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Authors

Soga, Kenichi
Schooling, Jennifer

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Author for correspondence:

Kenichi Soga

e-mail: ks207@cam.ac.uk

Infrastructure sensing

Kenichi Soga¹ and Jennifer Schooling²

¹University of California-Berkeley, Berkeley, CA 94720, USA and ²Cambridge Centre for Smart Infrastructure and Construction, University of Cambridge, Cambridge CB2 1PZ, UK

Design, construction, maintenance and upgrading of civil engineering infrastructure requires fresh thinking to minimize use of materials, energy and labour. This can only be achieved by understanding the performance of the infrastructure, both during its construction and throughout its design life, through innovative monitoring. Advances in sensor systems offer intriguing possibilities to radically alter methods of condition assessment and monitoring of infrastructure. In this paper, it is hypothesized that the future of infrastructure relies on smarter information; the rich information obtained from embedded sensors within infrastructure will act as a catalyst for new design, construction, operation and maintenance processes for integrated infrastructure systems linked directly with user behaviour patterns. Some examples of emerging sensor technologies for infrastructure sensing are given. They include distributed fibre-optics sensors, computer vision, wireless sensor networks, low-power micro-electromechanical systems, energy harvesting and citizens as sensors.

1. Introduction

Many governments around the world continue to invest in infrastructure to support their economic status. The economic potential and social well-being of cities rely heavily on physical infrastructure including buildings, water, energy, transport and communication networks. Although much of our physical infrastructure is constructed to last for many years (e.g. engineering design life of more than 100 years), its usage is linked to individual preferences and community needs, which can change dramatically every decade. That is, existing infrastructure is challenged by the need to increase load and usage—be that number of passengers carried, numbers of vehicles or volume of water used—and the requirement to maintain the existing infrastructure while operating at current capacity. Increased usage is not the sole concern; a demographic change to an older population will alter the way we use our infrastructure. We need to assess the resilience of our infrastructure against rapid changes in social networks, interactions and policies.

Ideally, infrastructure should be designed to be adaptable to satisfy the demands. However, the past engineering design philosophy has been rather rigid, based on a demand prediction given at that time. Therefore, we have to embrace the fact that much of our current existing infrastructure in cities will be fixed in space for many decades. The high cost involved in upgrading will lead to a desire to extend its life. These demanding challenges create issues on ageing infrastructure, which we see in our everyday life, and is rising to the top of the political agenda (e.g. UK National Infrastructure Plan [1], State of Nation [2], Report Card for America's Infrastructure [3]).

For future-proofing, active monitoring of construction and operational processes of civil engineering infrastructure is essential. This implies that structures are instrumented to assess their performance against engineering design parameters or predictive models. Emphasis on monitoring is not new in civil engineering. In fact, monitoring has been extensively used in civil engineering for decades ever since the use of observational method, where feedback from monitoring systems are used to inform and potentially modify the design and construction.

On the other hand, the civil engineering sector is often a late adopter of new sensing systems. Reasons for this include fragmented supply chains, reliance on past experience and practice, concerns about safety and robustness, etc. In many cases,

sensor systems developed in other industrial sectors (automobile, aerospace, electronics manufacturing, oil and gas) are modified to fit the immediate need. Typically, in the civil engineering sector this modification process is conducted using off-the-shelf technologies and the resulting products often do not fit well with the demand, producing unsatisfactory datasets for decision making and being perceived as too costly.

In recent years, sensor and communications research has been undergoing a revolution. Sensing is rapidly becoming part of everyday life for health, environment, security and living. An effective use of existing and new smart monitoring systems with better understanding of how people use the infrastructure services would lead to the realization of resilient adaptable infrastructure systems. There are possibilities to use other emerging sensor technologies (distributed fibre-optics sensing, wireless sensor networks (WSNs), low-power miniature sensors, energy harvesting for continuous monitoring, robotic inspections, satellite images, etc.) to address the particular needs to look after our infrastructure. Frost and Sullivan's Global Smart City Market report predicts that the smart infrastructure market will be worth \$300 billion in 2020 [4].

ISO 55000 standards on asset management [5] highlight the importance of the through-life management of physical infrastructure and emphasize realizing value rather than minimizing cost. The value of infrastructure now needs to be determined from a multi-stakeholder perspective. Infrastructure owners face this multi-perspective challenge and the challenge of balancing cost and risk originating from decreasing funding and increasing regulation. Infrastructure sensing can potentially support infrastructure owners to secure the best value for money throughout an infrastructure's lifetime and to make value-based infrastructure management decisions.

It is hypothesized in this paper that the future of infrastructure relies on smarter information; the rich information obtained from embedded sensors within infrastructure will act as a catalyst for new design, construction, operation and maintenance processes for infrastructure systems. However, there is a need to understand the capabilities and limitations of new sensing systems and what are the cost breakpoints that would gain acceptance. Hence, this paper first provides discussion on the need to quantify *the value of sensing* for infrastructure monitoring and then reviews various emerging sensing technologies that can realize the concept of 'smart infrastructure'.

2. The value of sensing

2.1. Why measure?

Maintaining the performance of linear infrastructure systems such as power supply, buried pipelines, railways and flood defence embankments is challenging because any localized structural defect or damage in a system can potentially disrupt the operation of the whole infrastructure as well as influencing the other neighbouring infrastructure.

The UK government mandated that all built assets procured by central government would be delivered using Building Information Modelling (BIM) Level 2 techniques, in which Level 2 means new-build (capital expenditure (CAPEX)) delivery (<http://www.bimtaskgroup.org/>). The main aim is to help develop a digitally enabled construction and facilities/asset sector. This initiative leads to the development of 'BIM Level 3', which includes asset lifetime areas (CAPEX + operational expenditure (OPEX)). In order to secure the best value for

money throughout an infrastructure's lifetime, infrastructure owners have to answer the following questions.

- How do we future-proof our infrastructure against changing requirements and against shocks?
- How do we operate, manage and maintain our infrastructure to deliver best whole-life value?
- Can human behaviour with data on user cost, human psychology and daily/weekly activity patterns at both the macro- and micro-levels be used to determine the value of infrastructure?
- What kind of institutional objective utility/optimization is needed for infrastructure owners?

To answer these questions, the quantification of infrastructure asset performance is essential and sensing coupled with infrastructure models and material models are needed. The models may be empirical, analytical or computational and probabilistic, if possible. The models need to utilize specific sensing data and potentially can do an inverse analysis to find the value of sensing, such as economical sensing requirements and sensor development for specific applications. New models can be developed based on newly available data previously not easily accessible, or existing models can be verified and modified based on data that new sensors can now measure. The models can be used to optimize sensor networks to provide a balance between the extent of data capture required and confidence in condition assessment for residual life or retrofit. For any infrastructure owner to invest in a new and potentially transformative sensing system, a quantitative evaluation of sensing value at monitoring points (such as for embedded sensors, moving sensors and citizen-based sensors) are needed.

Any sensing task should start from (i) identifying variables to be measured and (ii) developing a framework to quantify the value of sensing by converting the individual sensor measurements into something usable and valuable. For new structures, the emphasis will often be on giving an early warning of significant deterioration taking place (for example, rebar corrosion, concrete spalling, crack development, strain and stress changes and movements). For existing structures, the emphasis will usually be on monitoring the rate of an already active deterioration process. The two cases may be treated with the same basic approach: monitoring to assess the current condition and to estimate the residual life of the structure. The key challenge faced by many monitoring projects of linear infrastructure is the large overall expense of installing and maintaining a network of sensors, which may become obsolete due to fast technological advances. A sensing system that can accommodate these challenges in size and time is needed and distributed fibre-optics sensor systems, which are introduced in the next section, can be one of the solutions.

Understanding the interdependency of infrastructure systems is also the key to this value of sensing problem. It may be possible that a monitoring system for one infrastructure type is useful to examine the condition of another nearby infrastructure type. Such multipurpose monitoring systems can provide redundancy as well as additional information for decision making.

2.2. Life cycle of sensors and monitoring systems

Civil engineering structures are fixed in space and time (e.g. 120 year design life). Owing to different rates of technical

developments between monitoring system versus infrastructure usage, some data we will be using may be from older sensors and some of the sensors may be embedded now but data will be used in 50 years' time. At present, there is a mismatch between the lifespan of infrastructure and that of sensor systems, which makes the concept of whole-life cycle-based asset management difficult to achieve. Sensor systems to fulfil this concept need to be either long-life or adaptable for replacement. There are sensing systems potentially available for monitoring a variety of life cycle attributes. These include fibre-optics sensors that use long-lasting glass material as the sensor itself and digital images for damage mapping.

The data quality from sensors and monitoring systems changes with time and their possible error propagation due to ageing needs to be assessed so that system-level decisions made by whole-life cycle models are appropriate. The following questions related to the life cycle of sensors and monitoring systems need to be addressed.

- Do the currently available systems deliver to the requirements of the performance models to assess the whole-life cycle of buildings and infrastructure?
- What steps must be taken to ensure that the data to be harvested by embedded sensors are relevant, readable and useful throughout the life cycle?
- How long can sensors last?
- Can they easily be replaced as better solutions become available?

These questions lead to a demand for a whole-life cycle approach to monitoring and measurement systems. The approach should consider (i) data quality and its degradation with time, (ii) survival rates of hardware and software components and the associated error propagation and (iii) costs for management and maintenance. Any gaps among data formats need to be identified and good data transfer links are essential. This is because such links may produce errors. Such errors need to be quantified for accurate modelling and assessment of infrastructure performance.

2.3. Creating a business case for infrastructure sensing

The essential driver for infrastructure sensing should be to create a value for business and/or public in terms of immediate costs (e.g. sensor purchase) versus gains to be made downstream if sensors are put in place. That is, it is important to justify the capital cost involved in upfront investment in data capture/sensing. The cost of managing and maintaining the measurement and monitoring systems in the long term needs to be evaluated. The possibility to share the cost of acquiring data across government and private sectors also needs to be addressed.

In this regard, a knowledge database of monitoring systems and measured data is needed so that it is possible to conduct in-depth assessment of data quality and error propagation for measurement systems specifically designed to meet the performance requirements. The database should include immediate capital costs as well as cost of managing and maintaining the measurement and monitoring systems in the long term. It can also include data quality as well as error propagation, which will provide information to quantify the gains to be made downstream if the sensors are put in place.

