Association of Sensing Techniques with a Designed ICT Architecture in the ISTIMES Project: Application Example with the Monitoring of the Musmeci Bridge

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ABSTRACT

This work gives a brief description of the main activities and outcomes of the Integrated System for Transport Infrastructures surveillance and Monitoring by Electromagnetic Sensing (ISTIMES) project, which aimed at designing and implementing a system able to couple the capabilities of long-term monitoring and quick damage assessment of the critical transport infrastructures. This was performed thanks to the integrated use of the novel and state of art concepts of Earth observation, ground-based sensing techniques and ICT architecture. The paper will give a brief outline of the main results of the project by referring in particular to the demonstration activities at the test bed of the "Musmeci" Bridge in Potenza, Southern Italy.

KEYWORDS : *Long-term monitoring, satellite observation platforms, in-situ sensing technologies, ICT system architecture, integrated approach.*

INTRODUCTION

The integration of space based assets, airborne remote sensing observations and *in-situ* sensing techniques is now recognized as a technological option to ensure a global vision of infrastructures and the embedding territory, by providing at the same time a detailed situational awareness about the areas where criticalities arise. By this way, it is possible to really improve the monitoring and surveillance of critical infrastructures and perform a quick damage assessment during crisis events.
In this respect, in the three-years ISTIMES project (funded in the Joint Call FP7-ICT-SEC-2007 and ended on June 2012, www.istimes.eu) activities have been carried out with the main aim of the design, assessment and validation in preoperational phase of a system, based on an ICT architecture able to supervise an integrated large network of *in-situ* sensing techniques and space based observation platforms, for the monitoring of critical transport infrastructures [1].
The ISTIMES Consortium was built by nine partners: Technologies for Earth Observations and Natural Hazards (TERN), Italy; Institut Francais des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR), France; Telespazio, Italy; Dipartimento di Protezione Civile, Italy; Eidgenoessische Materialpruefungs- und Forschungsanstalt, Switzerland; Lund

University, Sweden; Tel Aviv University, Israel;Territorial Data Elaboration, Romany; Norsk Elektro Optik, Norway. The coordination of the project was in charge of TERN Consortium (Italy).
The ISTIMES system is based on two main technological pillars.
The first one regards an ICT system architecture exploiting web sensors and service-oriented technologies, which complies with specific end-user requirements, including interoperability, economical convenience, exportability, efficiency and reliability. The efforts have been focused mainly on: the creation of web based interfaces able to control "non-standard" sensors, as the ones proposed in the project; the standardization necessary to have a full interoperability and modularity of the monitoring system. In addition, the system is able to provide an easily accessible and transparent scheme for use by different end-users and to integrate the monitoring results and images with other kind of information, such as GIS layer and historical datasets relating to the monitored site.
The second pillar regards the development, exploitation and integration of a very wide range of heterogeneous electromagnetic sensors, static and mobile, capable to give a minimally or non-invasive monitoring of the infrastructure, so to not affect the normal use/service of the structure. In particular, the integration of state of-the state of-art sensors enables a ground-based network that is supported by specific satellite and airborne measurements. In particular, the project has exploited, assessed and improved many different non-invasive electromagnetic sensing technologies allowing both a global and local vision of the infrastructure. A strong effort has been devoted to "transfer" these technologies from the laboratory experience to actual on-field applications and to the development of data/integration, correlation approaches.
In the present paper we give an overview of the integration of electromagnetic technologies with new ICT tools that has allowed at enabling remotely controlled monitoring and surveillance at different temporal and spatial scales, by providing indexes and images for an always updated status of critical transport infrastructures. Results obtained on a bridge open to traffic are presented and discussed.

1 ICT ARCHITECTURE OVERVIEW

Within the first pillar of ISTIMES framework, an open networked architecture has been achieved; such an ICT architecture is able to accommodate a wide range of sensors, static and mobile, and can easily scaled up to allow the integration of additional sensors and interfacing with other networks.
Figure 1 depicts the main components of the ISTIMES architecture [2-3]:

- **Web-based interface components** for the electromagnetic sensors exploited in the project;
- **E-Infrastructure** for geospatial data storing and sharing;
- **Decision Support System (DSS)**, which helps decision makers providing inferences and situation indexes;
- **Presentation component**, which implements system-users interaction services and information publication and rendering.

