Micro-measurement and monitoring system for ageing underground infrastructure (Underground M3)

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**ABSTRACT:** Advances in the development of computer vision, miniature Micro-Electro-Mechanical Systems (MEMS) and Wireless Sensor Network (WSN) offer intriguing possibilities that can radically alter the paradigms underlying existing methods of condition assessment and monitoring of ageing civil engineering infrastructure. This paper describes some of the outcomes of the European Science Foundation project “Micro-Measurement and Monitoring System for Ageing Underground Infrastructures (Underground M3)”. The main aim of the project was to develop a system that uses a tiered approach to monitor the degree and rate of tunnel deterioration. The system comprises of (1) Tier 1: Micro-detection using advances in computer vision and (2) Tier 2: Micro-monitoring and communication using advances in MEMS and WSN. These potentially low-cost technologies will be able to reduce costs associated with end-of-life structures, which is essential to the viability of rehabilitation, repair and reuse. The paper describes the actual deployment and testing of these innovative monitoring tools in tunnels of London Underground, Prague Metro and Barcelona Metro.

1 **INTRODUCTION**

Deterioration of ageing civil engineering infrastructure and the associated increase in the proportion of budgets spent on maintenance present significant challenges to our society. Dense spatial and temporal information, integrated with appropriate data analytical tools, is required to assess and reduce the likelihood of, or improve the efficient response to failures of key elements of critical infrastructure resulting from degradation, overload, or disasters due to natural and/or man-made causes. The maintenance, refurbishment and safe operation of ageing infrastructure under severe financial constraints forces civil engineers to strive for technological advances which will allow them to sense, monitor and better understand the behaviour of their engineering systems under both normal and extreme operating conditions.

Nowhere is this more apparent than in large-scale critical systems such as the networks of tunnels that lie beneath our cities. Some of this infrastructure was constructed more than half a century ago and there is widespread evidence of deterioration. Old tunnels are in particular vulnerable to adjacent ground disturbance, for instance piling and deep excavations.

At the moment, network wide monitoring is prohibitively expensive and very limited in terms of obtaining the necessary data for quick assessment, especially in the case of emergencies due to natural or deliberately caused disasters. Advances in the development of computer vision and Micro-Electro-Mechanical Systems (MEMS) offer intriguing possibilities that can radically alter the paradigms under-lying existing methods of condition assessment and monitoring. Future monitoring systems will undoubtedly comprise Wireless Sensor Networks (WSN) and will be designed around the capabilities of autonomous nodes. Each node in the network will integrate specific sensing capabilities with communication, data processing and power supply.

This paper presents an overview of a European collaborative project “Micro-Measurement and Monitoring System for Ageing Underground
Infrastructures (Underground M3)” funded by the EUROCORES Smart Structural Systems Technologies (S3T) Programme of the European Science Foundation. The main aim of the project was to develop a system that uses a tiered approach to monitor the degree and rate of tunnel deterioration. The system comprises of (1) Tier 1: Micro-detection using advances in computer vision and (2) Tier 2: Micro-monitoring and communication using advances in MEMS and WSN. The paper describes the innovative monitoring tools developed in this project.

2 CONDITIONS OF AGEING TUNNELS

One of the main features of the project is the participations of underground railway owners and maintenance operators. The monitoring system developed for this project has been tested at three metro systems in Europe; Prague Metro, London Underground and Barcelona Metro.

London Underground Ltd (LUL) has 402 km of railway lines. Approximately 45% of this (181 km) are underground tunnels and many of them are 75–100 years old. 80% of the tunnels are made of cast-iron. Deterioration of the linings and change in earth pressures with time are concerns because these are associated with the decrease in the clearance between the tunnel linings and the trains, affecting the train operation.

The Barcelona Metro was founded in 1924. It currently has nine metro lines; six are operated by Ferrocarril Metropolità de Barcelona and three are operated by Ferrocarrils de la Generalitat de Catalunya. The network has a length of 124 km with 164 stations. Most of the tunnels are constructed by the cut-and-cover method and use masonry, steel, plain concrete, reinforced concrete, and diaphragm walls depending on the time of construction. More recent tunnels are made by shield machines. The concerns of the tunnel operators are wet areas, oxidation of reinforcement, and cracks and fissures.