At present, a strong, clear business case for smart sensing solutions and their key influence on enhanced resilience are

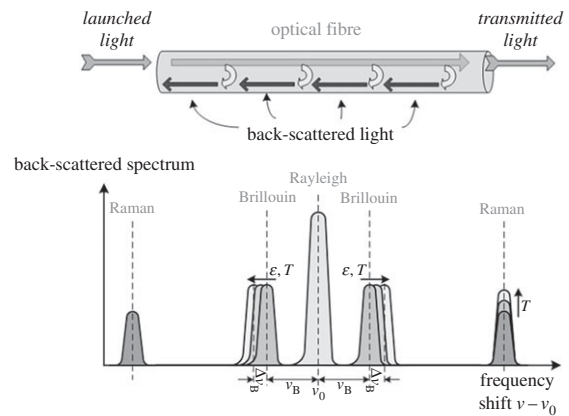


Figure 1. Back-scattering processes.

not yet available. These inhibit investment by infrastructure owners and local governments. The following four issues need to be assessed for sensor systems with technical, economic and societal points of view.

(1) *Integrated solutions.* While a number of key components for smart infrastructure solutions have been translated, there is a lack of fully integrated solutions which address the full data and information value chain from sensors through analysis to decision making for infrastructure management and city planning. Industry fragmentation creates challenges for any one organization to draw the different elements together and this discourages investment.

(2) *Security.* Ensuring secure operation from the earliest stage is very important. It is necessary to find the balance between the economic and security implications of different systems and to determine an optimal network layout, deployment, access control, privacy and firewall policies. The probability of malicious acts will depend on the nature of deployment and the activity that are designed to monitor. Preventing the sensor system from becoming dysfunctional is not feasible in many environments. However, the system can be designed to be resilient against individual loss if it is deployed in a decentralized manner with no single point of failure.

(3) *Industry appetite for innovation.* Infrastructure and construction are governed by strong regulatory requirements around safety and reliability, and the reputational damage caused by accidents or delays to service. This results in a cautious approach to introducing new technologies, tools and techniques.

(4) *Choice in the supply chain.* A lack of choice in the supply chain implies potential insecurity of supply, if the one firm offering a service or technology ceases to be able to do so. This can make clients and consultants reluctant to specify innovative technologies due to concerns regarding vulnerability of supply.

3. Examples of emerging sensing technologies for infrastructure sensing

3.1. Distributed fibre-optics sensing

The distributed fibre sensing technique use the response of an optical fibre by changes in ambient parameters like temperature, strain, vibration and noise (acoustic). As light travels through the glass material in an optical fibre, the majority of the light travels through but a small fraction of it is back-scattered. This scattering occurs due to inhomogeneity of the

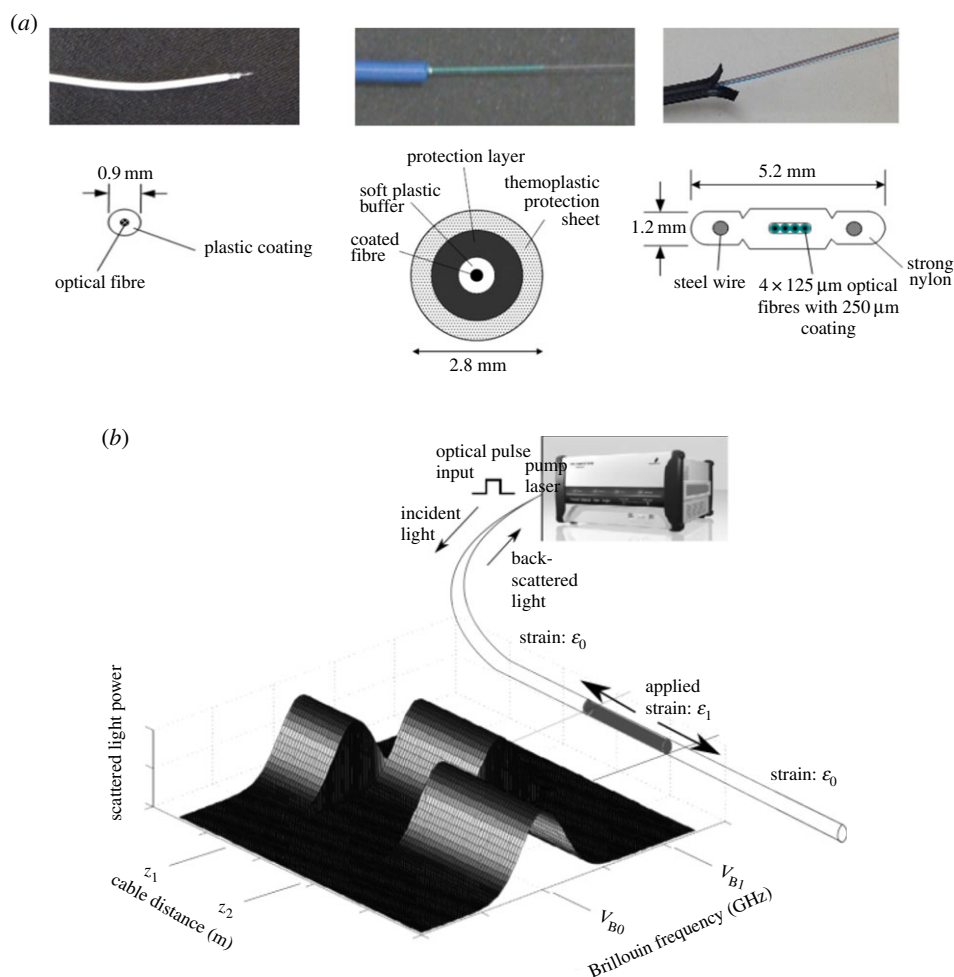


Figure 2. Fibre-optics sensing cable and an analyser (Brillouin optical time-domain reflectometry (BOTDR) system in this case); (a) fibre-optic cables for strain sensing and (b) BOTDR system. (Online version in colour.)

glass medium. The scattered light can either propagate in the same direction as the incident light or travel in the opposite direction; the latter is called back-scattering light (figure 1). There are three scattering processes: (i) Rayleigh, (ii) Brillouin, and (iii) Raman scattering. Rayleigh scattering propagates at the same frequency as the incident light. It is used to measure the loss distribution or attenuation along the length of the fibre by analysing the Rayleigh scattered light power. That is, a decrease in the scattered light power relates to the loss of light along the optical fibre. Brillouin scattering is temperature- and strain-dependent and the frequency shift of the Brillouin spectrum varies with longitudinal strain and temperature in a fibre. Raman scattering has spectrum power levels that vary according to temperature changes.

A typical distributed fibre-optics sensing system includes two components: optical fibre cables and an optical fibre analyser (figure 2). The latter performs a number of tasks such as data acquisition, data processing, transmission and storage. Different types of analyser detect different scattering signals. For example, Phase-OTDR (optical time-domain reflectometry) detects acoustically induced and dynamic multiple strain perturbations (e.g. [6]). It measures the phase between the Rayleigh scattered light from two sections of the fibre which define the gauge length. It senses vibration and acoustics for long distance. The Raman optical time-domain reflectometry (ROTDR) is a classical technology to measure temperature at many points along the length of an optical fibre (e.g. [7]).

The novel aspect of this new technology lies in the fact that standard optical fibre becomes the sensor and tens of kilometres of fibre can be sensed at once for continuous distributed measurement of the conditions around the optical fibre such as temperature, strain, acoustic noise, etc. Because of its simple and quick installation, distributed optical fibre sensing can be equally as practical as other conventional measurements. The cost of a standard optical fibre is potentially very low compared with point measurement sensors. The material itself (silica-based) is relatively inert and can be ideal for long-term monitoring when the fibre is embedded in structures. This implies that the quality of the data is expected to increase with time as the capability of analysers improves. Such features can potentially provide a relatively cheap but highly effective monitoring system for both the short and long term. Most of the capital investment relates to the analyser, which can be connected to a number of fibres or be shared at different sites. It is expected in the near future that more choice of analysers from more manufacturers would give a reduction in price with time.

Distributed temperature sensing (DTS) systems are based on a Raman scattering system, which can be used for power cable and transmission line monitoring, fire detection, and leakage detection at dikes, dams and sewers. It is widely used in down-hole temperature monitoring in oil and gas wells. Phase-OTDR can be used for security monitoring for long borders and perimeters at high-value facilities and

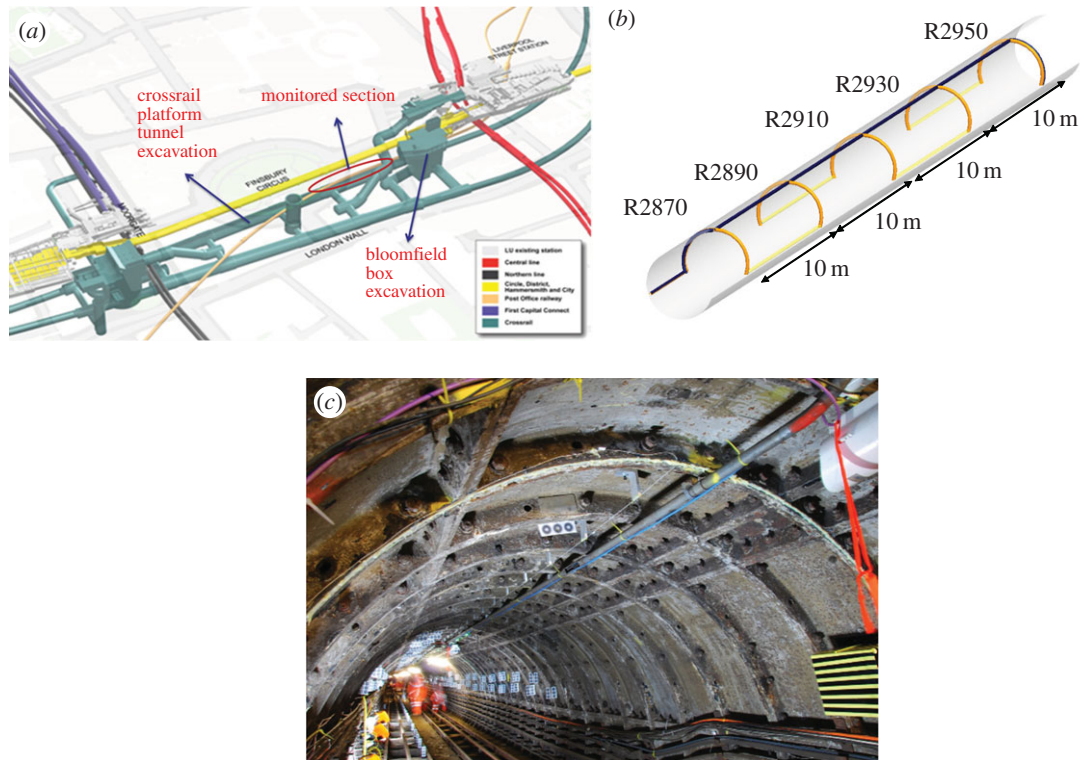


Figure 3. Installation of distributed fibre-optics strain sensing system at a tunnel construction site; (a) overview, (b) fibre-optic cable installation sections and (c) photo of fibre-optic cable installation. (Online version in colour.)

high-level security locations, or real-time position and speed monitoring of trains.