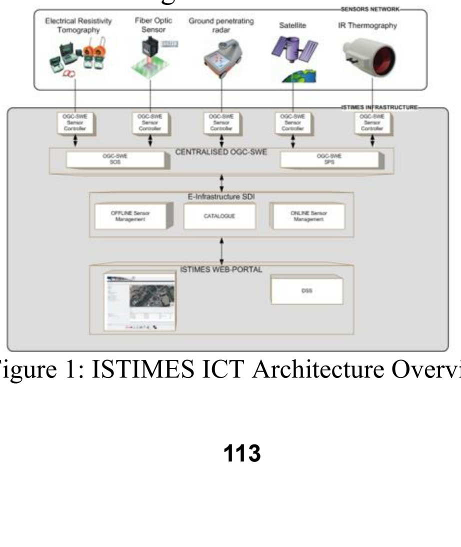


Figure 1: ISTIMES ICT Architecture Overview

ISTIMES ICT architecture leans on the OGC (Open Geoscience Consortium) SWE vision. It uses the Sensor Web Enablement (SWE), which enables sensor system discovery and control based on the Web and OGC's framework for geo-processing.
In this frame, the SWE defined the two standard WEB interfaces as:

- **Sensor Observation Service (SOS):** Defines a standard Web interface for accessing observation data from sensor systems.
- **Sensor Planning Service (SPS):** Defines a standard Web interface for preparing collection feasibility plans and a service to process collection requests for a sensor or a sensor constellation.

As matter of fact the flexibility of ISTIMES architecture allows at complying with the requirements of different stakeholder and end-user communities, as:
Maker: user in charge of decision making for what concerns the security and maintenance of the infrastructure under monitoring;
Scientific user: user with scientific expertise in the sensor measurements and/or in the physical parameters of the infrastructure under monitoring;
Generic user: any web user browsing to the public section of the system web application;
Sensor operator: user operating a sensor and performing the actual data acquisition, stored and processed by the system to monitor the infrastructure;
System administrator: user in charge of system administration from an ICT point of view, e.g. web master, sysop, sys-admin.
The web portal (see figure 2) enables the following functions as: test bed selection; listing/organization of sensors in a dynamic way; sensor positioning in a GIS viewer; sensor info details; catalogue metadata sensors access.

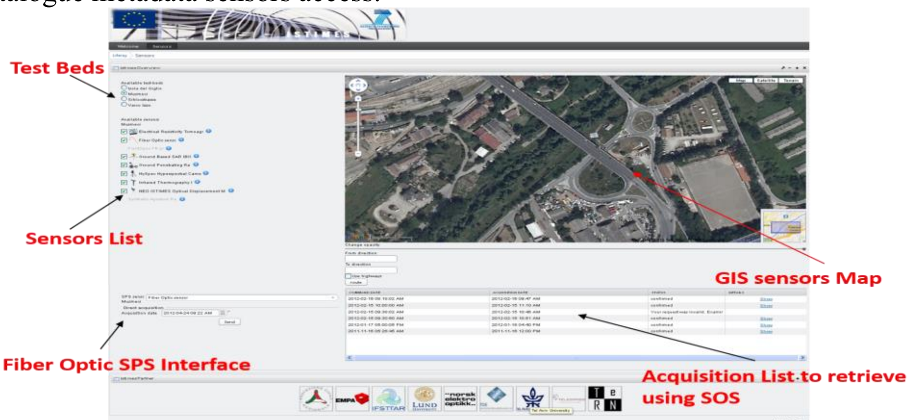


Figure 2: A snapshot of ISTIMES web portal commanding page

By means of the web portal, it is possible to perform commanding and data acquisition from on-line sensors, as the infrared camera and the optic fiber sensor. The other sensors were kept off-line, but the ICT architecture has been built up so to perform the data acquisition in the same way as the on-line sensors; thus the ICT architecture is transparent with respect to the kind of sensor.

