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Wireless structural health monitoring of bridges: present and future

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Abstract. Internationally the load carrying capacity of bridges is decreasing due to material deterioration while at the same time increasing live loads mean that they are often exposed to stresses for which they were not designed. However there are limited resources available to ensure that these bridges are fit for purpose, meaning that new approaches to bridge maintenance are required that optimize both their service lives as well as maintenance costs. Wireless sensor networks (WSNs) provide a tool that could support such an optimized maintenance program. In many situations WSNs have advantages over conventional wired monitoring systems in terms of installation time and cost. In order to evaluate the potential of these systems two WSNs were installed starting in July 2007 on the Humber Bridge and on a nearby approach bridge. As part of a corrosion prevention strategy, a relative humidity and temperature monitoring system was installed in the north anchorage chambers of the main suspension bridge where the main cables of the bridge are anchored into the foundation. This system allows the Bridgemaster to check whether the maximum relative humidity threshold, above which corrosion of the steel wires might occur, is not crossed. A second WSN which monitors aspects of deterioration on a reinforced concrete bridge located on the approach to the main suspension bridge was also installed. Though both systems have provided useful data to the owners, there are still challenges that must be overcome in terms of monitoring corrosion of steel, measuring live loading and data management before WSNs can become an effective tool for bridge managers.

Keywords: bridges; bridge inspection; bridge maintenance; monitoring; corrosion; weighing devices.

1. Introduction

Bridge infrastructure around the world is increasingly required to support higher loading both in terms of frequency and magnitude. At the same time this infrastructure is ageing resulting in increased levels of deterioration and maintenance. Unfortunately these increased requirements are juxtaposed against limited government budgets to support the maintenance and renewal of bridge infrastructure. As a result new bridge maintenance strategies are required so that bridge service lives and maintenance programs can be optimized. In order to develop these optimized strategies, engineers require critical data about bridge performance, potentially delivered in real-time. One way to obtain this data is through the use of a monitoring system.

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Traditional structural monitoring systems consist of sensor nodes that are wired into a central data acquisition unit. These systems have the advantage that by using wires to interconnect all the sensors, large quantities of data can be transmitted reliably and power can be supplied to the sensors. However the use of wires also means that installation times and overall system costs can be prohibitively high for maintenance programs with limited budgets. Recent technological developments have made the use of Wireless Sensor Networks (WSNs) a more appealing option. These networks eliminate the cost associated with the installation of cabling, allow for sensors to be placed in difficult to access locations and can be easily expanded to accommodate changing data requirements. However there are three main drawbacks with these networks. Firstly, wireless data transmission has less bandwidth and is not as robust when compared to wired data transmission and so care must be taken in order to ensure the integrity of the data. Secondly, if the network is to be truly wireless the sensors must also be battery powered which places further constraints on the power consumption of the sensor as well as the monitoring and data transmission rates. Finally, although a number of sensors have been developed for use in WSNs, these sensors do not necessarily provide all the data that engineers and managers require to make informed decisions about bridge infrastructure management.

In light of this background this paper will introduce two WSNs that have been installed on the Humber Bridge system in the UK, outlining what data was required and how it was monitored, the issues that arose with these networks and also how these networks have performed since installation. Although these networks have been successful in providing useful information to the bridge operators, they are still limited in terms of the breadth of data they can provide. This paper will also briefly explore some of the developments that are required in order for WSNs, and structural monitoring in general, to become a more useful and widely accepted tool for cost-effective bridge management in the future.

2. Wireless sensor networks at the Humber Bridge

The Humber Bridge, as seen in Fig. 1, is the fifth longest suspension bridge in the world with a central span of 1.41 km. It was opened to traffic on June 24th, 1981. Adjacent to the main suspension bridge are several smaller reinforced concrete bridges which, while not as visually impressive as the main bridge, are just as critical as they provide the only access points to the main span. As part of a larger project investigating the use of WSNs to monitor civil infrastructure, two WSNs have been installed at the Humber Bridge. In each case the objective of installing the network was to provide

Fig. 1 The Humber Bridge

the Bridgemaster and his staff with long-term data that would allow them to monitor critical parameters governing the performance of their structures. The first WSN was installed in the north anchorage chambers of the suspension bridge to provide environmental data on demand while the second system was installed on a near-by reinforced concrete approach bridge to monitor specific problems identified by the Bridgemaster.

