

# A Framework for Intelligent Sensor Network with Video Camera for Structural Health Monitoring of Bridges

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## Abstract

*Wireless sensor network (WSN) gives the characteristics of an effective, feasible and fairly reliable monitoring system which shows promise for Structural Health Monitoring (SHM) applications. Monitoring of civil structures generates a large amount of sensor data that is used for structural anomaly detection. Efficiently dealing with this large amount of data in a resource-constrained WSN is a challenge. This paper proposes a, WSN based, novel framework that triggers smart events from sensor data. These events are useful for both intelligent data recording and video camera control. The operation of this framework consists of active & passive sensing modes. In passive mode, selected nodes can intelligently interpret local sensor data to trigger appropriate events. In active mode, most of the sensing nodes perform high frequency sampling and record useful data. Unnecessary data is suppressed which improves the lifespan of the network and simplifies data management.*

## 1. Introduction

The process of continuously monitoring the status of a structure to detect damage can be defined as *Structural Health Monitoring (SHM)*. The importance of health monitoring of civil structures has gained considerable attention over the last two decades. A variety of methods have been employed for SHM, which have improved over time with the evolution of technology. One of the conventional methods is visual inspection by humans for any signs of apparent damage. But this technique does not prove to be very useful because it is limited to the visible defects only. Human judgment error and labor-intensive nature are other drawbacks of this approach. Another set of tools such as tomography equipment analyzes the internal

condition of a structure. Although these tools might be useful for local damage detection and analysis but they are not suitable for a global monitoring system. To implement a SHM successfully, we would like to propose monitoring the civil structures globally as well as locally, using sensors and cameras, and finally detect any abnormal behavior in real time to mitigate any catastrophic failures. Of course, this monitoring system has excellent potential to improve the regular operation and maintenance of the structures.

Comprehensive systems use a large number of sensors to monitor structure's health. Typically these systems comprise of vibration sensors, strain gauges and other similar sensors that are wired through cables to a central data acquisition system or a network of data acquisition systems. The data acquisition systems not only record all the data but also facilitate data interpretation. Problems with these systems include high initial cost, large complicated mesh of cables, difficult installation and maintenance, etc.

SHM can benefit from the recent research and development in the area of *Micro-Electro-Mechanical System (MEMS)* and *Wireless Sensor Network (WSN)*. MEMS technology has greatly improved the miniaturized sensors of different types including the accelerometers and tilt-meters that are extensively used in civil SHM. These new sensors consume lesser energy, are relatively inexpensive and have been shown to give promising responses when compared with the conventional wired sensors.

A WSN is composed of a large number of small nodes that have sensing, processing and wireless communication capabilities. Use of WSN for SHM gives us many advantages such as:

- System setup & maintenance cost is remarkably reduced.
- No cables are required for data transfer because the communication is wireless.
- Data processing & interpretation can be distributed across the network nodes.

- System becomes more fault-tolerant. In case of a partial system failure the rest of the system is capable of performing its task independently.
- Overall system response time improves due to anomaly detection through data processing on the nodes instead of central base station.

WSN based framework does not come only with the advantages, there are some limitations that have to be considered and further evaluated.

- Processing power & communication bandwidth available on the nodes are very limited.
- Each node has restricted battery life that has to be preserved by efficient consumption.
- A multi-hop protocol is to be established for communicating with the central base station.

Along with these, there are some other drawbacks in the use of WSN based system for SHM applications. The research continues to address these problems and to make WSN based solution more robust and reliable for this domain. The system has to perform the regular sensing operation not only under the normal circumstances but also during extreme weather and environmental conditions as well as after hazards occur. Another very important consideration is the maintenance cycle span and overall life of the system.

In this paper, we propose the basic characteristics of an efficient framework that can be employed to perform SHM for bridges. We use a WSN (MICA motes [1]) that exploits the distributed processing available on its nodes. Distributed data interpretation is used to intelligently detect local data trends (events) instead of just sending raw data to the base station in a dumb fashion. Examples of these events are “normal vibration detected”, “abnormal vibration detected” or “large structure tilt detected”. Using this technique we can also reduce network traffic and improve the battery life of the WSN. When a critical event is detected on the bridge, we can prompt a video camera to pan/tilt/zoom into the local area and monitor activity. Camera is attached to a video processing module that can provide video frames of the area of interest, synchronized with other sensor data. This way we can improve the conventional SHM system utilizing new technology. This framework has been tested in the laboratory environment.

