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Wireless sensor networks: creating 'smart infrastructure'

The deterioration of civil infrastructure is a significant issue throughout the world. To manage infrastructure in a way that ensures safe and efficient operation, managers and engineers require data about its short- and long-term performance. This paper reports on the trial installations of wireless sensor networks in a suspension bridge, slab bridge, rail tunnel and water supply pipeline. Each installation is introduced in terms of hardware, measured parameters, sensors, sampling regimes and installation and operational challenges. Preliminary results from each system are discussed to illustrate the variety of information that can be made available to managers and engineers, and how this information can be utilised and presented.

Much of the world's civil infrastructure suffers from significant levels of deterioration but there is insufficient investment for refurbishing or replacing components that are deemed to be inadequate.

As a result, management programmes are required to optimise and prioritise available resources by establishing which structures are in adequate condition, which require maintenance and which need replacement. This is a significant challenge, particularly as data about the present condition and performance of many assets are not available.

The availability of data with the required spatial and temporal resolution is thus a critical underlying requirement for the safe operation and informed asset management

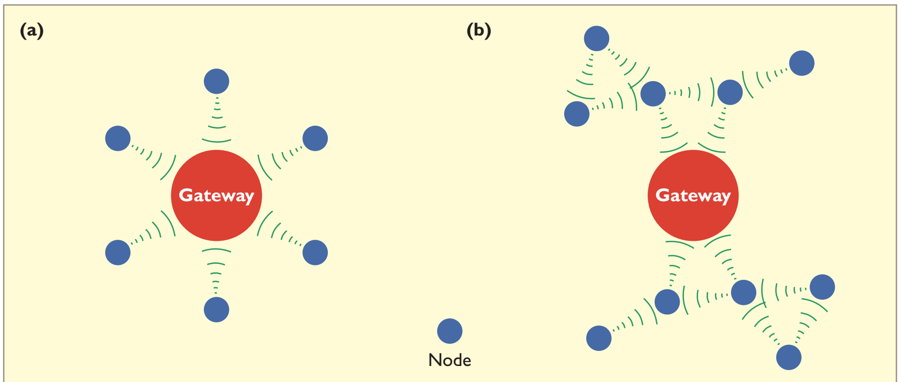

Figure 1. Potential wireless sensor network configurations: (a) star topology, where all nodes communicate direct to the gateway computer; (b) mesh topology, where nodes can communicate with each other

of civil engineering infrastructure.

One way to acquire data about structural performance is to install a monitoring system. Conventional monitoring systems employ a series of sensors connected together using wires to transfer the data and supply the power. These sensors are then connected to a data logger which stores the data and allows the user to access it either remotely or on site.

The sensors, cabling and installation for a conventional monitoring system can represent a large capital expenditure, especially for a system with many sensors. Given the limited funds available for maintenance and replacement of infrastructure, managers would prefer to spend the bulk of the available money on the infrastructure itself rather than on monitoring systems.

Wireless sensor networks

As part of an Engineering and Physical Sciences Research Council (EPSRC)-funded research project, a team of researchers from the University of Cambridge and Imperial College London are investigating the use of wireless sensor networks to see if they can offer an effective and economic alternative to conventional monitoring systems.

Like conventional systems, wireless networks consist of sensors and data loggers; however, the wires and associated installation costs are replaced with radio connections, which could result in significant cost savings. Developments in the field of microelectromechanical systems (MEMS) also mean that previously expensive sensors can now be replaced with inexpensive, low-power alternatives. There is often a trade-off in resolution, especially when measuring acceleration, between MEMS sensors and their traditional counterparts. However MEMS sensors have increasingly better resolutions and are usually accurate enough for civil infrastructure applications.

There are, however, some drawbacks. First, each sensor node must, in most cases, be battery powered (or self-sufficient in terms of power) and the replacement period should satisfy specific industry requirements. Second, the data-transmission bandwidth varies significantly depending on the chosen radio frequency and transmission power, which affects the power consumption, meaning that greater care has to be taken in deciding what data to transmit, how often and with what time lag.