Engineering design limits are often based on strain and/or stress developing in the structure. Many structures interact with distributed load. In the context of monitoring strain in piled foundations, tunnels, pipelines, slopes or embankments, capturing the continuous strain profile is often invaluable to pinpoint non-uniformly distributed soil–structure interaction loads and localized problem areas such as joint rotations and deformations. Brillouin scattering-based techniques such as time-domain techniques called ‘Brillouin optical time-domain reflectometry (BOTDR)’ and ‘Brillouin optical time-domain analysis (BOTDA)’ are well established for distributed strain measurement [8–10]. BOTDR relies on spontaneous Brillouin scattering, which uses the incident light to generate the Brillouin signal. BOTDA relies on stimulated Brillouin scattering, which uses an external excitation signal to amplify the Brillouin signal. As shown in figures 1 and 2, the frequency of this back-scattered light is shifted from the original input frequency by an amount linearly proportional to the temperature and strain applied at the scattering location. By resolving the back-scattered signal in time and frequency, a complete strain profile along the full length of the fibre can be obtained. There are other strain sensing techniques such as Brillouin Optical Frequency Domain Analysis (BOFDA) [11] and Brillouin Optical Correlation Domain Analysis (BOCDA) [12]. Further details can be found in Bao *et al.* [13].

The current state-of-the-art distributed fibre-optic strain measurement systems provide data in the micro-strain range with a spatial resolution (strain is averaged over a specified gauge length) of 0.2 m or less. This means that it is possible to have thousands of ‘strain gauges’ along a single cable connected to structures, embedded in civil engineering infrastructure.

Figure 3 shows an example of distributed strain fibre-optics sensor installation at a tunnel construction site in London.

A fibre-optic cable was attached to a 100-year-old cast-iron tunnel, which was subjected to movements when platform tunnels were excavated nearby, as shown by the monitored section in figure 3a. The cable was installed in both longitudinal direction and cross sections, as shown in figure 3b. The white cable shown in figure 3c is the attached fibre cable. Figure 4 shows the strain changes of the cable attached at Ring R2950 of the tunnel. The vertical axis is strain (tension positive), whereas the horizontal axis gives the location of the cable attached to the tunnel. At the early stage of monitoring, tension is observed on one side and compression is observed on the other side. This is because a side tunnel near the old cast-iron tunnel was built first, as shown in figure 5. The measured strain profile shows an inclined elongation of the tunnel. At the later stage of monitoring, the strain pattern changes; tension is observed at the two sides and compression is observed at the crown. The main tunnel was excavated underneath the monitored tunnel, which elongated vertically, as shown in figure 5. The distributed nature of the data not only provides the strain data, but also shows the mechanisms of tunnel deformation clearly, which is useful for engineers to assess the engineering performance of this tunnel construction. Further details of the project can be found in Gue *et al.* [14].

In the past 10 years, the Cambridge University Geotechnical Group and the Cambridge Centre for Smart Infrastructure and Construction (CSIC) have conducted extensive field trials and demonstrations of this technology for different civil engineering applications (figure 6). Further details can be found in Soga *et al.* [15,16] and Kechavarzi *et al.* [17].

3.2. Computer vision

Using BIM for asset management (BIM Level 3) relies heavily on having an accurate model of the as-built infrastructure. New infrastructures have at best a design of BIM model that may

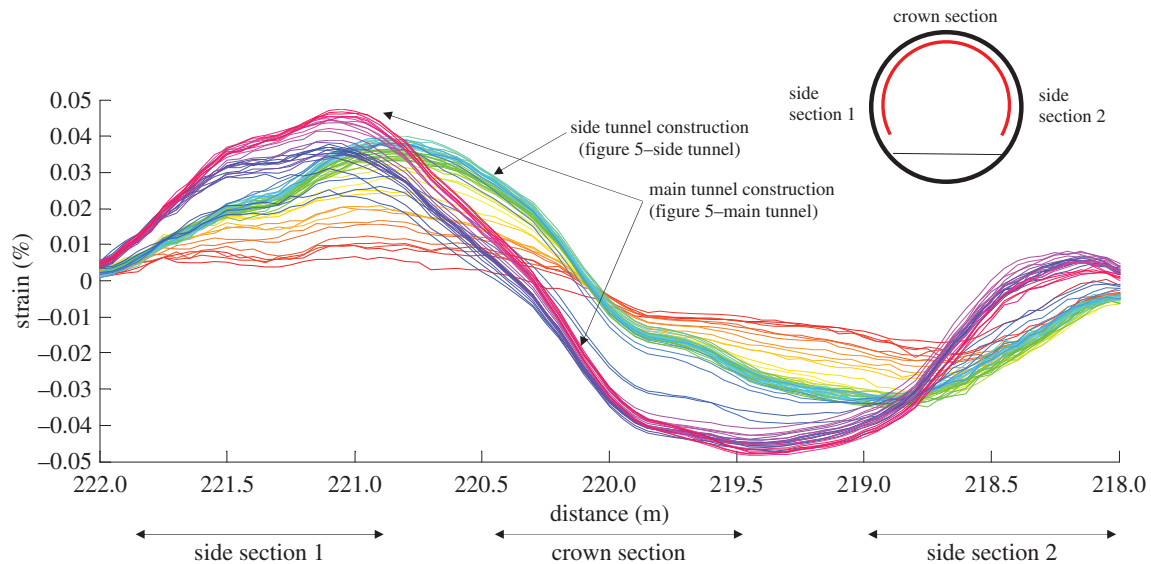


Figure 4. Example of distributed strain data at Ring 2950. (Online version in colour.)

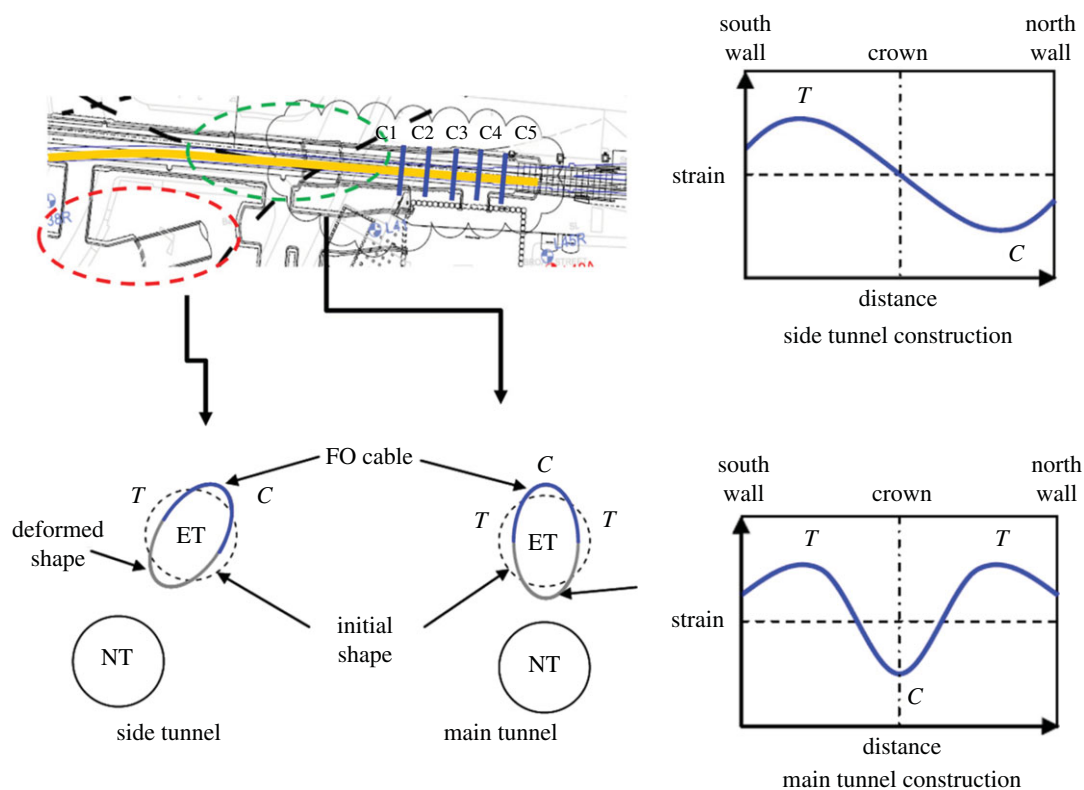


Figure 5. Observed mechanisms of the instrumented tunnel; FO, fibre-optics; ET, existing tunnel; NT, new tunnel. (Online version in colour.)

not have been updated throughout construction or afterwards, as changes and errors are common throughout the construction process. The majority of old infrastructure does not have usable as-built geometry information. Their current geometry and condition are possibly different from the initial design information. Over time, configurations can change, damaged/deteriorated areas may have been fixed and extensions may have been added. There is therefore a need to develop computer-vision-based sensing systems which can capture the as-is geometry and feed this back into the BIM model.