Prague Metro has three lines and consists of about 60 km of tracks running mostly underground and 57 stations. It is about 30 years old and is mostly Russian-built. In August 2002, the metro suffered flooding that occurred in Central Europe. 19 stations were flooded and several building movements have been attributed to this event. The long term effects of the damages caused by flooding are one of the major concerns of the underground operator.

At present the tunnels of the three metro systems are monitored if a specific problem has arisen in which case a system can be retrofitted before repair and strengthening work is undertaken so that the effectiveness of the refit can be examined. The current employable technologies for the assessment of such infrastructure range from network-wide visual inspection to surveying and deployment of instruments for monitoring performance at critical sections (or response to adjacent construction). These technologies have evolved with the maintenance needs, but three general limitations remain.

- High cost of equipment and data processing limits usage and/or constrains the scope and frequency of sampling and inspection.
- Measurement techniques that interfere with vehicle movements in tunnels are seriously discouraged, while direct access is very difficult. There is also a need to conduct quick inspection check as maintenance crews are moving.
- New technologies are needed for specific classes of problems, e.g. monitoring of joint rotations in tunnel lining.

This Underground M3 project comprises an integrated research program to evaluate and develop prototype monitoring systems for condition assessment of ageing underground infrastructure. The main aim is to develop a system that uses a tied approach to monitor the degree and rate of deterioration. The system comprises of (1) Tier 1: Micro-detection and (2) Tier 2: Micro-monitoring and communication.

3 TIER 1: MICRO-DETECTION

For maintenance works of underground structures, visual inspection is a common practice for detecting and monitoring anomalies such as cracks, spalling and staining. 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 are expected to result in a substantial progress in the effectiveness of monitoring, in particular of remote monitoring, like shaft inspection, where inspectors cannot easily access the inspection site.

One way to assist inspectors in organising a large collection of images and examining the tunnel surface is providing them with automatic tools that combine a large number of pictures into a single high-quality wide-angle composite view. This process is commonly referred to as image mosaicing. There are many image stitching software packages, such as Microsoft Image Composite Editor (ICE) and Autopano, the vast majority of which rely on a number of strict assumptions on the camera motion or on the scene geometry to be strictly true. In fact, these packages are genuinely designed for
generating panoramas, and they require images to be captured by a camera roughly rotating about its optical centre, or by capturing the plane at “infinity” (i.e. the scenes where all objects are distant and there is little or no parallax). The images from typical underground structure inspection do not meet such requirements and these packages fail to generate good mosaics, as shown in Figure 1 (Top).

A new computer vision system has been developed in this project to perform mosaicing of images captured inside a tunnel from a standard digital camera or videos. It can simultaneously cope with free camera motion and the more complex geometry of the scene. In the proposed system, starting from a set of pictures from a section of the tunnel linings, first the approximate 3D geometry of the scene and consequently warp each frame are recovered in order to generate a set of pictures that can be stitched together using any standard mosaicing technique. In fact, for images captured inside a tunnel, this warping procedure can be imagined as prompting pictures of a tunnel that has been flattened, or unrolled onto a plane (see Fig. 1 (bottom)). In order to do this, the system obtains the sparse 3D reconstruction of the tunnel using Structure from Motion (SfM) (Snavely et al., 2005) from the input images.

A sparse 3D model, i.e. a 3D point cloud, can be recovered from digital photographs, together with the camera poses, i.e. translations and rotations with respect to a given reference frame. The reconstruction procedure is composed of two modules: point track generation; and multiple view geometry estimation.

In the first module, interest points are extracted from each input image and matched across multiple frames in order to obtain a set of points that consistently appear in multiple images as shown in Figure 2. The 2D coordinates of such points are collected and concatenated forming 2D trajectories over the multiple frames. Success at this stage relies on the robustness of the extraction and matching scheme of the interest points.

An interest point is an image point whose neighbourhood (i.e. an image patch centred at that point) displays distinctive features that are stable under perturbations arising from some degree of perspective transformations, illumination variations and noise such that the same interest points can be extracted with high degree of reproducibility. This invariance allows key points to be matched across multiple images. The Scale Invariant Transform Features (SIFT) is an example of stable image feature (Lowe, 2004). Interest points are detected in scale-space, and are assigned descriptors that summarize their appearance by the orientation histogram of the intensity gradients within a patch, thus achieving invariance to scale, orientation, affine distortion, and partial invariance to illumination changes.