Currently, research in the area of wireless sensor networks focuses on laboratory-based studies[1] and short-term field deployments for water quality,[2] tunnel[3] and bridge[4] monitoring. Deployments on bridges, both large-scale[5] and long-term,[6] tend to focus on vibration monitoring. There has been very little research into large-scale, long-term deployments of wireless sensor networks for monitoring a number of different aspects of performance across multiple types of civil infrastructure.

The goal of the research was therefore to develop wireless sensor networks with a large number of deployed sensors that can be used across the three different types of infrastructure under investigation – bridges, tunnels and water distribution networks – and address their specific needs.

This paper reports on the first stage of the project, which involved installing smaller individual wireless sensor networks on each type of infrastructure as a proof of concept. Deployments on bridges, tunnels and water-transmission pipelines are described including the types of wireless sensing solutions used, the initial monitoring results and how the data are presented to the infrastructure manager.

Configuration options

A wireless sensor network consists of 'nodes', which have on-board computing power as well as a radio and may or may not have a sensor, that are typically battery powered and a 'gateway', which is a computer that connects the nodes to the outside world. The nodes can be connected using a variety of topological configurations.[7]

One of the most common configurations is the star-topology, as illustrated in Figure 1(a), where sensor nodes transmit to the gateway directly. The gateway acts as a data sink that receives the data from the network and can be accessed using a variety of internet communication options (e.g. asymmetric digital subscriber line (ADSL), WiFi, and mobile phone modems). A mesh topology, as illustrated in Figure 1(b), is another potential configuration for a wireless sensor network, whereby the nodes are connected to one another as well as the gateway.

The choice of topology depends on the application and, in this initial phase of the project, two different types of wireless sensor networks were trialled: one for bridges and tunnels, and a second for water-transmission pipelines and distribution networks.

For bridges and tunnels the primary concern was to acquire data about the long-term changes in performance at a number of different locations on the structure. This required a wireless sensor network with numerous closely spaced nodes that sample data at a relatively low frequency of the order of minutes or even hours. Since the nodes are closely spaced, it does not make sense to have radios that transmit all the way to the gateway as they consume more power, especially if there are objects in the way. Instead, a mesh topology is used so that the nodes can communicate with one another as well as the gateway so as to minimise the required transmission distance and find the most efficient transmission path.

Water transmission pipelines and distribution networks, on the other hand, require a remote sensing solution that can capture events over a much wider spatial area. In this instance, a variety of communication options are used including a cellular modem, single-hop low-power radio or a combination of both. A significant challenge and a main objective of the ongoing research is to monitor the hydraulic conditions over a highly variable time period (e.g. from milliseconds to hours), which requires much higher and adaptive sampling rates.

Bridge and tunnel monitoring

To evaluate the viability of wireless sensor networks for tunnel and bridge monitoring, several discrete networks were installed based on the Crossbow Micaz node platform,[8] a commercially available product that comes with a software library that can be modified to suit the specific application. The node has a low-power processor and radio so that it can

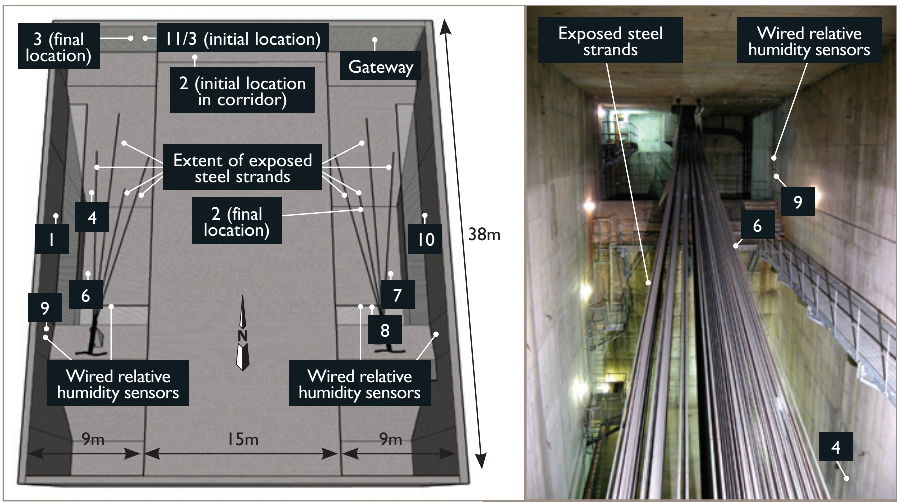

Figure 2. Wireless sensor network in the north anchorage chambers of the Humber Bridge: (a) three-dimensional view; (b) inside the north-west anchorage chamber

