Internet of Things (IoT) based monitoring of critical masonry infrastructure

School of Engineering

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Key Words

Infrastructure, monitoring, graphene, wireless sensor networks, nanocomposite

Overview

Infrastructure forms the backbone of our modern communities and the reliability and integrity of such physical assets are vital for ensuring national economic activity and prosperity. The UK Government Strategy for National Infrastructure [1] and consequent National Infrastructure Plan [2] recognises ageing of existing infrastructure as a key challenge around improving the nation’s infrastructure.

Most of the UK’s masonry infrastructure assets (such masonry arch bridges, viaducts and tunnels) are now deteriorating, since they have been in operation for more than 120 years and according to ICE, State of National Infrastructure Report (2014) are “in need of attention” or “at risk”. In addition, extreme loading and environmental conditions (e.g. flooding) that have not been considered during the initial design can result in long-term structural degradation leading to failure (Figure 1). Such structural failures can be catastrophic and can even lead to disruption to the interconnected nature of the infrastructure [3].

For example, during the 2009 floods in Cumbria, 4 masonry arch bridges collapsed, while 15 were severely damaged leading to nearly £34m in repair and replacement costs [4]. The economic and societal costs were even larger, with increased travel time estimated to cost businesses as much as £2M per week [5].

The increasing amount of civil infrastructure and the aging of existing infrastructure requires their regular inspection and maintenance. However, their relatively large size, complex construction and difficult access to some elements of their construction make such analysis challenging and time-consuming. Structural health monitoring (SHM) has attracted growing interest from researchers to improve the safety of engineering constructions such as buildings, bridges, tunnels or dams. SHM concerns processes that use integrated measuring systems to collect data and transform them to information on the actual state of the monitored structures. It is intended to support operators in their decision making with regard to required actions and maintenance.

Wireless Sensor Networks (WSN) such as strain sensors, inclinometers and vibrometers are the most widely used transducers for SHM, since strain, tilt measures and acceleration magnitudes can provide rich information regarding structural integrity. For example, excessive localized strains could suggest the presence of structural damage such as cracks while vibrometers can be used to capture the dynamic characteristics of the structure.

Recently, it has been shown that thin film sensors that incorporate nanomaterials can also be engineered to possess unique properties, such as flexibility, high...
sensitivity, and low cost. Various researchers have experimented with different types of fillers for making the composites smart for SHM [6]. One of the most promising candidates for sensing applications is low-dimensional carbon. Nanoscale carbon materials such as nanotubes, and graphene nanosheets (GNSs) have been explored for making self-sensing composites. [7] Printing technology has been demonstrated as a suitable method for the fabrication of electronic components with GNS-based inks. [8] The overall cost of sensor arrays can be reduced significantly if all the strain sensors are fabricated by printing methods using cost-effective nanocarbon materials.

The overall aim of this multi-disciplinary PhD project is to develop a cost-effective, easy to install graphene nanocomposite strain sensor network based on emerging Internet of Things (IoT) to monitor displacement and ambient vibrations of large infrastructure that are vulnerable to the risk of changing environmental conditions above and below ground. This project will address four synergetic objectives to:

1. Determine the target design specifications: electrical, mechanical and software interface for three months-long large infrastructure displacement and vibration monitoring exercise.
2. Develop an all printed graphene nanocomposite strain sensor.
3. Design and implement a prototype system based on the above objectives.
4. Conduct field trials in different built environmental settings.

The project aligns with the EPSRC research areas, such as Urban Resilience, Complexity Science, Sustainable Urban Environments, Environmental Change, also involving aspects of social and economic needs. This research will contribute to overcome current limitations regarding our knowledge of infrastructure performance and failure over long timeframes and in the light of adverse weather. This research advances a research programme for generating better understanding of the degradation of masonry infrastructure systems, alongside the EPSRC/LWEC strategic priority and societal challenge of transforming our cities in more resilient and sustainable environments.

In addition, relates to other research already funded by RCUK including: a) Building Resilience into Existing Masonry Infrastructure Assets (NE/M007987/1); b) Advanced structural health monitoring for stone masonry structures (EP/I006109/1); c) Fatigue behaviour and remaining service life of masonry arch bridges (EP/P069170/1); d) UKCRIC - Advanced Infrastructure Materials Lab (EP/P017622/1) etc.

**Methodology**

A major part of this project is the design of a system of complimentary sensor, data acquisition and wireless network components. Such a system must contain an interface to which sensing transducers can be connected, a computational core, storage for data acquisition and analysis, power supply and a wireless transceiver for both the transmission and reception of data. The network design will build upon existing research in the School of Engineering including previous EPSRC-funded instrumentation projects undertaken by the team at NCL for Adaptive Array Signal Processing and Estimation through Internet of Things and Wireless Sensor Networks.

