Terrestrial Laser Scanning for Preserving Cultural Heritage: Analysis of Geometric Anomalies for Ancient Structures

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Key words: terrestrial laser scanning, cultural heritage, geometric anomalies identification, high precision leveling, vertical displacements.

SUMMARY

Identifying the overhang, progressive changes of inclination, differential movements of the structure and detailing the study of structural elements are just some examples of the many fundamental information for structural engineers. Those data are required to study and analyze the behavior of a structure with the purpose to assess the stability . Laser scanning appears to be the best technology to provide an effective solution to those requirements. Surveying by means of a terrestrial laser scanner (TLS), allows to detect a huge number of information with relatively short time and high accuracy. Those data, then, do not necessarily need to be used to reconstruct the three dimensional surface model. Just analyzing the point clouds, interesting information along with useful products can be obtained in order to draw some considerations about the investigated structure. This research aims to suggest a new philosophy for using TLS in a diagnostic perspective in order to study structures along with their actual dimensions, their stability and so on. This new approach, characterized by a well-advanced vision, is really different from the traditional one because of the engineering point of view with respect to the usual application of TLS. Traditionally, indeed, laser scanning is chosen for artistic and architectural studies and the resulting three-dimensional model represents what often is of concern.

The research focuses on the Cathedral of Modena, one of the most important pieces of Romanesque culture in Europe (UNESCO World Heritage List since 1997). The overall motivation of this research is to preserve the cultural heritage we are responsible for, as long as spectators. Thus, the final purpose is to illustrate the methodology to compute anomalies in structural geometry by means of TLS in order to provide an accurate description of the structure that is particularly useful for structural engineers, architects and art historians. Both outdoor as well as indoor TLS surveys were performed. The geometry of the structure was properly described by analyzing point clouds; specific measurements were focused on constituent elements with the aim of detecting anomalies of the geometric configuration. Geometric anomalies might be read as the result of deformations occurred in the past or as future deformations due to an abnormal geometric configuration. Investigations about the identified anomalies will be presented together with differential movements obtained by high precision leveling focused on a network of benchmarks that were installed along the outside perimeter. The integration of independent techniques allows to check for consistency of results.

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1. INTRODUCTION

The laser scanning technique has recently become more and more popular for a wide range of applications because of its capability to acquire a lot of information with a high degree of detail and in relatively short time. Cultural heritage is surely one of the most promising field of application for the future development of laser scanning (Guarnieri et al., 2004a; Guarnieri et al., 2004b; Neubauer at al., 2005). This powerful methodology is also able to provide solutions to several needs and problems which have to be overcome when planning a successful and reliable survey. Consider, for example, the ability to detect artistic elements and architectural details with high degree of accuracy, also when they are difficult to be accessed due to complex scenarios such as towers (*i.e.* limited accessibility and visual obstructions) (Bertacchini et al., 2010). This is a key aspect both for researchers, engineers and specialists, who can in-depth study all aspects of concern from a comfortable and relaxed perspective, and also for the whole community. Indeed, people are often attracted by impressive evidence of the past and rarely realize the small treasures that surround them in the streets of cities and monuments. Unaware of art and history that surrounds them, citizens can be "awakened" by three-dimensional reconstructions that have high metric accuracy as well and are obtained on the basis of the points cloud detected by laser scanners. Thus, by making the cultural heritage virtually accessible to everyone, the laser scanner becomes essential tool for dissemination of artistic heritage (Guarnieri at al., 2010; Meyer at al., 2002). One more example of such valuable contribution is given by archaeology (Ioannides at al., 2006; Lambers at al., 2007): buried artifacts and findings coming out from excavations are often covered again because not enough funds are available for maintenance and for keeping visible what has been discovered. In practice, this means the impossibility for the community to appreciate the ancient findings, which remains the privilege of archaeologists who took part in the excavation. They themselves, however, face the source of many questions with no possibility to give answers. Surveying the excavation by a laser scanner enables archaeologists to continue their studies even after the closure of the excavation and to draw hypotheses also based on the integration with further information that might emerge from post-analyzes. Another positive aspect is the documentation and the memory of those layers that are inevitably sacrificed during an excavation in order to analyze the deeper stratigraphy.
It clearly appears that what has been described so far is mainly aimed to produce 2D or 3D products and surface models for qualitative analysis and documentation as well as spectacular 3D reconstructions for virtual tours and navigation. Those information are of great interest to art and history specialists or for planning interventions to restore artistic heritage. Together with this traditional approach, an innovative use of laser scanning technique is proposed for analyzing cultural heritage. It is based on measurements and analysis which are directly