The second module is classically formulated as a large-scale optimization problem (see Zisserman and Hartley (1999) for a detailed explanation of multiple view geometry). The output from the first module is used to initialize the optimizer, estimating the sparse point cloud and camera poses using overlapping triplets of images. The estimation is then refined by Bundle Adjustment (BA) (Lourakis and Argyros, 2004). The BA algorithm iteratively adjusts the positions of the 3D coordinates and the camera poses to minimize the sum of the distances between the reprojections of the reconstructed 3D points through the estimated cameras, and the interest points 2D coordinates. Figure 3 shows a sparse 3D reconstruction of three tunnels.

Cylinders are surface of zero Gaussian curvature, so it is possible to define a local isometry for flattening the curved surface onto a plane (Chaiyasarn et al., 2009). Moreover, given the constraints on the image collection process, cameras are located inside the cylinder and each ray intersects the surface in only a single visible point, defining for each image a one-to-one mapping between image samples and points on the surface. These facts allow us to define a warping that produces the flattened versions of the input images (see Fig. 4).
Figure 1 shows qualitative comparison between the mosaic images from the homography-based method and the proposed method. Perspective distortion is clearly removed in the result. An example of a larger composite image is shown in Figure 5. With this system it is possible to identify regions of change in images of the same scene taken at different times since the images have spatial coordinates assigned. This is much needed for inspection since engineers will be able to assess the deterioration rate of a structure and then devise regime for repair. The prototype of the system including the software and the apparatus for acquiring images is currently being developed so that it can be practically adopted in the underground structure inspection procedure.

4 TIER 2: MICRO-MONITORING AND COMMUNICATION

4.1 Micro Electro Mechanical Systems (MEMS)

Once significant anomalies or cracks are detected in a Tier 1 assessment using computer vision techniques, there is a need for more intensive monitoring. This will be a Tier 2 targeted micro-monitoring process. It is proposed that the solution for underground infra-structure monitoring is the use of low cost sensors of a distributed nature. Micro Electro Mechanical Systems or MEMS are small integrated devices or systems that combine electrical and mechanical components varied in size from micrometers to millimeters, 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 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 high 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 sensitive 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. In this project, potentially low-cost MEMS strain or displacement sensors were developed.

An example of MEMS resonant strain sensors that were developed for the project is shown in Figure 6. The basic principle of this MEM strain sensor is to couple the strains axially onto a vibrating beam, similar to the conventional vibrating wire strain gauges. The figure shows Double-Ended Tuning Fork (DETF) parallel-plate resonators with reduced coupling gaps (<1 µm) (Ferri et al., 2010). The added strain energy in the beam shifts its resonant frequency. The strain can be inferred by monitoring the shift in resonant frequency.

The small size of MEMS enables them to be used in situations where conventionally sized components are not applicable. Another advantage is their low power requirement (e.g. 500 micro watts to 40 milli watts). Due to the economies of scale achievable with conventional chip manufacturing processes, they can be produced at relatively low cost.

The fabrication process of the strain sensor has been previously reported in Ferri et al., (2008). The process is starting from silicon on insulator substrates. The silicon device layer is heavily doped and annealed in order to obtain a low sheet resistance. On the substrate, a low temperature oxide layer is then deposed and completely oxidized to shrink the gaps patterned on the initial oxide layer. The deep RIE is then utilized to patent the reduced gap oxide mask on the silicon device layer with reduced line widths. The process is ended by an isotropic wet etching in buffered oxide etch.

Mechanical modeling of the MEMS sensor has also been performed as shown in Figure 7 to estimate the sensitivity of the system. Since the resonant MEMS sensors are operated through a self-sustained electrostatic actuation using an electronic oscillation loop, no static bias current is needed for their operation and the dynamic power requirements can be comparatively small.

