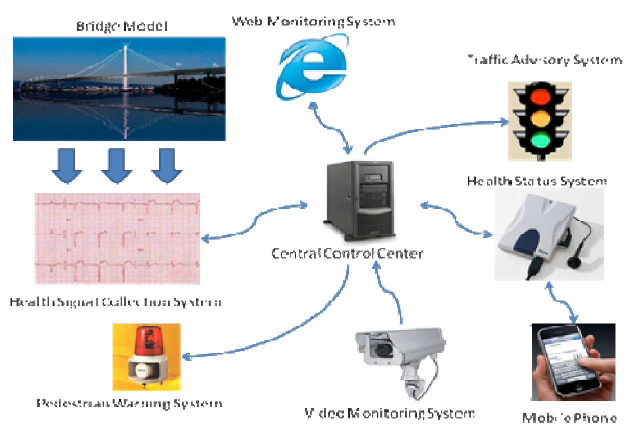

Fig. 1. Overview of the Remote Monitoring System

At the center stage is the *Bridge Model* which is the subject to be monitored for safety. Although it is a scaled-down physical model, explicit efforts were put in to ensure that all other components/signals are scaled proportionately

This work was supported in part by *Agilent Technologies* under the *Agilent Engineering Excellence Program*, which encourages the development of applications using the Agilent VEE Pro 8.0 Graphical Programming software and U2300 Series USB DAQ.

Wong Jin Xiang Terence is currently pursuing the Degree of Bachelor of Engineering in Electrical and Computer Engineering Department, National University of Singapore (e-mail: u0506030@nus.edu.sg).

so that the system emulates a real bridge as closely as possible.

The *Health Signal Collector* is a hardware device which accumulates and processes measurements from incoming sensors, thereafter conditioning them into generic signals which the data acquisition system can relate to (i.e., the Agilent USB DAQ). The collected information will then be passed to the *Central Control Center* for data analysis.

The *Central Control Center* will process and analyse the information from the *Health Signal Collector.* This is where a categorization of faults identified will be done, and a classification on the overall health status is made. These decision algorithms may treat the monitored system as a black-box and use simple signatory thresholds to compare the actual situations against, or they may use more elaborate model-based approaches to further identify the precise source and bottleneck of fault symptoms occurring. The *Central Control Center* will subsequently trigger appropriate supporting subsystems based on user-defined rules.

The *Traffic Advisory System* provides a visual early warning to road users of the bridge by showing lane status of the bridge using large external LED displays. This provides road users ample warning and sufficient time to reduce or stop the traffic in the case of a critical fault on the bridge.

The *Health Status System* sends periodic and critical updates on the health status of the bridge to the bridge maintenance engineers. It uses a GSM SMS modem to send SMS text messages to the mobile phones of the engineers.

The *Video Monitoring System* uses video cameras to provide real time round the clock surveillance of the bridge. The recorded footage together with the sensor data will assist engineers in determining the cause of the fault.

The *Web Monitoring System* allows maintenance engineers access and control of the *Remote Monitoring System* through the use of the Internet. Thus, it allows engineers to access the situation of the bridge anytime and anywhere in the world as long as there is internet connectivity.

In the ensuing sections, each of these components will be elaborated in details.

III. Bridge Model

The *Remote Monitoring System* requires a platform on which all the sensors can be installed and possibly having a realistic scenario to be tested on. With all these considerations in mind, a scaled-down version of a bridge is chosen to be the model of study in this project.

The selection of the bridge is the one of the most crucial part of the paper as it is the backbone on which the entire system rests on. Special considerations went into the selection of the type of material that the bridge is made of, and also the flexibility of construction options of the bridge.

The final model bridge was built using *K'NEX Education: Real Bridge Building Kit*, which contains numerous small plastic rods and pieces that can be connected in a variety of many different ways to construct the required structure, and thus having the ability to create realistic replicas of real world bridges.

The physical design of the "Firth of Forth Rail Bridge" was used as a reference for the model bridge. The Firth of Forth has two bridges in its name, the Road and Rail bridges [6]. In this paper, the "bridge" thus refers to a model of the "Firth of Forth Rail Bridge".

