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STRUCTURAL HEALTH MONITORING AT ROME UNDERGROUND, ROMA, ITALY

WHITE PAPER

Summary:

This white paper shows how Structural Health Monitoring (SHM), helps to improve the quality in the construction and long term monitoring in the B1 line Rome underground monitoring.

Introduction

GENESI has the ambitious goal of developing a new generation of WSNs for geotechnic and structural monitoring that are heterogeneous (in that they are made up of different kinds of sensors), energy efficient (capable of harvesting energy from multiple sources such as wind, sun, or vibrations), virtually perennial (in that they can be operational for several decades), smart (capable of evaluating risks and deciding a corresponding course of action in situ), and that use innovative transmission methods.

The sensor nodes (Figure 1) are small form (few centimeters), autonomous devices that are capable of exchanging data among themselves through wireless communications. They have been designed to meet the typical requirements of applications for geotechnic and structural monitoring.

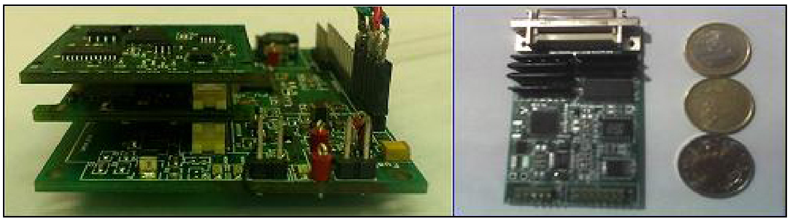


Figure 1 GENESI sensor node

Geotechnic and structural monitoring

A system for geotechnic and structural monitoring is made up of different types of sensors for measuring environmental and geotechical parameters as well as to quantify the structural response to solicitations. In traditional systems, the sensors are wired to a centralized system for data acquisition. The role of the monitoring system is then that of acquiring and processing data in real-time, in order to provide feedback on structural health as well as alarms on possible risks.

Geotechnical monitoring is an essential component of infrastructure construction, and in particular of underground constructions such as tunnels, as it supports design and triggers re-design of construction works, which is needed in case expected results are not aligned with those measured by the monitoring system. The objective of geotechnical monitoring is thus reduction of *risks*, where risks can be expressed as the product of the probability that a calamitous event is going to happen and the damages it generates economically, artistically, culturally and in terms of human life.

Let us consider, for instance, the digging of a tunnel in an urban context. In this case, the risk of damage to structures that are close to the excavation site is always present. For instance, pre-existing buildings could be damaged by sink holes caused by the digging activities. In risk planning and management one has to consider the causes for such damages, and has to set thresholds on a number of relevant monitored parameters which should not be exceeded during escavation. Such thresholds should be defined accounting for the expected and actual structural response of pre-existing structures. (Figure 2).

Figure 2 Singapore MRT Spring 2004 before and after the collapse (images taken from internet "The Code of Practice for Risk Management of Tunnel Works ITA Conference Seoul, April 25, 2006").

Monitoring enables risk determination and to take action to limit it, allowing e.g., the strengthening of existing structures that was not anticipated during the design phase. Furthermore, monitoring systems contribute to risk reduction, thus limiting damages to people and structures. Proper setting of alarms, enables the discovery of early criticalities, thus allowing technical workers to intervene and return the system to secure conditions, or to evacuate the structure and its surroundings.

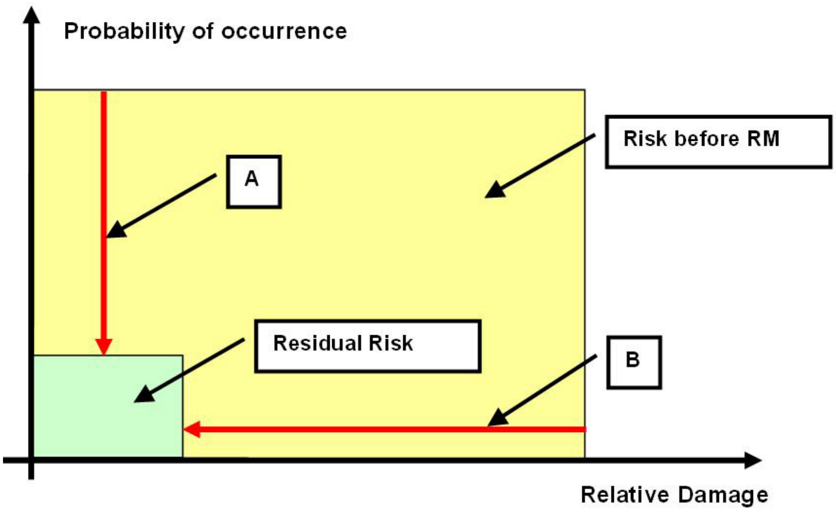


Figure 3 Risk reduction due to risk assement.