computed on the points cloud itself and it does not need to go through hard processing and modeling, which takes long time. Such innovative approach, which is based on the engineering perspective, aims to provide useful information for structural analyses and for this purpose it is focused on constituent elements rather than artistic elements. Indeed, preservation of historic and cultural heritage does not only mean restoration of artistic components, but also consolidation and design of interventions which are required to preserve the integrity of the whole structure for future generations. Studying the critical aspects of a structure in terms of stability is of fundamental importance for the purpose of protection and preservation: the structural analysis is accomplished through the application of numerical simulation models (finite elements algorithm) that evaluate the response of the structure in relation to different types of stresses. In order to obtain reliable results, it is useful to have three-dimensional and geo-referenced models of structures that needs to be of considerable detail and with high degree of metric accuracy. A detailed and reliable description becomes more essential in case of ancient structures to determine the vulnerability because those buildings are characterized by irregularities just during their construction that likely have been increased by changes occurred over time. By this way, laser scanning is particularly worthwhile for those who needs to evaluate the stability of the structure as well as its vulnerability in static terms (Gordon at al., 2004); moreover what is of concern is its complexity due to the construction phases, changes and modifications occurred over time and soliciting actions and weight. With ancient structures, a static analysis is fundamental to prevent unexpected collapse and to plan interventions for safeguarding and restoration.
The key concept is to emphasize the double value of laser scanning: the traditional use for qualitative and spectacular three-dimensional reconstructions as well as the innovative approach based on quantitative analysis computed on the geometry of the points cloud. Both these aspects help to strongly expand the application range of laser scanners for cultural heritage.
Below are details about the innovative proposed methodology for the diagnostic use of laser scanners with the final aim to support structural analysis by reliable and accurate measurements. The methodology will be described and applied to a specific case study, the Cathedral of Modena (Emilia Romagna Region – Italy), in order to highlight potentialities and confirm the usefulness of the proposed approach.

2. DIAGNOSTIC APPROACH: METHODOLOGY

The use of laser scanner technology as a diagnostic tool for structural analysis aims to extract information and parameters that are the starting point for advanced studies on the statics and the dynamics of a structure. Results are undoubtedly of great help to design and plan interventions of consolidation and safeguarding that become necessary as a result of the above analysis. The innovation of the proposed methodology is essentially to change the point of view for analyzing and interpreting laser scanner data on the basis of the final aim which led the survey. Compared to traditional approach, the difference mainly lies in results extraction as the final product is not the three-dimensional surface model for simple documentation, qualitative interpretation and consultation, but the quantitative and accurate identification of geometric anomalies of structural elements. Obviously, design and implementation of surveys as well as data processing are similar to any other laser scanning survey, regardless of what is the *a-posteriori* analysis to be performed on the points cloud.

This section briefly describes the methodology for successfully analyzing a laser scanner point cloud in order to identify anomalies in the geometric configuration of ancient structures. The procedure, aiming to become a sort of guidelines for cultural heritage applications, provides an helpful workflow which can be followed when planning to use laser scanning technique as a diagnostic tool for supporting structural analyses.

The general methodology is summarized by the flowchart represented in Figure 1: the procedure is characterized by three main steps; each one of them is described by more detailed operations. These operations are:

- choice of the equipment: it is essential to carefully choose among several types of laser scanners which are commercially available on the basis of the technical characteristics as well as the involved distance separating the instrument and the structure. It is also fundamental to pay attention to materials of which the structure consists in, because their reflectivity may influence the ability of laser scanner. The main parameter ruling the choice is the aimed final resolution.
- Plan and design the survey: a preliminary inspection of the site and the structure is suggested in order to properly design and plan the survey. Particularly, parameters to be defined are the number and the position of scans, which have to detect the whole object of interest with the final required resolution. This is essential step for data processing in order to be able to align all point clouds in a unique reference system.
- Installation of targets: depending on the chosen alignment strategy, this is optional step. Targets, that are markers with high reflectivity, needs to be installed if the alignment is achieved by homologous points (their coordinates are computed by total station measurements, supporting laser scanner survey, just when solutions are required with respect to a specific reference system); they are not mandatory in case of alignment approach.
- Carrying out the survey: it simply consists in detecting what is included within the laser scanner view by acquiring a series of points in the local arbitrary coordinate system (which is defined by the momentary position of the instrument).
- Noise removal and filtering: these operations consist in “cleaning” each point cloud because it is often characterized by disturbing elements, having nothing to do with the object of interest, and therefore add noise to results. Carefully removing what is irrelevant to the structure is fundamental in structural analysis where the request is usually to obtain a model containing exclusively the constituent elements.
- Alignment: it is the fundamental step in order to obtain a comprehensive and unique point cloud which is the basis for extracting any further information about the structure as well as for performing the desired analysis. The alignment process consists in unifying all scans, each one of them is referred to a specific reference system, into the same reference system and providing a global point cloud.
- Results and products: as soon as the global point cloud has been obtained, many products and information may be extracted such as the accurate definition of the height of the structure, plans, fronts and sections, three-dimensional surface model as well as more specific and advanced analysis and structural evaluations.