There are now a variety of laser- and optical-based systems that collect raw spatial and visual data (typically point clouds and images). The advances in digital photography have come to the stage that such technology can potentially replace more traditional and expensive surveying technologies. Structure from motion (SfM) is a system that is able to simultaneously

recover a three-dimensional point cloud model and camera positions using only images, as shown in figure 7a (e.g. [18,19]). Some SfM systems have recently been commercialized, such as Acute 3D. The software enables users to create a three-dimensional point cloud model from uploaded photographs and allows users to browse and navigate through the photographs. It can simultaneously cope with free camera motion and more complex geometry of the scene. Figure 7b,c shows a three-dimensional reconstruction of a tunnel and a rock cliff from their images. The accuracy is becoming close to that of traditional laser scanning methods. It is also becoming possible to detect the type of material of an object (i.e. concrete, steel, glass, wood, etc.) when the material is visible (e.g. [20]). A database of materials can be created so that semantics of a captured scene can be harvested via various computer learning techniques (e.g. deep learning).



Figure 6. Examples of fibre-optics (FO) strain measurement in geotechnical structures by Cambridge University and CSIC; (a) piles, (b) tunnels and (c) diaphragm walls for underground openings. (Online version in colour.)

For maintenance works of civil engineering structures, visual inspection is a common practice for detecting and monitoring anomalies such as cracks, spalling and staining. For typical civil engineering structures, the frequency of inspections ranges between 2 and 6 years. For example, the guideline from Federal Highway and Transit Administration [22] suggests that tunnel owners should establish a frequency for up-close inspections considering the age and condition of the tunnels. Visual inspection heavily relies on the experience of the inspectors; sometimes different inspectors examine the same structure at different times. Photographs and videos are commonly used as a mean of recording anomalies, although over years, image collections become large and difficult to organize and browse. Improving the ways that an image database is accessed and visualized is expected to result in substantial progress in the effectiveness of monitoring, in particular of tasks such as shaft inspection, where inspectors cannot easily access the inspection site.

One way to assist inspectors in organizing a large collection of images and examining the surface is providing them with automatic tools that combine a large number of pictures

into a single high-quality wide-angle composite view (figure 8). This process is commonly referred to as image registration, which involves transforming image sets from varying and unknown coordinate systems into one single coordinate system (e.g. [24]).

The goal of change detection is to identify the regions of change between multiple images of the same scene taken at different times. For example, changes to cracks may suggest deformation and additional reinforcement may be required to prevent further deformation. If the change is occurring rapidly, an urgent repair regime must be undertaken to prevent further ingress and harmful structural damage. But, if the change is slow, the regime may involve just a cosmetic repair. With the advances in computer vision, it is possible to identify and quantify regions of change in images of the same scene taken at different times because the images have spatial coordinates assigned. The system is inexpensive to implement and can reduce the workload for visual inspection significantly versus competing techniques, facilitating high-frequency and effective asset inspections. A prototype change detection system developed at Cambridge University

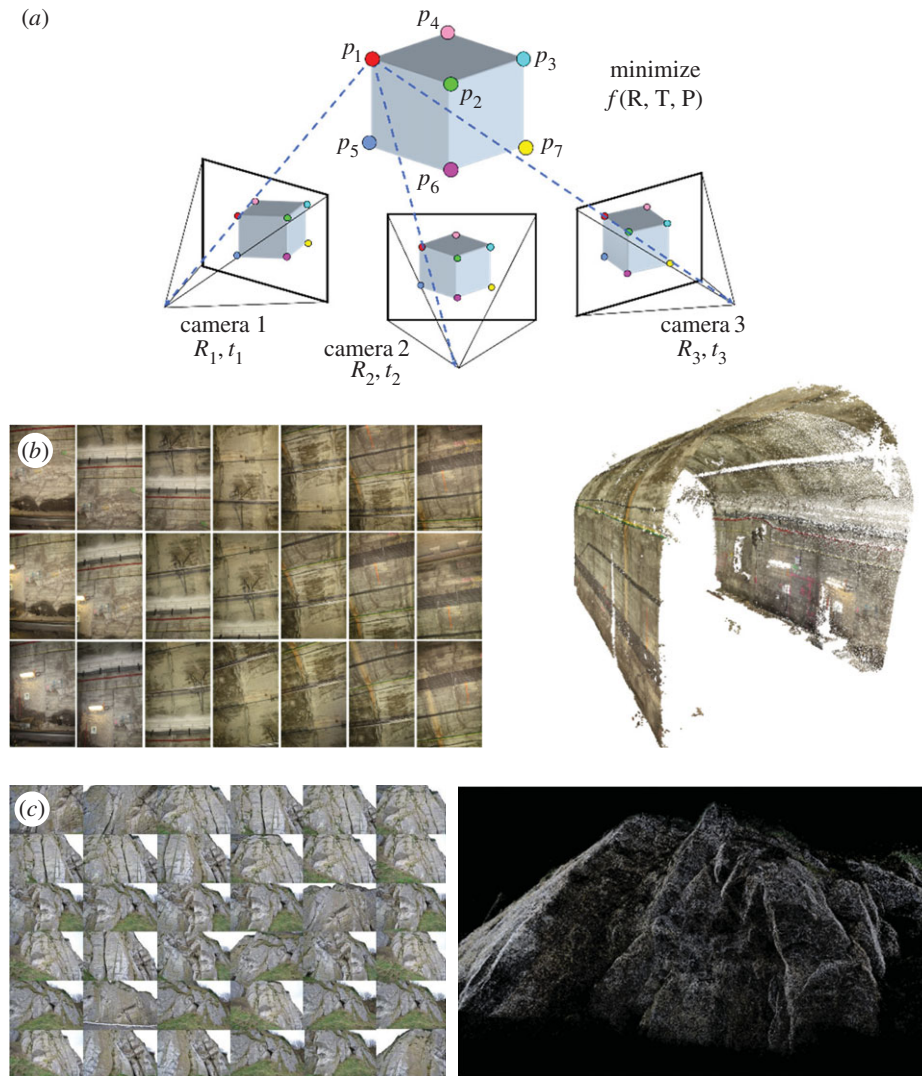


Figure 7. Three-dimensional point clouds generated from multiple photos; (a) three-dimensional reconstruction from multiple images, (b) tunnels [18] and (c) rock cliff (S. Stent 2014, personal communication). (Online version in colour.)

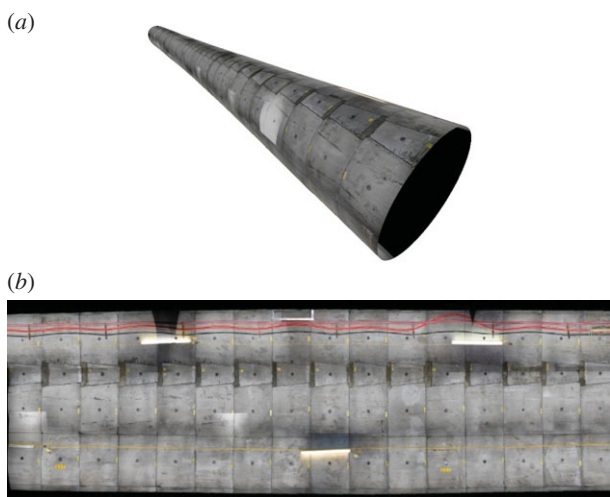


Figure 8. Image registration of a tunnel (after [23]); (a) image registration on a three-dimensional reconstructed object and (b) image mapping for inspection. (Online version in colour.)

was applied to a tunnel dataset from Prague Metro [18]. The query image is shown in figure 9a, taken in 2003. Figure 9b shows four chosen reference images (figure 9c) that have been pre-processed and overlaid on top of each other. All reference images were obtained in 2008. All four images are used in comparison with the query image so that a change

mask will cover an entire area of the query image. Several changes can be seen as labelled in figure 9a. These changes include a change in the colour of water patches, new holes being created and a new cable being added.

A system which is capable of automated monitoring and detection of visual changes on concrete tunnel linings has been recently developed by Stent *et al.* [23]. Figure 10 illustrates various distance functions, the geometric prior mask and a final change detection image for three sample queries. The geometric prior in all three cases correctly identifies and removes most of the nuisance change caused by off-surface features. Changes in the left-hand and central columns include leaking, fine chalk markings, discoloration and new items attached to the surface. The performance of the proposed change detection is seen to be close to ground truth. The right-hand column illustrates a failure case, caused by the unusual presence of some thread on the normally featureless red cable.

3.3. Wireless sensor networks

Installing traditional wired monitoring systems on large-scale civil infrastructure assets is time consuming and expensive. An alternative is to use WSNs that are faster to install and potentially cheaper on a sensor-by-sensor cost basis (figure 11a,b). The use of wireless sensor technology, which