Three long-term deployments, two at the Humber Bridge and one in the London Underground, were installed to evaluate the potential of wireless sensor networks for long-term monitoring

function for long periods of time without battery changes. The platform also allows networks to extend over large distances by using a communication technique known as multi-hop routing, where messages can be transmitted via intermediate nodes to reach the gateway.

Three long-term deployments, two at the Humber Bridge and one in the London Underground, were installed to evaluate the potential of wireless sensor networks for long-term monitoring.

Humber Bridge

The first of the long-term evaluation networks was installed in June 2007 in the north anchorage chambers of the Humber Bridge, the UK's longest suspension bridge. The steel strands that make up the main cables of the bridge are exposed to the environment in these chambers, so it is important to maintain relative humidity levels below 60%.[9] Thus all four anchorage chambers (there is one at the end of each main cable) have had dehumidification units installed.

A wired relative-humidity monitoring system that was previously installed had two main drawbacks: the data were only accessible from display units in the chambers and the two wired sensors in each chamber were not located in areas adjacent to the strands themselves, but rather in areas where it was more convenient to place the sensors and their wires. To make these critical data available to the bridge master in a more timely and comprehensive fashion, a wireless sensor network was installed as illustrated in Figure 2.

The sensors are located both next to the existing sensors for verification and also nearer the exposed strands so that a more accurate picture of the relative humidity levels in the chamber can be created.

When the network was first installed, the nodes in the north-west chamber (see Figure 2(a)) could not be seen by the gateway in the north-east chamber. This issue is discussed in greater detail elsewhere[10] but highlights one of the key potential problems with wireless sensor networks versus wired systems, which is network connectivity.

The first battery replacement was required after 10 months and the batteries for the remaining nodes were all changed after approximately 12 months. The time between battery replacements can be improved by using lithium as opposed to alkaline batteries but there is an associated cost penalty.

Ferriby Road Bridge

The second wireless sensor network was installed for long-term evaluation on the Ferriby Road Bridge, a three-span rein-