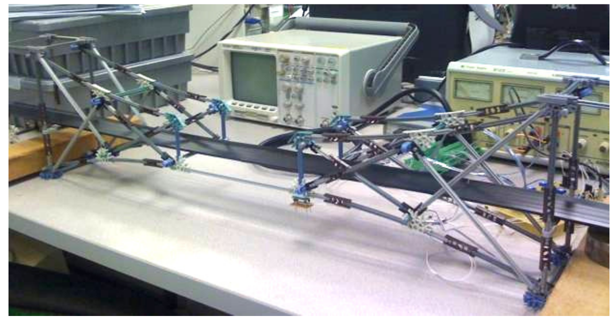

Fig. 2. Completed Bridge Model

Fig. 2 shows a photo of the completed model bridge with sensors already mounted on the bridge structure. Certain areas have been modified to incorporate the mounting of the required sensors onto the bridge.

IV. Health Signal Collector

The *Health Signal Collector,* shown in Fig. 3, is tasked to collect real time data from all the attached sensors and pass them on to the *Central Control Center.*

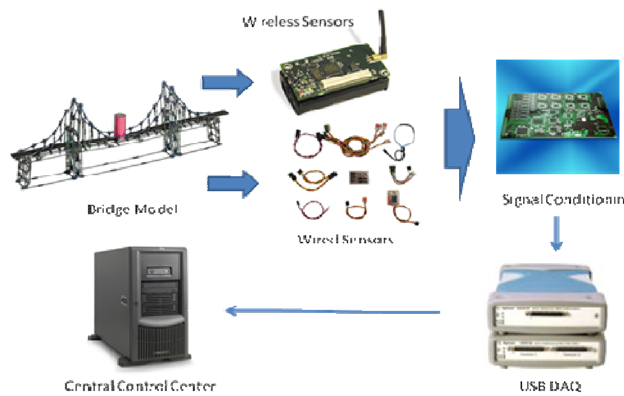

Fig. 3. Overview of the Health Collection System

The *Health Signal Collector* is designed to interface efficiently with commercial sensors available. The sensor information is acquired through the input analog ports of the Agilent USB DAQ unit. After which, the information is processed and passed to the *Central Control Center* for analysis.

A. Sensors

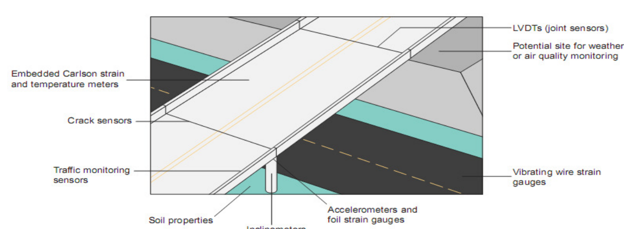

Fig. 4. Typical sensing parameters for a bridge

Fig. 4 shows an example of typical parameters that are observed in a real life application of a bridge monitoring system.

Careful selection of the physical variables which can reflect the health of a bridge structure is first done. They are identified to be:

- Strain (via strain gauges)
- Vibration (via accelerometers)
- Pressure (via load cells)

Accordingly, sensors (strain gauges to measure strain, accelerometers to measure vibration along three axes, load cells to measure pressure) which can yield these measurements over an adequate range associated with the bridge models are selected and amounted onto the bridge. MICAz wireless sensors are also mounted to reflect a realistic scenario for the need of wireless transmission of information from the bridge to a distant control centre.

B. Signal Conditioning Circuit

Signal conditioning is used to improve the *Signal to Noise* ratio of the output signals coming out from the strain gauges via the Wheatstone bridge [7]. The output voltage signal is usually very small, and thus an instrumentation amplifier is used to amplify the output voltage to an acceptable working range. The Texas Instruments INA128 precision, low power instrumentation amplifier is selected due to its excellent CMRR of 120dB and low drift voltage of max 0.5µV/°C maximum.

In order to integrate all the signal conditioning circuits in a compact form, a Printed Circuit Board (PCB) was designed and fabricated.

C. Measurements Collection

Information on the sensors is measured via the output voltage levels using the USB DAQ. The command *Meas:Volt:Dc? (@101)* is used to retrieve the voltage from channel 101 of the USB DAQ and input it into the virtual instrument on VEE Pro Software.

