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Low Power Wireless Sensors Networks for Structural Monitoring in Transportation Tunnels

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ABSTRACT: The London Underground possesses a large number of aging cast iron transportation tunnels whose structural integrity requires regular monitoring. Many of these tunnels are over 100 years old and their structural health is of concern as new tunnels and structures are built close by, affecting soil stability and inflicting prolonged structural stresses. Currently trained teams of engineers enter the tunnels and physically carry out structural inspections. This method is costly, however, and time consuming due to the inaccessibility of many tunnel areas. To cut costs and greatly reduce physical human involvement in structural inspection, low power wireless sensor networks (WSNs) can be deployed in tunnels to provide regular readings of various stresses including tunnel inclination and acceleration.

An original case study is now being conducted in the London Underground whereby new ultra low power WSN devices monitor the structural health of an existing tunnel affected by nearby excavation activities. This research examines the data collection, interpretation and transmission capabilities of 30 WSN devices in long-term tunnel deployment with minimal human intervention. Details are provided of the sensor node installation throughout a 40m section of tunnel.

The WSN detects structural movements by integrating various types of sensors. Additionally, the network makes use of various bandwidth frequencies to ensure reliable network communication. Our research has shown that structural data is recorded in real time by the sensor nodes, interpreted and relayed through the WSN for remote examination. We expect that the tunnel used for this trial will experience movements as soon as nearby excavation activities commence.

Figure 1. This London Underground tunnel was built in 1917 and is our research trial site.

1 INTRODUCTION

A great deal of investment goes into the multifaceted structural processes used to build the subterranean mass-rapid transportation tunnels and bridges that occupy fundamental social and commercial positions in our society. Maintenance of these structures is an indispensible, ongoing and labour intensive process. For this reason researchers and civil engineers look to WSN devices to provide a different method of studying and understanding the limitations of civil engineering structures (Hoult et al. 2009). To deal with the transportation needs of a growing London population, the London Underground is constructing and modifying a large number of tunnels within its network. Many of the existing London Underground tunnels are of the cast iron variety, built in the 19th and early 20th centuries.

Tunnel excavation is increasingly occurring directly adjacent or parallel to existing tunnels. These activities submit the tunnels to new and prolonged stresses that compromise their structural integrity. This issue was dealt with in one particular study that focused on the deployment of static sensors in London Underground tunnels with known crack locations (Hirai et al. 2010). In addition, though not directly examined in this research paper, excavation presents the danger of compromising over-ground structures such as Listed buildings.

To monitor the structural health of transportation tunnels, trained teams of engineers currently conduct physical assessments. Physical inspections are costly, time consuming and difficult due to the access challenges presented by remote areas of tunnel. Sensors that monitor structural data are also an option. Previously the high cost of sensors meant that construction budgets only

allowed for the limited application of sensor networks (Bennett et al. 2010). Today, however, the cost of sensors has declined significantly, offering new monitoring possibilities.
To cut costs and remove much of the physical human component of structural inspections, we have commenced a study in which 30 low power WSN devices are deployed in a London Underground tunnel to monitor structural health. The trial site for this research was built in 1917 and presents an environment identical to that of other London Underground and cast iron transportation tunnels. It is roughly ~3m in internal diameter and experiences regular lateral and longitudinal stresses due to its location directly above and parallel to a new tunnel being excavated, approximately ~11m in diameter.

2 ENVIRONMENTAL CONDITIONS OF THE TRIAL SECTION

This section highlights the three major environmental factors influencing our sensor deployment: tunnel conditions, soil conditions and networking conditions. The tunnel in which our sensors are deployed has an internal diameter of roughly 7ft to 9ft, a length of approximately 6.5 miles and an average depth of 21m. It is predicted that this tunnel will undergo either ovalisation or longitudinal bending in response to the excavation of the new tunnel.