2 SENSING TECHNOLOGIES OVERVIEW

The second pillar regards the development, exploitation and integration of a very wide range of heterogeneous electromagnetic sensors capable to give a minimally or non-invasive monitoring of the infrastructure, so to not affect the normal use/service of the structure. In particular, the integration of state of-the state of-art sensors enables a ground-based network that is supported by specific satellite [4] and airborne measurements. In particular, the project has exploited, assessed and improved many different non-invasive electromagnetic sensing technologies [5-7] allowing both a global and local vision of the infrastructure.

The technologies deployed during the project are mostly electromagnetic sensing technologies ones: *Synthetic Aperture Radar satellite based platform (SAR), Hyperspectral spectroscopy (HYS), Distributed Optic Fiber sensors(DOF), Electrical Resistivity Tomography (ERT), Ground Penetrating Radar (GPR) systems, Infrared Thermography(IRT), Ground based systems for displacement monitoring as Ground based SAR (GBSAR) and Optical Displacement camera (ODM).*
It is worth noting that the effectiveness of the overall system is based on the integration of the above mentioned sensing techniques with the aim to ensure a spatial-temporal monitoring of the structure at different scales, sampling periods, resolutions and depths of investigation. This allows also at coupling the capabilities of a long-term monitoring and quick damage assessment of the infrastructure during and just after the crisis events.

Figure 3 depicts the ISTIMES integrated observation strategy, able to comply with the requirements of a:

- **Global Vision**: to perform wide areas surveillance of the territory and of the embedded critical infrastructures; this vision is crucial in order to activate the ground- and airborne-based for a high resolution investigation of the more critical areas;
- **Local scale**: to provide multi-sensed information about the status of the infrastructure itself during the normal service behaviour and after the crisis event.

In this respect, the role of the space based assets, and in particular of the Synthetic Aperture Radar satellite based platform is crucial to make possible a "global monitoring". In this frame, SAR observations can be enhanced by the airborne platform surveys with hyperspectral and infrared sensors, so to gain information about the status of deterioration/damage of the surface of the infrastructure. The above remote sensing observations are complementary to the "ground based monitoring" (i.e., the monitoring of the infrastructure itself), which is enabled by the *in-situ* sensing techniques, both *in-situ* and mobile. In this way, it is possible to gain the other important information about the inner of the infrastructure and of the underground, with different degrees of depth investigation and spatial resolutions; this allows to obtain a detailed information about all the main constructive elements of the transport infrastructure.

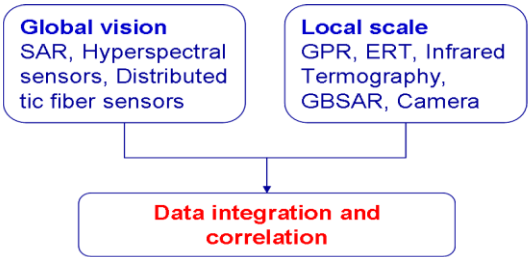


Figure 3: Classification of sensing technologies exploited and role of the integration in ISTIMES

As matter of fact, attention has been focused to the design of data integration and correlation approaches [8-10], which are based on tools as maximum likelihood, wavelets and short Fourier Transform with the specific aim to correlate data and images from different sensors. In this way it has been possible to gain reliable and interpretable information about the dynamical behaviour characterization (High frequency Infrared, Ground Based SAR, optical cameras) and the inner of the structure and underground (by combining GPR and ERT observations). In particular, for ERT and GPR observations, information fusion inversion approaches have been developed in order to join similar sensing techniques [9-10].

3 ILLUSTRATIONS: DEMONSTRATION AT "MUSMECI" BRIDGE

The main demonstration activity for ISTIMES project was carried at the test bed of the Basento bridge, which links the Town of Potenza (at NW) to the Basentana highway (at SE) (figure4 left). The bridge is formed by a reinforced-concrete shell lifting a reinforced box deck; the bridge is an infrastructure of high architectural value, which was designed and built under the supervision of the engineer Sergio Musmeci.