1) Strain

Since the data collected is a raw voltage signal, there is a need to convert it to µstrain by using this formula:

$$\frac{V_O}{V_{EX}} \approx \frac{GF \bullet \varepsilon}{4}, \tag{1}$$

where V_O, V_{EX} are the output and excitation voltages of the Wheatstone bridge, GF is the strain gauge factor, and ε is the strain.

Equation (1) can be re-written in terms of strain as:

$$\varepsilon \approx \frac{4}{GF} \bullet \frac{V_O}{V_{EX}} \tag{2}$$

The above equation is also used for the other strain gauges.

2) Load Cell

Similarly, for the load cell, it is connected to the analog input channel AI107. The raw signal is also converted to kilograms by using this formula based on the provided manufacturer's datasheet

$$W = S \bullet V_O \bullet \frac{V_{EX,\text{actual}}}{V_{EX,\text{nominal}}}, \tag{3}$$

where W is the weight, S is the sensitivity of the load cell and V_O is the output voltage of the load cell, $V_{EX,\ actual}$ and $V_{EX,\ nominal}$ are actual used and nominal excitation voltages of the load cell.

3) Accelerometer Module

As for the accelerometer, it is connected to analog input AI114 to AI116 with respects to X to Z axis. The formula, given in the manufacturer's datasheet, needed to convert the raw input voltage into acceleration in terms of G force is

$$a_x = (V_{O,x} - 1.66) / S \tag{4}$$

$$a_y = (V_{O,y} - 1.66) / S, \tag{5}$$

$$a_z = (V_{O,z} - 1.66) / S \tag{6}$$

where a_x, a_y *and* a_z refer to the acceleration in the x, y and z axes in terms of G force respectively, $V_{O,x}$, $V_{O,y}$ and $V_{O,z}$ refer to the output voltage of the accelerometer module in the x, y and z axes respectively and S is the sensitivity of the accelerometer module.

4) MICAz Wireless Sensors

Due to areas where hard wiring of sensors may be impossible, *MICAz* wireless sensors nodes can be deployed, enabling fault-tolerant self-healing mesh sensor networks. The *MICAz* node can detect ultra-small vibrations, acoustic noise, and magnetic disturbances, as well as conventional light, temperature, and proximity. It also includes a sensor-interface port that enables the use of specialized sensors.

The *Health Signal Collector* has the capability to support inputs from *MICAz* sensors. Currently it is being configured into fault detection by checking if the sensor values hold the following condition:

$$|y| = E_T \tag{7}$$

where y is the output and E_T refers to the threshold value. Exceeding the threshold signifies a fault.

V. CENTRAL CONTROL CENTER

The *Central Control Center* is the main control center of the *Remote Monitoring System*. It will retrieve conditioned sensor measurements from the *Health Signal Collection System* and make decisions based on known thresholds and algorithms to determine bridge health. This center is where the complex decision making algorithms will reside to filter false alarms from real ones, to categorize faults and the dangers they pose, and to carry out appropriate corrective actions. The algorithms are programmed entirely in software using VEE Pro 8.0.

A. Threshold Levels

Each individual sensor variable will be continuously compared against the preset signatory thresholds to yield three levels of warnings

1 - Normal
2 - Warning
3 - Critical fault

Should any of the thresholds associated with the measurements be triggered, the status of the monitored object will be change to reflect the following status.

B. *Determining Threshold Levels*

There are many methods available for setting threshold levels for the bridge under monitoring. One effective method is to use the known maximum stress level that the material can withstand. As it is dangerous to use the exact maximum value, it is advisable to refer to the safety limits set out by government regulations.

Another method is to use the maximum likelihood estimation theory to estimate the maximum limit. It is a popular statistical method used to calculate the best way of fitting a mathematical model to some data. Modeling real world data by estimating maximum likelihood offers a way of tuning the free parameters of the model to provide an optimum fit.

C. *Model-based Approach*

The model-based approach can also be used to derive the thresholds of the safety limits of the model bridge. A good model of the system is usually necessary for such an approach to work well. The model based approach can give a better indication of the safety limits by observing unusual deviations and trends from the recorded sensor data.