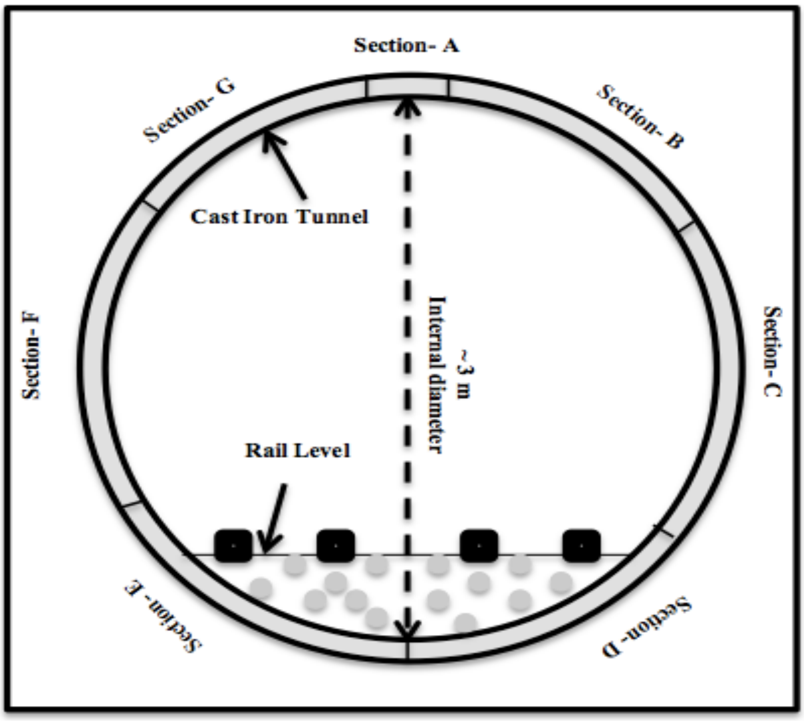

Figure 2. Cross-section of the tunnel under study, presently in an undeformed state.

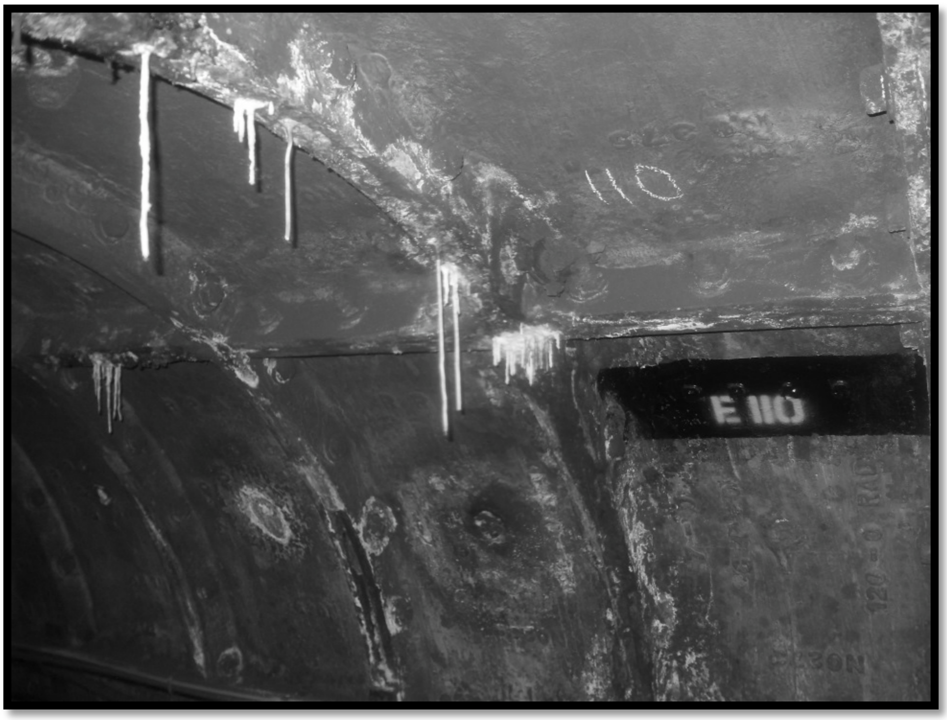

Figure 3. Staining, stalactite growth and rusting are seen in the joints.