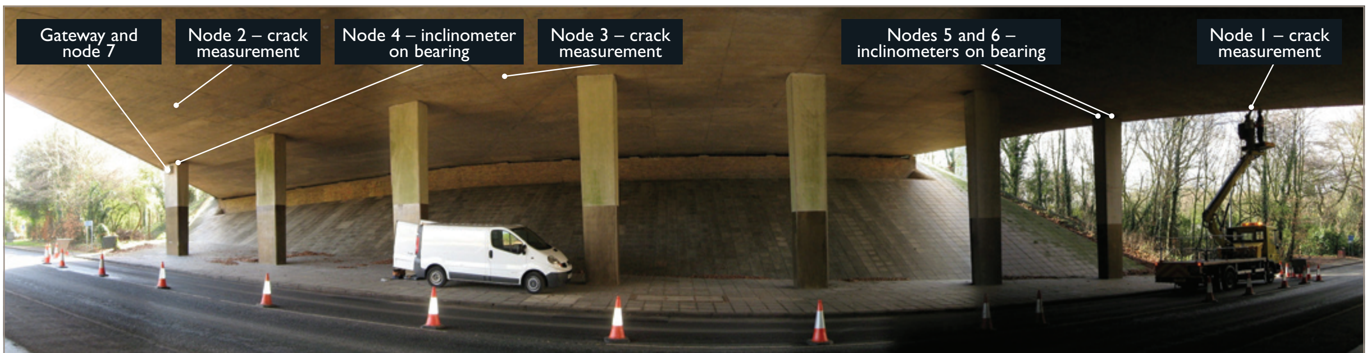

Figure 3. Ferriby Road Bridge wireless sensor network layout

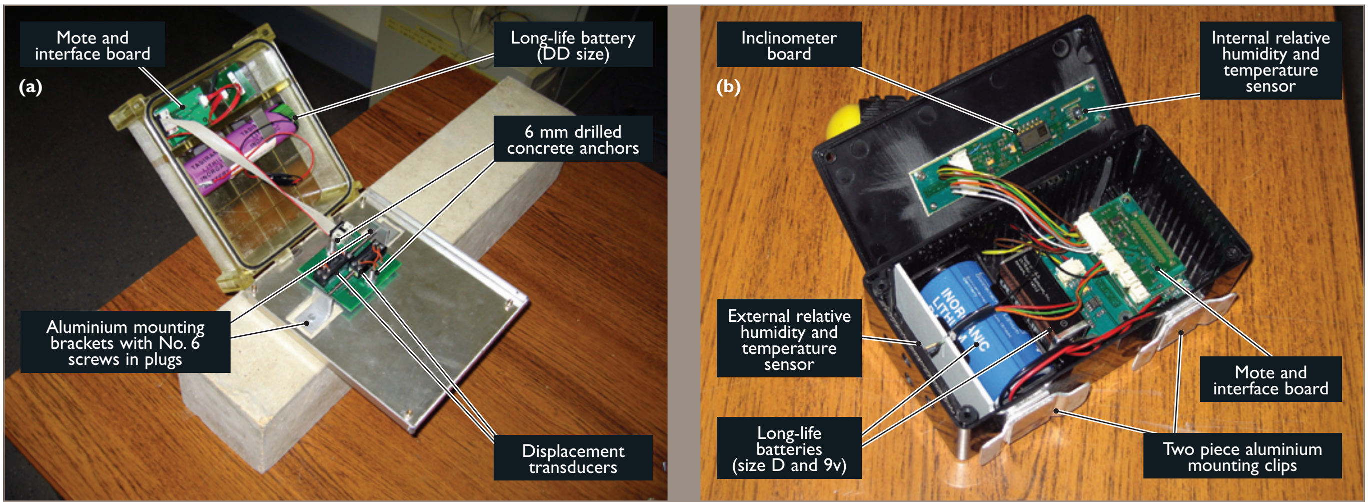

Figure 4. Ferriby Road Bridge sensors: (a) displacement transducer to measure crack widths as well as temperature and relative humidity; (b) inclinometers installed on elastomeric bearings

forced concrete bridge, which provides access to the north end of the Humber suspension bridge. In 2002, a principal inspection of this bridge noted that there were cracks, both transverse and longitudinal, in the soffit of the bridge deck. It was also noted at that time that some of the elastomeric bearings at the abutments appeared to be inclined transversely to the bridge. In both cases there is the potential for the problem to deteriorate such that maintenance would be required.

A wireless sensor network was thus installed in March 2008 to provide data about the change in both the crack widths and the bearing inclination as illustrated in Figure 3. Three nodes equipped with displacement transducers to measure the change in crack widths as well as relative humidity and temperature sensors, as seen in Figure 4(a), were attached to the soffit of the bridge using drilled concrete anchors. Three nodes equipped with inclinometers, as illustrated in Figure 4(b), to measure the inclination of the bearings were mounted to the elastomeric bearings using aluminium brackets. Each of these nodes transmitted data back to the gateway, which in this case was a compact low-power computer.

Due to the remote location of the gateway, it cannot easily be powered from a mains supply. Instead it is powered by a 12 V battery that is recharged using a solar panel attached to the side of the bridge, as seen in Figure 5. The solar panel system worked well from the time

Figure 5. Solar panel attached to the side of the Ferriby Road Bridge to recharge the gateway's battery – this worked well in summer but only intermittently in winter

of installation in March until November 2008. However, during the winter months the panel did not provide enough energy to recharge the battery completely, which resulted in the gateway being powered intermittently. Efficient sizing of the gateway power system is the subject of ongoing research.

Jubilee Line tunnel

The third wireless sensor network was installed in a section of the London Underground on the Jubilee line between Bond Street and Baker Street stations in June 2008 and is still operational (as of April 2009).

The network consists of 16 inclinometer nodes, six displacement transducer nodes (both the inclinometer and displacement transducer nodes are the same as those used at the Ferriby Road Bridge except for the housing) and four relay nodes. The tight clearances between the tunnel walls and the tube trains meant that each sensor had to be secured in a box protruding no more than 35 mm from the wall, as seen in Figure 6.