Currently the monitoring method used in the Central Control Center is based only on fixed signatory thresholds. However with data logging over extended, it can be possible to monitor the trends as well other than absolute values. Future plans are to convert the monitoring method to incorporate model based approach.

VI. SUPPORT SYSTEMS

This section will describe in detail the functions of each individual support system and how it interacts with the *Central Control Center*.

A. *Traffic Advisory System*

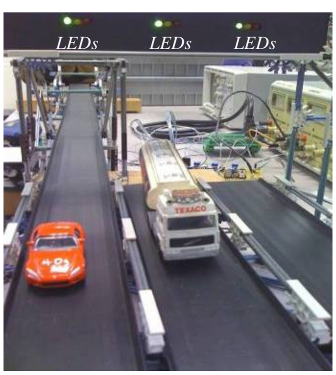

Fig. 5. Three lane traffic status display system

The *Traffic Advisory System* will control the availability of road lanes to road users to minimize uneven loading of the bridge, thus preserving the life of the bridge and minimizing hazards posed to road users. Since each road lane is attached with a strain gauge, the actual loading of each lane can be retrieved from the *Central Control Center*.

The status of each road lane is shown to the road users via a set of large and bright *Green-Yellow-Red* LEDs. The LEDs are directly connected to the output port of the USB DAQ and are controlled using the VEE Pro software. Fig. 5 shows the traffic status display system.

B. *Health Status System*

The *Health Status System* will send out periodic SMS (Short Message Service) alerts to the engineers in charge of the maintenance of the bridge and informing them of real time changes to the health of the bridge. The SMS alerts are sent out using the iTegno 3000 GSM data modem as shown in Fig. 6.

Fig. 6. iTegno 3000 SMS modem

C. *Pedestrian Warning System*

The *Pedestrian Warning System* allows users of the bridge to know emergency situation arising by activating a loud audible signal and bright flashing lights. A piezoelectric buzzer is used in this project for this purpose.

D. *Video Monitoring System*

The *Video Monitoring System* allows maintenance engineers to have 24/7 surveillance of the bridge condition. This is particularly useful and advantageous as it provides the maintenance engineers a better holistic view of the situation. Multiple cameras can be connected to the *Video Monitoring System* and in this paper, a generic USB Web camera is used. Once a fault is activated, it will take a snapshot of the bridge, thus providing the maintenance engineers a firsthand overview of the situation.

E. *Web Monitoring System*

The *Remote Monitoring System* can be viewed and controlled via the *Internet*. The *Web Monitoring System* uses the built-in Web server in Agilent VEE Pro 8.0, providing the engineers a means to monitor and troubleshoot faults in the *Remote Monitoring System* from a remote Web browser using standard HTTP protocol. This feature can be used to allow the followings

- Troubleshoot a fault in the *Remote Monitoring System*
- Retrieve real-time health status information
- Monitoring of off-site locations

VII. TEST RESULTS AND DEMONSTRATION SCENARIOS

The *Remote Monitoring System* has been completed and trial tests have been made to determine the functionality of the system.

A. *Test vehicles*

Three model vehicles shown in Fig. 7 were chosen to be the test subjects for the loading of the bridge. *Test Vehicles 2 and 3* have been selected to be heavier to simulate overloading of the bridge. Details of each test vehicle are given in Table I.

Fig. 7. Photo of Test Vehicles, from left to right, *Veh2, Veh1 and Veh3*

TABLE I
WEIGHT OF TEST VEHICLES

Test Vehicle	Color	Weight	Type	Purpose
Veh1	red	40 grams	static	normal
Veh2	white	180 grams	static	overloaded
Veh3	green	195 grams	radio controlled	overloaded

Test Vehicle 3 can be radio controlled to advance the bridge via a radio controller. This will help to eliminate any kind of human-induced uncertainties while running the test experiments in tests where a precise determination of specific faults are required..

B. *Test Scenarios*

The following test scenarios will test the functionality of the bridge and determine its proof of concept. However, due to the space constraint of this paper, important scenarios have been chosen to display the key features of the system.

