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The MASSIMO system for the safeguarding of historic buildings in a seismic area: operationally-oriented platforms

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Abstract

In this paper, the non-invasive system MASSIMO is presented for the monitoring and the seismic vulnerability mitigation of the cultural heritage. It integrates ground-based, airborne and spaceborne remote sensing tools with geophysical and in situ surveys to provide the multi-spatial (regional, urban and building scales) and multi-temporal (long-term, short-term, near-real-time and real-time scales) monitoring of test areas and buildings. The measurements are integrated through web-based GIS and 3D visual platforms to support decision-making stakeholders involved in urban planning and structural requalification. An application of this system is presented over the Calabria region for the town of Cosenza and a test historical complex.

Keywords: Cultural heritage, seismic monitoring, multi disciplinary approach, GIS, 3D software.

Introduction

The safeguarding of cultural heritages in Italy is a relevant topic both for the monitoring and the mitigation of seismic risk associated to historic buildings and urban landscape [Van

Grieken and Janssens, 2004]. Within such a framework, the protection and the preservation of “historic city cores” are non-trivial operational issues both for the development and the management of urban planning, as well as for security and decision making purposes. In fact, many old towns (in particular in South Italy) are located in high seismic risk areas, highlighting their vulnerability and the lack of any programming activities for the safeguarding of seismic-resistant structures. In this context, the start-up and the preservation of cultural heritages within their surroundings, depend on the knowledge about their material and structural features, as well as their corresponding seismic vulnerability [Soldovieri et al., 2011]. Unfortunately, current Italian rules do not provide any specific methodology or protocol that takes into account the temporal variability of such variables, especially in response to natural events. In this context, a holistic approach could be suitable, where traditional non-destructive testing (NDT) techniques are combined with new monitoring methods (e.g. remote sensing, geophysical and seismological analyses) [Soldovieri et al., 2011]. The latter, being non-invasive and non-cooperative, can ensure a time continuous monitoring of heritages on different spatial and temporal scales.

On these bases, in this paper an innovative monitoring system for the seismic risk monitoring of historic buildings (namely MASSIMO) is presented. It draws its origins from the homonymous research project MASSIMO (namely “Monitoraggio in Area Sismica di Sistemi Monumentali”), funded and supported by the Italian Ministry of Education, University and Research (MIUR). The system provides an innovative multi-disciplinary approach to monitor historic buildings in highly seismic areas, through the deployment and the combined use of non-invasive sensors and techniques. The latter include seismogenic sources analyses, aeromagnetic survey, ambient noise measurements through seismic stations, as well as space-borne, airborne and ground-based remote sensing tools (i.e. radar, optical, laser scanning and infrared thermal measurements). In detail, an innovative multi-spatial and multi-temporal methodology is implemented for environmental, built-up areas and building monitoring purposes. Results coming from multi-sensors investigations are integrated and assimilated through a web-based Geographic Information System (GIS) and a 3-dimensional (3D) visual platform. Meaningful results are presented for the Calabria region, with reference to the masonry building of Sant’Agostino Complex located in the Cosenza city core.

The paper is organized as follows. The case studies of the proposed approach are presented in Section “Case studies”. A brief description of the MASSIMO system is provided in Section “The MASSIMO system”. The methodology, as well as the sensors and the techniques adopted within the monitoring system are described in Section “Methodology: sensors and techniques”. The value-added products and some experimental results, obtained by integrating multi-sensors and multi-technique data, are discussed in Section “Value-added products: Experimental results”. Conclusions are drawn in Section “Conclusions”.

Case studies

In this section the case studies, where the proposed approach is applied and tested for environmental, built-up areas and building monitoring purposes, are briefly described, respectively: the Calabria region, Cosenza town and the Sant’Agostino Monumental Complex.

Calabria region

The Calabria region, together with the short chain of Peloritani Mountains at the north-easternmost tip of Sicily, is part of the Apenninic chain that is known among the Earth's scientists as the Calabrian-Peloritani Arc (ACP). It shows evidences of two main phenomena: (i) the subduction of the Ionian Sea lithosphere beneath the ACP; (ii) the expansion of the Tyrrhenian Sea accompanying the counter-clockwise rotation of the Italian peninsula and the eastward migration of the ACP. Calabria region has been struck by many historic destructive earthquakes, which raise its seismic risk at the highest levels in the Mediterranean area (see Fig. 1a). This implied severe consequence for human lives as well as the whole patrimony of cultural and historic heritages. Modern seismographic stations started to be installed in Calabria by Istituto Nazionale di Geofisica e Vulcanologia (INGV) and Calabria University (UniCal) only in the late 70-ies. Since then, any contribution to the experimental seismology could be suitable to improve the knowledge of the Calabrian seismicity.

Cosenza town

The town of Cosenza (*Consentia*) is one of the most important municipalities within Calabria region. Its landscape is characterized by a great variety of valleys, mountains and hills, such as the Crati river valley, the massif of Pollino to the Sila Plateau. The urban pattern comprises the old town on the hills around the Crati river valley and the modern town in the surrounding plain. The whole area hosts a great number of mobility and transport facilities as well as institutional structures. Moreover, the town suffered several renovations due to damages occurred in case of natural hazards (e.g. earthquakes, landslides, etc.). In fact, its complex and fragile territory, made of active faults, is vulnerable to hydrogeological disasters and seismic events.

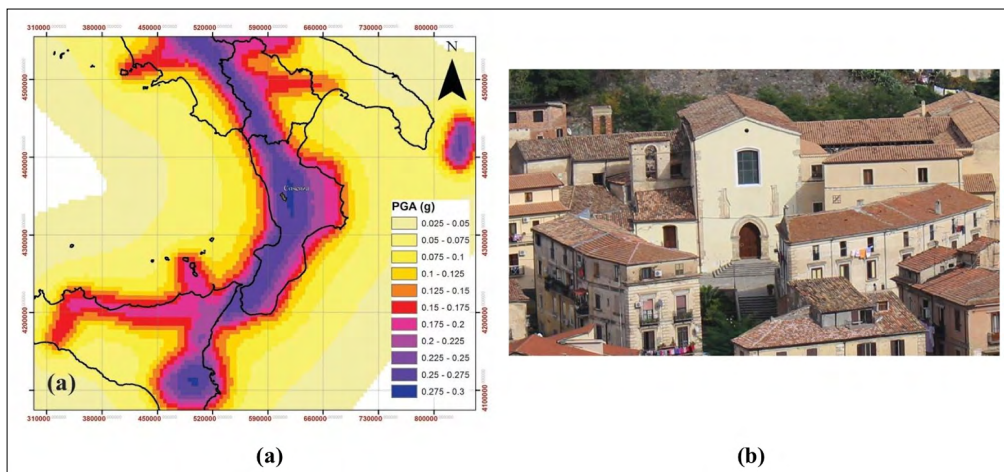


Figure 1 - (a) Calabrian seismic hazard map (in PGA, g) with probability of exceeding 0.1g in 50 years. (b) Sant'Agostino Monumental Complex.