Figure 3 illustrates how the systematic use of structural monitoring can reduce risk to an acceptable level (given that it can never be completely elimitated).

In Figure 3, the letter A is used to indicate that proper monitoring can decrease the probability that a calamitous event occurs, for instance, by showing that a given structure has problems so that these problems can be addressed and the risk (e.g. the structure collapse) can be avoided.

With the letter B we show how monitoring can decrease the damages due to a given event, with timely alerting of workers and maintainers via appropriate alarm systems, thus for instance allowing the structure evacuation, if needed.

Reduction of both probability of occurrance of calamitous events and of the damage associated to calamitous events in turn result in safer cities, and avoids human life losses and high economical costs which can happen in case an erroneous design and a loosely controlled construction environment leads to a structure collapse.

The GENESI system: a new approach to structural monitoring

Along with traditional monitoring systems for mechanized excavation of urban areas, the **GENESI project proposes a novel system for long lasting geotechnical and structural monitoring, that is based on low power energy harvesting enabled wireless sensor networks technology**.

The use of these nodes allows us to sense and transmit data wirelessly, reducing interference with construction works. The same technology can also be used for long lasting monitoring once the tunnel construction has been completed and the underground or roadway is operational. To this purpose, we have developed energy neutral solutions based on a low power communication stack and low power sensor nodes equipped with wind microturbine to harvest energy from passing by vehicles.

The GENESI technology has also been proven to result in time, and hence economic, savings because of a) its innovative, less intrusive approach to monitoring, which does not require laying cable and the in situ installation of data acquisition boxes, and results in fast deployable systems; and b) because of the ability to remotely operate, control, and reconfigure the system which also contributes to limited maintenance costs in the long run. When compared to existing monitoring systems GENESI also provides a high level of modularity (allowing the seamless addition and removal of devices and functionalities) and supports many different sensors, with a flexibility usually not found. The GENESI system for instance supports or can easily be extended to support all sensors typically used to measure movements, pressure, inclination, deformation, humidity, temperature, etc.

Another important innovation introduced by GENESI concerns the smart methodologies for data transmission and exchange. For instance, in case one or more of the nodes should be faulty, the system is capable of detecting it, bypassing those nodes, and gathering data through different routes that are robust and energy efficient. Therefore, relevant data always find a way to the final user (unless they cannot be produced because of damaged sensors).

Use of energy harvesting and of low power devices and communication stacks also allows long lasting monitoring services, enabling to keep under control structures over time thanks to their embedded intelligence.

The application of GENESI to monitoring of underground tunnels: The Rome Underground experiment

A deployment of the GENESI system has been performed in the tunnels of the "Metropolitana di Roma Linea B1". In particular we have monitored the tunnel under construction connecting the stops of "Conca d'Oro" and "Jonio."

The wireless sensor node technology is applied to vibrating strain gauges that are installed in instrumented concrete sections covering the walls of the tunnel.

The use of vibrating strain gauges is quite common for the monitoring of civil infrastructures and particularly in tunnel construction. They allow measurement of structural deformations of concrete and stell components, which are important to determine the solicitations of exogenous agents on the structure. This data allows the tunnel designers to determine how stable the tunnel is and to verify the presence of deformations in line with what expected based on the construction project assumptions.