2.1 Humber Bridge anchorage environmental monitoring system

The main suspension cables of the Humber Bridge are 680 mm in diameter and each one consists of 14,948 - 5 mm diameter high strength steel wires with an ultimate tensile strength of 1540 MPa. The forces in the cables are resisted by anchoring the cables into massive concrete foundations, which is done in four large chambers with one chamber located at each end of the two main cables. In order to connect the cables to the foundation, they have to be split into individual wire bundles, called strands, which are then wound around steel anchors embedded in mass concrete foundations as illustrated in Fig. 2. This connection detail means that the protective wrap that is used when the strands are bundled together to form the main cable cannot be used within the anchorage chamber and thus the individual steel wires are exposed to the surrounding air. Research (Nakamura and Suzumura 2005) has shown that if steel wires are subjected to relative humidity (RH) levels above 60% their susceptibility to corrosion increases significantly. As a result there is the potential for the steel wires that are exposed to the surrounding air in these chambers to corrode if the RH level is not properly controlled. To ensure that the critical RH threshold of 60% is not crossed, a dehumidification system has been installed in each anchorage. This dehumidification system is set to activate automatically if the RH in any of the chambers exceeds approximately 45% (a conservative threshold below 60% has been chosen to help ensure that corrosion does not occur). Two wired RH sensors were already present in each of the chambers, but the data from this system can only be accessed at wall-mounted display units within the anchorage chambers themselves. Also the wired sensors were located in positions that were convenient in terms of attaching the wires but did not give an indication of the RH variation in the chamber nor the RH in the vicinity of the steel strands. Thus to better evaluate the performance of the dehumidification system a web-based monitoring

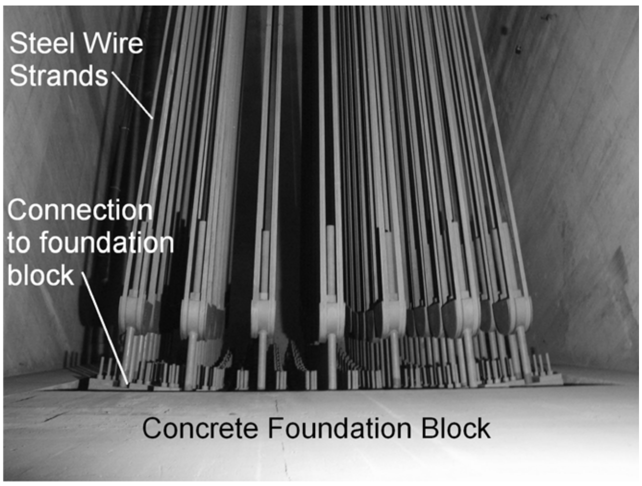
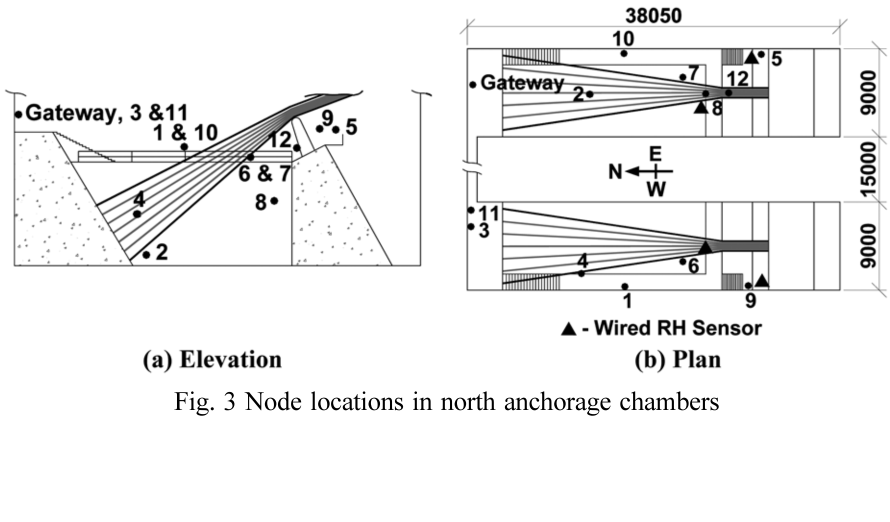


Fig. 2 Anchorage of strands into concrete foundation

system with sensors in a variety of locations was sought to provide real-time access to this data from anywhere in the world.