Sant'Agostino Monumental Complex

The Sant'Agostino Monumental Complex is a historical masonry structure founded as convent by the Augustinian Hermits in 1507 (see Fig. 1b). Located in the Cosenza old town and strictly closed to the Crati River, it includes the homonymous ancient church and the convent within a central cloister. Throughout its history, three main hazardous earthquakes damaged the building, respectively in 1638, 1870, 1905 [Guidoboni et al., 2007]). Throughout the history, it has had eight different owners and their intended uses. Currently, it hosts the Brettii and Enotri Civic Museum.

The MASSIMO system

In this section a brief description of the MASSIMO system is provided.

MASSIMO is an infrastructural system, developed and tested for the non-invasive monitoring of architectures (or infrastructures) within a seismic area. It provides a modular, portable and scalable methodology based on the multi-spatial and multi-temporal integration of data from remote sensing, geophysical and in situ measurement surveys. On the one hand, the proposed approach allows investigating both environmental phenomena and built-up areas from regional (up to hundreds of km²) to urban (lower than tens km²) spatial scales, at long- (annual) and short-term (monthly) domains. On the other hand, it provides the monitoring of critical infrastructures and cultural heritages (namely, the building spatial scale) at near real time and real time scales.

The system architecture is depicted through the block scheme in Figure 2. Thematic data coming from multi-disciplinary investigations are acquired and processed for the multi-spatial surveys of selected test sites at different temporal scales. Such data come from space-borne, airborne, proximal remote sensing analyses, geophysical and seismological investigations. On the other hand, a sensor area network is implemented, which consists of seismic stations deployed inside buildings. They allow providing the static and dynamic monitoring of structures at near-real-time and real-time scales through both supervised and unsupervised processing techniques. The data provided by multi-disciplinary investigations are processed through both commercial off-the-shelf (COTS) and open-source products (e.g. SAP©, Earthworm©, Apollo Server© and SeisComP© for seismic data; OASIS MANTAJ© for aeromagnetic data processing; ENVI-IDL© and Matlab© for space-borne and airborne remote sensing images; JRC 3D Reconstructor© for laser scanning data; NRG software© for thermal image analysis). Moreover, ad-hoc in-house processing algorithms, developed in ENVI-IDL©, Matlab©, ArcGIS© and MySQL© software environments, are used both when no COTS products are available and for the management of the whole amount of MASSIMO datasets. All these data are transmitted and stored within the system infrastructure through wired or wireless technology via TCP/UDP protocols. The infrastructure consists of three main elements, i.e. the storage or repository, the geo-database and the Relational Database Management System (RDBMS). The first module represents the simplest way to save metadata associated to geo-spatial and multi-temporal results. Its configuration is performed through a Window Server© operating system. The second module refers to the database of geographical data/results coming from multi-disciplinary investigations, properly saved as geo-referenced spatial layers. It is realized through Esri-ArcGIS© and Microsoft SQL© Server software applications. The third element is the most effective configuration to organize and manage geospatial data/results.

Once stored and managed within the MASSIMO system, all these data are made available through ad-hoc user-friendly interfaces. They allow to access, manage, display, integrate and assimilate multi-disciplinary results. In detail, two different interfaces are provided as value-added products of the whole investigation methodology, namely a web-GIS module and a 3D visual platform. The former is realized through web-based applications and tools within Esri-ArcGIS© software environment. The latter is implemented through a dedicated 3D Manager© software together with open-source web-based solutions (e.g. JavaScript, JQuery, Babylon and AJAX). Both platforms are connected both between them and to the system repository through a dedicated http/https Internet protocol.

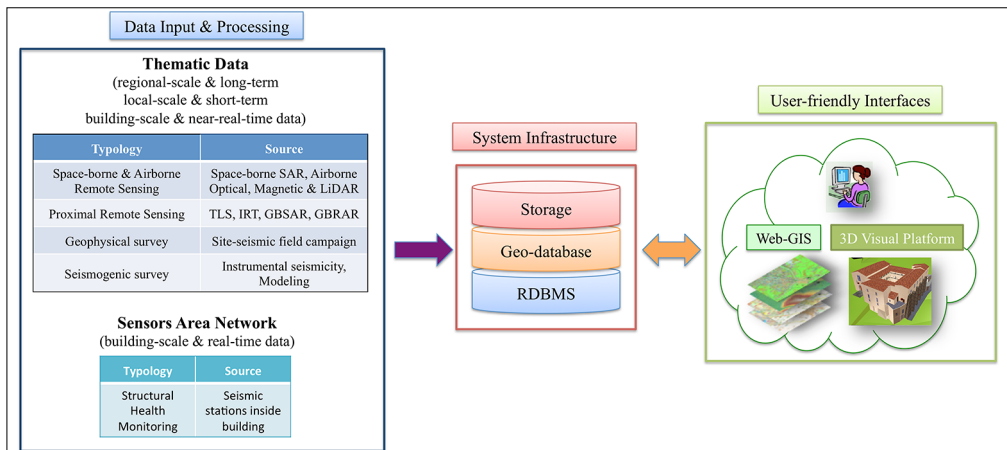


Figure 2 - MASSIMO system architecture.

Methodology: sensors and techniques

In this section the methodology, proposed for the monitoring of historic heritages within seismic areas, is described together with adopted sensors and techniques. The proposed methodology relies on a multi-spatial (scale) and multi-temporal approach, i.e. regional-scale & long-term survey, urban-scale & short-term survey and building-scale & near-real-time survey.