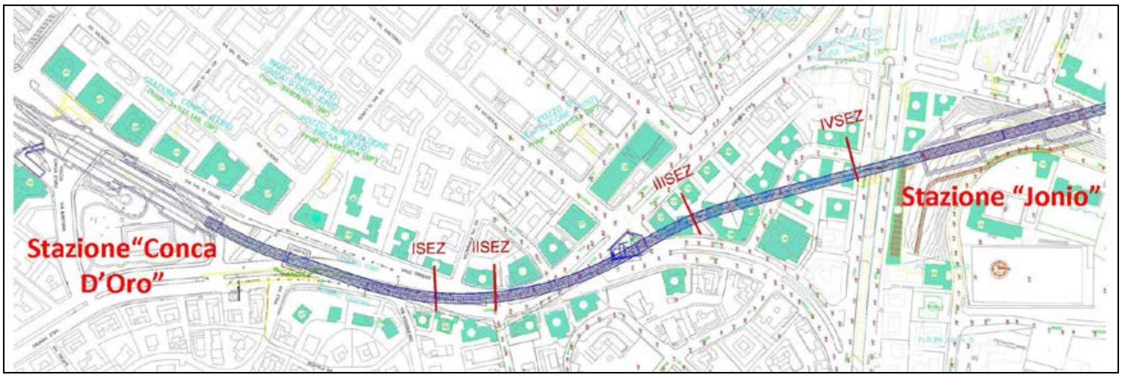


Figure 4 Location of GENESI monitoring sections along the tunnel of "B1 line Rome Underground", that connects Conca D'Oro station to Jonio station.

The experimental activity of GENESI requires the installation of four instrumented sections (Figure 4) in the tunnel. The ring of the tunnel walls has an internal diameter of 9 meters and it is made up of eight concrete blocks. Every instrumented section comprises two to three monitored concrete blocks (out of the eight), each equipped with six strain gauges whose purpose is to measure deformations in the concrete block structure (Figure 5 and 6).

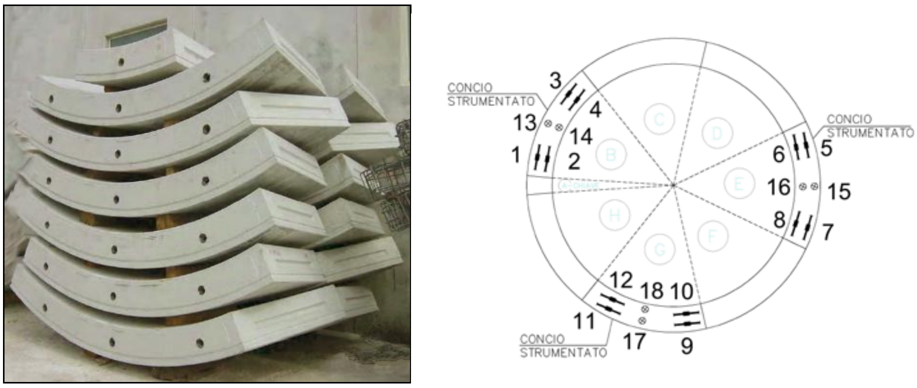


Figure 5 Concrete precast segments of the tunnel final lining (left image); strain gauges location in a tunnel final lining ring (right image).

Figure 6 Vibrating wire strain gauges installed on the steel supporting structures of the final lining segments and steel boxes for the future GENESI nodes housing.

Figure 6 shows both the strain gauges that are attached to the concrete reinforcement and the metal box soldered to the reinforcement, to collect the cables of the strain gauges and to contain the hardware of the wireless sensor node.

The context of the tunnels selected for the GENESI experiments is particularly “challenging.” Temperature can vary from -10 to 40 degrees Celsius; humidity can reach 100%; there is a high amount of dust and of water; nodes could be touched (and damaged) by passing workers or by excavation devices. As a consequence, the node housing must be carefully protected and their careful positioning is also very important.

In addition, an objective of the deployment was to reliably monitor the tunnel also during excavation, when the Tunnel Boring Machine (TBM) is in front and does not allow access to the instrumented sections. For this reason, sensor nodes were also placed on the TBM.

The WSN installed in the selected tunnel is made up of:

- Sensing nodes

- Relay nodes
- Gateway
- Debug relay nodes

Sensing nodes (Figures 7 and 8) are wireless nodes directly interfaced with the vibrating strain gauges. They allow data collection and their wireless transmission. They are embedded in the instrumented concrete blocks deployed by the TBM.