The network is designed to pick up three potential indicators of tunnel deterioration: distortion, concrete spalling at the tunnel crown and increased crack widths in the precast concrete tunnel-lining segments. The sensors are placed on five separate rings within the tunnel as illustrated in Figure 7. On four of the rings, inclinometers have been placed at four points around the lining to detect distortion, and a displacement transducer has been placed across the joint between the two precast concrete panels that form the crown to monitor movement. Two further displacement transducer nodes have been installed across cracks in the precast panels to ensure they are stable and not widening with time. Four relay nodes are provided so that a multi-hop network can be formed to transmit data from the various rings to the gateway.

The gateway for the system is composed of two pieces of equipment: a unit placed in the tunnel that receives data from the nodes; and a computer at the top of a ventilation shaft that logs the data via an ethernet connection to the unit in the tunnel. The reason for having a two-part gateway is that, to achieve a mobile-phone internet connection between the gateway and the offsite server, part of the system had to be outside of the tunnel where a mobile-phone signal can be obtained.

The ratio of dropped transmissions to the total number of transmissions gives an indication of network reliability. The average ratio for the London Underground nodes is approximately 9%, which is not unreasonable when one considers the potential interference from trains. The ratio could be improved by specifying that each dropped transmission is resent until successful, though this increases battery usage.

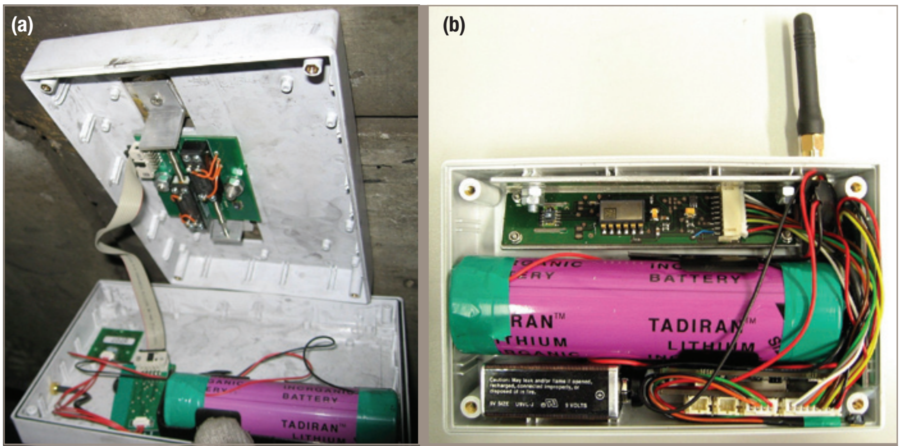

Figure 6. London Underground sensor nodes, which had to protrude no more than 35 mm from the tunnel wall: (a) displacement transducer to measure movement at tunnel crown and crack widths; (b) inclinometers installed on precast concrete tunnel lining panels

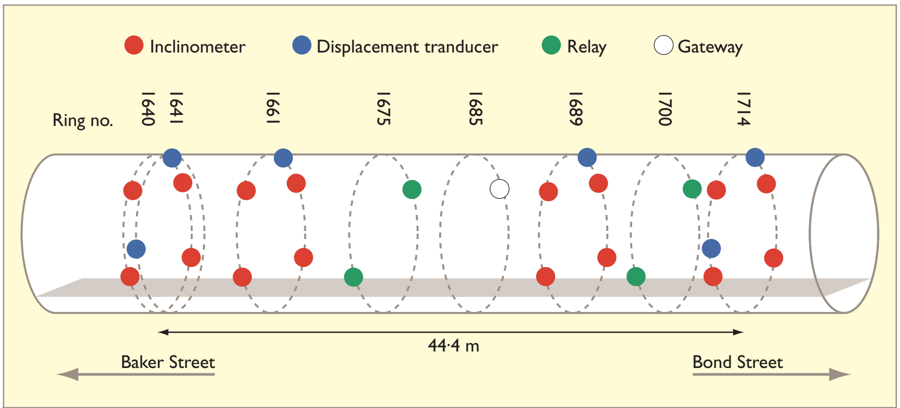

Figure 7. The London Underground wireless sensor network was arranged over five separate tunnel rings – relay nodes are used to transmit data to the gateway

Water supply system monitoring

The topology and spatial distribution of water-supply systems (transmission and distribution mains) require a different solution to the multi-hop mesh formations described in the previous section. Traditionally, the water industry uses 15-minute sampling intervals as the data are either collected manually or several times a day via mobile-phone-based communication protocols, such as the global system for mobile communications (GSM), short message service (SMS) or general packet radio service (GPRS).