Regional-scale & Long-term survey

The regional-scale analysis of the seismic environment (from hundreds to tens km²) is provided to monitor long-term (annual scale) surface and sub-surface phenomena that may impact on selected urban areas and buildings. To this purpose, the analysis of seismogenic sources is combined with airborne magnetic surveys, space-borne Synthetic Aperture Radar (SAR) and hyperspectral Optical sensors, to describe the regional seismic activity together with the sub-surface fault systems, surface deformation processes and land use mapping of the area, respectively.

Seismogenic sources analysis

The concepts of seismic hazard and seismic risk have intrinsic probabilistic natures. This depends essentially on the still insufficient knowledge about: (i) the physics of the

elastic energy storage in geological formations undergoing intense tectonic processes; (ii) the triggering and the propagation of subsurface fracturing phenomena. As a result, risk reduction measures, typically adopted for monitoring seismic-prone area and cultural heritages, have a similar statistic behavior. On these bases, in this work a set of activities has been foreseen for the analysis of seismogenic sources. Such activities aim to: (i) improve the instrumental monitoring of the regional seismicity for a better characterization of the seismic sources; (ii) characterize seismogenic structures through aeromagnetic surveys; (iii) simulate deterministic shaking scenarios to study the seismic response of monitored structures. Although based on statistical and modeling approaches, the proposed techniques allows to describe seismogenic structures over wide areas and in very short time, through advanced tools and consolidated processing algorithms.

Firstly, new seismic stations have been deployed and installed on Calabria region. In this regard, advanced processing techniques have been implemented to describe the geological structures and their geo-mechanical features. Expected outputs of seismic station data processing include the hypocenter coordinates and the quality indexes of recorded seismic events, as well as the so-called “fault plane solution” [Zhu and Helmberger, 1996].

To support and complement the monitoring of regional instrumental seismicity, magnetic surveys have been performed through high-resolution airborne sensors [Minelli et al., 2016]. They represent a powerful tool able to provide a detailed picture of crustal settings and highlight previously unrecognized upper crust fault geometry [Chiappini et al., 2002; Dentith et al., 2009]. In fact, the collected magnetic data contain information about crustal phenomena (namely crustal rocks magnetic anomalies) whose contribution can be evaluated and associated with seismogenic tectonic structures. Some constraints must be taken into account when performing aeromagnetic surveys, such as the high costs of measurement campaigns, the weather conditions, the urban restrictions, as well as the complexity of data processing and interpretability. However, the proposed technique offers several operational advantages such as the wide area coverage (down to hundred km²), the short acquisition time (up to daily time scale) and the depth of measured magnetic anomalies (about tens of km). To this purpose, two aeromagnetic surveys have been performed in Calabria on 2013-2014. The key tool of the measuring equipment is an airborne magnetometer able to measure the spatial changes of Earth’s magnetic field. The expected output is the crustal magnetic anomaly field, used to characterize geometrical and geological properties of seismogenic structures on a spatial gridding of 1 km.

Once the characterization of both regional instrumental seismicity and seismogenic sources is provided, the faults identified through the expertise of Database of Individual Seismogenic Sources (DISS) [DISSWG, 2010] have been used as basic input to simulate deterministic shaking scenarios for different classes of magnitudes. In fact, it is not possible to predict “a priori” future rupture processes as well as define the fault portion exposed to such ruptures. The simulations have been accomplished through the Deterministic Stochastic Method [Pacor et al., 2005] to provide a wide dataset of synthetic waveforms, each one representing a specific shaking scenario expected at the bedrock for the interested area. This analysis provides statistically-based descriptors typically used for environmental and engineering purposes (e.g. the peak ground acceleration PGA or the pseudo-spectral acceleration PSA). The synthetic waveforms are made available through the web-GIS platform of the MASSIMO system.

Surface deformation analysis: space-borne SAR

The monitoring of surface deformations in dense urban areas is crucial to ensure the sustainable development and the multi-hazards risk monitoring of infrastructures and surrounding environments [Zebker and Goldstein, 1986]. In fact, both natural and anthropogenic factors (e.g. mining activities, earthquakes, landslides) can cause ground uplifts and subsidence phenomena with severe damages on urban infrastructures. Hence, measuring surface deformations allow assessing and monitoring the main causes of ground displacement in view of multi-risk mitigation plans. Among the different techniques typically used to retrieve surface deformations, multi-temporal differential SAR interferometry (DInSAR) plays a key role for operational fields of investigations, e.g. the seismology, the volcanology and the hydrology [Zhou et al., 2009]. It is based on a multi-interferograms analysis able to retrieve surface deformation phenomena over a selected time-span. This technique suffers from temporal and spatial decorrelation issues, atmospheric effects and geometric distortion phenomena. Moreover it provides surface displacements along one single direction (namely the sensor line of sight, LoS). Despite that, it allows providing some operational advantages, i.e. the wide area coverage (up to thousands of km²), the high spatial resolution (data point every few meters), the high temporal resolution and coverage (dense and long-term time series) and the high measurement accuracy (up to mm/yr) [Bamler and Hartl, 1998]. In this work, surface deformation phenomena have been analyzed processing X-band COSMO-SkyMed© SAR data through the Small Baseline Subsets (SBAS) approach [Berardino et al., 2002]. Expected outputs are georeferenced mean surface deformation velocity maps (in mm/yr) and time series of ground displacements (in mm). They are stored in the MASSIMO database and made available as geospatial layers through the web-based GIS platform.

Land mapping analysis: Hyperspectral imagery

Land mapping analysis is an important issue for public administrations, which allows to (i) discriminate built-up areas with respect to rural and vegetated fields; (ii) identify historic buildings and critical infrastructures within their surroundings; (iii) assess the presence of dangerous materials (e.g., asbestos); (iv) provide geospatial land inventories for exploiting environmental resources [Nex et al., 2015]. In this framework, airborne hyperspectral imagery represents a valuable solution to extract information about urban areas and structures exploiting their different spectral signatures [Borengasser et al., 2008]. Despite the dependency on sunlight and weather conditions as well as the high costs of measurement campaign, airborne hyperspectral sensors are characterized by a very high spectral resolution (hundreds of narrow spectral channels), huge spatial coverage (tens of km²), high spatial resolution (cm scale) and daily revisit-time. These advances make the data suitable for land-monitoring analysis and vulnerability mitigation purposes. In this work, the land cover mapping has been achieved by processing IMSpectorV10E acquisitions of the airborne IPERGEO© sensor through the Spectral Angle Mapper (SAM) classification technique [Kruse et al., 1993]. The expected output is the land cover map of the observed area, which is stored in the MASSIMO database and made available as geospatial layer through the web-based GIS platform.