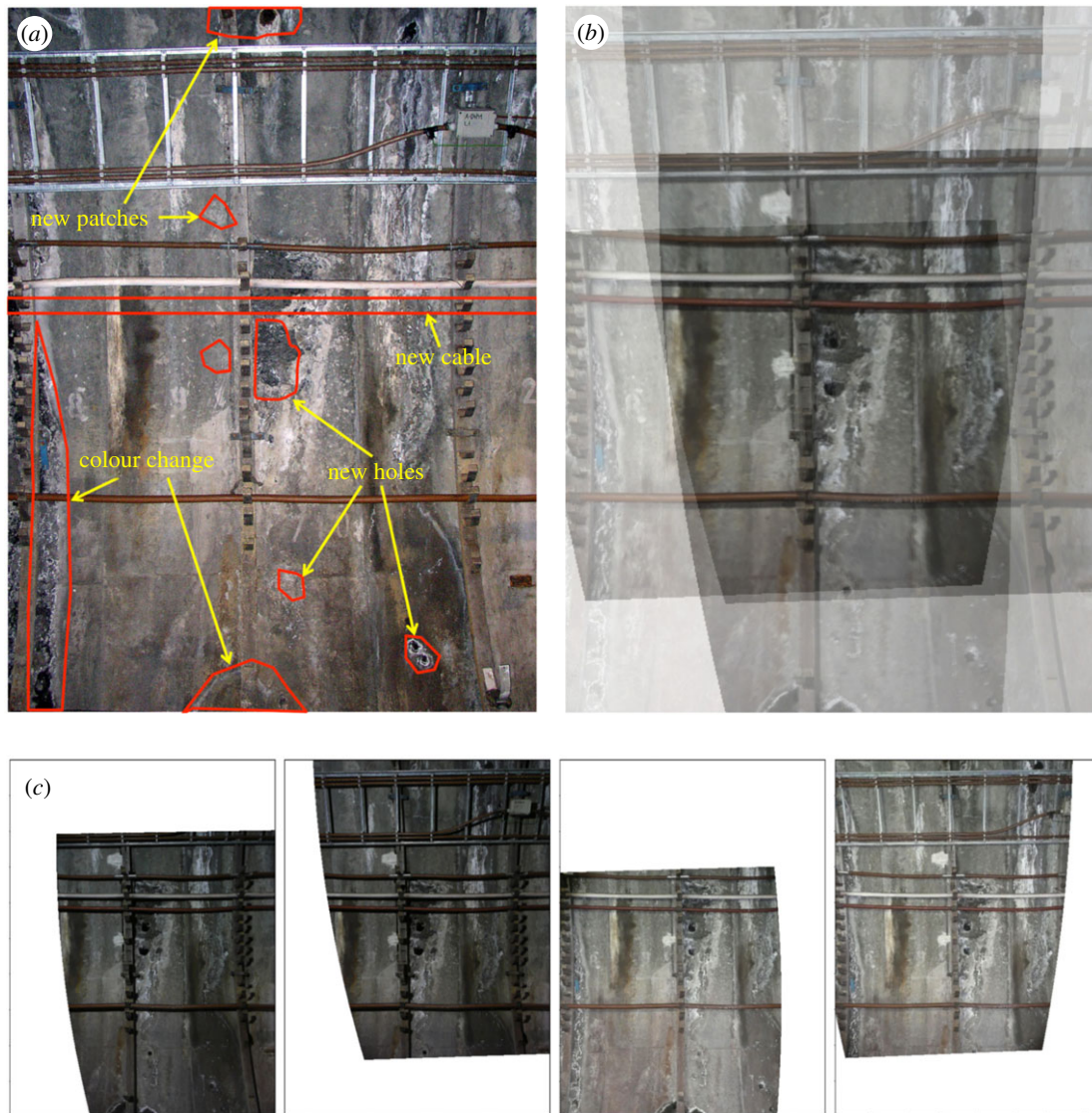


Figure 9. (a) A query image, (b) four reference images after pre-processing and over-laying on top of each other and (c) individual reference images after the geometric adjustment step [18]. (Online version in colour.)

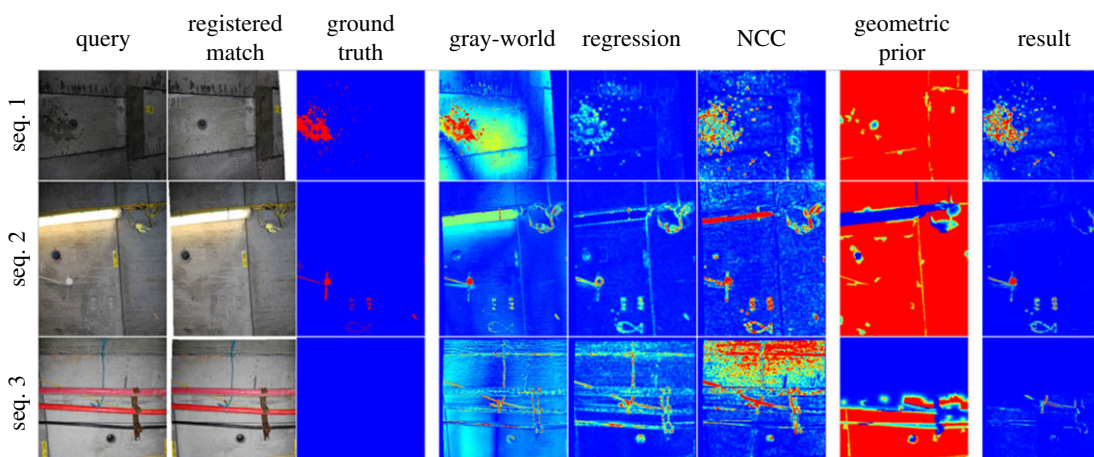


Figure 10. Illustrative results for three cases. By column: (1) query image, (2) registered matching image, (3) ground truth, (4) Gray-world, (5) multi-scale retinex (MSR), (6) greyscale normalized cross-correlation (NCC), (7) mean-shift segmentation-based geometric prior and (8) final probabilistic change mask. [23]. (Online version in colour.)

transmits the sensor data using radio, allows a rapid deployment due to elimination of some of the cabling and thus has significant potential benefits for infrastructure monitoring. Combined with micro-electromechanical system (MEMS) sensors (see the next section), there is the opportunity for significant overall cost savings for large-scale monitoring

(e.g. [25]). The advantages of WSNs for monitoring the behaviour of civil engineering infrastructure are (i) a large number of sensors can be deployed without needing to install cabling, (ii) sensing is possible at difficult-to-access sites, and (iii) quick deployment allows contractors and infrastructure owners to make better engineering decisions.

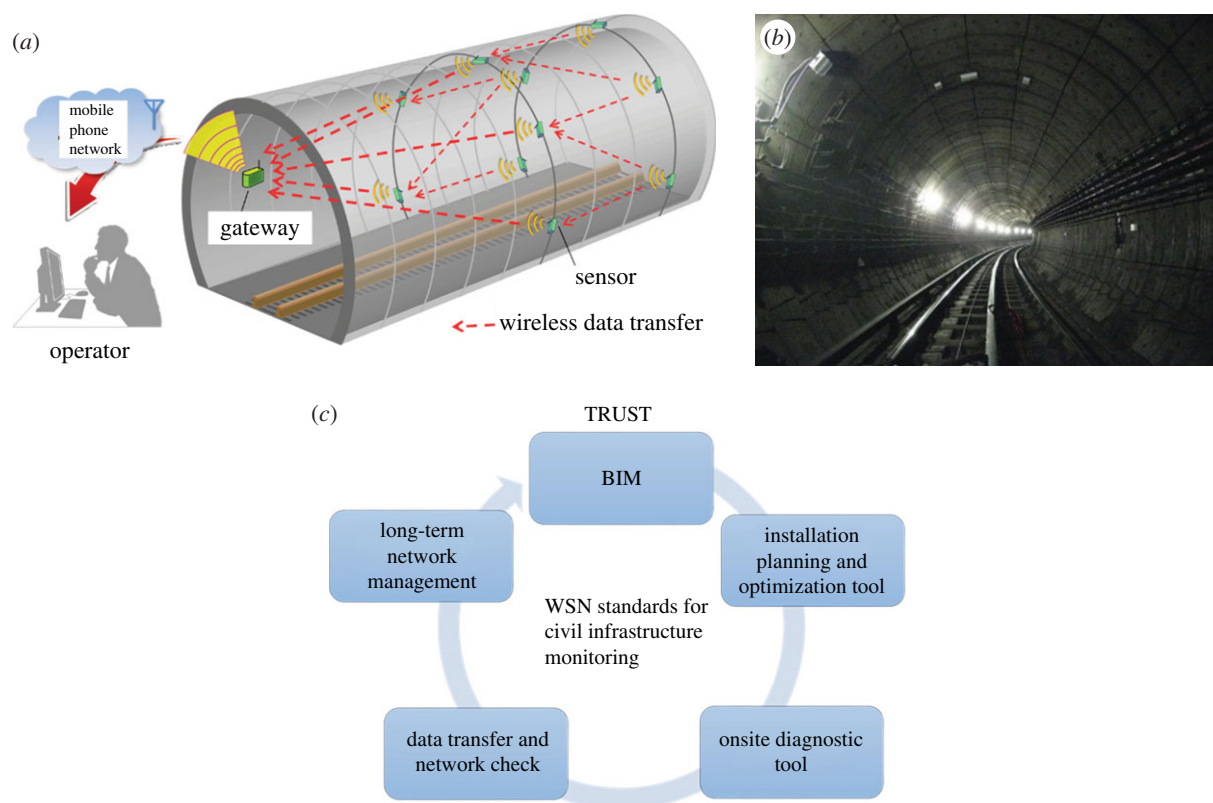


Figure 11. Wireless Sensor Network (WSN) for infrastructure monitoring; (a) WSN in a tunnel, (b) WSN installed in a tunnel for deformation monitoring and (c) trust in WSN. (Online version in colour.)

There has been an active research community on WSN for civil engineering applications for the past 20 years [26]. It is a mature and increasingly commercially established technology. The hardware is robust and reliable and there are a number of well-defined and standardized WSN communication protocols and power management mechanisms (TinyOS, Contiki, etc.). The current research/development in this area focuses on new algorithms for embedded data processing, integration of new sensor technologies, use of energy-harvesting technologies and miniaturization.

A typical WSN mote consists of microcontrollers (MCUs), radios and sensors, which are required to be low-power devices. Currently low-power MCUs are Texas Instruments msp430, ATMEL AVR-8-bit/16-bit and ATMEL ARM-Cortex Mx (32-bit). 8-bit/16-bit MCUs consume less power than 32-bit MCUs. The TI's msp430FRx family has a mean current consumption of approximately 5 mA (15 mW) in active mode and μA –nA (μW –nW) in low-power mode without radio. When complex floating point operations are required, 32-bit MCUs, such as the ATMEL ARM-Cortex M3 are needed. The current consumption is 10–20 mA in active mode and μA in sleep mode.

IEEE 802.15.4-compliant radios such as Texas Instruments' CC2420/CC2520 have current consumptions of 4 mA in active, μA in sleep modes, approximately 18–30 mA when transmitting and approximately 20 mA when receiving. Inbuilt sensors tend to be of very low power (of the order of mA), but external sensors can consume more power owing to factors such as warming time, lack of sleep modes, sampling rates, etc. Other hardware components, such as antialiasing filters and external memory, consume current in the order of mA– μA .

Power is consumed when a WSN is communicating ineffectively (to dynamically maintain the network topology) or

running time-consuming applications. Where sampling rates and transmission rates can be high (for example, in applications of structural dynamics and control), the battery lifetime can be from a few days to a few months. In such cases, the duty cycle protocols for energy saving may lose relevance due to the requirements of data sampling, data processing and data transmission. However, for static applications (low sampling and transmission rates), the battery lifetimes can be extended from months to years.

