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Smart Infrastructure: Pervasive WSNs for a more Sustainable Europe

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ABSTRACT: The construction industry is a significant contributor to CO_2 production with cement production accounting for approximately 5% of total CO_2 production. One way to reduce this negative impact is to extend the service life of structures beyond their original design lives. However, in order to extend the service life of a structure, managers and engineers need to be able to ensure the structure can continue to meet both its serviceability and ultimate load carrying requirements. If managers and engineers could be provided with both real-time and long-term information about how the structure was performing, this could assist them in extending the useful lives of many structures. One approach to supplying this information is to deploy extensive networks of sensors that, when coupled with an effective data visualization tool, provide alerts about areas of critical concern as well as key data on structural condition and performance. Unfortunately traditional wired monitoring systems can be very expensive to install and difficult to manage, particularly when using a large number of sensors. Wireless Sensor Networks (WSNs), on the other hand, provide flexibility in terms of sensor placement, simplifying the addition and removal of sensors to an existing system, and can be installed faster and more economically than their wired counterparts. Research has been undertaken to develop WSNs from off-the-shelf components and to investigate the possibility of pervasive monitoring. This paper outlines three small-scale WSNs that were deployed on a bridge and in a tunnel to determine the viability of these systems. The potential for using the data from these systems to reduce the impact of civil infrastructure on the environment will be discussed. Plans for a large-scale WSN deployment on multiple civil infrastructure assets will then be introduced. Finally, issues relating to sensor types, system robustness and data management that must be overcome before WSNs can become a useful tool for managers and engineers will be outlined.

1 INTRODUCTION

The production of CO_2 from various human activities is widely recognized as a contributing factor towards climate change. One of the most significant sources of CO_2 production is the construction industry where, for example, one cubic metre of reinforced concrete creates approximately 400kg of CO_2 emissions (Nielsen 2008) and global cement production accounts for approximately 5% of total CO_2 emissions (Worrell et al. 2001). This value is, of course, only an approximation as it depends on a number of variables such as the percentage of reinforcement, driving distances to site etc. One way to reduce these emissions is to keep existing structures in service longer so as to delay or possibly avoid further CO_2 emissions

associated with their demolition and reconstruction. Keeping reinforced concrete structures in service longer also has the added benefit that they will reabsorb some of the CO_2 through carbonation (Nielsen 2008). However, in order to be able to keep a structure in service, especially past its intended design life, engineers and infrastructure managers need to know when the structure requires maintenance, repair or is no longer fit for purpose. This requires data about the structure.

One way to acquire some of this data is to install a monitoring system. Traditionally such monitoring systems have consisted of sensors that are connected using wires to data loggers. The installation of these systems is expensive in terms of sensor, cabling and labour costs with the result being that monitoring has not been installed on the vast majority of structures. However if the service lives of civil structures are to be maximized, thus minimizing their environmental impact, engineers and infrastructure managers require a full picture of how all their structures are performing. Wireless sensor networks (WSNs) are a tool that can be used to help realize this vision as they offer several advantages over wired monitoring systems as will be discussed.

1.1 Wireless Sensor Networks

A wireless sensor network consists of nodes, which may or may not have sensors attached to them, and a gateway. Each node is typically battery powered and consists of a low power central processing unit (CPU) and a radio. In this paper the Crossbow MICAz platform is used for all the nodes. They can also provide an interface for various sensors, which are often based on microelectromechanical systems (MEMS) technology. The advantage of MEMS based sensors is that they have very low power consumption so that battery life can be maximized. The nodes then sample data from the sensors at a varying rate depending on the application and transmit it via radio, in this case at a frequency of 2.4GHz, back to the gateway. The gateway is a computer that is powered all the time and offers some form of connectivity with the outside world be it through the Internet, a mobile phone connection or simply removable data storage. There are several different network topologies that a WSN can have but in this paper all the networks that were deployed used a mesh formation. This means that nodes can transmit to other nodes, and attempt to find the optimum transmission path to the gateway, which may or may not be via other nodes.

1.2 Pervasive Monitoring of Civil Infrastructure

Current research investigating the use of WSNs for monitoring civil infrastructure tends to focus on short-term deployments for both tunnels (Cheekiralla 2004) and bridges (Lynch et al. 2006). Very few of these deployments are on a large-scale (Kim et al. 2007) or for extended periods of time (Feltrin et al. 2007) and those that are tend to focus on vibration monitoring. However, if engineers and managers are to have improved knowledge of the condition of their infrastructure and make well-informed decisions based on this knowledge then there needs to be a paradigm shift towards large-scale, long-term WSN deployments.

