1. INTRODUCTION

Structural health monitoring (SHM) is the practise of monitoring a structure over its lifetime to detect changes in its structural properties that may indicate a reduction in performance. It may be used to monitor aeronautical, mechanical, civil, electrical, and other systems, but the focus here will be on civil systems such as buildings and bridges. The change in structural properties may be sudden, such as those due to earthquake motion or violent wind gusts, or it may be slower due to corrosion for example.

SHM is particularly important for structures such as data server farms, biotechnology or other high technology manufacturing facilities and other buildings where valuable or hazardous building contents are at risk due to excess vibrations or other movements and where continuity of service is important. It is usually performed for one or more of the following three reasons.

1.1 Damage Detection

This is perhaps the most obvious and common reason. The structure is continuously monitored and any changes in its response are noted. For example, frequency shift methods (of modal frequencies) are a well-known class of damage detection techniques that may be used to infer damage to a structure (McConnell 1995). The aim is to make a rapid and accurate assessment the safety of a structure following an event, such as an earthquake, without requiring a dangerous and expensive manual inspection.

1.2 Long Term Monitoring for Deterioration

This differs from damage detection in that it aims to detect changes in a structure that take place over many years. The aim here is to be assured of the structural performance and continued value of the asset under “normal” conditions.

1.3 Determine “As Built” Structural Properties

A short term monitoring program can be used to determine the actual dynamic properties of a structure. These can be used by the designers to compare with design values to verify design assumptions. Ambient or forced vibrations can be used to determine these properties at different levels of motion.

2. TRADITIONAL METHODS OF STRUCTURAL HEALTH MONITORING

SHM projects can be divided into those undertaken over a short term for research purposes, and those performed over a long period for long term health monitoring.

The short-term projects typically involve a relatively large number of sensors, many hundreds of metres of cable and a multi-channel recording system. This can take many days to set up. Figure 1 shows a typical example.

For long term monitoring projects, typically from one to three accelerometers are installed at key points within the structure and possibly cabled together. The reason for this small number of sensors is the cost of the equipment and its installation and operation.

Figure 1. Typical conventional structural health monitoring project (from Glassar 2004)

The small number of sensors means that only very limited information may be obtained about the structure. For example, it would be quite possible for one element of the structure, such as a beam, to completely fail but this not be reflected in the recordings obtained from the few instruments on the structure (Farrar et al 2001).

Data from these sensors is usually collected manually, following an event of interest, and taken back to a laboratory for analysis. In some more recent installations a modem is connected to the recorder so that the data may be transmitted to the laboratory, thus removing one of the steps.

3. RECENT ADVANCES

Recent developments in electronics, sensors and communications systems have come together to provide the opportunity for a new means of performing many sensing tasks such as SHM. The developments in electronics are due to the continuing decrease in the size of each transistor used to manufacture modern electronics components such as microprocessors and memories. This is often referred to as Moores law in honour of the man who, in 1965, proposed the exponential increase with time of the number of transistors per integrated circuit. Figure 2 is a plot showing this over the last forty years or so. The increasing number of transistors, and faster switching time, means that increasingly powerful processors are possible as are larger storage devices.