In order to provide the bridge managers with the required access to the data in this critical area of the bridge, a WSN was installed in the north-west and north-east anchorage chambers. The use of a wireless system meant that sensors could be installed quickly in a variety of locations, including adjacent to the steel strands, and then the sensors could be moved easily if data at other locations was required. These two chambers are connected by a 15 m long, 2 m high and approximately 1 m wide corridor. The network consists of a gateway, 10 nodes with RH and temperature sensors, one inclination sensor node and one data relay node. The nodes are programmed to take readings from the sensors at intervals of between three and five minutes. Although this data acquisition rate is possibly higher than necessary, decreasing it would not have a significant impact on the battery life as maintaining network connectivity would then consume most of the power. The gateway is a Crossbow Stargate powered with a 6V mains adapter. The nodes are Crossbow MICAz motes that have limited available memory for storing data, which has advantages and disadvantages over nodes with both data logging and transmission capabilities. The main advantage is that by only storing the latest data from the sensor, the power consumed by the CPU in accessing this memory is minimized. The major disadvantage is that since only one reading is stored in memory at the node, the data is lost if it is not transmitted successfully. Since the RH and temperature values in the anchorage are unlikely to change significantly from one reading to another, the loss of occasional data packets was not deemed to be critical in comparison to the extended operational life provided by the mote. Fig. 3 illustrates the layout of the nodes in the anchorage chambers. Three of the wireless sensors have been placed next to the existing wired sensors for data verification purposes. The gateway then transmits the data using an ADSL Internet connection back to the central server at the University of Cambridge.

When the network was first installed in July 2007, it was found that the nodes in the west anchorage chamber were unable to communicate with the nodes in the east anchorage chamber or with the gateway. This problem was the result of a loss of transmission strength between the west and east chambers caused by the corridor (as shown in Fig. 3(b)) connecting the two chambers. This problem was overcome by using 5 dB gain external antennas in place of the original MICAz antennas, which appeared to have minimal gain based on a comparison of transmission distances. These antennas were installed on the gateway and on a relay node (node 11) that was added to the network and installed at the other end of the corridor to the gateway. This problem is an excellent



(a) Elevation (b) Plan

Fig. 3 Node locations in north anchorage chambers

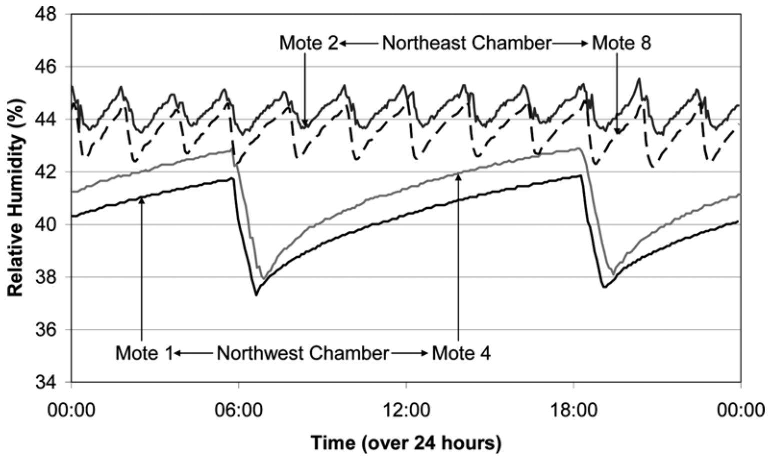


Fig. 4 RH data for west and east chambers

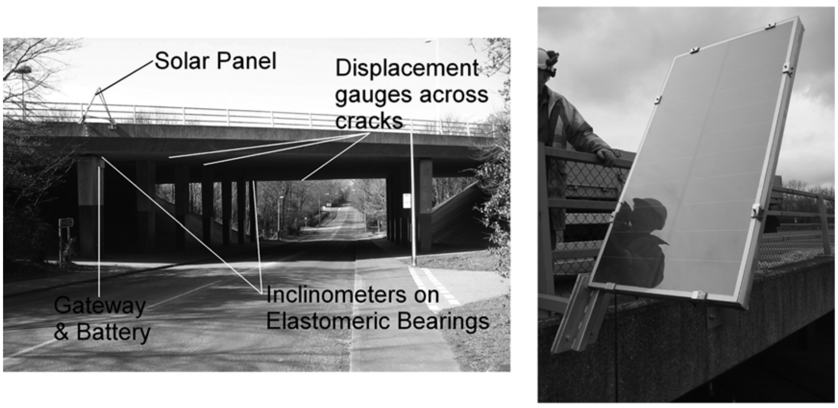
illustration of one of the main issues with WSN installation, which is network connectivity. Until the network is installed it is virtually impossible to predict where areas of fading (significant drops in radio transmission strength) will occur. In many civil engineering applications, for example train tunnels or highway bridges, site possession times are very short so there may be very limited time available to setup and test a WSN. Thus the development of tools which enable wireless signal strength to be predicted for any given network configuration is a particularly important topic that requires further research if WSNs are to be adopted more widely by infrastructure managers.