## 2. Related work

The area of WSN has greatly benefited from the research carried out towards Smart Dust by Pister et al. [12]. The application of WSN has been shown in

many different areas. Due to the limitation of the resources available on the WSN nodes, only the applications that have low sampling rates and energy requirements have been reported. The examples of these applications are habitat monitoring [3], product quality monitoring through atmosphere control [2]. On the other hand, the data rate is much higher in SHM application. Some researchers have developed new platforms to overcome the limitations of sensor node hardware [4, 5].

In the area of WSN, researchers have been working on the services that are required in most of the applications. Time synchronization between the nodes of the network is one such service. Data from different sensor nodes can be accurately synchronized if a good time synchronization service is functional. Ganeriwal et al. [9] propose a hierarchical approach for time synchronization among nodes. It is called Timing-sync Protocol for Sensor Networks (TPSN). Similarly, there are other key issues related to system deployment and operation. These are discussed in [6].

The research community in SHM has been in the process of evaluating and exploring the features of monitoring systems with WSN. We are mainly interested in addressing real life problems using novel technologies within context of a complete SHM system as discussed in [10].

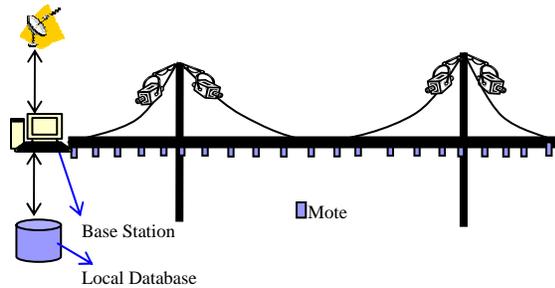
As part of this effort, first, we would like to address the issue of efficiently handling large amount of vibration data on resource-constrained WSN. In this paper, we propose techniques that improve data traffic on the network. At the same time, we emphasize the usefulness of the proposed framework for interpreting data to trigger certain events related to the data trend. Another novel contribution of this study will be the integration of video processing unit that enhances the capability of the SHM. Autonomous camera control and data synchronization between the video and sensor data are the key features of our framework.

## 3. Proposed system architecture

### 3.1 Apparatus

For testing and evaluation, MICA series motes have been used for this study. This platform is equipped with Atmel’s microcontroller running on 8MHz, 868/916 MHz multi-channel RF transceiver with effective data rate of 4-10Kbps, 512KB of serial flash memory for data storage and can run up to one year on AA Batteries (using sleep modes) [1]. A sensor board, with different sensors, is attached to the main mote. Acceleration and temperature sensors are used in this framework. TinyOS, a component based

operating system, runs on motes [7]. Information about these motes shows that they have limited computing resources available. Motes build a network and send data to the base station. It records this data into a local data store and also transmits to a remote observatory through wireless internet access. Figure 1 illustrates the point.



**Figure 1. Apparatus deployment on the bridge**

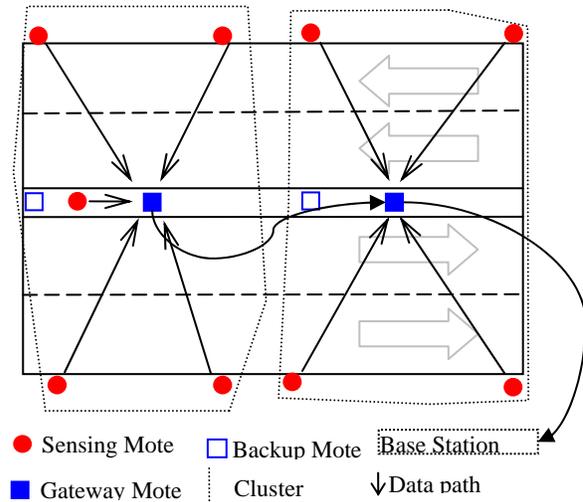
The video cameras are used to monitor the traffic and other activities on the bridge from a remote observatory. The set of cameras should be deployed so that using pan/tilt/zoom complete area of the bridge can be covered. For simplification, we have used only one camera in our experiments in the lab. A standard PC was used as the video processing unit. It can send & receive messages from the WSN nodes on the bridge. These messages are routed through the base station of the WSN. This is further explained in section 4.