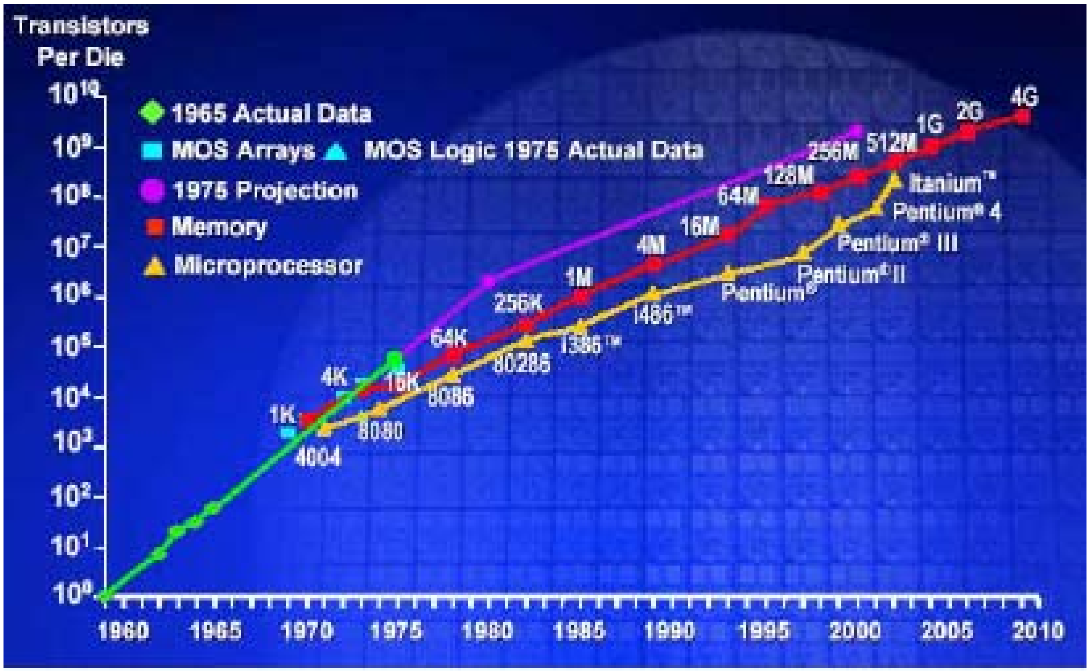

Figure 2. Increasing density of electronics components (from Stephens & Beckman 2004)

The second area of advance is in sensors. Over the last decade or so, MEMS (micro-electro-mechanical systems) devices have proliferated. They are built using methods similar to those used to manufacture integrated circuits. This means that devices can be made smaller and more cheaply than previously. In particular, MEMS accelerometers are now available covering a wide range of price and performance. Devices range in price from around one dollar to a few thousand dollars, and in noise level from tens of milli-g to below one micro-g. Figure 3 shows some examples.

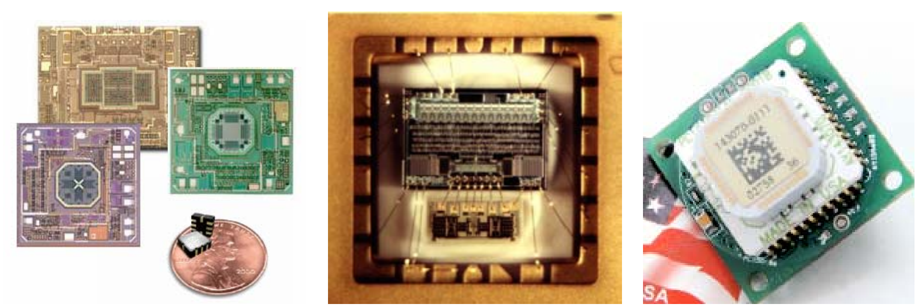

Figure 3. MEMS accelerometers from Analog Devices, Silicon Designs and AppliedMEMs

The third area of advances is in communications. Both the rapid expansion and acceptance of the Internet and the growth in popularity of wireless communications are important here. The Internet provides a low cost means of making data available to interested parties anywhere in the world. It is designed to reliably transmit large volumes of data from one computer system to another over long or short distances. Wireless communications on the other hand can be used over relatively short distances (metres to kilometres). In addition to point-to-point communications, wireless systems make it easy to broadcast messages to many devices simultaneously. This is useful in many monitoring situations.

4. WIRELESS SENSOR NETWORKS

These three advances have spawned a new type of system called a Wireless Sensor Network (WSN) where many sensors (tens or hundreds) are installed in a relatively small area. Each sensor device is small, low cost and low power. Typically, they are only tens of millimetres across, cost tens to hundreds of dollars each and can run off battery power for a year or so.

One of the defining attributes of the sensors in a WSN is that each sensor includes a means of wireless communication. This enables each sensor to communicate with its neighbours providing many benefits. One benefit is that the communications range of each sensor need only be sufficient to reach a small number of neighbours who can pass information back to a central collection point or gateway. It also opens up the possibility of collaborative decision making where each sensor contributes some information to a joint decision making process. Much research is currently under way in these areas (Kim et al 2004; Kottapalli et al 2003; and Okada 2004).