In reality, the hydraulic conditions vary continuously and occasionally large pressure variations occur due to regular operational changes, malfunctioning control valves or aggressive pump optimisation. These pressure variations, known as pressure transients (or surges), occur over a short period of time and have the potential to dislodge sediments that have formed on the pipe wall, reduce

Figure 8. Water-pressure measurement node: (a) pressure sensor and node viewed down manhole; (b) close-up of pressure sensor

water quality and damage the pipe itself if they remain undetected.

Existing telemetry systems cannot capture pressure transients and therefore one of the primary research objectives was to develop a novel data-acquisition solution which can continuously monitor the hydraulic conditions and capture both sudden and long-term variations in hydraulic conditions. The ultimate objective is to sample pressure continuously at a sampling rate within the range of 10–200 samples per second while satisfying the industry requirement for a 5-year battery life.

A first-generation prototype device was used, which was developed by the infrastructure sensing laboratory at Imperial College London around the Imote2 node, another commercially available wireless sensor network node. This has a more powerful central processing unit than the Micaz to process larger volumes of data. The data are continuously sampled, compressed and communicated at discrete intervals via GSM/GPRS.

On average, the battery life was 8–10 weeks for a 3·6 V battery with a capacity of 38 Ah. While the prototype sensor provided a convenient development platform, it has relatively high power consumption. To satisfy industry expectations regarding battery life without compromising the functionalities for continuous sampling and event-based communication, a second-generation node is currently being developed which includes a thorough redesign in terms of hardware, embedded software, radio and power management.

As an initial proof-of-concept, 12 nodes with GPRS connectivity and an additional 20 nodes that were GPRS-enabled but not connected were produced and deployed to monitor the hydraulic conditions in a 1·2 m diameter cast-iron transmission mains. The trial lasted 6 months. Some of the sensor nodes were moved during the study so a total of 76 locations were monitored. The installed nodes were attached to sensors measuring pressure in the water flow, as illustrated in Figure 8.

The major advantage of the developed prototype over existing telemetry solutions was the capability to capture dynamic hydraulic conditions and the possibility to stream real-time data on demand, or when an event occurs, over the internet. This has the potential to

- allow the detection of pipe bursts in near real-time, which is critical for large-diameter water mains
- guarantee the safe and near steady-state operation of water-supply systems by detecting and analysing sudden variations in flow velocity and pressure.

Monitoring results

The two types of networks, spatially dense wireless sensor networks with low-frequency data-sampling rates and spatially sparse wireless sensor networks with high-frequency data-sampling rates, demonstrate the flexibility in addressing specific application needs and constraints. For larger deployments the choice of wireless sensor network system will depend on the specific application, although in some cases it may well involve a combination of the two systems described here. The final phase of this project will investigate the deployment of a much larger network in the Hammersmith area of London. This network will consist of approximately 100 nodes and involve monitoring both a section of the London Underground as well as the Hammersmith flyover.

Spatially dense, low sampling rate

The data from the wireless sensor network in the Humber Bridge north anchorage chambers are available in real time via a web interface and Google Earth model from anywhere in the world.

One interesting trend the system has identified is the difference in performance between the dehumidification units in the north-west and north-east chambers, which are automatically activated when the sensor in the dehumidifier indicates that a preset relative humidity threshold has been crossed. It can be seen from Figure 9 that the relative humidity in the north-west chamber varies over a far greater range than in the north-east chamber but, interestingly, the north-west chamber's dehumidifier consumes less energy because it powers on less often.