As part of the EPSRC funded Smart Infrastructure project, researchers at the University of Cambridge are investigating the potential of using WSNs for pervasive monitoring of civil infrastructure. The ultimate goal of this project is to develop vast WSNs that link together multiple types of civil infrastructure allowing for the evaluation of a structure not only using data on its own performance but also using data from the surrounding infrastructure. For example, a bridge manager could be notified of a tunnel collapse in the vicinity which may undermine the foundations of the bridge, for example. Whilst such an incident is at the extreme end of what could be conceived, these systems could also allow deterioration of a structure to be tracked much more accurately than with the current approach, which is based primarily on

visual inspections. As a first step towards this pervasive monitoring, three small-scale WSNs have been installed on bridge and tunnel infrastructure in the UK. The first of these systems was installed in the north anchorage chamber of the Humber Bridge. The second was installed on a three span reinforced concrete bridge that provides access to the main Humber suspension bridge whilst the third was installed in a London Underground tunnel.

This paper will briefly introduce each of these systems and discuss the potential environmental benefits that could be derived through having access to the data these systems provide. Finally a planned large-scale WSN deployment will be presented and some of the challenges associated with that deployment will be discussed.

2 LONG-TERM WSN DEPLOYMENTS

2.1 Humber Bridge Anchorage chamber monitoring

The Humber Bridge was opened in 1982 and is the UK's longest suspension bridge. The deck of the bridge is supported by two main cables containing 14948 individual steel wires. At each end of the cables the wires are split into bundles that are then anchored into concrete foundations in an area of the bridge known as the anchorage chamber. In this chamber the wires are exposed to the surrounding environment and it has been shown by other researchers (Nakamura and Suzumura 2005) that there is the potential for corrosion of these wires if the relative humidity (RH) in the chamber exceeds 60%. To prevent this each chamber is equipped with a dehumidifier that keeps the RH level below the critical threshold of 60% (and typically below 45%). In each chamber there is also a wired RH monitoring system but this system has two limitations: (i) the sensors are placed on walls or suspended in midair but are not placed near the actual exposed strands and (ii) the data can only be viewed from a console within the anchorage itself. Thus the bridge managers do not know the precise environmental conditions near the strands and do not have real-time access to this data.

To overcome these limitations and provide the Humber Bridge management team with accurate data about the performance of the dehumidification system a WSN was installed in the north anchorage chambers in July 2007 as illustrated in Figure 1(a). It is introduced in greater detail elsewhere (Hoult et al. 2008). The key attributes of the system are that it overcomes the limitations of the wired monitoring system by (i) allowing sensors to be placed virtually anywhere in the anchorage chambers and by (ii) providing real-time access to this data. Currently three of the sensors are positioned next to the existing wired RH sensors, four are positioned near the exposed wire strands and the remaining three are positioned in locations that help to optimize the radio wave propagation environment. The advantage of these wireless sensor nodes is that they can be moved around the chamber with relative ease as there is no requirement for wiring. So if an area is found to be of particular concern, the sensors can be redistributed accordingly. The gateway is connected to a server at the University of Cambridge via an Asymmetric Digital Subscriber Line (ADSL) connection. The data is accessible in real-time via the Internet from anywhere in the world, which means that the management team always has access to this critical data. It is worth noting that the first battery changes were required 10 months after installation as this is one of the key considerations for WSNs.

The system offers several potential benefits in terms of minimizing the environmental impact of the Humber Bridge. First of all, by having real-time access it can be ensured that the wires are not exposed to a corrosive environment thus optimizing the service life of the bridge. Secondly, with such ready access to the data, the maximum RH level at which the dehumidifiers activate, which is currently set at 45%, can be optimized to minimize power consumption. Finally, an unexpected benefit of the system was discovered when it detected a difference in operation between the dehumidifiers in the northwest chamber versus the northeast chamber as illustrated

in Figure 1(b). The Figure shows that the dehumidifier in the northwest chamber activates far less frequently but when it does the resulting change in humidity is far greater. It turns out that this dehumidification pattern is far more economical than the pattern used in the northeast chamber with a resulting savings in power consumption of 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 2008). Before the installation of the WSN no one was aware that the dehumidifiers had different settings and of the potential for cost savings.

