

# Poster Abstract: Wireless Sensor Network-Based Tunnel Monitoring\*

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## ABSTRACT

In this paper we describe the development and deployment of a wireless sensor network (WSN) to monitor a train tunnel during adjacent construction activity. The tunnel in question is a part of the London Underground system. Construction of tunnels beneath the existing tunnel is expected to cause deformations. The expected deformation values were determined by a detailed geotechnical analysis. A real-time monitoring system, comprising of 18 sensing units and a base-station, was installed along the critical zone of the tunnel to measure the deformations. The sensing units report their data to the base-station at periodic intervals. The system was used for making continuous measurements for a period of 72 days. This window of time covered the period during which the tunnel boring machine (TBM) was active near the critical zone. The deployed WSN provided accurate data for measuring the displacements and this is corroborated from the tunnel contractor's data.

## Categories and Subject Descriptors

C.2.1 [Computer Communication Networks]: Wireless Communication; C.3 [Special-Purpose and Application-Based Systems]: Embedded Systems

## General Terms

Design, Deployment

## 1. INTRODUCTION

The existing state of infrastructure needs to be known to apply any repair techniques. Monitoring systems are commonly used to know the existing state of the infrastructure. Nearly all monitoring systems in Civil Engineering are wire-based systems. The primary purpose of the wires is for data communication, and may also be used for powering the sensors. Wire-based systems are expensive to install and maintain, and instrumenting an existing structure with a wire-based system has some practical difficulties. Wireless monitoring systems, to a great extent are devoid of these problems. Being modular in nature, these systems can be moved to new locations as needed. The availability of low-powered and cheap computing power (microcontrollers, DSP chips etc.), radio frequency (RF) integrated circuits, and the development of new wireless standards has fueled interest in wireless sensor systems. Wireless sensor technology is one of the promising technologies of the future

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[5]. Active research is being done in the use of wireless sensor systems for structural and environmental monitoring. In this paper, we discuss a wireless sensor network (WSN) based tunnel monitoring application.

## 2. TUNNEL MONITORING APPLICATION

### 2.1 Background

The wireless sensor system developed was deployed in a section of the London Underground tunnel system near Highbury & Islington Station. Adjacent construction activity was expected to cause deformations in the existing tunnel and a potential disruption of the tunnel services. The construction activity comprised of construction of two tunnels (dia 8.1 m) using a tunnel boring machine (TBM) beneath the existing tunnel. These tunnels were a part of the Channel Tunnel Rail Link (CTRL) project and run from Stratford station to King's Cross station.

The most likely deformation that the tunnel could undergo was sagging with the most vertical displacement directly above the construction activity. The other possible deformation being the ovalization of the tunnel's critical cross-section. The critical cross-section was directly above the construction activity. The expected vertical displacements, obtained by a geotechnical analysis, were between 10-30 mm depending upon the soil volume loss. The expected deformation due to ovalization of the critical cross-section was between 1-3 mm.

### 2.2 Goals of the monitoring activity

The goal of this endeavor was to use a wireless sensing system to measure vertical displacements and hence evaluate the potential of WSN for infrastructure monitoring. Electrolevels are commonly used to measure the vertical displacements in a tunnel. These are sensitive instruments that measure slope. Slope is integrated over length to get displacement. The electrolevel system is not redundant and is expensive to install. Moreover, the errors in slope measurement get accumulated in calculating the displacements. On the other hand, a wireless sensing system would be much cheaper and easier to install. The main challenge of developing a sensing system was the limited "design" and "test" time available. The whole system had to be developed and tested before a "strict" deadline.

## 3. DEVELOPMENT AND DEPLOYMENT DETAILS

In order to monitor the vertical displacements, a wireless sensing system was developed. One of the main requirements on the technology was non-obtrusiveness as there is little room in the tunnel

outside the dynamic envelope of the train. This ruled out the possibility of using existing technologies like laser-based surveying instruments for measuring displacements. Commercial off-the-shelf (COTS) wireless sensing systems that were considered are: Mica [4] motes and i-Beans [3]. Each of them had limitations which made us to develop our own wireless sensing system. The detailed design and development of the sensing system can be found in [2, 1].