The net difference in power consumption per year between the two dehumidification strategies is 9·3 MWh, which means that the dehumidifier in the north-east anchorage is producing 4 t more carbon dioxide per year than the dehumidifier in the north-west anchorage. By adjusting the automatic dehumidification controller settings based on the data obtained from the wireless sensor network, there is the potential for both financial and environmental benefits to be realised.

The data from the Ferriby Road Bridge network are also available anywhere in the world via a web interface as well as a Google Earth interface. The advantage of using this type of display is that the structure can be visualised in three dimensions in its true location in space. This allows users to see other important features in the vicinity, which in the future could include other wireless sensor networks. If an event occurs in one area, infrastructure managers would be able to see what relevant data are available in the vicinity of that structure and access it at the click of a mouse. The data produced by the Ferriby Road Bridge network to this point have been unremarkable, which is to be expected as deterioration is generally a long-term process and so trends will only become evident over the course of years or even decades.

The Jubilee line monitoring system has been operational since June 2008. This wireless sensor network has been installed in the same tunnel section as a wired system of vibrating-wire strain gauges as well as a fibre-optic strain-measurement system. This juxtaposition of sensor technologies should provide an excellent opportunity both to verify the data from each system as well as allowing direct comparisons of installation time and cost.

Although the movements have been very small and so are not presented here for the sake of brevity, it is worth noting that all three sensor technologies have indicated the same trend in the results. A comprehensive comparative analysis of these data is currently underway and will be published at a later date.

An interesting diurnal trend that the system has picked up is illustrated in Figure 10, which shows the change in temperature and relative humidity in the tunnel over the course of a 24 h period. It is suspected that this trend for the temperature to increase during the day before decreasing in the evening is due to radiant heat from the trains (and the commuters inside) as they pass through the tunnels as well as the warmer air from the stations being circulated through the tunnels due to the motion of the trains.

The relative humidity trends tend to be more variable than the temperature readings as quite often an initial peak occurs between 05:00 and 10:00 as illustrated in Figure 10, but this is not always the case. Once again, it is assumed that the effect is caused by trains circulating the air from the stations throughout the tunnels. Thus this greater variability in relative humidity data is the result of the relative humidity in the tunnels being partially dependent on the relative humidity in the stations, which is in turn related to the outdoor relative humidity.

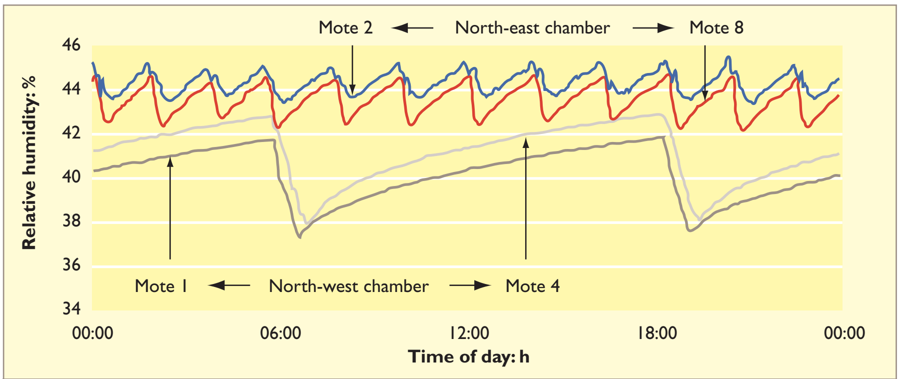

Figure 9. Relative humidity in the north-west Humber Bridge anchorage chamber varies far more than that of the north-east chamber, yet the dehumidifier uses less energy as it powers on less often