Urban-scale & Short-term survey

The local-scale analysis of the urban landscape (from tens km² to hundred m² scale) is provided to monitor and assess short-term (monthly scale) processes and phenomena, which may impact on selected historic structures. To this purpose, geological and geotechnical surveys of the area are integrated with airborne Light Detection And Ranging (LiDAR) analysis to describe the site seismic response, the surface geology, the topographic profile and the built-up area structural features.

Site-seismic response analysis

The knowledge about the surface geology and the geotechnical/geometrical characteristics of soils is a key factor to study the seismic response of an earthquake-prone area as well as to characterize the amount of ground shaking and soil-structure interaction [Foti et al., 2011]. In this framework, different techniques based on both active and passive seismic surveys are available [Borcherdt, 1994]. The former require an external source of vibration together with a long-term network of seismic stations. The latter detect only the environmental noise vibration through a temporary short-term (daily) seismic network. In this work, the geophysical/geotechnical properties of the subsoil have been identified by means of ambient noise measurements performed at single station. The objective is to: (i) identify the type of subsoils within the study area; (ii) evaluate the stiffness of the different strata by means of shear wave velocity (V_s) measurements with depth; (iii) identify the natural oscillation frequencies of the subsoil. The complexity of the proposed approach requires accurate contact acquisitions, ad hoc-processing techniques and expert personnel. Despite that, it represents a simple, flexible and low-cost solution able to estimate directly the resonance frequency of subsoil through high-resolution sensors. The output is the spectral ratio between horizontal and vertical components of the ambient vibrations (HV), measured at the same point. It is stored in the MASSIMO database and made available through the web-based GIS platform.

Topographic and built area analysis: Airborne LiDAR

The topographic analysis about seismic areas is fundamental to describe the terrain and surface properties with the mapping of areas prone to natural and/or anthropogenic disasters (e.g. earthquakes, landslides, subsidence). On the other hand, the knowledge about built-up areas is useful for discriminating urbanized areas with respect to rural and vegetated fields, as well as for updating land registers in urban and risk mitigation plans. Within such a framework, airborne LiDAR is a powerful tool to provide accurate 3D measurements of observed scenarios [Ackerman, 1999]. It exploits the laser scanner information to retrieve the position and the elevation of surface targets (together with other attributes) by measuring the time lapse between laser pulse transmission and reception. This technique suffers from several constraints, such as the weather and urban restrictions, the high costs per unit area and poor penetration depth in densely vegetated areas. However, it offers several operational benefits such as sub-meter spatial resolution, real-time and near-real-time operability, daily revisit-time, and sub-meter measurement accuracy [Ackerman, 1999]. In this work, an airborne LiDAR measurement campaign has been carried out with the RIEGL LMS-Q680i sensor, to achieve the topographic characterization of the urban environment and the location of the built-up areas. Expected outputs are the Digital Terrain

Model (DTM), Digital Surface Model (DSM) and the map of building footprints with geometrical information (e.g. height, area, perimeter and volume). These maps are stored in the MASSIMO database and made available as geospatial layers through the web-based GIS platform.

Building-scale & Near-real-time survey

The building-scale analysis of historic buildings is concerned to provide near-real-time monitoring about the conservation status of building. To this purpose, the analysis of geometric, structural, material and vibrating building properties is provided through proximal remotely sensing tools (i.e. terrestrial laser scanning, infrared thermal cameras, real aperture radar) and ambient vibration test.

Geometrical and structural reconstruction: Terrestrial Laser Scanning

The geometrical and structural reconstruction of buildings represents a key step oriented to the 3D reconstruction of the interested volume, the crack patterns analysis as well as the identification of main bearing structures and building properties for modeling purposes. The model can be designed for safety assessment purposes or simple evaluation analyses about the conservation status of the interested structure. Within such a framework, distance-metric long-range and phase-comparison terrestrial laser scanning (TLS) represents a key tool widely implemented for the 3D architectural modeling [Chau-Chang Wang, 2011; Pesci et al., 2013]. It provides 3D point clouds, where each point contains information of reflectivity, target-sensor distance, coordinates and optionally some texturing information of observed structures [Casula et al., 2009; Costanzo et al., 2014]. Some constraints may limit the use of TLS sensors, e.g. the weather conditions, the range and quality of data (depending on the reflectivity of observed targets) as well as the complex interpretation of results. However, it offers powerful and low-cost solutions for both geometrical and structural building surveys, such as the provision of fast acquisitions (less than ten minutes for each scan), the sunlight independency, the high spatial resolution of measurements (up to sub-mm), as well as the capability to observe areas not accessible by human operators. In this work, TLS surveys have been performed by the Z+F® Imager 5010c phase shift long-range sensor for geometrical and structural analyses. Expected outputs are 3D building modeling and 2D morphological maps evaluated with respect to fitting planes. They are stored as 3D/2D maps in the MASSIMO database and made available through the 3D visual platform.

Material properties analysis: Infrared Thermography

The analysis about the material properties of a built structure is fundamental to evaluate its conservation status, together with its construction properties and anomalies [Meola, 2013]. It is known that masonry structures deteriorate over time mainly due to natural forces of decay, thermal stresses, water infiltration and anthropogenic factors (reconstruction and restoration activities). This results in variations of concrete compaction and voiding, masonry micro cracking and reinforcement deterioration. In this framework, infrared thermography (IRT) represents a valuable tool able to measure the emissive power of a target area over a wide range of temperatures, in the far range of IR spectrum [Meola, 2013]. This measurement is converted into a thermal digital image known as thermogram, where

different colors correspond to the various temperatures of the target. Such temperatures can be correlated to geometrical, structural and construction material properties of buildings in order to highlight possible degradation sources. Although IRT provides only the surface temperature of targets and is strongly affected by surrounding weather conditions, it offers several operational benefits, i.e.: i) high resolution thermal images over a wide range of temperatures; ii) the detection of material anomalies and hidden features related to geometrical and structural issues; iii) the monitoring of inaccessible areas and targets. In this study, the Camera Avio InfReC® R300SR-S Thermal Imager (NEC R300SR) has been used for IRT surveys on a masonry historic building to monitor its conservation status and possible anomalies (e.g., voids, cracks, disbanding) in different materials. Expected outputs are 2D thermal images of monitored structures, which are stored in the MASSIMO database and made available through the 3D visual platform.