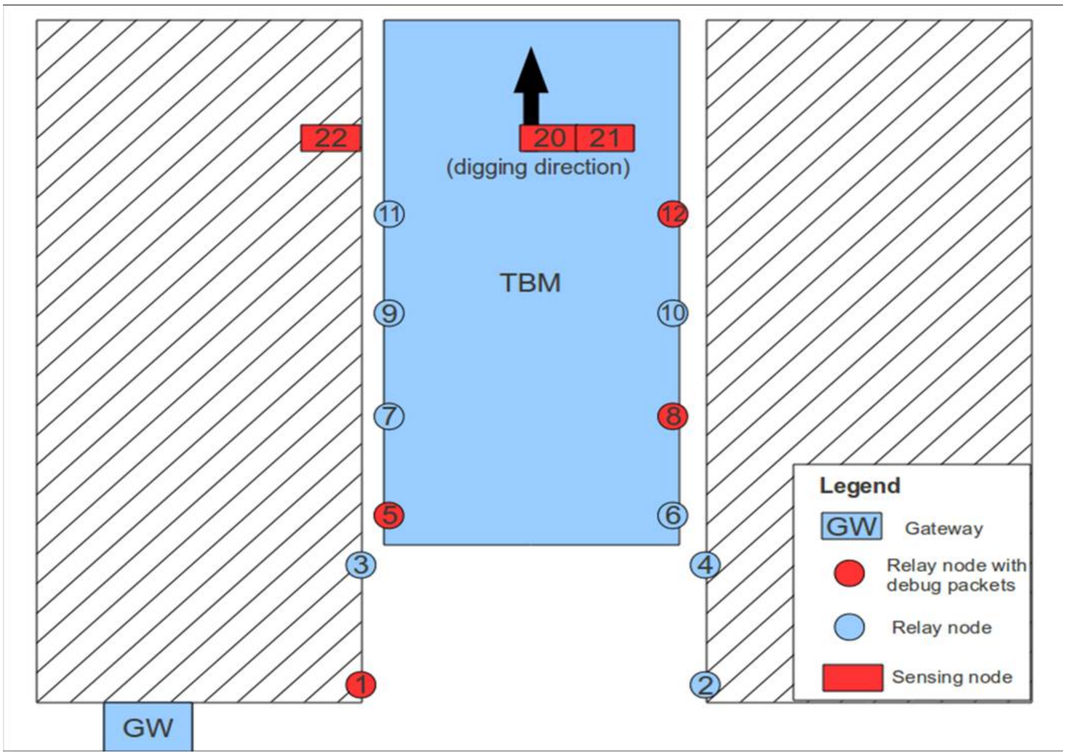


Figure 7 Schematic example of GENESI wireless sensors network into the tunnel.

Figure 8 "Sensing node" interfaced with the vibrating wire strain gauges of a concrete segment.

The relay nodes (Figures 7 and 9) are positioned on the final walls of the tunnel and on the tunnel boring machine to act as bridges, enabling multi-hop wireless communications of the data to the gateway.

The gateway (Figures 7 and 10) is positioned at the start of the tunnel. It collects the data and is equipped with a modem to transmit the data via Internet to an FTP server. In our deployment connection to the Internet was through a 3G connection.

The debug relay nodes (Figure 7) are relay nodes that can also perform debug functions for the sole purpose of system management.