5. STRUCTURAL HEALTH MONITORING USING A WSN

Wireless sensor networks are now being applied to the SHM problem. They allow a structure to be monitored at many points, allowing detailed information about real structures to be determined. A typical SHM system consists of at least two different types of components. The first is the sensor itself with associated electronics and radio. The most common sensor is an accelerometer, but displacement sensors may also be used - to monitor the seating of a bridge girder for example. The sensing device may forward the raw data continuously, or it may perform some type of data compression such as event detection or wavelet compression. The data is then transmitted via the radio back to the collection point. Figure 4 shows a typical example.

Figure 4. A typical sensing node (Crossbow 2005) and gateway device (Dust Inc 2005)

The second component is the gateway that collects the data from the sensors in the network. It uses a radio similar to those present in each sensor device to receive the data. It is commonly connected to a PC, which is in turn connected to the Internet. This device can also be used to send configuration information out to the sensor nodes. A typical gateway device is also shown in Figure 4.

Each sensing node can perform some processing, decision making and data buffering to minimise communication, and thus power requirements. However, the SHM problem is fundamentally more difficult than say the environmental monitoring problem in the volume of data that must be processed. Civil structures have significant modal frequencies that range from around 0.1Hz up to around 100Hz. Therefore sampling at rates of around 100Hz may be required.

A two-tiered approach is being adopted by many workers to overcome this data volume issue (e.g. Kottapalli et al 2003). With this approach, each sensor passes its data on to a local master device, and in turn, each local master device passes its data on to the global master device as shown in Figure 5. While each sensor node is battery powered, both the local master nodes and the global master may be mains or solar powered allowing for more computing and storage capability.

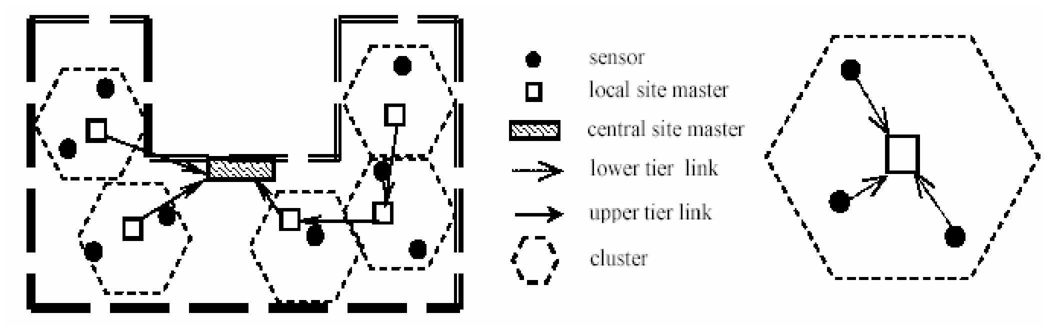

Figure 5. A two-tier network (Kottapalli et al, 2003)

The SHM problem is often treated as a System Identification problem. That is, the measurements are used to determine parameters for a model of the structure. It is then a matter of determining these parameters on a regular basis and checking for trends or discontinuities. A variety of techniques are being used for this, from standard Box-Jenkins models to complete finite element models. For example, Shinozuka et al (2004) use a neural network technique to construct and update a finite element model of a bridge based on the recordings of the bridge sensor network.

6. DIFFICULTIES TO BE ADDRESSED

Using WSNs for SHM is still a relatively new field and there are a number of issues still to be fully resolved. However, because of the potential of the method, there is much research and development work currently being undertaken in the field. Many of the issues are technical and these are being investigated by both University researchers and commercial organisations wishing to develop products in the area.

6.1 Time Synchronisation

For the recordings from sensors to be useful, they must all be synchronised to each other and preferably also to absolute time. Because of power consumption constraints, it is not possible to equip each sensor with a GPS receiver (Elson et al, 2002). Therefore, some form of time synchronisation between devices must be used.

Some implementations use the gateway or base station as a master time source and use communication messages to transmit timing information out to all the sensors. Examples of this type of implementation are the Flooding Time Synchronisation Protocol (Maroti et al, 2004) and the earlier Reference Broadcast Synchronization

(Elson et al, 2002). Other implementations such as Wisden (Xu et al, 2004) record the amount of time data spends in each sensor as it is passed towards the gateway. This time can then be subtracted from the gateways local time to determine what time the data was acquired. Still other methods use a hybrid approach (Ganeriwal et al, 2003).