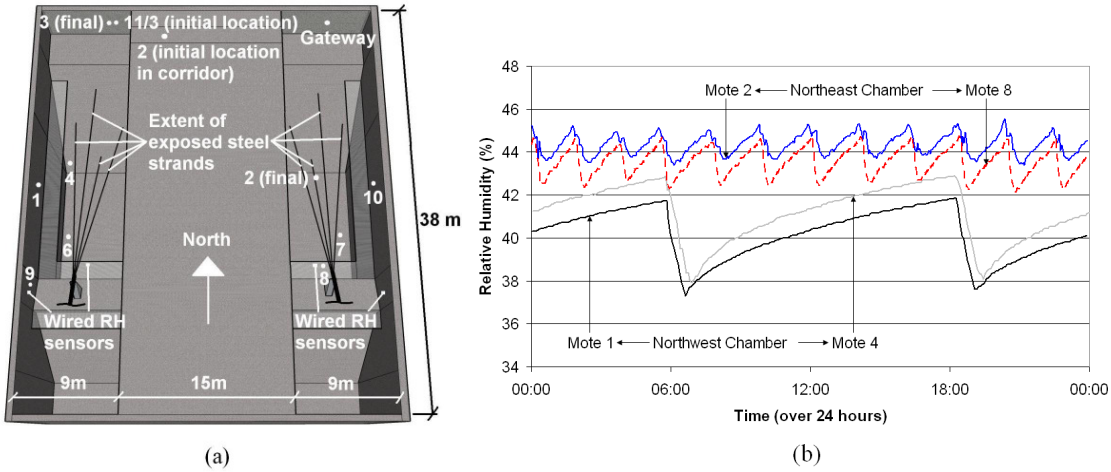

Figure 1 – Humber Bridge north anchorage chamber (a) WSN layout and (b) monitoring results

2.2 *Ferriby road bridge monitoring*

In March 2008 a WSN was installed on a three-span reinforced concrete approach bridge, just to the north of the main Humber suspension bridge known as the Ferriby Road Bridge. This system was installed to monitor several defects that had been highlighted during a principal inspection of the bridge in 2002, namely the presence of extensive cracking on the soffit of the bridge and a noticeable transverse inclination of the elastomeric bearings. If the crack widths or the transverse bearing inclination were to increase beyond a critical limit, remedial action would be required. The WSN consisted of seven nodes as illustrated in Figure 2. Three of these nodes use bespoke sensor boards connected to linear potentiometric displacement transducers (LPDTs) to monitor changes in the width of the cracks in the soffit. Three other nodes use bespoke sensor boards with inclinometers to monitor change in the inclination of the elastomeric bearings. Each of these six nodes is also equipped with RH and temperature sensors to allow for environmental compensation of the readings. A final node (Node 7) next to the gateway monitors temperature. The gateway for the system is powered by a 12V lead-acid battery attached to a solar panel and transmits data back to a server at the University of Cambridge using a mobile phone connection. The data from this network is also accessible in real-time via the Internet.

Figure 2 – Layout of the Ferriby Road Bridge WSN

To date the system has picked up very little change in the crack widths (<0.02mm) over the first nine months of monitoring. Whilst changes in the bearing inclination have been more significant, these changes have been driven by diurnal and seasonal thermal changes and have not represented a long-term trend. This lack of fluctuations in the data is expected to be the case with most long-term monitoring applications. The systems will be used to ensure long-term trends stay within allowable limits rather than detecting large discrete events. The critical point will be deciding what these allowable limits are for a given structure and ensuring that engineers and managers are made aware of any problems in a timely fashion so that effective action can be taken, as will be discussed later. The gateway lost power on several days during the winter months, which was a result of the solar panel not providing enough energy. However further discussion of this is beyond the scope of this paper.

It is interesting to note what the potential environmental impact of needing to replace the Ferribly Road Bridge would be. First of all, based on the estimate of 400kg of CO_2 produced for every $1m^3$ of reinforced concrete and a reinforced concrete volume of approximately $5750m^3$ required for the Ferriby Road Bridge, rebuilding the bridge would generate 2300tonnes of CO_2. And this value only accounts for the construction of the bridge and not associated activities such as transport of materials and disruption to traffic. For example, if the Ferriby Road Bridge must be replaced this means that the main suspension bridge is no longer accessible and thus vehicle users hoping to cross the Humber estuary must instead drive around it resulting in further CO_2 emissions. As such there is a significant and quantifiable environmental benefit in extending the service life of the structure and being able to plan more effectively based on the data provided. For example, if it was noticed that the condition of the Ferriby Road Bridge was deteriorating, plans could be put in place for the construction of a new bridge while the current bridge was still in service. The data from the WSN could be used to evaluate the condition of the current bridge on a day-to-day basis ensuring that it was still safe. This would then allow for a potentially seamless transition from one bridge to another eliminating the environmental damage caused by rerouting traffic.