1) *Static loading of lanes*

In this scenario, each lane of the bridge is placed with different vehicle loads as follows in Table II:

TABLE II
LANE CONFIGURATION OF TEST SCENARIO 1

Lane	Test vehicle	Weight	Purpose
1	Veh1 (x1)	40 grams	normal
2	Veh1 (x3)	120 grams	medium loading
3	Veh2 (x1)	180 grams	overloading

Three units of *Veh1* were placed on Lane 2 to simulate medium loading of the road and one unit of *Veh2* was used on Lane 3 to replicate overloading of the bridge. The results are shown in the *Remote Monitoring System's GUI* in Fig. 8. As expected, the icons reflected the correct status of the loading of the bridge.

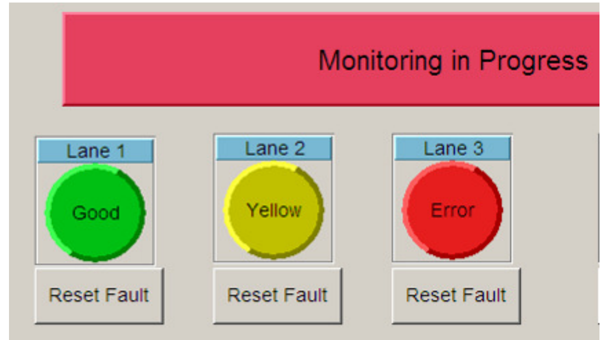

Fig. 8. Test Scenario 1 results

Since Lane 3 had a critical fault, the alarm of the *Pedestrian Warning System* was activated. At the same time, a SMS message was sent to the engineers informing them of the situation. Similarly, a snapshot of the bridge was taken to record the incident for analysis by the *Video Monitoring System.* A sample of photo taken is shown in Fig. 9.

Once any critical fault is triggered, the fault state is held till it is cleared by the operator. The fault can be reset by clicking on the *"Reset Fault"* button once the fault is rectified or it has been deemed as a false alarm.

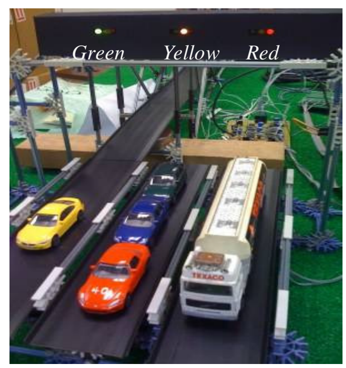

Fig. 9 Sample photo taken during Test Scenario 1

2) *Dynamic loading of lanes*

In this scenario, *Veh3* is used to travel past the mid section of the bridge, simulating dynamic loading.

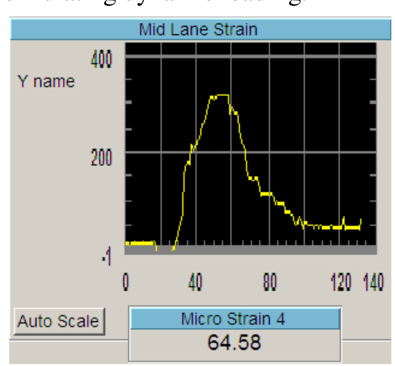

Fig. 10. Mid Lane strain readings with Test Vehicle 3

The strain readings build up as *Test Vehicle 3* travels along the bridge as shown in Fig, 10. The strain value peaked at about 330 µstrain when *Test Vehicle 3* is at the mid-section of the bridge where the strain gauge is mounted. Similarly in

Scenario 1, the alarm will be activated, a SMS will be sent and a photo will be taken to record the incident at the point of triggering of the peak value.

3) Undue Vibration

In this test, undue vibration is simulated by lateral movement imparted deliberately to the bridge. Three levels of test vibration have been decided, from low to medium to high. The results of the different levels of vibration are shown in Figs. 11 to 13.