Vibration properties analysis: RAR and Ambient Vibration Test

The vibration monitoring of buildings is an operational task, which allows evaluating the dynamic properties of buildings thus identifying the main resonant frequencies of structural elements with corresponding vibration modes. This information is useful to characterize the response of such elements especially in case of earthquakes, based on their different geometrical, structural and material construction properties. In this framework, Interferometric Real Aperture Radar (InRAR) has demonstrated to be a powerful tool [Luzi et al., 2012]. It provides non-contact sub-millimeter displacement and high-resolution time series (down to few ms) of vibrating structures by comparing electromagnetic wave phases of signals, reflected at different times from the target. This technique provides relative displacements of structures along the sensor LOS only, with very hard point localization issues. However, it allows the continuous and simultaneous monitoring of all structural targets within the sensor beam, providing high-resolution displacements with high accuracy (up to sub-mm scale) and repeatability (less than hourly scale), independently of daylight and weather conditions. In this work, an InRAR campaign has been performed by the IBIS-L© system on the Sant'Agostino Monumental Complex to assess the resonant frequencies and vibrating modes of structural elements solicited by ambient stresses. Expected outputs are displacements profiles (in mm) and PSD (mm^2/Hz), which are stored in the MASSIMO database and made available through a 3D visual platform.

Together with InRAR analysis, ambient vibration tests inside building have been performed to assess the resonance frequencies of the monitored structure and detect those components related to the soil-building interaction [Borcherdt, 1994; Foti et al., 2011]. Despite the constraints of the proposed approach discussed in Section “Site-seismic response analysis”, it allows monitoring the dynamic behavior of the structure in both discontinuous (i.e., near-real-time) and continuous (i.e., real-time) temporal scales through supervised and unsupervised algorithms. Moreover, it offers operational benefits in terms of high portability, flexibility, resolution and sensitivity of measurement equipment. In detail, a network of velocimeters has been deployed to collect ambient vibrations inside building. Expected outputs are horizontal to vertical noise spectral ratios (HVNSR), PSD and cross PSD (CPSD). They are stored in the MASSIMO database and made available through the 3D visual platform.

Value-added products: Experimental results

In this section the value-added products of the MASSIMO system are described together with some experimental results: the web-based GIS and the 3D visual platforms.

Web-based GIS platform

In this work, a web-based GIS platform has been developed through web-based tools of an ArcGIS© infrastructure to provide an exhaustive interface for the web-based visualization, management and post-processing of geospatial data. The latter refer to the results of investigation gathered at regional and local scales for long and short-term surveys, respectively. The platform consists of three different interfaces: (a) a desktop environment, to manage, display and post-process data stored in the MASSIMO storage; (b) a server interface, to manage and organize the geospatial database; (c) a web-service interface, to provide interactive maps / results to end-users.

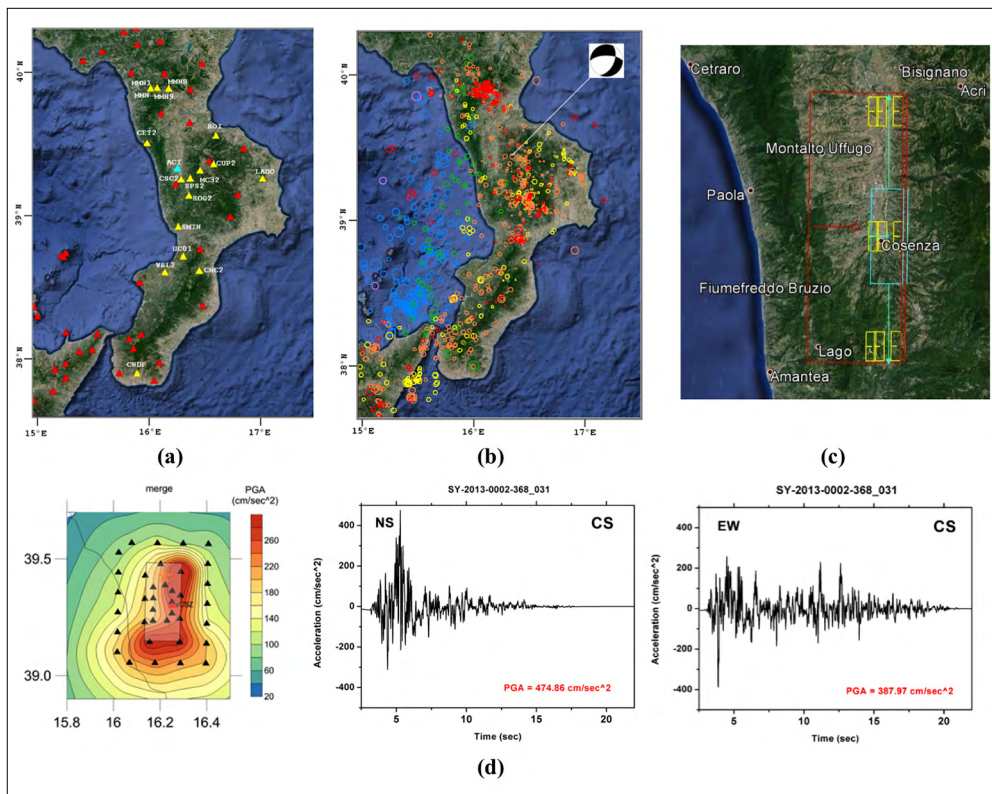


Figure 3 - Results of seismogenic source analysis in Calabria region. (a) UniCal (yellow and cyan spots) and INGV (blue spots) seismic monitoring systems. (b) Regional seismicity map. (c) Simulated shaking scenarios for the Cosenza urban area. (d) Simulation a sample M7 earthquake.