2.3 London Underground Monitoring

In June 2008 a WSN was installed over a two week period of night time track possessions in a London Underground tunnel (10 – 4 hour shifts) between Bond Street and Baker Street stations. The goal of this installation was to measure the long-term movement of a segment of precast-concrete lined tunnel. One of the issues facing London Underground is the effect that construction on the surface has on their below ground infrastructure and how they can manage any issues so that the Tube can remain operational indefinitely. The faster installation times that are possible with WSNs versus wired systems are very attractive for this type of application due to the limited possession times available. The system installed here consisted of 26 nodes in total as illustrated in Figure 3. Sixteen of these nodes are inclinometers that are attached to the precast concrete tunnel lining panels. These nodes are intended to measure changes in the orientation of the panels. There are also six LPDT nodes, four of which measure displacement across the crown of the tunnel and the other two monitor crack width changes in two of the precast lining panels. Both the inclinometer and LPDT nodes cost approximately €200 each. Finally there are an additional four nodes that allow data from the other nodes to be relayed back to the gateway. Because of the lack of Internet connectivity in the tunnels the gateway for this system consists of two parts. A Crossbow MIB600 in the tunnel receives transmissions from the nodes and sends the data via Ethernet to a Linux computer at the top of a ventilation shaft 500m away. This computer connects to the Internet using a mobile phone connection. As with the previous two networks this allows for real-time monitoring of the system.

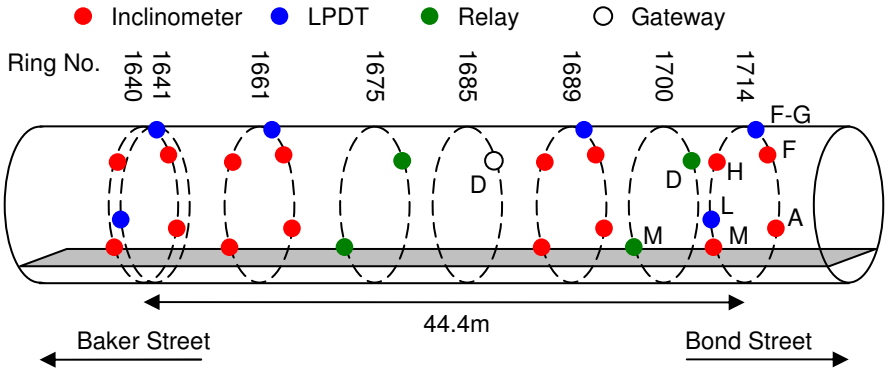

Figure 3 – Layout of the London Underground WSN

Not enough data has been acquired to date to draw conclusions about the structural performance of this section of tunnel. However it is clear that long-term closure and reconstruction of any section of the Underground network would have a disastrous effect from an environmental perspective. Not only would the financial costs be almost incalculable but the CO_2 emitted by the increased surface traffic would also be dramatic. So from this perspective one can easily see the need and the justification for making timely decisions about repair and maintenance based on the most accurate and up-to-date information possible.

3 LARGE-SCALE WSN DEPLOYMENT

The individual WSN deployments of section 2 have all proved successful in their own right and have provided the individual infrastructure owners with valuable data about the condition of individual assets. However, if infrastructure managers and engineers also had access to data and information about other assets in the area, could that allow them to make better decisions about how to manage not only that asset but also all the infrastructure under their control? As a step towards answering that question a large-scale WSN will be deployed in London. The network will be installed in an area where bridge and geotechnical assets are in close proximity. This will allow for both the use of common WSN hardware and the sharing of data between infrastructure operators. The goal of this deployment is to determine whether pervasive monitoring is both technically and logistically feasible but also to see if the data provided by such a network can be used effectively. It is this effective use of the data that is one the key hurdles that pervasive monitoring, not just wireless monitoring, must overcome if it is to be used as a tool for extending the service life of infrastructure.

4 CHALLENGES FACING WIRELESS SENSOR NETWORKS

There are three key challenges that must be overcome if pervasive WSNs are truly to become a useful tool for infrastructure management: (i) lack of appropriate sensors, (ii) robustness of the systems and (iii) data selection, visualization and management.