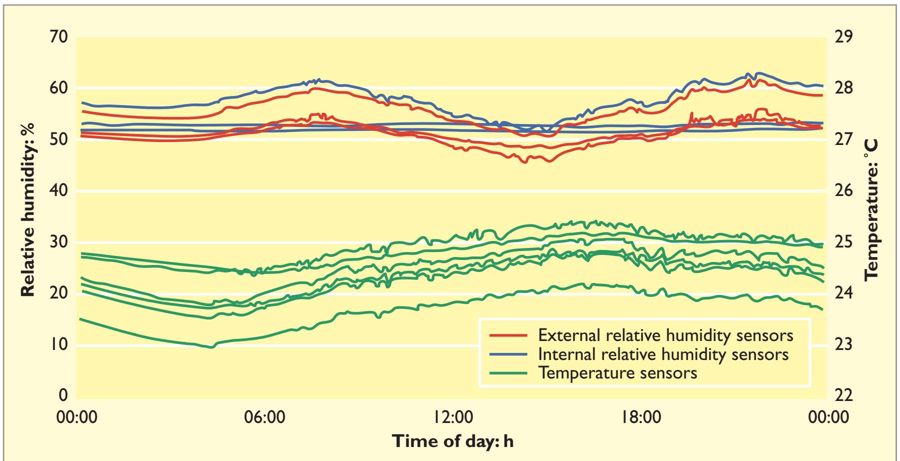

Figure 10. Relative humidity changes in London Underground are less consistent than temperature changes and appear to be linked to the humidity in the stations and outside

Spatially sparse, high sampling rate

Continuously sampling and periodically communicating large volumes of data (200 samples per second at 16-bit resolution) presents unique challenges in terms of hardware and software design in light of the need for extremely efficient power management.

The acquired data presented an insight into physical processes as they showed the significant variability in the hydraulic conditions of which pipeline operators had no previous knowledge. The data are extensively used for the further development of Pipenet, a turn-key failure diagnosis system for water-transmission pipelines.[11] Figure 11 shows 1 week of continuously acquired pressure data, with a sampling rate of 200 samples per second, during which time a pressure transient event occurred.

The deployed sensor nodes operated under extreme environmental conditions as they were frequently flooded. Ingress protection rating 68 enclosures were required, meaning that they are sealed against dust penetration and capable of submersion in water below 1 m.

Conclusions

Wireless sensor networks have the potential to be cost-effective tools that can be deployed on all types of civil infrastructure and provide managers with critical real-time data on performance. However, the wireless nature of these systems also has drawbacks in terms of power demand and data-transmission bandwidth.

As part of a project to evaluate whether wireless sensor networks can be used for pervasive monitoring of civil infrastructure, initial small-scale deployments are being trialled on bridge, tunnel and water-supply infrastructure. These deployments involve long-term monitoring of both low-frequency (readings taken every few minutes) and high-frequency (readings taken at 200 Hz) data-rate applications.

Both the bridge and tunnel systems involve the use of displacement, inclination and environmental sensors to monitor long-term changes in these values. The water mains monitoring network, on the other hand, required the capture of both short-term (sudden) and long-term changes that could have adverse effects on the operational conditions and water quality, and detect supply failures.

In each case the systems have given the infrastructure managers real-time access to data that was previously either unavailable to them or not available in a timely fashion. The success of each deployment has laid a solid foundation for further development towards large-scale pervasive wireless sensor networks for civil infrastructure.

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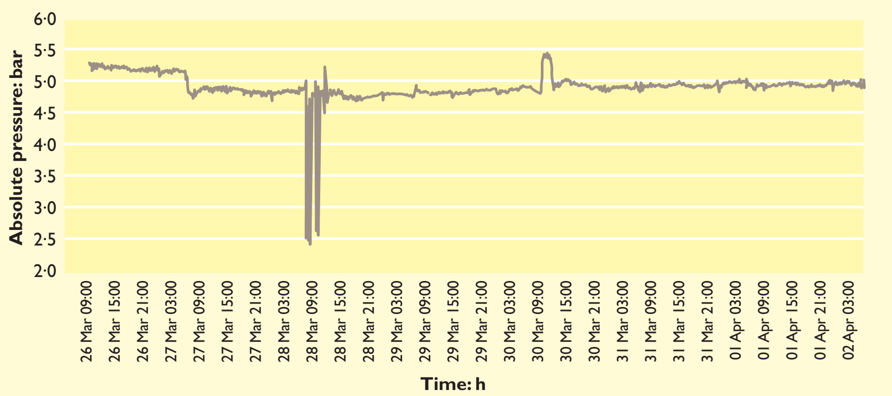

Figure 11. Mains water pipe pressure measured continuously at 200 samples per second over a period of 1 week revealed a potentially damaging pressure surge

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