Overall the RH and temperature monitoring system in the anchorage has performed well since it was installed 10 months ago in June 2007. In fact, as illustrated in Fig. 4, the data has provided the Bridgemaster with useful feedback about the operation of his dehumidification units and identified the potential for significantly reducing operating costs of the dehumidifying system. One can see from the graph in Fig. 4 that the RH from nodes 2 and 8 located in the north-east chamber varies over a much smaller range than the RH for nodes 1 and 4, located in the north-west chamber. This indicates that the dehumidification unit in the north-east chamber turns on and off far more frequently than the unit in the north-west chamber. In fact the unit in the north-west chamber is potentially more efficient as its total 'on time' during a day is approximately 105 minutes versus 300 minutes for the unit in the east chamber, a difference of a factor of three. Until this monitoring system was installed, the bridge manager was unaware of this difference in the operation of the two units and the potential to reduce the energy used by changing the settings on the dehumidification unit in the north-east chamber to match the unit in the north-west chamber. The power consumption of the dehumidifying units in each chamber is 7.82 kWh meaning that the resulting power savings from using the north-west chamber dehumidification strategy in both chambers could be 9.3 MWh per year. This has the potential to reduce the amount of carbon dioxide produced in powering the system by 4 tonnes per annum based on the assumption that 0.43 kg of CO_2 is generated for every kWh of electricity used (National Energy Foundation 2007).

There have been three main issues relating to the reliability of the network: battery life, hardware failure and hardware performance. The first node to exhaust its batteries was node 10 which ran out of power in mid-April 2008, approximately 10 months after the network was first deployed. The rest of the nodes were still using their initial set of batteries at the time of writing. There have been two node hardware failures to this point as both nodes 5 and 10 stopped transmitting sensor data at different points during the past 10 months. In the case of node 10, which stopped working after 5 months, the sensor board was replaced and the problem has not reoccurred. In the case of node 5, both the mote and the sensor board have been replaced as the node stopped transmitting data on more than one occasion. Replacing both the mote and the sensor board seemed to rectify the problem. In terms of hardware performance, an issue occurred with the gateway whereby multiple data points from the same sensor were recorded as having arrived at nearly identical times. Since the sensors are programmed to send data back every three to five minutes, having data recorded from the same sensor at intervals of less than one second indicated that there was a potential fault with the gateway. It was discovered that it was a result of having a database running on the gateway. At installation the database software (as supplied by Crossbow) was able to record data sent by the nodes while still being able to service queries from the main server hosted at the University of Cambridge. However after several months the gateway (which has less processing power than a standard desktop PC) became unable to both process the ever larger database and manage background tasks such as updating its own clock. This in turn meant that the clock slowed down and the data values, which are time stamped based on this clock, received incorrect time stamps. This problem was overcome by removing the database from the gateway and instead writing the raw data to text files on the gateway, which requires far less processing power. It is possible with the aid of hindsight that this problem could have been avoided. Similarly if the demand for WSN technology increases node hardware failures would likely be reduced as is usually the case with maturing electronic technologies. However, eliminating electronic hardware failures is not possible. Thus, both the mote hardware failures and the gateway performance issue illustrate the need for redundancy if the data being monitored is safety critical. Otherwise there is the potential for data to be lost due to software and hardware failures, although this problem is not unique to wireless systems.

2.2 Ferriby Road Bridge – reinforced concrete bridge monitoring system

A second WSN has been installed on the Ferriby Road Bridge as illustrated in Fig. 5, a reinforced concrete approach bridge which was completed in 1979, to the north of the main suspension bridge.