These methods have shown that they can time-stamp data with an accuracy of a few microseconds while consuming minimal amounts of power. This is sufficient for the majority of SHM applications.

6.2 Data Volume

Some very simple calculations show that a typical WSN based SHM system will gather a large volume of data. The trick is to extract the *information* we want from the *data*. Let us assume a sample rate of 100Hz, a resolution of 16 bits and a sensor collecting three channels of data. This gives a bit rate of 4800 bps, which is manageable for a low power radio, but it would not be desirable for the radio to be powered the whole time. If it was, and we had a network of 100 sensors, this would give an aggregate data rate of 480,000 bps, which is a high continuous data rate for any radio. There are a number of different solutions to this problem.

The first is to use event detection in much the same manner as is used by digital seismographs. The sensor continuously monitors the signal and “triggers” when it appears that an event of interest is occurring. The full waveform of each “triggered” event is then transmitted back to the gateway or central node at less than real-time rates. The advantage of this method is that no energy is wasted transmitting data that does not contain any information. One disadvantage is that some events of interest may be missed because of the difficulty of triggering on them. Another potential problem is that if many events occur over a short time period, more data may be banked up in a sensor than it can store and data will be lost.

A second approach is to use some type of data compression. In this approach, a compressed version of the full waveform is transmitted to the central collection point. During periods of quiescence, most compression algorithms will compress the data to a greater extent, so packets of data will need to be sent less often saving power.

The third approach is to process the data at the sensor node to extract properties of the signal such as modal frequencies. It is these properties that are then transmitted rather than the raw data itself, usually reducing the data volume by many orders of magnitude. The attraction of this approach comes from the fact that, using current technologies, it takes about one thousand times as much energy to transmit one bit of information as it does to perform one instruction (Culler et al, 2004). Therefore, quite sophisticated processing can be performed for the same energy as would be used to transmit the full waveform.

Of course, a combination of the above methods is possible, and is probably better than using any one method alone.

6.3 Network Topologies and Communications

This is the area of WSNs that has received the most research interest over the last decade. New protocols have had to be developed to allow networks to "self-organise" and support multi-hop communications – a fundamental attribute of WSNs. The aim is to allow a large number of sensor devices to be "dropped" in an area and for them to automatically arrange themselves so that data can be transmitted from sensor to sensor and ultimately the gateway or local master device.

6.4 Power Consumption

For sensor nodes to be small, easy to install and maintain, they must be able to run without mains power for many months or years. This places a significant constraint on the power consumption of the device, which affects all other design decisions. Environmental monitoring sensors typically run from two AA batteries for approximately one year. It is felt that with continuing advances in sensors, processing and communications devices, this should be possible for SHM applications as well. In fact with the Stanford University two-tiered approach it is estimated that two AA alkaline batteries should power their sensor for eighteen months assuming five "extreme events" per year and two short recordings each day (Kottapalli et al, 2003). This is achieved using a low power accelerometer that is powered on five times a second to check the signal level. If it is time for a scheduled recording, or it appears that an "event" is occurring, a higher resolution (and higher power) accelerometer is powered up and sampled at a higher sample rate (e.g. 100Hz) for as long as required. The sensor synchronises itself with the local master, sends its information and then returns to its low power mode.

7. OPPORTUNITIES

The work reported on here is mostly being performed in the US, Europe and Japan. It is felt that there is an opportunity for similar work to be undertaken in Australasia. Australia has two co-operative research centres (CRCs) working in related fields, the CRC for Sensor Signal and Information Processing and the CRC for Smart Internet Technology but they are focusing on other areas. Between them, Australia and New Zealand have the required expertise in structural engineering, communications and commercialisation of electronic instruments to make a significant impact in this area.

8. CONCLUSION

Recent advances in electronic components, MEMS sensors and wireless communications have created the opportunity to monitor structures in ways that were not previously possible. A network of tens or hundreds of sensors can be deployed throughout a structure that will sense the structure and wirelessly communicate their information to a central collection point. Some processing of the data may be performed along the way simplifying the interpretation of what is presented to the user. Such networks provide a cost effective monitoring system for the asset owner.

There is an opportunity for collaboration between organisations in Australia and New Zealand for the further development and commercialisation of such systems.

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