2.1 Tunnel Condition

The instrumented section of the tunnel is in reasonably good physical condition, comprised of 80 rings of 7 segments each. There are no cracks or evidence of other type of ring or segment failure. Many of the bolts are rusted or missing, however, and there is evidence of water leakage in many of the rings with staining, stalactite growth and some rusting seen in the joints. There are longitudinal lines of missing bolts as well as bolts missing at occasional intervals. Additionally there is evidence of on-going water passage through the flanges, seen in stalactite growth, but its source could not be identified. Redundant signalling and telecommunication cables exist on both sides of the tunnel. The invert in the monitored area is made of a concrete block, outwardly appearing in good condition. The quality and consistency of the concrete block is not known, though, and it is possible that there is an underlying layer of gravelly material beneath the concrete surface. Readings from our temperature and humidity sensors indicate that throughout the year the tunnel has a relatively constant temperature and humidity level. Temperature measurements taken both inside and outside the sensor nodes range from approximately 16 °C to 18 °C. Humidity sensors placed in open areas of the tunnel environment returned measurements ranging from 68% to 85% humidity, depending on the particular stretch of tunnel.

2.2 Ground Conditions

The tunnel is located within the London Clay formation at approximately 25mbgl (axis level). The new tunnel is mainly being excavated within the London Clay, with up to a few meters of its invert being excavated at the upper layers of the Lambeth Group formation. Groundwater level is assumed to be at the top of the River Terrace Deposits at roughly 6mbgl

Table 1. Soil profile at the underground tunnel station area.

Top of Stratum	Approximate ground level [mATD]	Description
Made Ground	114	Engineered fill, waste heaps, construction fill, demolition rubble and previous building foundations.
River Terrace Deposits	109	Typically sand and gravel with clayey and silty sand sediments occurring locally as discontinuous beds, cobbles may also be present.
London Clay	106	The London Clay is heavily over-consolidated and can be divided into a number of units, with the lower units.
Lambeth Group	76	The Lambeth Group comprises variable ground conditions both laterally and vertically. The Upper Mottled Beds and Lower Mottled Beds are the most clayey units and the basal Upnor Formation is the most granular.
Thanet Sand	58	Silty fine to medium sand, with increasing clay and silt content in lower part of the formation.
Chalk	49	Variably weathered and fractured pure white limestone with flint bands and marl seams.

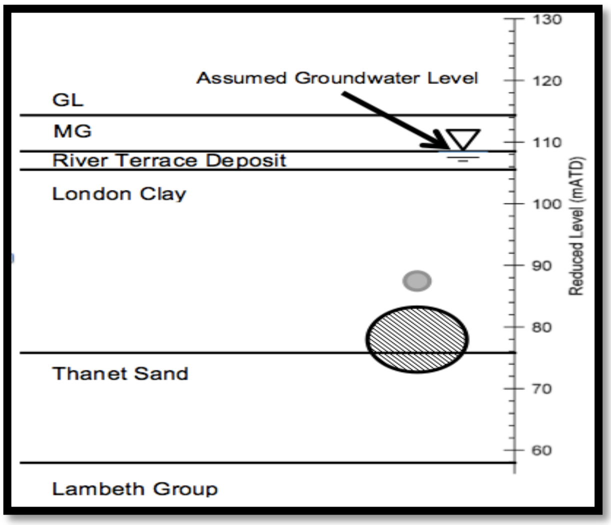

Figure 4. Soil profile surrounding the tunnel and the final location of the new tunnel to be excavated below.

