A Combined Use of NDT Techniques and Proximal Remote Sensing Tools for Monumental Heritage Monitoring

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Abstract

The mitigation of seismic vulnerability related to both cultural and historical buildings is a very important issue especially when considering monumental heritages located on seismic areas, since it allows defining the seismic risk of selected structures. Within such a framework, Non Destructive Testing (NDT) techniques and proximal remotely sensed tools play a key role for providing the damage detection and the conservation status evaluation of heritages, especially in response to seismic hazards. Based on this rationale, the proposed study aims at providing a methodology relevant to the integrated use of Terrestrial Laser Scanner (TLS), Infrared Thermal Camera (IR-TC) and Real Aperture Radar (RAR) sensors for both the structural health monitoring and the seismic risk mitigation of monumental heritages. Some preliminary results, gathered for the Brettii & Enotri Museum in Cosenza and the San Nicola Church in Briatico, are properly described to show the benefits of both the proposed approach and the powerful capabilities of proximal remote sensing tools to support classical measurement techniques for the monumental heritages monitoring in a seismic area. Furthermore, some future perspectives are summarized in order to integrate and improve the results of the structural analyses.

Keywords: Non Destructive Testing (NDT), Terrestrial Laser Scanner (TLS), Infrared Thermal Camera (IR-TC), Real Aperture Radar (RAR), Monumental Heritage, Structural Health Monitoring (SHM), Seismic risk Mitigation (SRM)

1. Introduction

The start-up and the implementation of a monumental heritage depends not only on the material properties and the structural behaviour of the heritage itself, but also on its seismic vulnerability factor, i.e. the potentiality to suffer damages in response to seismic stresses with different intensities [1]. This parameter is very important especially when considering monumental heritages located on seismic areas, since it allows defining the seismic risk of selected structures. Within such a framework, Non Destructive Testing (NDT) techniques play a key role for providing the damage detection and the time-variable conservation status evaluation of monumental heritages, especially in response to seismic hazards [2]. The output provided by NDT techniques is very important to evaluate both the material properties and the structural behaviour of observed buildings, in order to define ad hoc countermeasures for Structural Health Monitoring (SHM) and Seismic Risk Mitigation (SRM) purposes [2-3]. The latter concerns the use of tools, sensors, methodologies, activities and technologies that allow achieving a damage detection and characterization strategy of monumental heritages to evaluate their health status in response to climate changes and natural events (i.e. earthquake, flooding, landslide and so on). Strictly connected to the SHM and the SRM of monumental heritages, proximal remote sensing techniques, such as the Laser Scanning (LS), the Infrared Thermography (IR-T) and...
the Radar Interferometry, can provide technological advantages especially for supporting, improving and integrating the use of classical techniques. In fact, LS is effectively used for the 3D modelling of buildings and its radiometric features, with millimetre accuracy [4]. The IR-T is a powerful technique that allows highlighting, detecting and monitoring structural features of observed heritages based on their capability to reflect the infrared radiation [5]. The Radar Interferometry is a coherent radar methodology able to evaluate the type and the severity of structural damages, thus providing the Line Of Sight (LOS) displacement time series of vibrating structures with sub-millimetre accuracy [6]. All these techniques have demonstrated their powerful capabilities in the field of monumental heritage monitoring for risk assessment operations (e.g. risk reduction, early warning and disaster emergency management) as well as for recovery and reconstruction purposes [4-7].

In this paper, a feasibility study on the combined used of classical surveys and new-emerging NDT techniques together with Terrestrial Laser Scanner (TLS), IR Thermal Camera (IR-TC) and Real Aperture Radar (RAR) sensors is presented for both the SHM and the SRM of monumental heritages. The main innovative aspect of the proposed work concerns the integration among established methodologies and proximal remote sensing tools for improving the static and the dynamic monitoring of monumental heritages in a seismic area. Some preliminary results are presented for the Brettii & Enotri Museum in Cosenza and San Nicola Church in Briatico (Calabria, Italy) to show the benefits of the proposed approach for the systematic, non-invasive and non-destructive monumental heritages monitoring.

The paper is organized as follows. In section 2, the methodology at the basis of the SHM and the SRM of monumental heritages is described in terms of NDT techniques and proximal remote sensing tools. In section 3, some meaningful preliminary results are presented for the buildings in order to compare the geometrical and detailed measures obtained through both classical technique and TLS. Finally, conclusions and future perspectives are drawn in section 4.

2. Methodology

In this section, the methodology at the basis of the proposed approach for the SHM and the SRM of monumental heritages is described. In particular, the physical rationale and the technical details of both classical techniques and proximal remote sensing tools used in this work are provided independently for a major clarity to the reader.