In the following some meaningful results are presented for the test site of Calabria region and Cosenza urban area, in order to show the powerful capabilities of the web-based GIS

platform for environmental monitoring analyses at different spatial and temporal scales. Starting from the regional & long-term scale, Figure 3a shows the map of seismic stations installed in the whole Calabria region to support geological and seismological investigations of the area. Figure 3b shows the seismicity map of Calabria region for the period January 2015-February 2016, where the beach-ball represents the fault plane solution of a small earthquake ($mL=2.5$) occurred on February 12th, 2016. This demonstrates the high sensitivity of seismic stations for detecting and characterizing low-magnitude earthquakes in support of seismological studies. To corroborate the instrumental seismicity survey, seismogenic structures corresponding to specific earthquakes of M7, M6 and M5 class magnitudes have been properly simulated and described for the town of Cosenza (see red, cyan and yellow boxes in Fig. 3c, respectively). This range includes the magnitude values that dominates the relative contributions to ground motion (PGA) for near-site seismic sources in the study area. A total number of 243, 405 and 156 shaking scenarios have been simulated for earthquakes of M7, M6 and M5 magnitudes, respectively. Sample results relevant to an earthquake of M7 magnitude, are provided in Figure 3d. They show the PGA map (left panel) as well as synthetic accelerograms along the North-South and the East-West components (middle and right panels, respectively). They can be used to support the analysis of site seismic response and evaluate the dynamic response of urban structures.

Zooming at the urban spatial scale, Figure 4a shows the surface deformation velocity map (in mm/yr) of Cosenza urban area measured on a spatial gridding of 10×10 m and a spatial coverage of about 40×40 km for the time period May 2011-January 2014. Experimental results show that the area is characterized by slow surface deformation phenomena with velocity values included in a range of ± 2.5 mm/yr, with an accuracy of about ± 1 mm/yr and a zero mean value. This demonstrates the almost stability of the observed scenario. In detail, negligible subsidence (uplift) phenomena, i.e. deformations away from (towards) the quasi-vertical sensor LOS, can be observed in the whole urban area. To support the analysis of surface deformation processes, Figure 4b shows the hyperspectral-based land-use classification map of the urban scenario with a spatial resolution and coverage of about 0.5×0.5 m and 40×40 km, respectively. It allows identifying and discriminating natural environmental categories (i.e., vegetated fields, terrain rural areas and streams) with respect the urbanized features of the area (i.e., roads and the main building roof typologies). A total number of 10 classes is considered and classified effectively, with an overall accuracy greater than 90% and a kappa coefficient close to 1. An in-depth analysis is further accomplished both to recognize the ancient buildings of Cosenza town and to detect potentially dangerous materials for the environment (e.g. asbestos). To this purpose, some roof typologies are selected considering the roof construction features of the South Italy landscape, i.e., brick and shingles, concrete and bitumen, metallic, and asbestos building roofs. Experimental results are depicted in Figure 4c, which allow distinguishing the historic city core from the more recent part of the town. Few asbestos roofs relevant to industrial buildings are further recognized in the area. All the classes are classified effectively with overall, producer and user accuracy values greater than 90%.

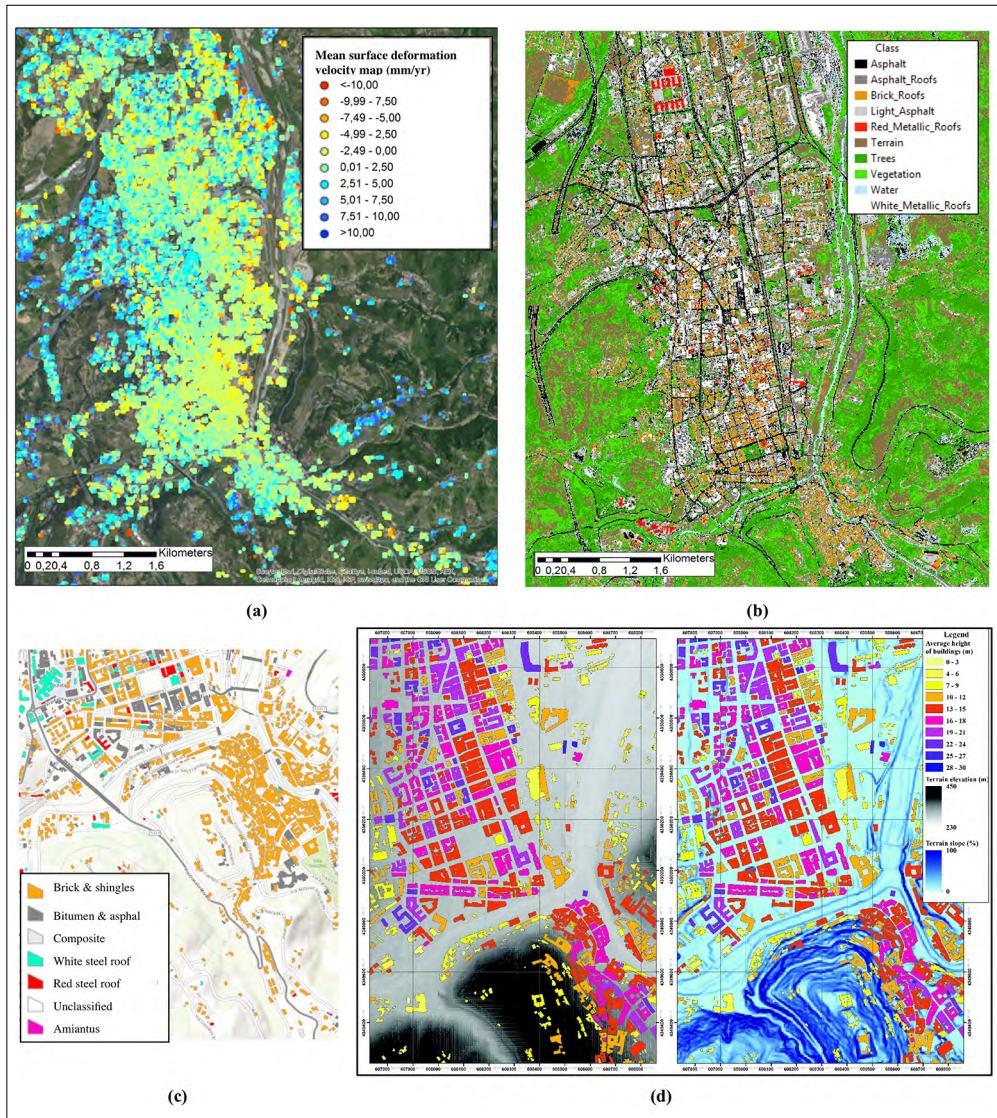


Figure 4 - Experimental results obtained through the remotely sensed monitoring of Cosenza town. (a) SAR-based Mean surface deformation velocity map (in mm/yr). (b) Land use classification map of the whole urban area. (c) Building roof classification in the historic city core. (d) Building elevation (in m) projected over the DTM (left panel) and the slope map (right panel) of Cosenza.