The sensor element in this integrated project will be a printable GNS based strain sensor. The creation of these sensors will include the formulation of polymer-GNS based inks, design of optimized single and multi-sensor arrays and development of printing processes. The nanocomposites will be made from a suspension of graphene nanoparticles obtained using the low cost liquid phase exfoliation (LPE) technique, [8] in an elastomeric polymer matrix (e.g. styrene-butadiene rubber (SBR), polydimethylsiloxanes (PDMS)). The change in resistance due to conformational changes (piezoresistance) in the carbon nanoparticles network during displacement offers excellent sensitivity to strain signals [9]. The design of these nanosensors will be specifically adapted to the associated IoT-based monitoring system.

Sensors will be able to collect temperature, strain as well as vibration data. These sensor signals will be digitized using an analog filter (antialiasing) which will then be sampled by an Analog-to-Digital Converter. Subsequent processing will include digital filtering (averaging, etc.) and a Feedback Jitter Controller. The sensor network will consist of a two tier strategy in a star topology where the wireless sensing units communicate with a wired site master which stores the data. This strategy is adopted so that low-power transceivers can be used to maximise network lifetime and allows for large capacity data storage at the site master.

The array of wireless sensors developed will be applied and tested in Lambton Bridge. Lambton Bridge is a private bridge on the Lambton Estate and is located in Durham. The bridge is Grade 2 listed and has been much affected by subsidence resulting from former coal mines on the estate and is subject to a weight restrictions. Results will be verified against other monitoring techniques such as tell-tales, laser-scanners and level meters. Access to the bridge and installation of the equipment developed seasons has been obtained.
**Proposed deliverables:**

**D1:** A laboratory prototype fully sustained and functional  
**D2:** A field-ready prototype system for live monitoring of infrastructure in the field  
**D3:** Identification of field test site and installation of the prototype sensor  
**D4:** Harvesting of data from conventional methods of displacement measurement (e.g. total stations, levels) and comparison with those obtained from the prototype.  
**D5:** Verification of the equipment and write up and submission of the thesis.

Potential industrial collaborators in this research are: a) Network Rail; b) BH Associates; c) Arup; d) Helifix Ltd; e) AECOM

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**Timeline**

The research activities will be broken down into four key tasks (see also Table 1 for deliverables).

The **first task** (Months 1 to 18) will focus on the extensive review of the literature in the area of wireless monitoring of civil infrastructure, to the development of the printable GNS based strain sensor and the electronics hardware for the network nodes. Important system parameters, such as the backbone transmission technology, network size, required sampling and data rates, network lifetime and sensor types will be specified. During the wireless network specification phase, emphasis will be placed on optimising the energy requirements of the network in order to maximise the network lifetime and enable long-term monitoring.

The **second task** (months 12 to 30) will develop scenarios for field tests and deploy the network on a real test infrastructure asset e.g. Lambton bridge in Durham. Depending on the location of the test site, data will be collected over the Internet via connection to cellular network base-station and data series analysis techniques will be developed to enable event detection and continuous critical monitoring of the infrastructure under consideration.

The **third task** (months 24 to 36) will concentrate on the joint optimisation and refinement of the networking and data analysis techniques, and will develop a graphical interface for the visualisation and live publishing of data on the Internet. Finally, we will look into the suitability of the data for structural engineers and potentially investigate the potential whether such system can be used as an alarming platform in order to: Resolve issues faster by correlating infrastructure problems.

The **fourth task** will last for 6 months and will include the verification of the equipment and writing up and submission of the PhD thesis.

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**Table 1. Proposed time plan showing deliverables**

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**Training & Skills**

The student will be based at the School of Engineering, Newcastle University and will receive extensive training and develop skills and expertise in fabrication with graphene materials, electronics design, measurement, networking and data analysis processing techniques that are relevant to monitoring of infrastructure from the acquired sensor data. He/she will develop skills in efficient real-time programming techniques for IoT based embedded devices that operate using low energy and limited resources, and expertise in power and energy budget analysis. These skills are relevant to and in high demand by the telecommunications and signal processing industries. The student will develop oral and communication skills by writing reports and presenting scientific outcomes to conferences, Journals and meetings with industry. In particular, the student will be encouraged to produce at least two conference papers and two journal papers during the period of the study which will develop scientific writing as well as networking skills. Also, the research is highly likely to lead to patents, publications in high-impact international journals and conference presentations. The research outcomes will lead to a product that is currently not available in the market and will enable Engineers and asset managers to continuously monitor critical infrastructure using a cost-effective and ubiquitous approach. Therefore, it has the potential of generating a spin-off company that can be run by the PhD student after graduation with the support of the University and supervisors. Furthermore, the student will benefit from the extensive research expertise and guidance of the supervisors.

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**References & Further Reading**

How to apply
You must apply through the University’s online postgraduate application system. To do this please ‘Create a new account’.

All relevant fields should be completed, but fields marked with a red asterisk must be completed. The following information will help us to process your application. You will need to:

• insert the programme code **8080F** in the programme of study section
• select ‘PhD’ as the programme of study
• insert the studentship code **ENG011** in the studentship/partnership reference field
• attach a covering letter and CV. The covering letter must state the title of the studentship, quote reference code **ENG011** and state how your interests and experience relate to the project
• attach degree transcripts and certificates and, if English is not your first language, a copy of your English language qualifications

Further Information
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