In this project interfaces were developed to connect displacement transducers and high-resolution inclinometers to commercially available nodes because there was not a readily available off-the-shelf solution. At present further development is needed before most commercially available sensors can be employed in a ‘plug and play’ manner in WSNs which places a limit on the creation of pervasive monitoring networks. Until infrastructure managers can install systems that can be purchased off-the-shelf, WSNs will remain largely in the realm of university researchers. However a more significant stumbling block is that currently sensors

do not exist to accurately and measure reliably two of the most significant structural deterioration mechanisms: fatigue and corrosion of steel elements. Until this void in available sensors is filled, it will be very difficult to offer engineers and managers a comprehensive picture of structural performance.

Although not dealt with explicitly in this paper, there have been several issues to do with node connectivity (Hoult et al. 2008) and reliability that were encountered in all three small-scale deployments outlined above. In both the Humber Bridge anchorage deployment and at the Ferriby Road Bridge considerable time was spent, many man hours spread over several months in both cases, getting all the nodes in the WSN to communicate with the gateway. In all three deployments, nodes have been replaced after the initial system was installed due to sensors malfunctioning. Whilst in a research environment such problems can be dealt with, and to some extent are expected, if WSNs are to become pervasive they will invariably end up being installed by maintenance crews with limited or no formal training in areas such as radio wave propagation or electronics repair. Hence these systems will be required to be functioning once they are installed. Whilst this is not an impossible situation to envisage (one only need to look at the mobile phone industry to see how pervasive deployment improves the quality of both available connections and hardware) it is still an area that needs to be addressed before infrastructure managers would be willing to adopt these systems.

One of the key aspects of any structural assessment tool is data management. Presenting decision makers with pages of numeric data will not allow them to isolate the salient data. Presenting the data in a graphical format is an obvious improvement although if it is not clear what aspect or area of the structure the data relates to it still becomes difficult to use this data in a meaningful way. In this project data visualization tools have been developed that allow the user to see the data for each node in a graphical format overlaid on a 3-D model of the structure created in Google Earth. While this visualization tool is very effective, infrastructure managers are often more concerned about being alerted when action needs to be taken. Thus another element of the user interface will involve providing alerts when thresholds are crossed. However, though setting a threshold is straightforward, deciding what that threshold should be is often not. For the anchorage chamber WSN setting the RH threshold to be 60% would be logical as this is the critical value. But what is the critical crack width in the soffit of the Ferriby Road Bridge or the critical rotation of a concrete tunnel lining panel? One approach would be to trigger an alert when any movement at all occurs but this is probably too conservative in many cases. Certainly closing the London Underground every time a slight amount of movement was detected would lead to severe economic and, as mentioned earlier, environmental consequences. Indeed there is not a simple answer to the question and it is the subject of ongoing research within this project. A final overarching question is that of what to measure? For example, some researchers, in the absence of accurate corrosion sensors, measure structural vibrations to infer corrosion damage (e.g. Capozucca 2008). However, most real civil structural systems involve innumerable variables that can affect the dynamic properties (e.g. geometric and material variations, changing boundary conditions, environmental effects) and so it can be extremely difficult to isolate the effects of corrosion. Thus another point of ongoing research is to determine what to measure for a given structure.

5 CONCLUSIONS

The construction industry produces significant amounts of CO_2 emissions meaning that civil engineers have a role to play in mitigating climate change. One way to reduce the amount of CO_2 produced is extend the service life of existing structures. However this can only been done if engineers and infrastructure managers have a better understanding of how their structures are performing, which in turn requires extensive data. One potential technique for providing this data is the use of a WSN. WSNs potentially offer significant economic and practical advantages

over conventional wired monitoring systems since they do not require wiring to be installed and often use inexpensive MEMS sensors. Three small-scale WSNs have been deployed as part of ongoing research at the University of Cambridge investigating the use of WSNs for pervasive monitoring of civil infrastructure. The first deployment in the north anchorage chambers of the Humber Bridge monitors RH and temperature in an area where the RH level is critical. The system offers the potential to reduce CO_2 emissions through optimized management of a humidification system and through ensuring that the wires of the main suspension cable are maintained in good condition. A second network on a nearby reinforced concrete bridge as well as a third network in the London Underground allows managers and engineers to monitor changes in the structural geometry and condition. By monitoring long-term trends in the data it is hoped engineers and managers will be able to schedule maintenance and repairs more effectively and thus optimize the service life of these structures. A large-scale deployment is planned in London that will monitor bridge and geotechnical assets in close proximity to one another as the next step towards developing pervasive monitoring solutions. Whilst the developments so far have been promising, issues related to sensors, robustness and data management must still be overcome if WSNs are to be an effective tool that will allow the service life of civil infrastructure assets to be optimized.

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