The transmission range depends on the radio technology. The most popular radios, which use the 2.4 GHz ISM band, can reach from 100 m to a few kilometres outdoors with high gain and powerful antennas. However, for longer transmission range, the transmission power needs to be higher (30–100 mW). For 868 MHz radios, the transmission range increases considerably (5–10 km) without increasing the current consumption (10–20 mA), but data volume becomes limited. For example, with 2.4 GHz, it is possible to transmit up to 80–110 bytes of data when using the well-established IEEE 802.15.4 standard (250 kbps bit rate). But with 868 MHz, the payload is 30–50 bytes (20 kbps bit rate). There is interest in low-power wireless area networks (LPWANs) for very long distance transmission but the data transmission is a few bytes only.

It is possible to use multi-hops to increase the wireless coverage of a WSN system using multiple gateways. This provides scalability and improves performance metrics such as data throughput, latency and power consumption. A single gateway can have 65 000+ motes but practical deployments consider up to a few hundred (100+). Scalability depends on the core communication protocols and an appropriate protocol needs to be selected for meeting the scalability requirements.

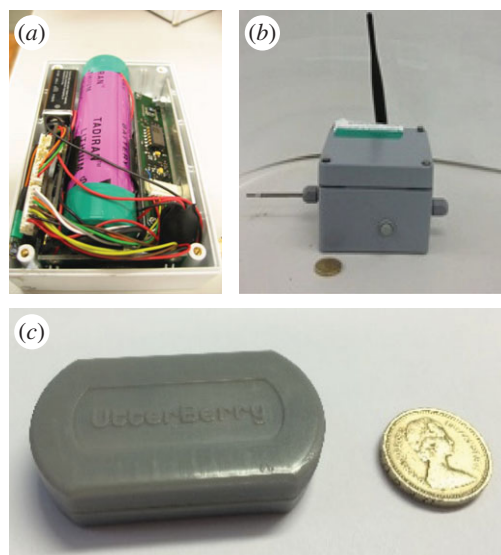


Figure 12. Evolution of wireless sensor system for infrastructure sensing; (a) 2007 original, (b) 2011 Wisen Mote and (c) 2014 Utterberry. (Online version in colour.)

Although advantages of WSNs for condition monitoring of infrastructure have been identified, deployment of WSNs in a real environment remains challenging (e.g. [27]). There is also a perception that a wireless system may not be as reliable and robust as a wired system. The current limitations of WSNs for civil engineering infrastructure monitoring are: (i) sensor installation and establishment of a working wireless network currently requires expert knowledge, making it difficult for the clients to fully appreciate the reliability and risk involved, (ii) interoperability of different WSN systems is very limited, and (iii) no standards and/or guidance are available for clients to specify WSN systems that would allow better communication between WSN providers and clients.

One of the main focuses of WSNs for civil engineering applications therefore should be to develop an integrated framework for planning, deployment and management of large-scale WSNs so that users can trust the data coming from a WSN, as shown in figure 11c. Although the WSN research community has looked into wireless communication, energy efficiency, limited network scalability and several other problems, an integrated system for planning, deploying and managing large-scale sensor networks is still missing. The current methods used when installing a WSN for monitoring civil infrastructure involves significant trial and error at the deployment site and significant dependence on personal experience. This makes it extremely difficult to cost-effectively deploy and manage large-scale WSNs that the end user can trust. To achieve this, a guidance document on WSN for civil engineering infrastructure has been developed by the Cambridge Centre for Smart Infrastructure and Construction [26].

As discussed earlier, a new generation of WSN hardware has sufficient processing capabilities to permit the development of computationally demanding signal-processing algorithms. This would allow adaptive data collection and local processing of data for the extraction of failure signals. The availability of more computationally powerful platforms also allows common implementation of various data collection scenarios, in-network processing and compression algorithms. Figure 12 shows the evolution of

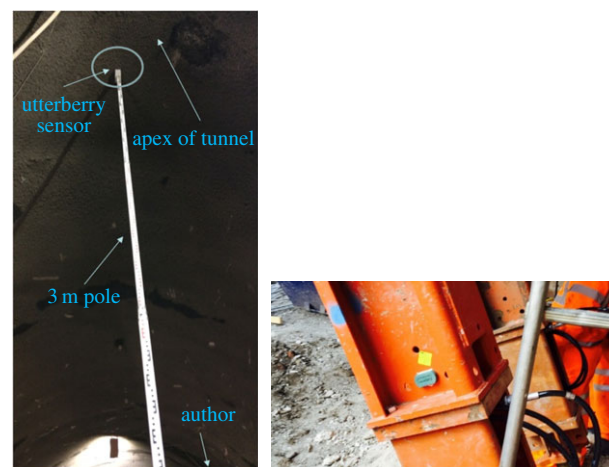


Figure 13. Installation of Utterberry at construction sites (H Bevan 2015, personal communication). (Online version in colour.)

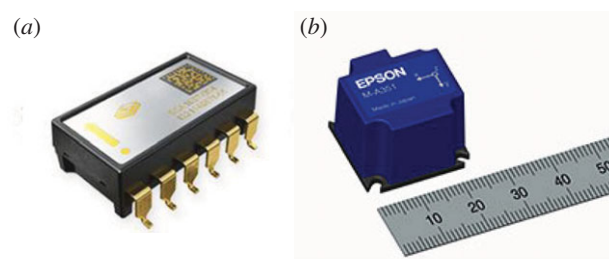


Figure 14. Examples of MEM sensors for civil engineering applications; (a) inclinometer—SCA103T by Murata-VTI Technologies and (b) accelerometer—M-A351A by EPSON. (Online version in colour.)

WSN motes developed at Cambridge University, which have been successfully deployed in field environment [28–31]. The latest one is ‘UtterBerry’ (Bevan H. 2014, personal communication). UtterBerry sensors are miniature, wireless, ultra-low-power sensors combined with artificial intelligence, specifically designed for infrastructure monitoring. They use an artificial intelligence algorithm to perform on-board calculations to derive acceleration, inclination and displacement in real time without human intervention. Because of its small size and lightweight, it can be installed easily and placed in potentially unsafe or difficult-to-access sites. The sensors are self-calibrating after deployment and optimize their data communications within the sensor network according to environmental conditions. The sensors collect, process and interpret data, reporting it to users remotely on any Internet-enabled device and analyse trends in readings so that engineers can predict future events. An example of its field implementation is shown in figure 13.

3.4. Low-power micro-electromechanical system sensors

MEMS are small integrated devices or systems that combine electrical and mechanical components varied in size from micrometres to millimetres (or even smaller for the next generation nanoelectromechanical systems (NEMS)), which can merge the function of computation and communication with sensing and actuation to produce a system of miniature dimensions. MEMS extend the fabrication techniques for the

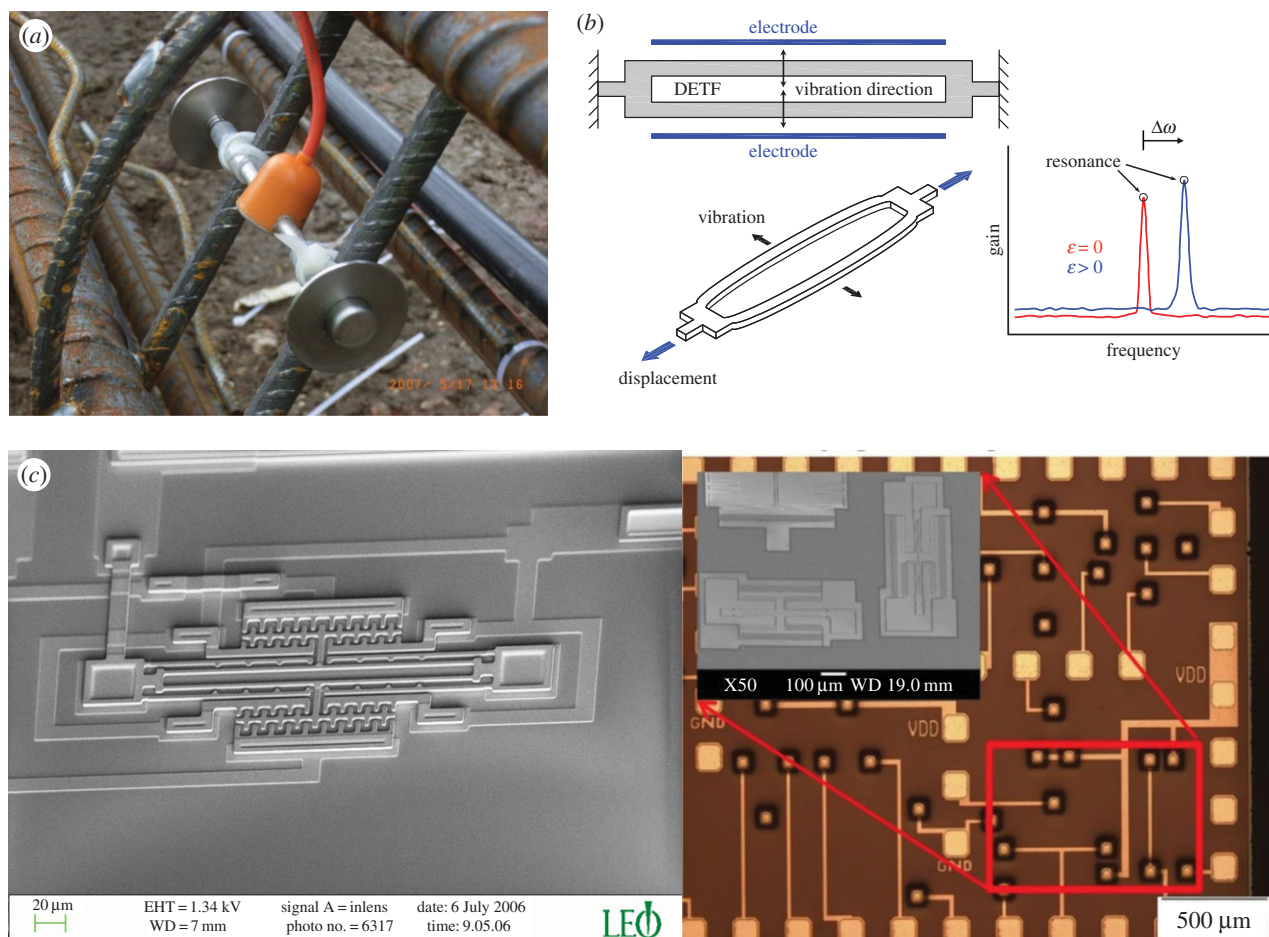


Figure 15. MEM strain sensor; (a) conventional vibration wire strain gauges, (b) concept of a resonant strain device and (c) MEM strain gauges. (Online version in colour.)

semiconductor industry to include mechanical elements, and the inherently small size of MEMS enables high-level integration of micromachined components or structures to realize multiple functions or capabilities on the same silicon chip for greater utility.