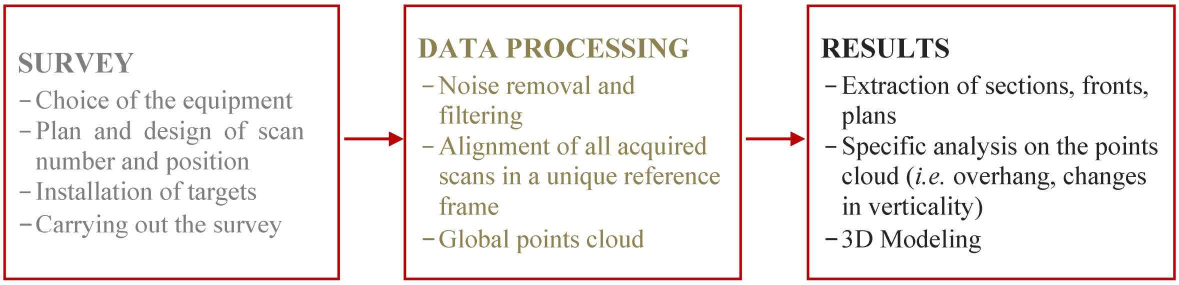

Figure 1. Outline of the described methodology: diagnostic approach for analyzing laser scanning data for structural analysis applications.

Below is the application of the methodology to a specific case study in order to better describe the procedure. Brief description of survey and data processing follows; an extensive description of conceivable analysis and products for structural purposes will be given.

3. CASE STUDY: THE CATHEDRAL OF MODENA

3.1 Survey: planning and execution

The chosen case study is an impressive and valuable example of ancient structure with static vulnerability mainly due to subsequent construction steps. The Cathedral of Modena, which is included within the UNESCO World Heritage List since 1997, is one of the most important pieces of Romanesque culture in Europe (Figure 2).

Figure 2. The Cathedral of Modena, UNESCO World Heritage List since 1997 (pictures source: http://www.unesco.mo.it).

As already mentioned, a key step is the choice of the most appropriate type of instrument. The laser scanner used for surveying the Cathedral of Modena is a high-resolution terrestrial laser scanner, *ScanStation2* by *Leica Geosystems*, which is particularly suitable for architectonic use. It also provides a reliable reference for the verticality because of the internal dual-axis compensator which allows to adjust for the identification of precise verticality. The survey is planned by taking into account shape and size of the structure and by taking care of positioning the laser scanner in order to detect the whole structure. The difficulty increases when the structure has many discontinuities, overhangs, undercuts and architectural elements such as in the described case sudy. A careful plan of field operations is basic both to avoid problems during the alignment process and to make sure that the global point cloud is able to properly describe the complexity of the structure. Moreover it is essential to optimize the number of scans in order to avoid redundancy. Indeed, capturing redundant points adds nothing to the resulting three-dimensional model; on the contrary it is a disadvantage because of the massive amount of data that is hard to be managed. Left Figure 3 shows the design of outside survey of the Cathedral of Modena. Scans have been performed both in elevation and on the ground (right Figure 3) in order to ensure reliable and accurate return of the laser pulse and avoid high incidence angles which add noise to the point cloud. Upper part of fronts and roofs are better described by varying scanning positions as well as changing perspectives. Scanning resolution has always been set up at 8 mm with respect to the mean acquisition distance which characterizes each scan.

Figure 3. Surveying the Cathedral of Modena: design of the external laser scanner positions (left); the laser scanner while operating (right).

3.2 Data processing: alignment strategy

Once all scans have been performed multiple point clouds, each one depicting a portion of the structure, result. Each point cloud is firstly processed for removing noise and for cutting all acquired points which do not belong to the investigated structure. Then, the alignment process allows to combine these point clouds to create the overall 3D model of the detected points.