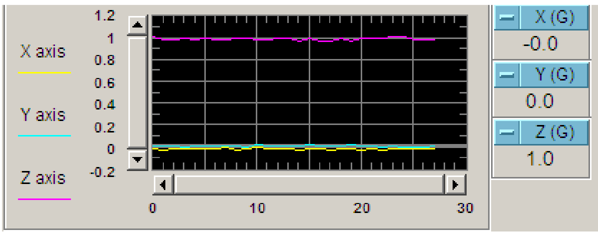

Fig. 11. Accelerometer readings with low rocking vibration

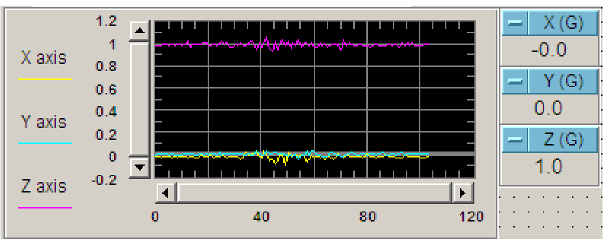

Fig. 12. Accelerometer readings with medium rocking vibration

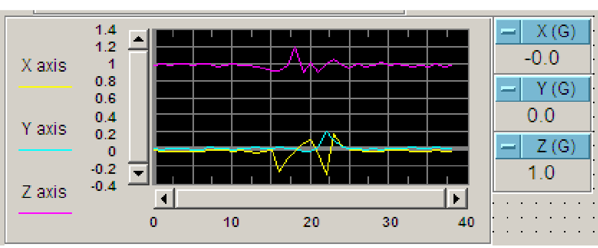

Fig. 13 Accelerometer readings with high rocking vibration

Upon detection of the high rocking vibration, a fault is triggered in the *Central Control Center*. Likewise in the above scenario, the alarm will be activated, a SMS will be sent and a photo will be taken to record the incident at the point of triggering.

4) Premptive Action Via Wireless Sensor

In practical situations, the time to limit to a critical fault signal can be very short and limited, and a strategy may be to detect undue vibrations occurring a certain radius away from where the bridge is located. In some situations, wireless sensors may have to be used at these distant locations. In this test, we use a *MICAz* wireless sensors. Heavy vibration was applied to one of the *MICAz* wireless sensors, resulting in the triggering of a fault. Because of the propagation delay due to the wireless transmission, there is a slight delay as opposed to the hard wired sensors but for the purpose of detecting vibrational waves away from the bridge, this short delay is tolerable.

5) Web Monitoring

Given the proper credentials, the status of the bridge can be viewed remotely anytime via the internet by logging into the system by keying in the server name, for example: "*//server-name/viewpanel?monitoring*". In Fig 14, the user interface of the *Remote Monitoring System* is shown in an Internet Explorer window, where all bridge variables can be seen in one glance in real-time.

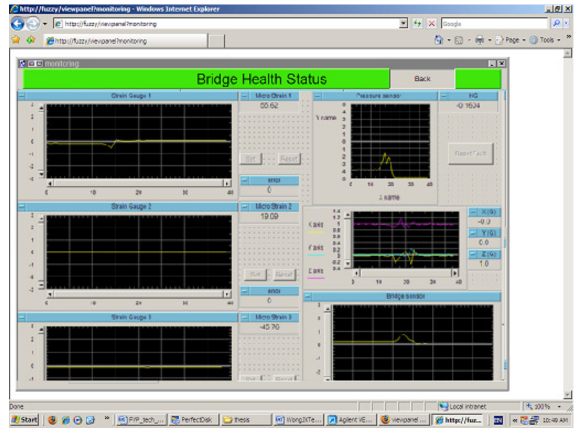

Fig. 14. *Remote Monitoring System in Internet Explorer window*

C. *Test Scenario Results*

The above test scenarios have proven the functionally of the *Remote Monitoring System*. It has been shown that a remote monitoring system is feasible using Agilent's USB DAQ device and VEE Pro Graphical Programming software.

VIII. Conclusions

This paper has presented the final year project on the design and development of a remote monitoring system for a bridge. Essentially, the system monitors the health of the bridge based on continuous measurements of physical variables from sensors mounted strategically on the structure, and fuses the available information to yield a decision on the corrective actions to be taken to minimize the possibility of a disaster occurring due to a bridge structural failure. The project is entirely powered from an instrumentation and control engine which is based on the VEE Pro Graphical Programming software and U2300 Series USB DAQ. A working prototype has been successfully constructed and tested.

References

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