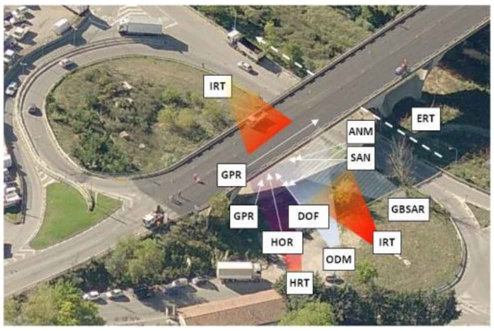


Figure 4: Location of Musmeci bridge in an aerial view (left) - Locations of sensors on the Musmeci Bridge in an upper view (right)

At Musmeci bridge test bed following sensors have been exploited /installed for the diagnostics and monitoring (see figure 4 right): Synthetic Aperture Radar; Distributed Optical Fiber sensor; Infrared Thermography by using cooled camera (Cooled IRT); Hyperspectral Spectroscopy; Infrared Thermography by using uncooled camera (Uncooled IRT); Ground Penetrating Radar by using a mobile system (Mobile GPR); Ground Penetrating Radar by using a manual system (Manual GPR); Electrical Resistivity Tomography; Optical Displacement camera; Ground Based SAR (GBSAR). In addition, further measurements were performed with several techniques not originally expected in the ISTIMES project as: Seismic Ambient Noise (SAN), Accelerometric Noise Measurements (ANM); Holographic Radar by using the RASCAN-4/4000. In particular, ANM, consisting of a suite of three 3-directional accelerometers, and SAN, consisting of a three-directional velocimeter, have been placed on the shell and on the deck so to have a reliable benchmark for the other vibrational techniques such as GBSAR and ODM [6]. The overall arrangement of sensors enabled one to focus on the observational effort on the three main elements of the bridge such as: the shell, the deck and the asphalt layer.

For the Synthetic Aperture Radar (SAR), we used data acquired by the last-generation SAR system mounted on board the TerraSAR-X satellite; such a satellite is at the state of art, it was launched on June 2007 and is an orbiting sun-synchronous one in a polar orbit (97° inclination) at about 500Km altitude. The operative wavelength of the system is 0.031cm corresponding to the X-Band portions of the electromagnetic spectrum. The SAR measurements were motivated by possibility to acquire information about the deformation of the Musmeci deck and of the surrounding area via the use of multi-pass differential interferometric techniques. This sensing technique allows monitoring the component of the deformation along the radar line of sight, with a sub-wavelength accuracy, of natural scatterers that act as ground reflectors showing temporal persistent scattering properties (Persistent Scatterers), i.e., that do not change in time the scattering properties as in the opposite case of the vegetation. Natural scatterers possibly to be investigated are generally man-made structures such are roofs, iron poles down grids and, depending on the system resolution, even asphalt. Acquiring measurements on ascending and descending orbits, where the radar line of sight is almost opposite, allows separating the vertical and horizontal displacement components. A total of 43 stripmap mode (i.e. the standard acquisition configuration with about 3m ground resolution) images collected over ascending orbits (i.e. with the sensor velocity vector oriented toward the North) in the period from February 2010 to September 2011 has been acquired. The incidence angle (offset with respect to the local vertical direction) useful to determine the measured displacement component (which is along the radar line of sight) is about 40°; the ground component of the radar line is directed toward East, with a small rotation (about 10°) toward the North. The data have been processed by means of an advanced processing chain developed at IREA-CNR [4]. Figure 5 (left) shows the distribution of the points that have been measured by using this processing chain, the colour is associated to the thermal dilation coefficient (cm/°K). With respect to the results with the medium resolution (average 10 m), a dramatic improvement in the number of monitored scatterers can be appreciated. Particularly, on the Musmeci bridge there is quasi total coverage of the flank tracks of the bridge. The colour also indicates that the bridge is sensitive, with different spatial behaviour, to the temperature distribution.