(a) Basic network layout **(b) Solar panel**

Fig. 5 The Ferriby Road Bridge

This network is designed to supplement the regular inspection program that this bridge undergoes. During the bridge's last principal inspection in the summer of 2002 it was noted that transverse cracks had formed on the soffit at the mid-span of the central span and that longitudinal cracks had formed between the columns. Additionally it was observed that many of the elastomeric bearings at the abutments were inclined transversely to the span of the bridge. Whilst neither of these issues required immediate attention at the time of inspection both have the potential to become severe issues over the course of time. However one of the problems with visual inspections is consistency. For example, although a crack may be noted from inspection to inspection, one inspector's interpretation of its width and extent may vary from another's. Thus monitoring would allow for the variation in deterioration to be accurately tracked over time and provide a more objective way of tracking this deterioration.

In order to install a wired system to do this, it would require the installation of both the sensors and the cabling on the soffit of the bridge, which could result in closures of the road under the bridge and hence additional associated delay costs on top of the installation costs. Instead a WSN was installed on this bridge that consisted of six sensor nodes in the first instance. Three of these nodes measure inclination of the elastomeric bearings as well as RH and temperature both inside and outside the box housing the sensor. The other three sensors measure the change in crack widths on the soffit of the bridge as well as RH and temperature. The WSN was installed over the course of two days in March and April 2008. It is anticipated that this installation time could be reduced significantly with more experience installing the sensors.

This network is also innovative in that it provides fully wireless long-term monitoring. The sensor nodes are powered using long-life lithium batteries which should allow the inclinometer and displacement sensors to operate for 1.5 years and 8 years respectively between battery replacements. The difference between the two battery lives is due to the different power demands of the sensors and battery sizes used. The gateway is also battery powered and transmits data by wireless, unlike the gateway in the anchorage network which relies on mains power and transmits data over an ADSL Internet connection. The 12V battery is recharged by a solar panel mounted on the side of the bridge as shown in Figs. 5(a) and (b). It should be noted that, unlike the nodes which are mounted under the bridge, the solar panel is clearly visible from a control room that is staffed 24 hours a day. Thus malicious damage to the panel, while possible, was not believed to be a significant threat and was mitigated by placing a sheet of polycarbonate in front of the panel to prevent impact damage. On more remote bridges vandalism would be a greater concern and so protection of the solar panel would have to be given more thought. A mobile phone connection allows the data to be downloaded wirelessly to the same central server used by the anchorage network. These two features mean that bridges in virtually any location in the UK can be remotely

Fig. 6 Node layout at the Ferriby Road Bridge

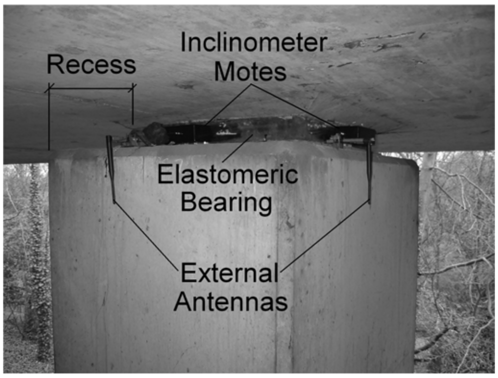


Fig. 7 Location of nodes 5 and 6

monitored, irrespective of the availability of electricity and Internet connections as the data can also be stored locally at the gateway if an Internet connection is not available.

As with the anchorage network, there were initial radio transmission problems that had to be overcome before the Ferriby Road Bridge WSN was fully operational. Fig. 6 shows the general layout of the nodes with the distance from the gateway to the most distant node (node 1) being approximately 40 m. After the initial deployment data was only consistently received from nodes 1, 4 and 7 with data being received intermittently from node 3. No signal was received from nodes 2, 5 and 6.