The majority of the MEMS applications in civil infrastructure monitoring act as sensors, which have emerged as a highly sensitive monitoring candidate for structural control and assessment, health monitoring, damage repair and system preservation of civil infrastructure. MEMS sensors will offer major advantages in terms of smaller size, lower power consumption, more sensitivity to input variations, cheaper cost due to mass production and less invasive than larger devices, and extend the performance and lifetimes over conventional systems. A range of MEMS sensors is now available in civil applications, which can measure acceleration, inclination, temperature and pressure.

Tilt measurement is common in civil engineering. MEMS sensors can measure both static and dynamic accelerations and therefore, they can be used to measure inclinations that are typically static accelerations. The inclinometer includes uniaxial or biaxial accelerometers, which measure the gravity. The commercial MEMS inclinometer commonly incorporates an on-board microprocessor to automatically compensate the temperature effect of the tilt data. For instance, SCA103T by Murata-VTI Technologies is a three-dimensional-MEMS-based single axis inclinometer family that uses the differential measurement principle (figure 14a). It has a resolution of 0.001° , with a range of 15° .

An accelerometer is a sensor that measures acceleration forces. The acceleration forces can cause a deflection of an inertial mass suspended by springs from its initial position, which is converted to an electrical signal as the sensor output. The accelerometer can be used to sense orientation, acceleration and vibration, which are essential in civil infrastructure monitoring to detect and diagnose any deviation from normal conditions. The application of MEMS technology to accelerometers is becoming popular. MEMS accelerometers based on microfabrication technologies have been demonstrated to be an attractive and cheaper alternative to conventional accelerometers because of lower power consumption and potential integration of sensing and built-in signal conditional units within one device. The resolution is rapidly increasing. For example, EPSON produces an ultra-high sensitivity accelerometer with a resolution of $0.06 \mu\text{g}$ (M-A351A, figure 14b).

Strain sensing is highly critical for civil infrastructure applications. The conventional metal film strain gauge and vibrating wire strain sensors (figure 15a) are not very well suited for wireless sensing civil applications, in which a number of strain sensors are required to be deployed within large-scale infrastructure. Thus, high-resolution, lower-power and small-size MEMS strain sensors are in demand to replace the conventional strain gauges. At Cambridge University, a novel MEMS strain sensor has been developed ([32]; in collaboration with Consiglio Nazionale delle Ricerche (CNR)). Double-ended tuning fork (DETF) parallel-plate resonators with reduced coupling gaps (less than $1 \mu\text{m}$) have been

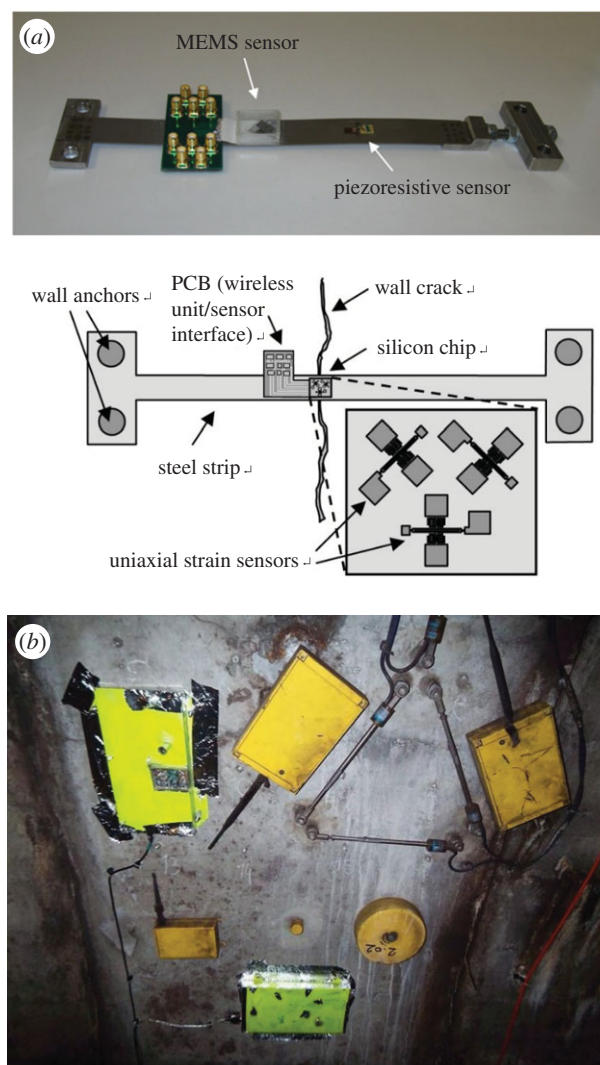


Figure 16. (a) Crackmeter with MEM strain sensor and (b) installation of a crackmeter in Prague Metro. (Online version in colour.)

fabricated, as shown in figure 15b. Vacuum-packaged MEMS strain gauges demonstrated a resolution of approximately $4 \text{ n}\epsilon$ and power dissipation of less than $3 \text{ }\mu\text{W}$ including circuit-level temperature compensation (up to 85°C).

Using a newly developed MEMS strain sensor, a prototype MEMS crackmeter was manufactured with a thin steel bar fixed across a crack on the tunnel wall, onto which a multi-directional MEMS strain sensor was soldered (figure 16). A movement of the wall crack (contraction or expansion) can be detected by the sensors through the strain generated on the steel bar and transferred to the silicon chip. The prototype MEMS crackmeter was deployed in Prague Metro, as shown in figure 16b. Further details can be found in Ferri *et al.* [33,34].

3.5. Energy harvesting for low-power sensors

Owing to the remote situation, the conventional method to power sensor systems is to use a battery, which is limited to its life cycle. Replacement is difficult when the sensors are embedded or hard to reach. MEMS sensors offer major advantages in terms of low power consumption. The powering of MEMS devices by capturing and storing energy from external sources present in the environment offers an

opportunity to replace or augment batteries, as shown in figure 17 (e.g. [35,36]). Energy-harvesting technologies complement or replace existing battery solutions, reducing extensive battery replacement maintenance costs and the burden on hazardous waste disposal while providing enabling technology for long-term condition monitoring of assets in a range of remote and/or inaccessible locations. Figure 18 shows the time variation of air velocity measured by a miniature anemometer installed inside a London Underground tunnel. The velocity increases as a train passes. A quick calculation shows that a maximum of 0.3 mW can be obtained when a small wind turbine with a cross-section of 1 cm^2 is installed.

An innovative vibration energy harvester (VEH) using the concept of parametric resonance has been developed [37–39]. The technology departs from the convention (ordinary resonance; figure 19a) and employs parametric resonance as a means of mechanical amplification by exploiting its nonlinear resonant characteristics at high amplitudes to widen the frequency band. This resonant phenomenon is induced when an external excitation results in a periodic modulation of an internal system parameter. In contrast with ordinary resonance, the driving force is usually perpendicular to the direction of the oscillatory displacement. An energy level of $10\text{--}100 \text{ mW}$ can be obtained for a macro-scale device, whereas the technology has been implemented into MEMS-scale device, as shown in figure 19b. The harvesters convert the mechanical energy into electricity in a decentralized manner at the device level, essentially equipping the wireless systems to generate their own power. This technology works by harnessing vibration energy from ambient vibration sources such as freight, rail, tunnels and traffic on bridges. An example of the deployment of a parametric resonance-based VEH device is shown in figure 19c.

3.6. Citizens as sensors

Our understanding of mobility in a city can be improved by better tracking of where and how people move in space and time. Integrating such infrastructure information will lead to better management and operation, and allow cutting-edge technologies to be tested. The rich information provided will act as a catalyst for new design, construction and maintenance processes for integrated transport service systems linked directly with user behaviour patterns. For example, figure 20 shows the temporal daily concentration of Twitter presence 20 m from a rail station compared to rail trips in progress from the National Travel Survey data. A good correlation is shown between the two and such social media data can be used to evaluate the usage of infrastructure in real time.

When the demand for a road or railway exceeds the supply, a time delay is incurred as a result of the congestion generated. The individual interactions of increasing and decreasing transport volumes result in changes to the journey time. As transport volume and therefore density increases, transport speed will reduce in order to safely manage the increased volume. It is now possible to crowdsource travel journey times from GPS-enabled phones in addition to conventional traffic count data from the automated traffic counter system. There is potential application of the real-time infrastructure usage data for road and railway maintenance planning and operation, for example.