### 3.2 Network architecture

The network of motes is organized into a group of clusters. Each cluster has one functional Gateway Mote (GM) at a given time and about 4-8 Sensing Mote (SM). Responsibility of a GM is to coordinate the communication between the SMs and base station. At the same time, GM is responsible for passing the messages between the GMs of neighboring clusters, thus completing the route to the base station. Certainly the GMs will have to cope up with the network traffic from within the cluster and from the other neighboring clusters. This means that the GM should have higher network bandwidth. Considering the current availability of the hardware, we suggest the use of MICAZ Motes. They have 2.4GHz radio transceiver giving network bandwidth nearly 6 times that of MICA2 Motes. Figure 2 show the top view of suggested WSN layout. The dotted line shows the cluster boundary and arrows show the direction of data flow.

Backup Motes are available for redundancy in case of a node failure. The backup mote normally stays in sleep mode but periodically sends a heartbeat

message to the GMs in range and confirms their availability. In case of an absent GM, it takes its responsibilities in the cluster and tries to continue the normal operations.



**Figure 2. Network architecture on the bridge**

## 4. System operation

### 4.1 Initialization

There are some essential services that have to be incorporated for a WSN to operate in a meaningful fashion. We cover sensor localization and time synchronization here.

GM occupies a critical position in the network as explained in the previous section. Localization is carried out through a handshaking protocol.

In the first phase, base station initiates a localization message for the GMs, which propagate through the GMs and each one of them establishes a neighbor-list. Since this message is initiated from base station, each GM knows which neighbors to use for reaching base station.

In the second phase, GMs build up their local SM-list through a similar handshake with SMs. Every GM uses an assigned time-slice for this phase. This ensures that an SM lying in area of coverage of more than one GMs only gets first cluster assignment. But this SM can store a list of GMs that are in communication range, which will help in the future in case of primary GM failure. Later during normal operation of WSN some other housekeeping messages are periodically transferred which help in both time synchronization and sensor localization.

Time synchronization is one of the critical services of a WSN when it is being used for SHM.

The data from different sensors has to be synchronized precisely. A scheme proposed by Ganeriwal et al. [9] works fairly well for this application.

## 4.2 Event detection

WSN can start sensing operation once the initial setup services have completed. The sampling rate of the temperature data is very low and only one mote from a cluster has to send the temperature once after every 5 minutes. On the other hand, the accelerometer measures vibration and can also be used for tilt detection. The sampling frequency on accelerometer may be over 100Hz for SHM applications depending on the frequency band of interest. If all the SMs in the network sense simultaneously at this rate, we will have too large a data to handle efficiently.

We propose an event detection technique that also helps in reducing unnecessary network traffic. We assume that vibration data is unnecessary if the activity metric value is below a low threshold ( $T_L$ ) value. We have used mean shift vector as the activity metric.

$$M(\mu) = 1/n_x \sum_{i=1}^{n_x} (x_i - \mu_o)$$

where  $\mu_o$  is initial mean value,  $n_x$  is the number of data points and  $x_i$  is one data point. In our experiments, we have used 15 for  $n_x$  and 10 for  $T_L$  but these are parameters that can be manually tweaked to suite noise conditions or user preference. The values can also be changed on run-time throughout the network. According to the tests, this metric performs reasonably well in the lab setup. Figure 3.a shows the vibration data from one sensor.