2.1 Classical measurement techniques

Classical measurement techniques are here implemented for monumental heritage monitoring in a seismic area according to the following rationale. The visual, the geometrical and the structural surveys of a selected heritage are performed subsequently to provide information about the conservation status and then evaluate its 3-Dimensional (3D) numerical modelling. The visual survey allows both providing a general overview of the selected heritage (with the reconstruction of its macro-details) and highlighting the most significant construction features (e.g. floors, arches, decorations, windows, doors, and so on) together with the detection of possible surface degradation and collapse morphologies (e.g. cracks, misalignment, etc). The geometrical survey aims at providing (i) the general planimetry of the observed structure with the definition of its spatial coverage and elevation features, (ii) the detailed planimetry of each floor inside the heritage, (iii) the reconstruction of all the structural elements inside the building in terms of (general and/or partial) geometrical sections and prospects.

The structural survey allows providing a detailed description of all the structural elements inside the heritage, with special attention to the bearing structures and the concrete elements.
2.2 Proximal Remotely Sensed Tools

In this section, the proximal remote sensing tools, implemented in this study for the monumental heritages monitoring, are properly described in terms of technical details, monitoring capabilities and expected outcomes.

2.2.1 Terrestrial Laser Scanner (TLS)

The Terrestrial Laser Scanner (TLS) is a powerful ground-based laser sensor effectively used for the 3D modelling, analysis and monitoring of structures in the field of archaeological, geodetic and cultural heritages monitoring [4]. The instrument used in this study is a phase comparison TLS sensor, which measures the phase difference between the signal emitted and then reflected by the target surface thus providing the distances between an arbitrary reference point internal to the sensor and the illuminated spot on the target surface. It allows achieving the high-resolution topographic reconstruction of the selected heritage in terms of ground coverage, coordinates and structural details, together with (i) the analysis of its radiometric features and visually-based details in red, green and blue (RGB) colours, (ii) the detection of building fractures, (iii) the generation of morphological maps for observed heritages [4]. In this study, the Z+F IMAGER 5010C TLS is used (see Fig. 1a), which is a long range class 1 TLS equipped with an integrated calibrated High Dynamic Range (HDR) camera that provides 80Mpixel full panorama digital images. All the technical details of the TLS sensor used in this study are provided in Table 1.

2.2.2 Infrared Thermal Camera (ITC)

IR-T is a powerful non-destructive and non-contact diagnostic technique based on the measurement of the heat energy and its conversion into an electrical signal, which is represented by thermal digital image [5]. The IR-TC devices are calibrated to measure the emissive power of a target area over a wide range of temperatures in the wavelength range of the far IR spectrum. After a first focusing phase of the emitted IR radiation, the electrical response signal is converted into a digital picture where different colours correspond to the various temperature levels of the target surface [5]. In this work, the IR-T surveys have been executed by using the Camera Avio InfReC R300SR-S Thermal Imager (NEC R300SR), see Fig. 1(b). The device allows measuring a range of temperature between -40°C and 120°C, corresponding to emitted maximum wavelengths ranging from about 7.4μm to 12.4μm, with a resolution of 0.03°C at 30°C environmental temperature. Moreover, the instrument can be used in a super resolution mode, which enables capturing images with 640(H) x 480(V) pixel definition and an instantaneous field of view of about 0.8mrad. All the technical details of the used IR-TC device are provided in Table 1.

2.2.3 Real Aperture Radar (RAR)

A Real Aperture Radar (RAR) is an active, coherent, band-limited, high-resolution, microwave sensor, which is able to measure the radar-target distance of illuminated scattering surfaces along the sensor Line-of-Sight (LOS) by simply measuring the time lapse between the electromagnetic wave transmitted by sensor and then reflected by the observed targets towards the radar antenna [6]. Based on this rationale, it has been widely demonstrated that a RAR has powerful interferometric capabilities for providing displacement variation measurements of vibrating structures down to few millisecond and with a sub-millimetre range accuracy [6]. In fact, RAR interferometry technique allows measuring time-variable changes in the position of an object by comparing the reflected electromagnetic wave phases
at different times, with accuracy depending on radar system specifications. As a result, it represents a very useful remote sensing NDT tool for both static and dynamic monitoring of heritages (e.g. monumental, cultural, historical and civil structures) in a seismic area.

In this study, the IBIS-S system marketed by Ingegneria dei Sistemi (IdS) company is used (see Fig. 1c). It consists of (i) a 17.2 GHz Stepped-Frequency Continuous Wave (SF-CW) radar with a bandwidth of 300 MHz, (ii) a control module connected to the sensor, (iii) a 12 V power-supply unit. All the technical details of the IBIS-S system are provided in Table 1.