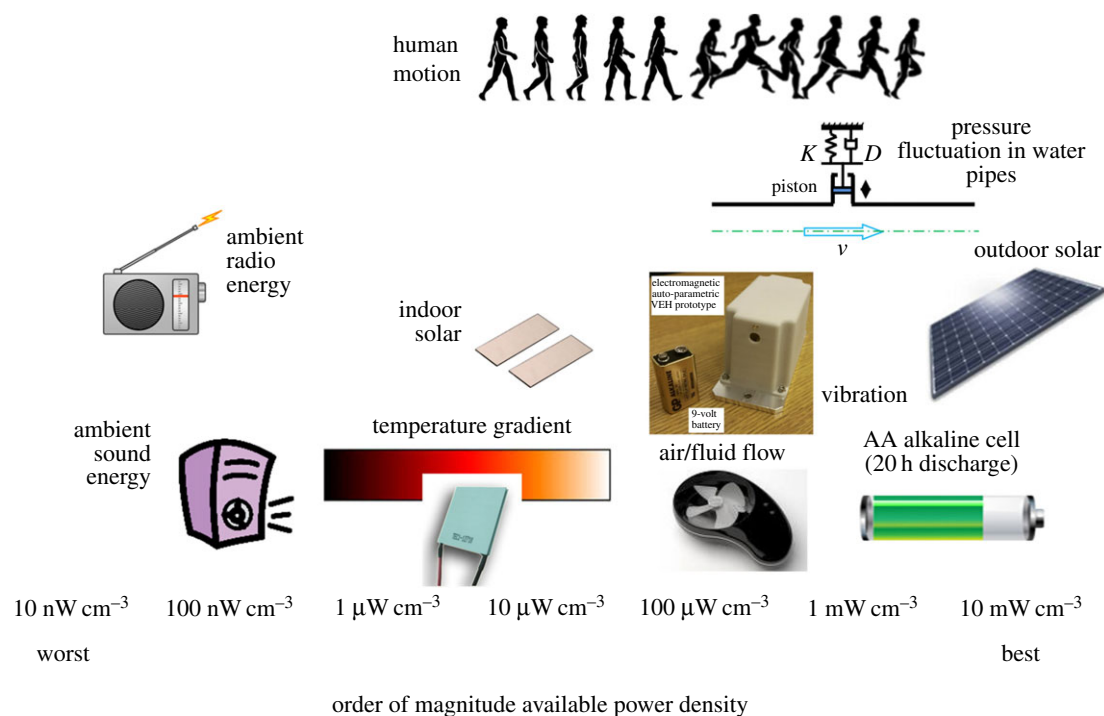


Figure 17. Opportunities in energy harvesting for infrastructure sensing. (Online version in colour.)

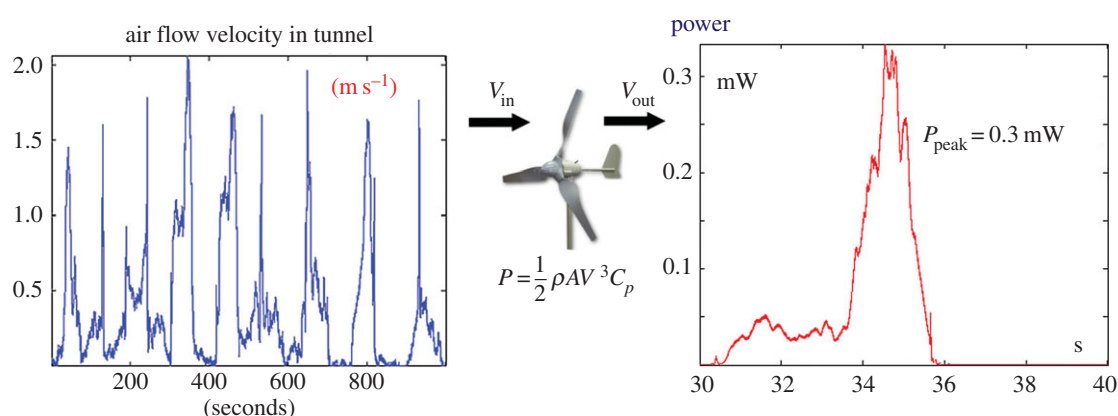


Figure 18. Miniature anemometer installed in a London Underground tunnel. (Online version in colour.)

As an addition to conventional monitoring and measurement systems, it is now possible to take advantage of the 'citizens as sensors' crowdsourcing aspect of citizen science. Examples include monitoring and measuring of real-time data using smart phones/watches from occupants and customers that provide data on how they feel about the usage of infrastructure. There are already several technologies to gather data about space usage. These techniques will include instrumentation of users' mobile devices through (i) novel energy-aware software applications capable of gathering data from the phone's local sensors, (ii) back-end techniques to understand movement of crowds through WiFi and cellular logging, (iii) use of data from geo-social networks such as Facebook/Twitter and transportation cards, (iv) embedding qualitative techniques of measurement of user preferences (e.g. voice strengths) in order to measure their willingness to change and adapt, and (v) the installation of cheap sensing systems. The data collected can often be of a sensitive nature and privacy protection methods are needed for users, including

anonymization techniques and ongoing development of 'privacy by design' principles.

If large quantities of data can be collected for real-time understanding of human activities, the outputs of the models can inform infrastructure owners about people movement and use of space, and provide guidance on future usage and efficiency. The data will feed parameters to describe current behaviour of existing users and their willingness to change in response to new environments if infrastructure is temporarily closed or modified for improvement. The data will also allow development of models that consider the interplay of new technology and infrastructure usage with users' reaction. Such models will guide how we build new infrastructure and maintain old infrastructure more economically and efficiently.

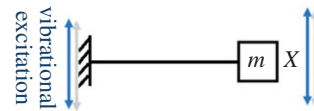
4. Conclusion

Infrastructure is a large part of our society's assets, and efficient management and maintenance of infrastructure should

(a)
direct excitation

fundamental mode of resonance: $\omega = \omega_0$

$$\ddot{x} + \frac{2c_1}{m}\dot{x} + \frac{c_2}{m}\dot{x}|\dot{x}| + \frac{\mu}{m}x^3 + \omega_0^2 x = \omega^2 A \cos(\omega t)$$



parametric excitation

principal (first order) parametric resonance: $\omega = 2\omega_0$

$$\ddot{x} + \frac{2c_1}{m}\dot{x} + \frac{c_2}{m}\dot{x}|\dot{x}| + \frac{\mu}{m}x^3 + (\omega_0^2 - \frac{\omega^2 A}{l} \cos(\omega t))x = 0$$

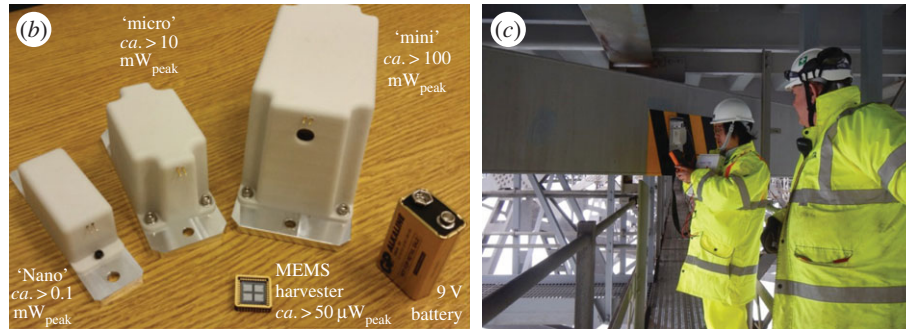
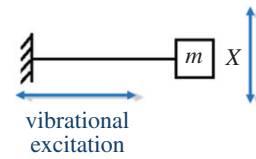


Figure 19. Parametric vibration energy harvesting; (a) direct resonance versus parametric resonance, (b) parametric vibration energy-harvesting (VEH) devices and (c) installation of VEH on a bridge. (Online version in colour.)

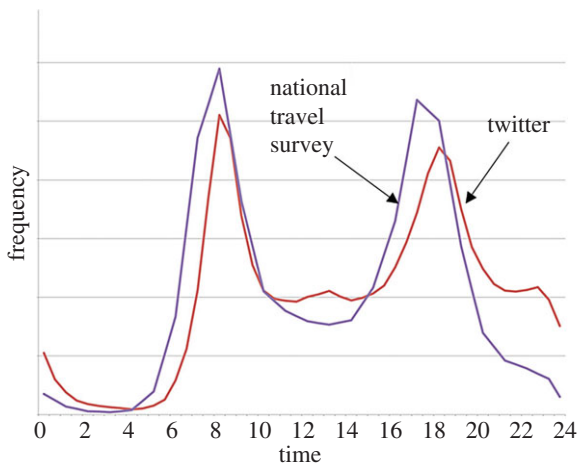


Figure 20. Temporal concentration of Twitter presence 20 m from a rail station compared to rail trips in progress from National Travel Survey data. (Online version in colour.)

be a perpetual, ongoing commitment. But little is known of the long-term performance of such infrastructure. In recent years, sensor and communications research has been undergoing a quiet revolution, promising to have significant impacts on a new generation of monitoring technologies for civil engineering infrastructure. The application of emerging technologies to advanced health monitoring of critical infrastructure assets can potentially reduce the risk of failure.

Civil engineering structures are fixed in space and time (e.g. 120 year design life). A localized structural defect or damage at an early stage in a system can potentially disrupt the operation of the whole infrastructure as well as influencing other neighbouring infrastructure. But each of these elements is operated with different business models and is guided by

different performance metrics. Infrastructure owners need to deal with systems that involve different degrees of interconnectedness and time scales in terms of ageing and the requirements for repair and maintenance. Also there is a mismatch between the lifespan of infrastructure and that of sensor systems, which makes the concept of whole-life cycle-based asset management difficult to achieve. Sensor systems to fulfil this concept need to be either long-life or adaptable for replacement. The future outlook is that any innovative sensor systems that can measure the usage of the infrastructure for a long time will help to develop this whole-life cycle concept. In this paper, the concept of whole-life cycle monitoring has been introduced and discussed. Potential technical challenges have been identified to realize this. New emerging sensor technologies such as distributed fibre-optic sensing, computer vision, WSN, MEMS, energy-harvesting devices and citizens as sensors are introduced.

To accelerate the usage of such emerging technologies, field demonstrations are essential so that confidence within the community can be built. It is also necessary to develop a business case that quantifies the value of sensing. The most obvious opportunity is the increased safety levels they can provide by monitoring the effects of adjacent new constructions and with natural disasters such as floods and earthquakes. At the same time, infrastructure owners need to provide the market 'pull' for smart technologies in response to the challenging targets set by the public. This can be done by actively encouraging innovations in the industry and specifying new technologies to build confidence within the industry.

In summary, the trend in the infrastructure sector is a move from supply of an 'infrastructure' to supply of 'whole-life support'. This creates demand for life cycle monitoring and the associated sensing technology. The long-term engineering

performance data combined with engineering decision analysis will transform the industry to a whole-life approach—design and commissioning, the construction process, exploitation and use, and eventual de-commissioning. Ultimately, the development of ‘smart’ infrastructure means true realization of performance-based design and maintenance.

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