Looking at the same urban-scale, Figure 4d shows the LiDAR-based footprints of the built-up area with average height information (in m), superimposed to the surface elevation (in m) and the terrain slope (in %) maps (see left and right panel in Fig. 4d, respectively) of Cosenza city core. A spatial resolution and coverage of about 0.5×0.5 m and 15×15 km is conceived, respectively. It can be observed that most of the buildings exhibits average height values lower than about 20 m. The only exception is represented by some critical

structures in the recent part of the town (e.g. hospital, schools, etc.) as well as some aggregate buildings and significant heritages within the historic city core (i.e. theatres and religious structures). Most of the buildings within the recent part of the town are located on flat areas with low elevation and slope values. Conversely the old town is located at the top of reliefs with surrounding high-slope areas. As a result, the exposing level of the built-area increases as you move away from the recent part of the town approaching to the historic city core.

Following the investigation of local topography and built-up areas, Figure 5 shows the HV profiles obtained from the ambient noise measurements at single station in the surroundings of Sant'Agostino Monumental Complex. The results of local site seismic response show some slight amplification peaks concentrated on a wide band of frequencies (2.8-5.5Hz). The variability of the resonant frequency reflects the complex and heterogeneous geology of the area, which is located along an ancient coastline and is characterized by flooding rivers and fluvial deposits of different nature.

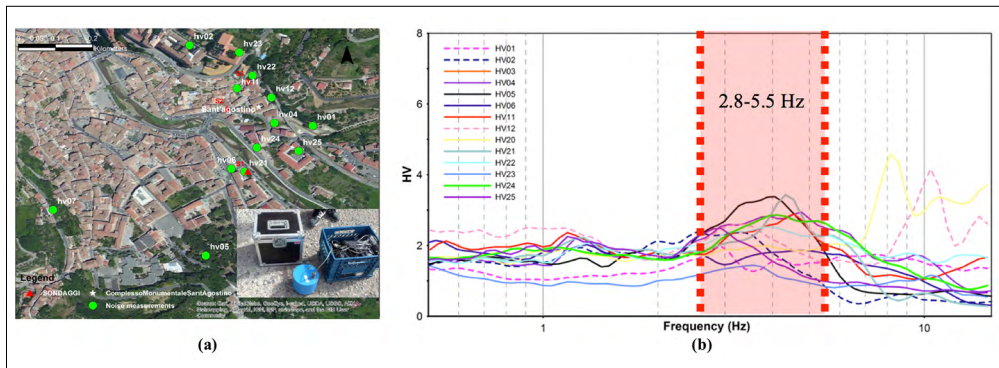


Figure 5 - Experimental results relevant to the analysis of site seismic effect for the Cosenza urban area. (a) Location of ambient vibration tests at single station. (b) HV profiles.

3D visual platform

In this work, a 3D / 4D visual platform has been developed through a dedicated 3D Manager software for the visualization and the use of data coming from the building-scale & near-real-time surveys of monitored historic buildings. The platform is accessible through a web-based interface within conventional client-server architecture. The end-user may have access to the platform by connecting to a server application through web-browser and common Internet protocols. The platform allows the interactive navigation of the structure within a 3D spatial domain. Each geometrical element can be modified dynamically and contain information about attributes coming from multi-disciplinary investigations. This aspect justifies the 4D nature of the platform. All the data can be provided on high-definition monitors and with stereoscopic display functionalities. A simple sketch of the 3D visual platform is provided in Figure 6a. It shows the TLS-based 3D modeling of the Sant'Agostino Monumental Complex, together with texture features, structural components, building layers and the location of measurement points (red spots in Fig. 6a). A spatial

resolution down to 3 mm is provided by TLS-surveys, with an 80 Mpixel optical resolution and a measurement accuracy of about 1 mm. Each measurement point can be selected dynamically to show relevant results achieved through building-scale investigations and properly stored into the MASSIMO repository. Meaningful results are shown in Figure 6b for the church façade of the Complex, where TLS and IRT measurements are combined to highlight structural, geometrical and material building anomalies. In detail, TLS and IRT sensors provides spatial and thermal resolution values of about 1.6 mm and 0.03°C, respectively. The TLS-based 2D morphological map (in mm) of the structure (see upper panel in Fig. 6b) allows showing sub-cm irregularities in central part of the façade (near the window) and immediately above the lancet arch. These results agree with historic surveys of the building, which demonstrate the presence of an old rosette window and a “hidden arch” at the entrance door of the church. Same anomalies are clearly detected by IRT images of the façade (see lower panel in Fig. 6b). They highlight an arch shape above the door with a surface temperature of about 2°C higher than surroundings. This result allows supposing the presence of a transition element between the large portal and the now absent rosette window, or a specific material used to protect the portal during the rebuilding works of the façade.