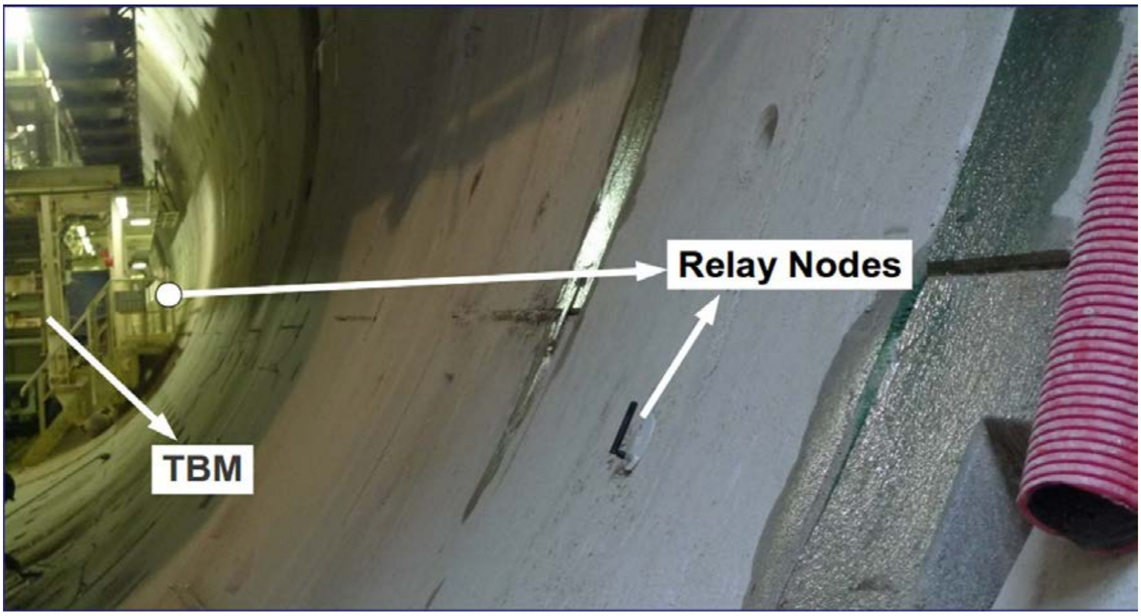


Figure 9 "Relay node" located on the tunnel final lining and on the TBM

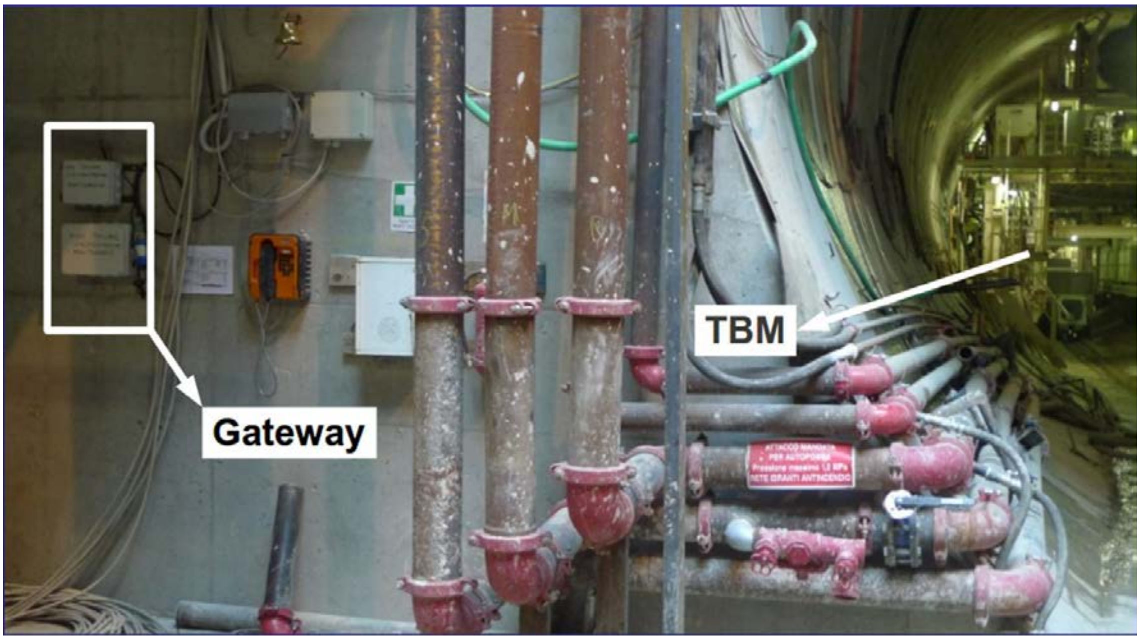


Figure 10 "Gateway" located at the entrance of the tunnel.