As part of this project, a prototype MEMS crackmeter was developed with a thin steel strip fixed across a crack or joints on the tunnel, onto which a multi-directional MEMS strain sensor is soldered (Fig. 8) (Ferri et al., 2009, 2010a). The MEMS devices are bonded to a thin steel bar by epoxy glue, packaged in vacuum and tested by applying strain to the bar, showing good tolerances to packaging parasitics, measurement reversibility, and strain sensitivity of 10 Hz/µε. The steel strip is equipped by a nut which allows for changing the unstrained length of the strain sensor. This crackmeter will be deployed at a section in Prague Metro in the near future. We plan to report the performance of the developed MEMS in the future.

4.2 Wireless sensor network

The use of wireless sensor technology, which 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 underground monitoring. Combined with MEMS sensors, there is the opportunity for significant overall cost savings for large scale monitoring (Hoult et al., 2009; Stajano et al., 2010).

A prototype WSN system developed in this project was recently installed at a section of London Underground, Prague Metro and Barcelona.

Figure 6. Double-Ended Tuning Fork (DETF) parallel-plate resonators.

Figure 7. Mechanical modeling of the MEMS sensor.
Metro (see Fig. 9). It consisted of several WSN motes and a gateway, which were manufactured by Cross-bow Technology Inc. They were packaged and installed in such a way that they can survive for long-term monitoring (see Fig. 10). The effective mote-to-mote range was found to be approximately 15 meters and the layout installed included both star and mesh topologies as illustrated in Figure 8. Further details of the deployments can be found in Bennett et al., (2010a, b).

A limited number of motes were used in this trial so that it has predictable network topology to assess the performance of the WSN system. The gateway was connected to the internet via a router and GPRS. The system is currently tested to identify deployment and operational challenges in using sensor networks for monitoring and management of ageing underground infrastructure.

The WSN hardware that is used in this research has processing capabilities to prompt the development of computationally demanding signal processing algorithms which 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 8. MEMS crackmeter.

Figure 9. WSN deployment in three tunnels.
As the size of a WSN increases, an effective deployment is essential as there is limited engineering hours to install it in a real operational underground railway system. The installation has to be done as fast as possible, but the established communication network needs to be robust and redundant. In this project WSN deployment tools were developed for system configuration and management, for data collection and visualization and for in-situ debugging.

Figure 11 shows one of such tools, in which the locations of relay motes are optimized by considering communicable distance, reliability, robustness and data transmit capacity. Figure 11(a) illustrates possible communication paths for potential positions of relay motes at the Prague metro site, whereas Figure 11(b) shows the relay mote locations that are optimized for minimum communication distances using a heuristics based optimization method. For each sensor, there are at least two non-overlapped routes to the gateway and the data flow quantity (throughput) does not exceed the upper bound set beforehand. It is also possible to apply other objective functions such as minimizing the setting cost, the hopping number (the transfer number) for each route, the energy consumption, or combinations of these. Further details can be found in Hirai and Soga (2010).
Since underground infrastructure may not be frequently accessible, the developed system also needs to employ low power consumption in conjunction with the ability to harvest power from its immediate environment. The project also investigated the possibility of developing an energy harvesting unit that will power the MEMS sensors and the WSN system. An example of the developed MEM power harvesters is shown in Figure 12 (Wong et al., 2009).

This solution is practical as the sensors are used for long-term monitoring and as a result measurements are not required to be made frequently. It envisaged to use the energy available in the surrounding environment. For underground railways, the obvious choice is harnessing energy from pressure fluctuations while the trains are running. But other possibilities are currently being assessed.

5 CONCLUSIONS

In this project a new monitoring system was developed. The vision of the Underground M3 project is effective monitoring of ageing underground infrastructure using computer vision techniques and the widespread installation of miniature, low-cost, low-power wireless sensors on key components of the infrastructure. These sensors will be multiply redundant through overlapping networks and provide substantial on-board processing capabilities to reduce the volume of data transmitted to base stations. The sensors have the potential to be built into an economically viable generic WSN monitoring system providing key decision support capabilities to the system managers. The challenges of this project have been therefore to validate the capability of the recently developed computer vision techniques in the underground environments and to demonstrate how large numbers of small, low-cost sensors can be employed and integrated into large-scale engineering systems in order to improve performance and extend the lifetime while continuously evaluating and managing uncertainties and risks.

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REFERENCES