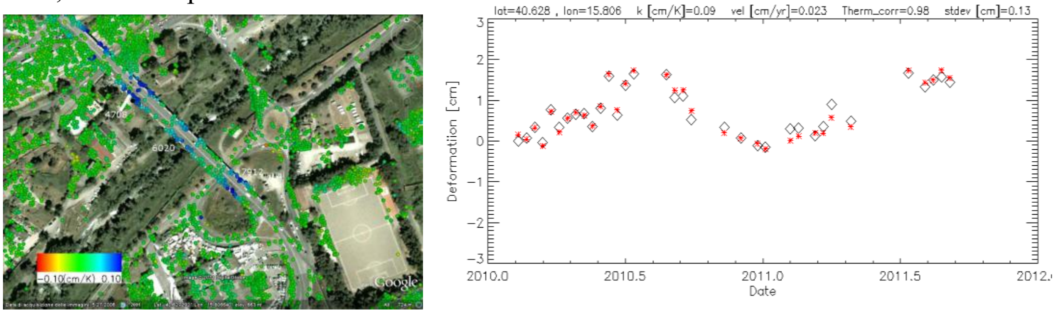


Figure 5: Distribution of the monitored pixels along the Musmeci bridge issued from TerraSAR-X dataset overlaid to a Google map image: colormap matches thermal dilation coefficient (cm/°K) (left) - Time series of a point of the Musmeci bridge exhibiting thermal dilations of 0.09cm/°K: radar measurements are reported as black diamond whereas red stars represent deformation associated with average temperatures (right)

Figure 5 (right) depicts the time series of the deformation of one of the most significant points of the bridge, which is compared with the temperature history at the site; this permits to point out how the bridge deformations are mainly associated to seasonal thermal dilations. The correlation of the SAR time series with temperature distribution is 0.99 whereas the standard deviation of the difference is 1.3mm.

Figure 6 gives an overview of results obtained on the Musmeci bridge with ground based sensing technologies while the bridge remained opened to traffic during experiments.

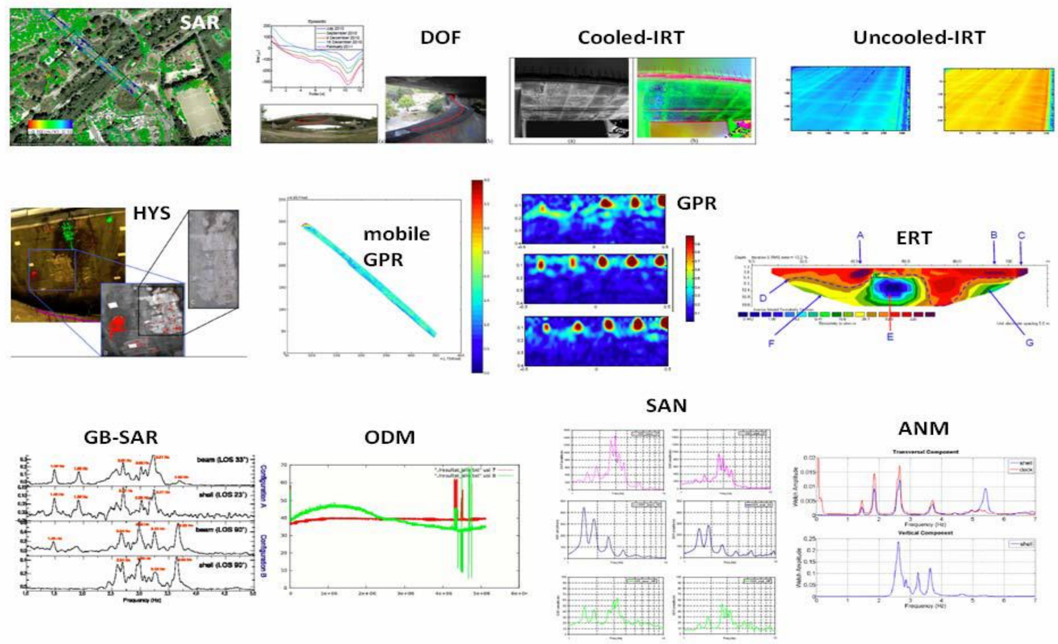
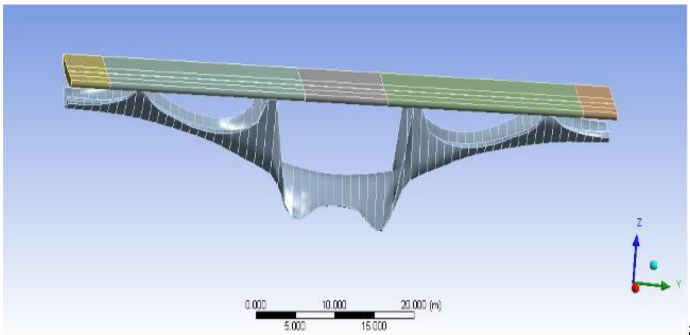