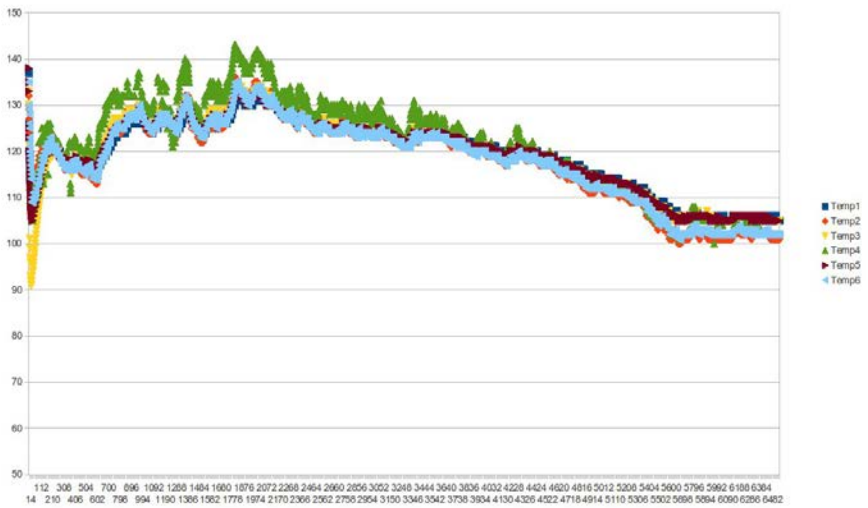
In the selected tunnels we have deployed nine sensing nodes, twelve relay nodes and ten debug relay nodes. All nodes are powered by batteries. The gateway is plugged in to a power line. Every node has an antenna (CC2420 transceiver at 2.4GHz). The sensing nodes are embedded in the concrete blocks and automatically deployed by the TBM. Relay nodes are deployed manually by construction workers. Nodes follow a protocol which automatically allows them to self-organize into a network upon deployment. When new nodes are added or removed the network automatically detects the change, and nodes reorganize themselves to enable reliable data communication.

The node connectivity decreases remarkably when nodes are housed in their boxes in concrete blocks, namely, transmission range decreases from 50/80 meters down to 15/20 meters. Threfore, relay nodes have been added close to sensing nodes. Additional relay nodes on the TBM further improve network connectivity, allowing reliable data gathering in all phases of construction works.

Network management, interest dissemination and data gathering is performed through DiSSense, an energy efficient protocol stack for wireless sensor networks we have developed. DiSSense periodically collects the data from the sensing nodes and transmits it to the Gateway, where data is processed and remotely accessible for users.

The deployment in Rome underground has shown that the GENESI system is reliable. All sensed data could be recovered. The percentage of real-time communicated data was quite high (over 90%). The network operated with an extremely low duty cycle (0,22%), resulting in an expected network lifetime (time till the first node depletes a 2x1800mAh alkaline battery) of 4 years, which is enough to cover construction works. Long lasting operation of the system has then been envisioned by adding wind microturbines to the nodes which allow the exploitation of air flows in the tunnel for energy harvesting.

Data reported to the central server, has been processed and made available to the stakeholders using the Tre Esse Engineering Web Data Monitor. In the following figure we report a sample of the displayed results



GENESI allows us to solve a series of problems typical of the traditional monitoring systems and presents numerous advantages with respect to them:

- GENESI provides a standard platform which can be used for different monitoring purposes, avoiding the use of different centralization panels depending on the type of installed instrumentation. The GENESI nodes can be interfaced to a multitude of sensors, having different electronic characteristics in terms of type of sensors (transducers), power supply, signal output, interface/connection, etc.
- GENESI processes the raw data using SHM algorithms and has the ability to assess potential risk through the management of alarm systems.
- GENESI doesn’t require cable installation, which is needed in traditional monitoring systems , thus allowing significant cost savings .
- GENESI allows us to overcome obstacles and propagation issues which may occur when using wireless communication, by the network intelligently reorganizing and finding new routes to the final destination.
- GENESI is simple to install: nodes can be moved, added and removed easily. This keeps to the bare minimum interference with normal operation at the building site.
- Ease of data acquisition. The data can be either downloaded directly from the individual "Sensing nodes ", which are equipped with an internal rewritable memory, or can be sent through the "Gateway" to a remote server from which they can be accessed and downloaded.
- Easy set-up of the network. The configuration or reconfiguration of the network, in terms of both sampling and reporting frequency, and of the alarm thresholds, is done wirelessly from remote access, without the need of accessing the datalogger.

- The whole GENESI technology is self-configurable and designed to be long-lasting, hence the infrastructure management costs are sensibly reduced.

Please contact us for further information on the GENESI SHM system and questions regarding our monitoring systems.

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