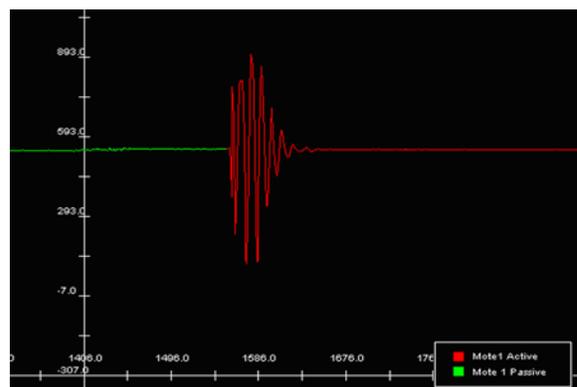
Using above mentioned method we detect two events in the vibration data.

- First one is “normal vibration detected”. SENSE\_EVENT label is assigned to this event, which is triggered when mean shift vector magnitude is higher threshold value of  $T_L$ . (See Figure 3).
- Second one is “abnormal vibration detected”. CAMERA\_EVENT label is used for this event, shows that mean shift value is higher than another threshold  $T_H$ . We have used  $T_H = 25$  in our experiments.

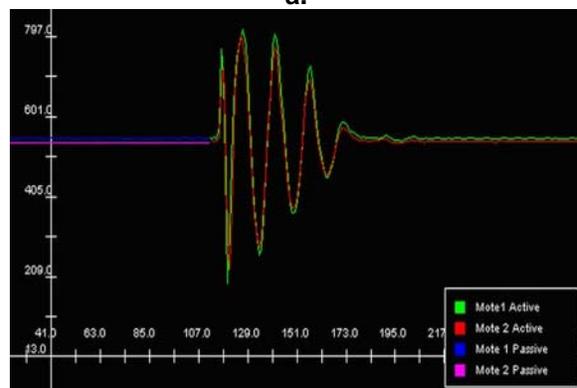
During the normal mode of operation, with no vibrations in a cluster, the SMs are in Passive Mode. Only one SM is performing sensing and others are in sleep mode. This SM uses a lower sampling frequency for conservation of the battery life. Since we had

assumed that we are not interested in any vibration readings below  $T_L$ , therefore, we can reduce the sampling frequency but we do not want to go too low so as to miss high frequency data in the start. We have used values close to 80Hz for the Passive Mode sampling frequency.

Once a SENSE\_EVENT has been detected by the sensing SM in a cluster, it sends the message in its cluster to the other SMs to switch to wakeup mode and start sensing at a higher frequency (we used 150Hz). All the SMs in that cluster switch to Active Mode now. They remain in Active Mode for a limited time but before going back to Passive Mode the mean shift value will be checked and the decision will be taken accordingly. During the Active Mode SMs use local flash to store the data and start sending the data to the local GM during the allotted time slice. Figure 3 shows single and two mote case of SENS\_EVENT and change in mode is depicted through color coding.



a.



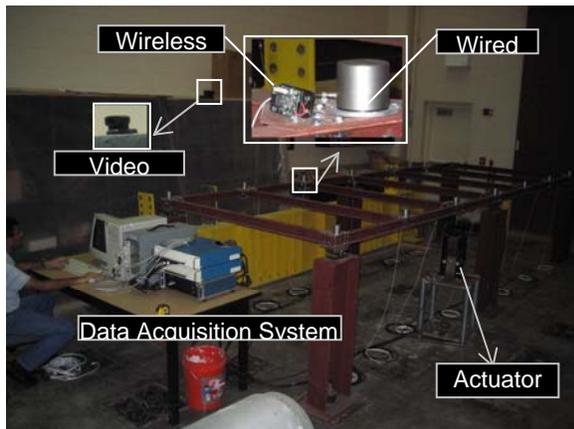
b.

**Figure 3. Vibration detection (Time vs. Sensor reading)**

- Single mote data: The color change from green to red depicts that mean shift exceeded the threshold value  $T_L = 10$ .
- Two time synchronized motes. SENSE\_EVENT detected simultaneously and the change is color coded.