![Proximal remotely sensed tools](image)

Figure 1. Proximal remotely sensed tools. (a) TLS. (b) ITC. (c) RAR.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Terrestrial Laser Scanner</th>
<th>IR Thermal Camera</th>
<th>Real Aperture Radar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>Z+F IMAGER 5010C</td>
<td>NEC R300SR</td>
<td>IBIS-S</td>
</tr>
<tr>
<td>Working Distance</td>
<td>Up to 187.3 m</td>
<td>-</td>
<td>2 - 1000 m</td>
</tr>
<tr>
<td>Accuracy</td>
<td>3 mm</td>
<td>±1°C or ±1% @ 30°C</td>
<td>&lt; 0.1 mm</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.1 mm</td>
<td>0.03°C @ 30°C</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Acquisition</td>
<td>1.016 million pixel/sec</td>
<td>60 Hz</td>
<td>&lt; 1 h</td>
</tr>
</tbody>
</table>

### 3. Experimental Results

In this section some preliminary but meaningful experimental results are presented to show the benefits obtained by combining classical measurement techniques and ground-based proximal remote sensing tools for the SHM and the SRM of monumental heritages. Experiments have been accomplished in two seismic areas of Calabria Region (Italy) with special attention to the internal colonnade of the monumental compound of the Brettii & Enotri Museum in Cosenza (Fig. 2a) and to the facade of the San Nicola Church in Briatico (Fig. 2b). In detail, the two selected case studies are illustrated by integrating and comparing the results gathered through both classical survey methodologies and TLS sensor.
3.1 Case study 1 - Brettii & Enotri Museum

The first case study is represented by the internal colonnade of the Sant'Agostino compound, a monumental and historical masonry heritage dating back to 1507, which has been characterized by several changes in terms of historical properties and intended use. The whole compound has been subject to several architectural and structural renovations due to the damages occurred after severe historical earthquakes (e.g. the massive seismic events recorded in Calabria on 1638, 1854, 1870 and 1905). Since 2009, the Sant'Agostino compound has become the civic pole of Brettii & Enotri Museum, which hosts a wide archaeological collection from Cosenza and its surrounding provinces, covering a broad chronological span. The Figure 3 shows the planimetry of the building with the indication of the columns and the sections hereinafter analysed.
A preliminary evaluation has been performed, with reduced noise, on the sections of the colonnade discovered by the steel tubes (A-A and B-B in Fig.3) in order to compare the profiles obtained by direct measurements and the reconstructions executed on the base of the point clouds carried out by TLS (Fig. 4), with a resolution of about 6.3mm (at the 10m distance). In particular, the width of the P2-P5 and P7-P10 columns on the three floors has been estimated together with a deviation factor that quantifies the discrepancies resulting by different instruments of measurement. This factor has been evaluated as ratio between the difference of the two measures and their average, whose values are reported in Table 2 showing a good agreement with a maximum difference of about 2cm and a deviation of 5.28%.

In order to check the misalignment of the columns (Δ), the lines linking the centres of the columns on the upper levels and those corresponding to the base of the colonnade are properly drawn in Fig. 4. The Δ values have been measured as distance at the base between these lines and their hypothetical verticals, see Table 3. The numerical comparison among the measurements from the 2nd to the 1st level of the columns shows a difference always lower than 2 cm, about twice respect to the used resolution of the laser scanner instrument; whereas, the misalignments between the 1st and the 3rd level suggest a good agreement of the different measurement techniques providing values lower than 1cm, except for P5 and P9 columns.

The TLS capability to improve the detailed survey has been investigated by analysing the health status of some structural elements. The point clouds, obtained by the scans of the columns at a distance lower than 2m and resolution of 3.1mm (at 10m distance), have been meshed to realise an understandable and measurable sketch. The results of the direct detailed analyses and the triangular meshes are pictured in Fig. 5. The TLS-based data seem to detect...
the main characteristics of the structural element: the crack patterns, the natural and squared stones and the filled mortar. Furthermore, all representative details of the health state of the element are observable both on the drawing and on the mesh, comparably.

Figure 4. Comparison between classical and TLS geometrical surveys gathered on two sections of the colonnade of the Sant’Agostino compound: section A-A (a,c) and section B-B (b,d)
3.2 Case study 2 - San Nicola Church

The second test building is the San Nicola Church in Briatico, built in 1930 after the demolition of the previous church following the 1905 and 1908 calabrian earthquakes. With respect to the selected test building, the geometrical analysis has been conducted on the openings of the facade. In particular, each opening has been properly measured (see Fig. 6a) and then compared with those detected by TLS-based point cloud (see Fig. 6b). The TLS survey has been accomplished at a minimum distance of about 30m and with a spatial resolution of 1.6mm (at 10m distance). Experimental results show a good agreement between the measurements obtained by classical and TLS surveys especially in the lower part of the facade. Conversely, less negligible differences can be observed in the middle-upper part of the church.