The analysis about structural and material properties are corroborated by InRAR investigations to observe the vibrating properties of the façade during the ringing bells of the tolls at the noon, see Figure 6c. Results are provided in terms of PSD profiles evaluated for relevant target points over the façade (see left panel in Fig. 6c). They show noisy frequency patterns for the whole structure, which is then poor sensible and stable with respect to bells-induced vibrations (see blue and green curves in the right panel image of Fig. 6c). Conversely, a frequency pattern rich of harmonics is observed for the central window of the façade, which is then more sensible to stresses induced by the toll of the bells (see red curve in the right panel image of Fig. 6c). To properly characterize the dynamic behavior of the monitored structure, HVSNR profiles derived from ambient vibration tests are evaluated on the church buttresses at two different levels (i.e. the ground and the third floor of the structure), see continuous and dotted black curves in Figure 6d, respectively. These curves are compared with those obtained by external measurements performed in front and the backsides of the building (see red and blue curve in Fig. 6d, respectively). Experimental results show a good agreement among overall the profiles with the only exception of the one evaluated at the third floor of the church buttress (dotted black curve). A clear peak of seismic amplification is identified at 4.5 Hz, which is further highlighted by ambient vibration tests inside and outside the structure. To corroborate such results, a network of seismic stations is implemented inside the Complex, where real time seismic acquisitions are collected to analyze the response of the structure with respect to natural (e.g. seismic events) and anthropogenic (e.g. urban traffic) stresses (see Fig. 6e). It provides a real-time and near-real-time monitoring of the whole structure for seismic assessment and risk mitigation purposes. The latter could be considered another important value-added product of the proposed methodology.

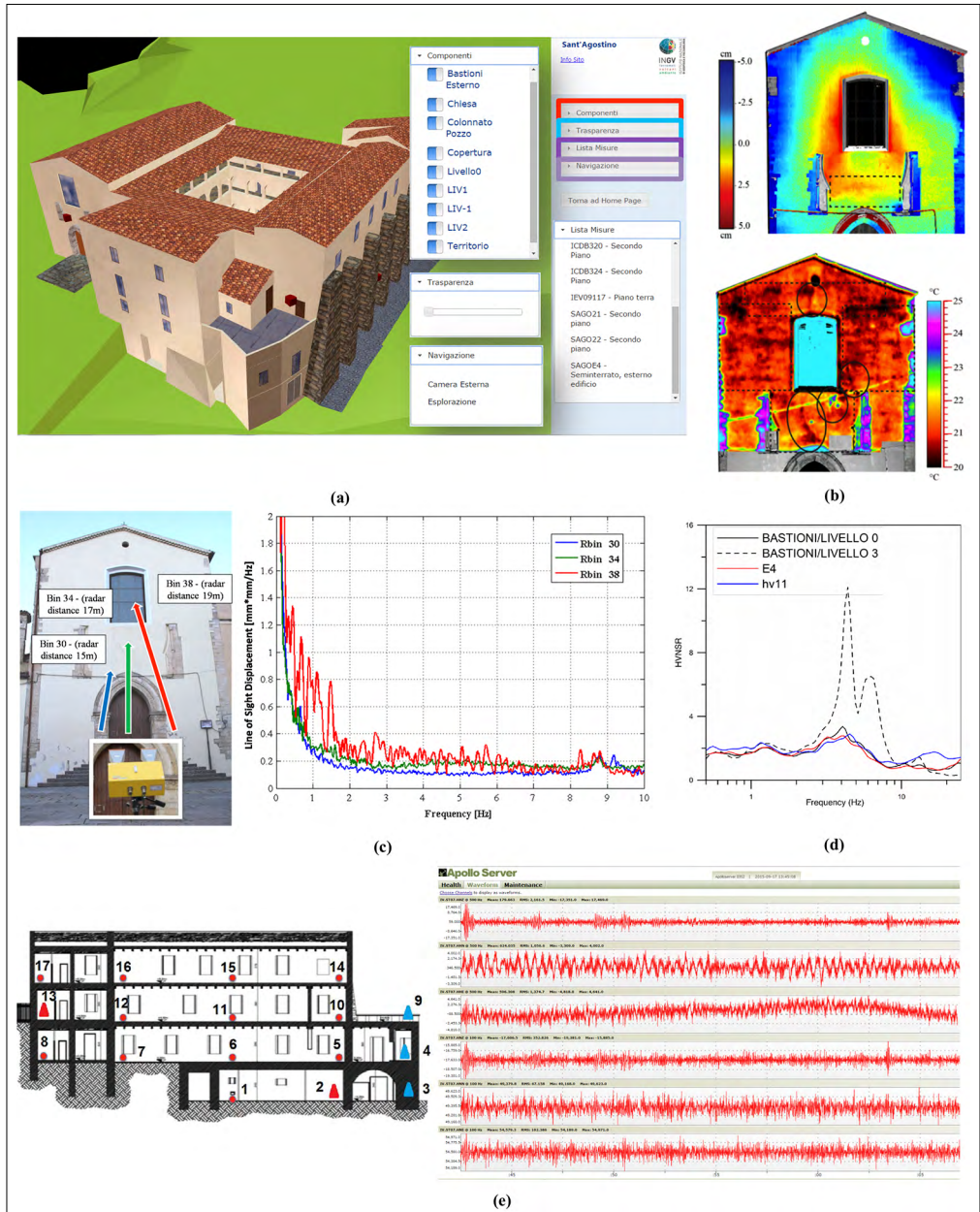


Figure 6 - Experimental results relevant to the near-real-time monitoring of Sant'Agostino Complex. (a) Simplified 3D TLS model of the Complex, with both image textures and some measurement points (red spots in figure). (b) TLS-based 2D morphological map (upper panel) and IR-TC image (lower panel) of the church façade. (c) InRAR-based acquisition geometry (left panel) and PSD measurements (right panel) for the church façade. (d) HVSNR profiles evaluated for the church buttresses inside the building (continuous and dotted black curves), and outside the church in front and the backsides of the structure (red and blue curves). (e) Seismic network inside the building (left panel) together with real time seismic acquisitions (right panel).

Conclusions

In this paper, an innovative monitoring system called MASSIMO is presented for the seismic risk monitoring of cultural heritage. Based on a multi-sensors infrastructure, a multi-spatial and multi-temporal methodology is implemented, which combines classical techniques, remote sensing tools, geophysical surveys and seismogenic analysis of the territory. In addition to the innovative aspects of the MASSIMO system from both systematic and methodological viewpoints, the proposed approach allows to access, manage, display, integrate and assimilate results coming from multi-disciplinary investigations by means of user-friendly interfaces, namely a web-GIS module and a 3D visual platform. The latter represent the value-added products of the whole investigation methodology. Experimental results, obtained for the Calabria region, the town of Cosenza and the Sant'Agostino Monumental Complex, show the effectiveness of the proposed approach. The results can be used to provide guidelines for local and national Institutions about possible consolidation / restoration / prevention planning, for the safeguarding of historical buildings.

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