Nodes 5 and 6 were inclinometer sensors that were attached to the elastomeric bearing above the column, which meant that they were in the narrow gap between the top of the column and the underside of the bridge slab as illustrated in Fig. 7. It was considered that this recess was limiting the transmission range of these sensors. In order to overcome this problem, external antennas that extended beyond this recess were attached to nodes 5 and 6 as demonstrated in Fig. 7. Node 2 was a linear potentiometric displacement transducer (LPDT) crack width measurement sensor node mounted on the underside of the slab approximately 6 m away from the gateway. As this location was clearly visible from the road below it was preferable not to use an external antenna so that the node was as inconspicuous as possible in order to minimize the possibility of vandalism, so an external 5 dB gain antenna was mounted on the gateway. As a result of these changes data could be received from nodes 1, 2, 4, 5, 6 and 7. However data was no longer being received from node 3. This was felt to be as a result of changing the location of the gateway antenna, which caused node 3 to fall into a region of fading. The solution to this issue has not yet been developed although due to the unpredictable nature of radio transmission it is not possible to guarantee the success of any solution. These transmission problems illustrate that the ability to ensure network connectivity is one of the key obstacles to be overcome in order for WSNs to gain widespread acceptance. On the Ferriby Road Bridge, as with the anchorage, network connectivity was developed through a trial and error approach however on structures where possession times are limited this approach would be less than ideal. The answer to this problem is not clear as the current state of the art for radio wave propagation modelling can only suggest the likelihood of fading and not indicate the exact locations of it. Similarly onsite testing to locate areas of fading is influenced by the presence of the personnel and their equipment. As a result a system might well work correctly while the testing is taking place but may not work during everyday operation when the installers have left. Overcoming these transmission issues by installing more relay nodes has cost implications in terms of equipment, delay and personnel costs and so would need to be optimized in order to make the use of WSNs a cost-effective option. This is a challenging area of research that is being examined separately as part of the current project.

3. Future sensing requirements

Although these initial WSN deployments have shown promise, there remain several key issues that need to be addressed. One such issue is that the sensor technology does not currently exist to accurately measure the extent and location of corrosion in reinforced concrete structures or suspension bridge cables, with either wired or wireless systems. At present inaccurate indirect measurements indicating the likelihood of corrosion are employed. Another concern in terms of developing an effective bridge monitoring system is the need to be able to measure live load on the structure. Various weigh-in-motion (WIM) systems are available commercially but both cost and concerns relating to accuracy has limited their widespread adoption. Finally, one must also give careful consideration to what data is required in order to maintain properly the bridge inventory whilst avoiding the pitfall of monitoring for the sake of monitoring.

The following section outlines the significance of each of these issues and identifies some of the key challenges to be overcome if WSNs are to be integrated into the bridge monitoring systems of the future.

3.1 Corrosion sensors

Deterioration caused by corrosion affects the capacity of all structures that have steel elements by reducing the area of steel available to resist the applied loads. In order to estimate the reduced structural capacity and remaining service life of the structure, engineers need to know the *extent* (the remaining cross-sectional area of steel), *location* and the *rate* of corrosion. However these values are not easily estimated even if the corrosion is visible and become especially difficult to quantify for structures where the load carrying steel members are embedded, such as in reinforced concrete, or wrapped such as in suspension bridges.

A wide variety of techniques for measuring corrosion in reinforced concrete structures have been proposed and used including half-cell, chloride ingress, eddy current, linear polarization, acoustic emission and thermographic measurements. Unfortunately each of these tests has limitations which call into question their ability to predict the three key parameters of extent, location and rate. For example, half-cell and chloride ingress measurements provide an indication of the likelihood of corrosion but do not actually quantify the extent of corrosion or rate, and only provide information about a specific location on the structure. Proponents claim that linear polarization provides some indication of the rate of corrosion but again only at a specific location on the structure. The measured rate from a linear polarization test is highly dependant on a number of factors including the moisture and chloride content of the concrete as well as the temperature, which makes the accuracy of the test questionable unless precise data exists (Carino 1999). Acoustic emission and thermographic monitoring offer the possibility of being able to monitor the entire structure but can only indicate the location of corrosion meaning that other techniques are required to then determine the extent and rate of corrosion.

In the case of suspension bridge cables, far fewer techniques are available to estimate the key parameters engineers require. Currently, in order to estimate the extent of corrosion, the protective wrapping must be removed from the cables. The strands are then wedged apart and the individual wires exposed in these areas are inspected visually (Mayrbaurl and Camo 2004). However, only a small percentage of the wires can be inspected using this technique meaning that critical areas of corrosion may not be uncovered.

The rate of corrosion in large multi-wire cables is currently monitored using acoustic emission techniques where systems are installed to listen for the characteristic noise of a breaking steel wire. While this approach may be appropriate for use with suspension cables, there is a lack of published research and validation testing.

As indicated by the preceding discussion there is a need for the structural engineering and sensor development communities to reconsider how the extent, location and rate of corrosion can be determined. Can microelectromechanical systems (MEMS) sensors be developed that detect corrosion products within concrete for example? And if so, can these sensors then be included in a WSN that also allows other critical parameters to be measured thus providing the bridge manager with a complete picture of the bridge's performance? Or is the required tool a scanning device of some kind that can be passed over the structure during an inspection providing a complete picture of the condition of the steel elements? Recent work using magnetic flux leakage scanning devices has shown promise for detecting flaws in prestressed concrete structures (Mietz and Fischer 2007) and cable stayed structures (Christen *et al.* 2003). However further research will be required to see if this technique can be used to detect the extent of corrosion as well.