2.3 *Network Conditions*

Because the research site is a relatively small tunnel made from cast iron, there is a lot of signal reflection. To ensure reliable and successful data transmission between WSN devices, we have used a combination mesh and star network arrangement.

All 30 nodes of the network take measurements and transmit data to the gateway. The gateway is located at the beginning of the monitored stretch of tunnel. The gateway receives and saves data in the computer. From the computer the data can be accessed remotely from mobile phones, tablets, laptops or any device with internet connectivity.

Some of the network sensor nodes are in awake mode at all the times, transmitting once a second, while other nodes only wake for short periods, transmitting every 4 hours to ensure the network remains active. We are using IPv6 for its communication capabilities and features such as network security, multicasting extensibility and long address (Jankiewicz & Loughney 2011).

3 SENSOR NODE DEVICES

Hardware, software and networks are the main concerns when designing a reliable WSN deployment. These devices were first submitted to lab testing that simulated real-life conditions as far as possible. To obtain high performance, we designed very low power consumption devices. Low power integrated components created long-term data collection capabilities without the need for regular human intervention.

All devices have a 32-bit ARM Cortex processor (Seal 2000) but use different radio frequencies, ranging from 800MHz to 2.4 GHz. Some sensor nodes have more than one sensor. The sensors measure data and perform a simple computation to ensure data has been successfully transmitted to the gateway.

The devices vary slightly in size but are approximately ~ 5cm x 2.5cm x 1.2cm in dimension. Their main components are a processor, sensor and radio. They are very lightweight at around ~10 to 20g depending on the sensor and the connectors deployed (Hyde 2002). All devices have an internal antenna and a working transmission range up to 50m.

For the WSNs that perform frequent measurements and monitoring such as receiving and sending radio communication, power consumption was the major concern for system architects (R. B. Smith 2007). The usual path for data transmission is a mesh network, but if the gateway did not receive the data from a particular sensor node after a prescribed period of time, the sensor transmits the data to the gateway via the star network. Mesh networks generally consume less power than star networks, but star networks eliminate data loss through direct gateway connections.

In this study one sensor is deployed on each selected ring except for Ring 40, either on or between the flanges. Rings 1, 8 and 15 have three sensors each installed on their flanges. To study the movement of the planes we added one node to each of the six segments of Ring 40.

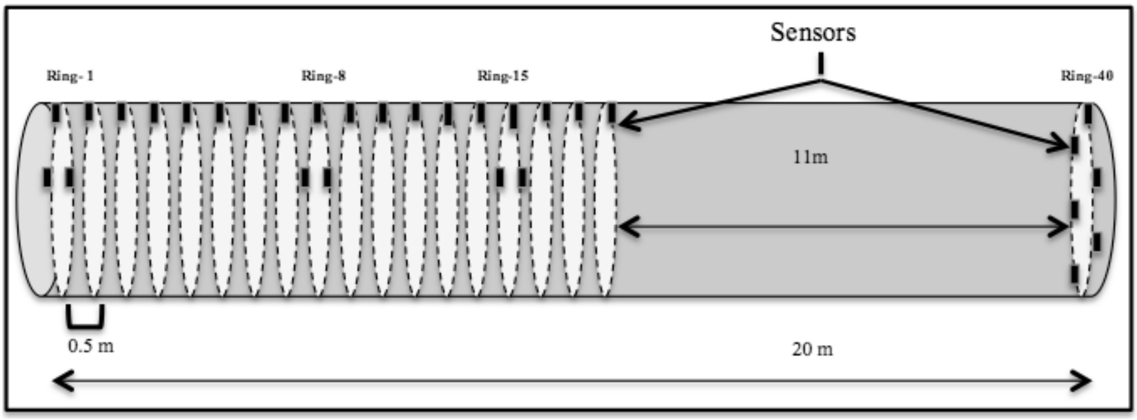

Figure 6. The sensor arrangement of a segment of the monitered tunnel section.