The wireless sensing system consisted of 18 sensing units (size: 15 cm \* 10 cm \* 7.5 cm), a base-station and a hydraulic reference line; each sensing unit consists of a pressure transducer, microcontroller, RF transmitter and signal and power conditioning hardware. Each unit was powered by 6 C-cell alkaline batteries. The sensing units were connected to the hydraulic reference line that was laid out along the critical zone. The sensing units measured the absolute pressure at various points on the hydraulic reference line. The vertical displacements were calculated using the relative change in pressure. One of the sensing units (one farthest from the construction activity) was used as the reference for calculating the pressure changes. The base-station was a RF receiver unit connected to a laptop, which was shelved in an access shaft near the tunnel. Since, the train tunnel was operational, the system was deployed during the engineering hours of the tunnel. The engineering hours are a four hour window (1 am to 5 am) every night when the trains are not operating. It took four days and two persons to install the whole system. The system was operational from October 17, 2003 to December 29, 2003.

Each sensor unit collected a pressure reading from the transducer every 10 seconds, temperature and voltage supply to the unit every minute, and transmitted these readings to the base-station. The data was packeted using a pre-defined format and was sent to the base-station using the RF transmitter. The base-station laptop stored the data on its hard-disk and also transmitted this data to a remote server using a wireless modem. The base-station performed the calculations to measure the displacements from the pressure readings. These readings were not corrected for temperature effects. Post-processing was done to calculate the displacements [1].

## 4. RESULTS

The first TBM (up line tunnel) passed the site on 29<sup>th</sup> October, 2003. The centerline of this tunnel passed below approximately the 53 meter mark of our horizontal alignment scale. The majority of the sensors reported a downward movement over the course of a week, followed by stabilizing. Most sensors showed a downward movement between 5 and 15 mm which is a reasonable observation. The second TBM (down line tunnel) passed beneath roughly the 33 meter mark on our horizontal scale on December 8. To calculate the displacements, the sensor data was re-zeroed just before the second tunneling took place. This removed the effects of movement after the first tunneling. Any long-term drift in the measurements of the sensor modules was also removed by the re-zeroing. The second passing of a TBM caused sensors to report a settlement between 5 and 10 mm. This is quite similar to the results of the first passing. Good correlation with the data from the tunnel contractor is found but the exact values are not publicly available.

### 4.1 Performance of the system

Of the 18 sensors installed, only 11 of them worked without problems. Four of the sensors reported unreliable data and the base station could receive only intermittent messages from two of the sensors. It was observed that many of the readings were lost because

of the collisions that occur when two transmitters try to transmit data at the same time. This could have been avoided by using an appropriate medium access control (MAC) scheme. Because of the time constraint in designing the whole system, this was not done. In order to avoid a cyclic pattern of collisions, the sensing units were programmed so that they send data at a random interval within a window of 0.5 milliseconds after the microcontroller collects data from the pressure transducers. This decreased the likelihood of two transmitters sending the data at the same time. But this was not sufficient as is evident from the data loss. The data during nighttime hours, after being corrected for temperature effects and pressure spikes, provided results which were steady to within a millimeter over a period of several days. Pressure changes in the tunnel caused noise of several millimeters in the readings during the hours that the trains were operating. On the longer term, there was a drift of several millimeters. For the present application, where the system had to monitor a sudden event of TBM passing, an accuracy of 1 millimeter was sufficient. The six C-cell alkaline batteries ran each sensor for approximately two months before the voltage dropped too low to provide five volts to the circuit board. This was sufficient to cover the two events [1].

## 5. CONCLUSIONS

A wireless sensing system to monitor displacements was designed and deployed that provided good correlation with the contractor's data. It was simple to install and no maintenance of the system was required during the monitoring period. The system can be improved by using an RF transceiver instead of the RF transmitter. Alternatively, the Mica motes with sufficient modifications would improve the communication and power-management of the wireless sensing unit. For future monitoring applications, these improvements will provide more fine-grained data. This endeavor shows that wireless sensor networks have a great potential for infrastructure monitoring applications.

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