Figure 6: Examples of the results obtained on the Musmeci bridge for each used technique

ODM: displacement of the bridge (red=sideways movement, green=up and down) shows the daily displacement induced by environmental variations.
DOF measurements were carried out during several months. In particular, results obtained show a strain peek at a distance of about two meter from the concrete pillar. A detailed visual inspection have shown that at this position a small crack, not detected during the installation, was present in the concrete. The large extent of the peak measured by the fiber can be explained by considering that the optical fiber sensor has a spatial resolution of ≈ 1 m, so the highly localized strains consequent to crack opening are spatially averaged. Therefore, the resulting curvature provided by the optical fiber sensor in the midsection is lower than the actual one, after crack formation. This limitation can be overcome either by use of sophisticated data processing approaches. Further analysis, thanks to environmental complementary measurements, have shown that the measured strain exhibits a very linear correlation with the temperature in the interval between 14-30°C.
GPR and IRT techniques coupled with adapted processing analysis were used to retrieve inner structure information. GBSAR, ANM and SAN were used for frequency analysis and a good agreement between results was found.
In particular, ANM provided informations on the dynamic characteristics of the bridge (first 5 eigenfrequencies and corresponding damping) that well fit the results of modal analyses carried out using finite elements simulation [11]. From numerical analyses, a main 1.45Hz transversal mode shape has been detected (see Figure 7).



a)

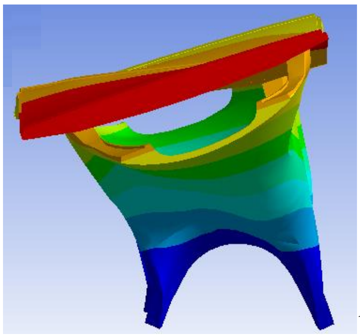

b)

Figure 7 – a) Finite element numerical model ; b) fundamental mode shape – transversal direction

Finally, the equivalent viscous damping factor at the fundamental frequency characterizing the deck and the shell of the Musmeci bridge, was evaluated by applying the half-power bandwidth method [12]. The method consists on the estimation of the structural eigenfrequencies (in this case, we use only the fundamental one) and then evaluates a specified fraction of the maximum amplitude (bandwidth frequencies) corresponding to each natural frequency. The equivalent damping evaluated using the ANM and GBSAR data showed similar values ranging around ξ=4.1.

CONCLUSION

ISTIMES project has allowed to study a technological solution to perform both long term monitoring and quick damage assessment of the critical transport infrastructures by exploiting and integrating electromagnetic remote sensing observations with *in-situ* techniques. The feasibility of the system has been tested by demonstration activities at different challenging test beds. The flexibility of the concept at the basis of the system will allow at deploying it also in the more general frame of the critical infrastructures beyond the transport ones considered in the project.
In addition, ISTIMES system is able to overcome the conventional, and rather limiting, vision of damage detection, since it can give an answer also to the needs of:

- Tracking long term movement or degradation of materials in critical structures;
- Assessing structural integrity after the risk phenomenon;

- Validating modifications to an existing structure;
- Assessing safety and performance of structures affected by external works;
- Enhancing effectiveness of resources as construction declines and maintenance needs increase;
- Providing a feedback loop to design;
- Providing suggestions and recommendations towards performance-based design philosophy.

Finally, outcomes of ISTIMES can be relevant also for the Civil Protection Community necessities as: early warning and crisis management in the case of attacks and hazards; prevention of the risks due to the ageing of the infrastructure with a particular interest in the soft risk, the latter being the slow degradation of the structure leading to eventual catastrophe.

ACKNOWLEDGEMENTS

The research leading to these results has received funding from the European Community's Seventh Framework Programme (FP7/2007-2013) under Grant Agreement n° 225663.

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