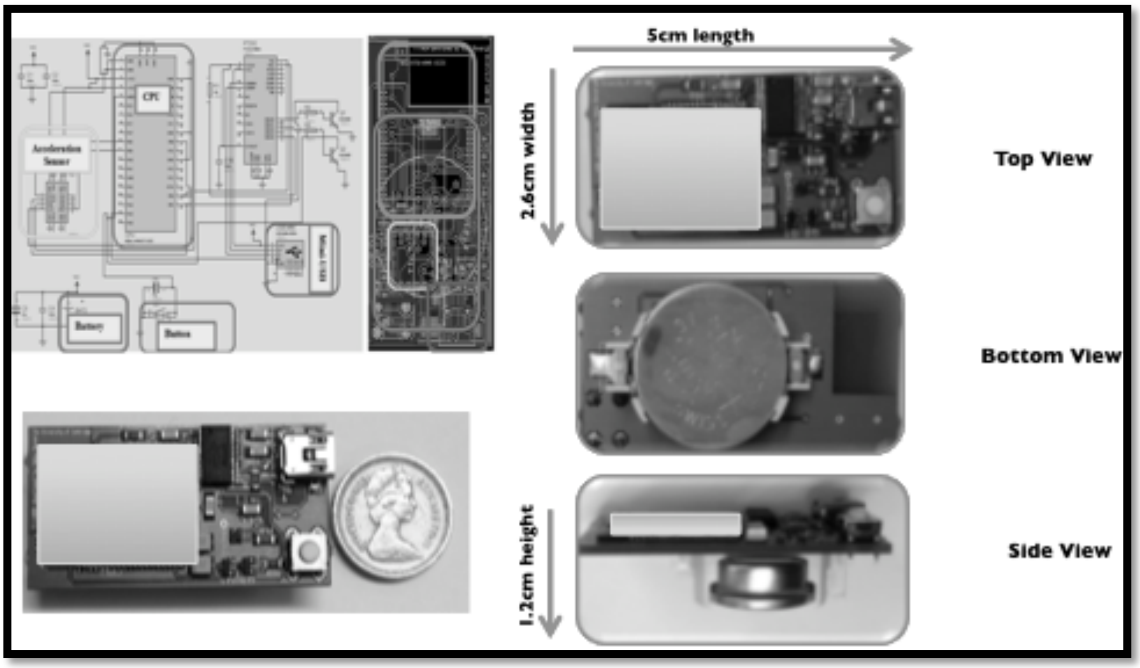

Figure 7. WSN devices.

4 MONITORING RESULTS

The low power WSN installation has been successful for the last 6 months. We constantly collect data, monitoring any changes in the infrastructure. We expect changes in inclination/tilt and acceleration data in the coming weeks as tunnel excavation occurs.

The combination star and mesh network ensures that all sensors communicate their data with an approximate 98.96% success rate. Using the sleep and deep sleep functionality modes in the processors, the devices consume very little battery energy. We have also achieved lightweight and robust device designs that are significantly smaller than any comparable device on the market. This makes the devices portable and easy to apply.

5 CONCLUSIONS

The low power WSN is installed in an aging cast iron running tunnel in the London Underground. This tunnel environment replicates that of other transportation tunnels within the London Underground network and offers an ideal setting for testing our sensors. The sensors have proven to successfully and reliably transmit data for remote access and analysis.

The WSN uses a combination star and mesh network. Nodes communicate their measurement data between each other and the gateway to reduce noise measurements. All data is also saved in a local computer within the tunnel. The computer is remotely accessible via electronic communication devices anywhere in the world where an internet connection is available.

This trial will demonstrate the monitoring and cost benefits of having a safe, low power wireless system deployed in subterranean structures while excavation occurs nearby. Our WSN will measure and record the time and extent of any movement or deformation in a monitored ring segment.

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