3.2 Load sensors

The two WSN systems presented in this paper track long-term trends relating to environmental conditions and structural deterioration. However, there are also instances when the parameter to be monitored is directly affected by the loading on the structure at the time the sensor readings are taken. An example of this would be the force in the cables of a cable-stayed bridge. In order for the measured force to be useful in an assessment of the bridge, the engineer needs to know what the live loading (due to traffic, trains etc.) was on the bridge at the time the forces were measured. Otherwise the engineer does not know how the measured force relates to the capacity of the bridge. Thus there is a need to develop accurate methods of determining the live loading on the bridge that can then be correlated with the data from other sensors to allow the performance of the bridge to be determined.

There are two challenges that must be overcome in order to do this: first a reliable method of measuring the live load must be found and then a method of integrating this technology into a WSN must be developed. There exist several techniques to determine the weight of vehicles in motion using weigh in motion (WIM) sensor technology (European Commission 2001) including capacitance strip sensors, structures instrumented with strain gauges and vehicle instrumentation (referred to as on-board weigh-in-motion). Capacitance strip sensors are thin mats that measure the change in capacitance as a vehicle passes over them which can then be related to the weight of the vehicle. The data from these systems are difficult to interpret due to the complex dynamic interaction between the suspension systems of the vehicles and the strip mounted on the road or bridge surface. These effects can be reduced by using multiple mats and statistical correction algorithms (Stergioulas *et al.* 2000). Another possibility for measuring the load is to instrument the structure itself. The CULWAY system has been shown to provide accurate measurements of vehicle weights (Hood and Peters 1992). This system uses reinforced concrete culverts instrumented with strain gauges to determine the weight of vehicles that pass over them. The dynamic effects are minimized because there is no bump in the road (as can occur with mats) to excite the vehicle and other dynamic effects are damped by the mass of earth between the road surface and the instrumented culvert. Another possibility is to obtain the weight of transport vehicles from sensors mounted on the suspension systems which allow weight data to be transmitted in real-time using wireless transmission technologies. Such a system is already available on some commercial vehicles (for example log-trucks in Australia) and its wider application for monitoring heavy vehicle loads is currently being evaluated in New South Wales, Australia. This is an extension of an existing wireless information system for monitoring the precise location of very heavy trucks using GPS data transmitted back to a monitoring base station (New South Wales Government 2008). One can imagine a system whereby vehicles passing over the bridge transmit their loading, speed and location to the gateway which can then transmit this information back to the central database along with other data from sensors mounted on the bridge itself.

Whilst both a strain gauge instrumented bridge and instrumented vehicles are viable options for measuring the load on a bridge to correlate with the rest of the sensor data, they do present challenges in terms of the development of WSN technology. For example, the ideal situation in terms of assessment would be to have sensor readings taken only for the critical loading scenario. However, this would require a triggering mechanism whereby the gateway sends out a message based on either a sensor reading crossing a threshold or the data received from an instrumented vehicle activating the sensors to take readings. It is unlikely the sensors could be activated to take the critical reading at exactly the right moment since vehicle speeds, shapes and sizes vary resulting in different potential loading patterns. Instead a window of readings would need to be taken to ensure the critical response of the specific element under investigation was recorded. Depending on how often the sensors were activated and their sampling rate, the power required for the sensors and transmission of data could be significant. In order to do this with a wireless system, methods of reducing energy consumption and extending battery life, such as power harvesting, would need to be considered. Thus creating WSNs to be used to support bridge assessment will require advances not only in weigh-in-motion measurement technologies but also in sensor and network operation as well as energy performance.

3.3 Data management

Currently many bridge managers have reservations about the practicality of extensive monitoring, both wired and wireless, on the bridge network. They see the use of monitoring systems as being limited to specific structures where problems have already been identified and which can be easily measured with the available sensor technology. Even in these cases they are concerned about the usefulness of the data from these systems as the quantity of data acquired can quickly become overwhelming making it essentially useless. If structural health monitoring (SHM) systems, including wireless SHM systems, are to be used more widely and become a useful tool in bridge management, three key data management issues need to be addressed: data volume, data quality and data visualization.