The numerical evaluation between the survey techniques is reported in Table 4 together with the deviation factor. Experimental results show that the two proposed techniques supply the same values for the entrance portals of the church; conversely the deviation factor assumes maximum values greater than 2% for the 10th and 12th segments. Generally, the measures seem barely influenced by survey technique for the closest distances from sensor to target; instead, the variation increases with the measurement distance.
Figure 6. Comparison between geometrical survey (a) and TLS (b) on the prospectus of the San Nicola Church.

Table 4. Geometrical measures of the openings: comparison between classical geometrical survey and TLS.

<table>
<thead>
<tr>
<th>segment</th>
<th>terrestrial laser scanner measure (cm)</th>
<th>classical geometrical survey measure (cm)</th>
<th>deviation factor (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>250.1</td>
<td>250.0</td>
<td>0.05</td>
</tr>
<tr>
<td>2</td>
<td>151.3</td>
<td>151.0</td>
<td>0.21</td>
</tr>
<tr>
<td>3</td>
<td>393.8</td>
<td>393.0</td>
<td>0.20</td>
</tr>
<tr>
<td>4</td>
<td>191.0</td>
<td>190.0</td>
<td>0.54</td>
</tr>
<tr>
<td>5</td>
<td>250.3</td>
<td>250.0</td>
<td>0.10</td>
</tr>
<tr>
<td>6</td>
<td>151.6</td>
<td>151.0</td>
<td>0.39</td>
</tr>
<tr>
<td>7</td>
<td>101.7</td>
<td>100.0</td>
<td>1.73</td>
</tr>
<tr>
<td>8</td>
<td>246.7</td>
<td>245.0</td>
<td>0.68</td>
</tr>
<tr>
<td>9</td>
<td>100.1</td>
<td>100.0</td>
<td>0.05</td>
</tr>
<tr>
<td>10</td>
<td>103.1</td>
<td>100.0</td>
<td>3.05</td>
</tr>
<tr>
<td>11</td>
<td>253.8</td>
<td>250.0</td>
<td>1.53</td>
</tr>
<tr>
<td>12</td>
<td>102.9</td>
<td>100.0</td>
<td>2.85</td>
</tr>
</tbody>
</table>

4. Conclusions and Perspectives

In this paper, the powerful capabilities of proximal remote sensing tool (i.e. TLS sensor) have been described to support, integrate and improve the measurements obtained by classical geometrical surveys for both the SHM and the SRM of monumental heritages. Both proposed case studies allow to observe a meaningful agreement between the measurements carried out by the different techniques, showing relevant differences in limited cases. The future perspectives aim to integrate the different NDT surveys used to investigate the proposed case studies.
For example, bearing elements and different materials under the plaster have been detected by the thermographic survey, useful knowledge to integrate the structural modelling. Indeed, investigating the buttresses and the columns of the Sant'Agostino compound were discovered: stone blocks, bricks and wall weaving.

Furthermore, the survey performed on the San Nicola church (see Fig.7) will be used to support the check of the continuity surface among the base support, the concrete cover and the plasters. In fact, the bearing elements, edified in reinforced concrete, are currently suffering widespread cracks. This instability is due to both the carbonation phenomenon and the marine aerosol, which have caused the oxidation of the steel bars. Therefore, these phenomena, associated to the increase in volume of the concrete, have been producing widespread detachment areas characterised by an incipient collapse. The use of the thermal images may enable the quickly identification of the risk areas, without the assistance of scaffolding. In addition, the thermography can be used to verify the absence of construction defects following the consolidation work.

![Figure 7. Thermal images of the San Nicola Church.](image)

Moreover, the integrated analysis of 2D TLS-based morphological maps (evaluated with respect to a reference fitting planes) and Interferometric RAR-based displacements can be used in order to support the structural analyses and monitoring over time. In Figs. 8 some preliminary results are shown for the church cloister inside the museum by properly combining the measurements provided by TLS and Interferometric RAR. In detail, Fig.8(a) shows the 2D morphological map (in cm) relevant to one of the four inner cloister walls (evaluated with respect to a reference fitting plane), where some structural anomalies of the wall can be clearly highlighted. To properly integrate the morphological and radiometric survey of the colonnade, the structural vibrating properties of the monitored wall have been evaluated through the interferometric processing of RAR measurement campaigns, whose results are provided in terms of LOS displacement (see Fig. 8b) and Power Spectral Density (PSD) (see Fig. 8c) for the radar bins associated to the higher part of the selected target.

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Figure 8. Experimental results for the wall of the church cloister inside the museum. (a) 2-D morphological map (in cm) superimposed to the 3D TLS-based model of the structure. (b) LOS displacement and (c) PSD for the radar bins associated to the higher part of the wall.

References