CAMERA\_EVENT is triggered when the activity metric is higher than some threshold value  $T_H$ . It means that there is significant vibration in that section,

therefore, it should be visually observed. This event message is passed to the base station through the intermediate GMs, then the base station uses the location information about the sending mote and requests camera to pan/tilt/zoom into the corresponding section of the bridge. A controller at a remote location can look at the live video if he/she wishes; otherwise the video clip related to an activity can be recorded into the database. Since we have the data about the SM that triggered this event, we can synchronize this data with the video frames. Figure 4 shows a camera overlooking the structure being used in the lab.



**Figure 4. Lab setup (in parallel with conventional sensors)**

### 4.3 Optimization techniques

To improve the performance of the WSN, we propose some optimizations.

- To uniformly use the resources within a cluster, we switch the passive sensing responsibility among the local SMs in a round-robin manner.
- To reduce the amount of data being transmitted, a packet of data gets a common time-stamp instead of individual one's for each data values. Timestamp for individual data values can be recovered on the base station using the current sampling frequency information.
- Each value of accelerometer data is in 10-bit digital form. By default the TinyOS component returns this data in a 16-bit variable and about 37.5% of the bit-space is wasted. We recover this bit space through data packing on the sending end and then unpacking on the receiving end.

## 5. Conclusion

Experiments show that effective distributed processing can enhance the effectiveness of the SHM

system. To further enhance the efficiency of this system domain specific data compression on the nodes could be helpful.

Many factors affect the performance of a SHM system. This includes environmental conditions, which have to be observed in a real-life outdoor scenario over a longer period of time. It also remains to be seen that how well these algorithms perform in real-world situation with problems like node failures, complex civil structures, extreme weather conditions etc. Only then a complete transition from the conventional SHM to the WSN based SHM can be made.

We have tested the triggering of a video camera using event detection on mote data. Another possibility is doing the reverse of this, i.e. triggering sensors in an area if unusual activity is observed in the video. There is interesting work in computer vision community for activity recognition and detection of abnormal activities in videos [11]. For example, the normal activity on a bridge is the traffic in a continuous flow but if there is a heavy truck broken down on the bridge that will be abnormal activity. This might induce heavy loading of the bridge structure which could affect its health. We will further evaluate system trigger based on real time processed streaming video data.

## 6. References

- [1] Crossbow Technology Inc. (<http://www.xbow.com>)
- [2] Wireless Vineyard ([www.intel.com/labs/features/rs01031.htm](http://www.intel.com/labs/features/rs01031.htm))
- [3] A. Mainwaring, J. Polastre, R. Szewczyk, D. Culler, and J. Anderson, "WSNs for habitat monitoring", *WSNA '02, ACM*, 2002.
- [4] Straser, E. G. and A. S. Kiremidjian, "A modular Wireless Damage Monitoring System for Structures", Report #128, John A. Blume Earthquake Engineering Center, 1998
- [5] J. P. Lynch, A. Sundararajanb, K. H. Law, H. Sohn and C. R. Farrar, "Design of a Wireless Active Sensing Unit for Structural Health Monitoring", *International Symposium on Smart Structures and Materials*, San Diego, CA, 2004.
- [6] S Sundresh, G. Agha, Ki. Mechitov, W. Y. Kim, and Y. Kwon, "Coordination Services for Wireless Sensor Networks", *Intl. Workshop on Advanced Sensors, SHM and Smart Structures*, 2003.
- [7] TinyOS (<http://www.tinyos.net>)
- [8] A. Kottapalli, A. S. Kiremidjian, J. P. Lynch, E. C., T. W. Kenny, K. H. Law, Y. Lei, "Two-tiered wireless sensor network architecture for structural health monitoring", *Proc. SPIE Smart Structures and Materials 2003*.
- [9] S. Ganeriwal, R. Kumar, M. B. Srivastava, "Timing-sync Protocol for Sensor Networks", *SenSys '03*, 2003.
- [10] N. Catbas, M. Shah, J. Burkett, and A. Basharat, "Challenges in Structural Health Monitoring", *Fourth IWSC*, 2004
- [11] I. Junejo, O. Javed, M. Shah, "Multi Feature Path Modeling for Video Surveillance", *ICPR*, 2004.