Given the current availability and cost of computer memory it is tempting simply to record all the data collected by a SHM. However this should be avoided for two reasons. Firstly, most of this data is not critical to the operation of the bridge and so does not need to be recorded. Secondly, transmitting all the data and not just the critical data represents an inefficient use of power and bandwidth in a WSN. Thus careful thought should be given to which measurements are actually useful for the evaluation and assessment of the bridge, and the correct level of decimation performed on the data. The responsibility of determining which data is critical lies with the structural engineering and NDT communities. For example, for load capacity assessment purposes it may be useful to have the full strain – load interaction diagram for a given structural element when a vehicle is crossing the bridge, whereas in other instances it may only be important to know whether a certain threshold has been crossed. However, neither the assessor nor the manager is concerned with the strain data gathered outside of this critical vehicle crossing window. Thus intelligent WSN systems should be able to reduce the volume of data so that only the critical data for assessment and management is stored and presented.

Another consideration that affects the data volume is the choice of sensors and sensor location. The development of MEMS sensors has created the opportunity for inexpensive monitoring of a variety of parameters and the potential to install monitoring systems that might consist of thousands of sensors. In some cases this may well be the correct approach, especially if the sensors are simply monitoring whether a specific threshold is crossed. If, on the other hand, the sensors produce large quantities of data, there is the possibility of data saturation whereby the results presented to engineers are too extensive and complicated to be understood properly. If this is the case it is possible that the results will simply be ignored. Thus when developing a WSN, only critical parameters should be monitored rather than monitoring other aspects of performance simply because it is possible.

Finally, in order to make the data as useful as possible, 3-D visualization techniques need to be developed to allow bridge managers and assessors to quickly and easily understand the relevance of the data. If each sensor can be illustrated on a 3-D model of the structure then the relevance of the data can be better understood. If the data has also been properly managed it should also be straightforward to present the critical values, such as the minima or maxima, in a pop-up window over the sensor for example. A 3-D interface was developed for both the Humber Bridge anchorage and the Ferriby Road Bridge WSNs that works in conjunction with Google Earth. This allowed the Bridgemaster to not only see the location of the sensors on the structures but also see the location of the sensor networks with respect to the surrounding infrastructure, which is especially useful when multiple WSNs are installed within the same network.

If the use of WSNs on bridges is to become pervasive, the concerns of bridge managers with regards to the significance and use of the data must be addressed. Further research into WSN technology must give consideration to data volume, quality and visualization. If these issues are dealt with properly then WSNs could become an essential tool for use in a comprehensive bridge management system. However, it should be emphasized that the overarching consideration in terms of monitoring and data management should always be what is critical to measure in order to assess the bridge's performance and capacity.

4. Conclusions

As bridge infrastructure around the world continues to age and deteriorate it behoves the engineering community to develop better ways to manage this infrastructure given the limited resources that exist for maintenance and replacement. One such tool that is available as part of a total management strategy is the use of wireless sensor networks for structural health monitoring. These networks have the potential to be cost-effective and provide critical data for engineers and managers to assist them to make decisions about the condition of individual structures as well as the overall bridge network. WSNs have been installed at the Humber Bridge and on the adjacent Ferriby Road Bridge. A relative humidity and temperature monitoring system installed in the north anchorage has been operating successfully for 10 months since June 2007. The network has provided managers with valuable insights into the operation of the dehumidification system in this area and created the potential for significant cost and energy savings. The second WSN was installed on a reinforced concrete approach bridge and was designed to monitor potential issues that have been noted during visual inspections. Although this network has only been operational since March 2008, it has shown that is possible to use battery power not only for the sensors but also for the greater power requirements of the gateway, and to transmit the data back to a central server using a mobile phone connection. There is still much work to be done if WSNs are to become an indispensable tool for bridge managers and engineers. For example, techniques to measure corrosion in reinforced concrete structures still need to be developed as only then can the capacity of many of these structures be assessed accurately. Also, for the data from WSNs to be useful in assessing the capacity of bridges, there has to be a method of tying load measurements on the bridge together with other sensor data so that the structural performance can be properly evaluated. Finally, careful thought needs to be given to exactly what should be measured on each specific bridge so that only the relevant data is captured. Work also needs to be done to ensure that this data is processed and presented in a timely and effective manner so that it supports the decision making process rather than detracting from it. Even though the present WSN developments are encouraging, much work needs to be done to move towards a fully integrated future.

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