The alignment strategy is based on identifying a suitable number of homologous points (three as a minimum) within each scan. Such points are special reflective targets which are recognized by the instrument during the scanning operations. They have been placed on walls of the structure itself and on nearby buildings by planning their number and position to ensure high accuracy (sub-centimeter) of the overall three-dimensional digital model. The alignment of point clouds was performed by means of *Cyclone 6.0* software suite by *Leica Geosystems*, which computes rotation and translation parameters by imposing the overlap of those targets pairs. The accuracy is given by the distance of homologous targets after the alignment has been performed (comparison of coordinates). Concerning all alignments computed to create the whole point cloud representing the Cathedral of Modena, the final accuracy is about 1 cm.
Both inside and outside surveys was required for a comprehensive description of the Cathedral of Modena. This goal is much more complex because the alignment needs to be divided into steps: first of all in and out scans need to be separately aligned; once both internal and external global point clouds are available, they may be aligned to the same reference system in order to provide the whole 3D model of the structure. The former is based on targets pairs or surface matching, while the latter requires to use the total station as a supporting tool for measuring some in and out targets (being as more homogeneously distributed as possible). The full alignment is accomplished by estimating their precise coordinates with respect to a unique reference system and by fixing them in both in and out point clouds. By this way the consistency of the whole 3D model is achieved as well. The same approach has been used at the Cathedral of Modena; further examples also exist in literature (Bertacchini et al., 2010).

3.3 Results: identification of geometric anomalies by laser scanning

The above mentioned procedure follows traditional criteria of laser scanning technique. As soon as the comprehensive 3D point cloud of the structure is available, the innovative methodology for using laser scanning data as a diagnostic tool supporting structural analysis may be described. This paragraph shows how performing a careful investigation of the point cloud with the purpose to analyze geometric parameters and to extract useful information for assessing the stability of the structure. A very useful product is the identification of the overhang, whose value and modification trend over time are particularly remarkable in case of towers. Such data are helpful if individually read; they become even more interesting if combined together with examination of various historical construction steps in order to make hypothesis about deformations eventually occurred over time.
Analysis of verticality is carried out by cutting the point cloud and providing sections at regular intervals of height. Then, the trend of vertical axis is computed by identifying the center of mass for each section and joining them (Bertacchini et al, 2010). The reconstruction of vertical axis may be refined through the extraction of more sections by a smaller interval without complicating the analysis. This approach has also been applied to identify the Ghirlandina tower overhang and to evaluate its static vulnerability. The Ghirlandina tower is the tower of Modena, which is included in the UNESCO World Heritage List together with the Cathedral of Modena. In the past, these structures were connected by a buttress which was then removed. Both monuments took a long time to be finished and their final geometry has

been strongly influenced by the presence of the contiguous structure. Reciprocal differential movements affecting both structures are the reason why monitoring by high-precision leveling as well as laser scanning surveys have been required.

By this method of investigation, accurate analysis of geometric features, such as height and overhang, can be carried out with the purpose of identifying structural anomalies. Besides analyzing the overhang, which is essential for towers, other considerations may be extracted. Structural assessments may be specifically required by structural engineers on the basis of evidences of degradation and cracking or it may be the result of analysis carried out on laser scanner point clouds which reveal fundamental information for supporting and improving the in-depth structural analysis (including anomalies in accurate finite element modeling).

At this purpose, the analysis carried out on the Cathedral of Modena provides very interesting examples of further investigations. In this case the overhang of all sides has been defined by carrying out a detailed analysis of deflections from the verticality with respect to the direction orthogonal to the plane of the wall and also with respect to the plane of the wall itself. Both deflections have been considered and composed in order to obtain the resulting overhanging. This is extremely important for structural engineers in order to assess stresses which lead to open outwards of the structure. These considerations are closely tied to evidences of cracks that only expert eyes are able to detect; such visual inspection is helpful to provide confirmation of the obtained results. The mentioned analysis was performed on external walls by examining key architectural elements such as columns, which are well identifiable on the point cloud and also uniformly distributed along the structure. Columns have been found to be representative of the wall behavior because they develop vertically along the entire height of the structure. The deflection angle is estimated by comparing the vertical direction, which is known by means of the dual-axis compensator of the laser scanner as soon as it has been leveled, to the longitudinal axis of the column, which is extracted by the point cloud itself. Map in Figure 4 summarizes overhanging directions which have been identified by the combination of deflections in the plane and deflections towards the direction normal to the plane in the orthogonal direction. These directions refer to external walls. Then, the same analysis has been performed on internal columns in order to assess whether there is homogeneous behavior between outside and inside or whether differential movements occur. The latter scenario is very dangerous for the stability of the structure.

Further investigations can be performed by analyzing key horizontal elements such as ledges and eaves, which extend longitudinally along the sides of the structure and are distributed at different heights. The verification of the effective horizontality of architectural elements, which should be horizontal, has been carried out on outside facades of the Cathedral by means of polylines directly outlined on the point clouds. Having a resolution of about 8 mm, the point cloud allows to accurate outline polylines according to actual geometry of eaves and ledges. By this way the angle between such polyline and the horizontal plane may be computed. To ensure significance to the analysis, the facade has been divided into several parts in order to identify differential movements of portions of the facade (anomaly). Results highlight a differential behavior along the longitudinal extension of the facade.

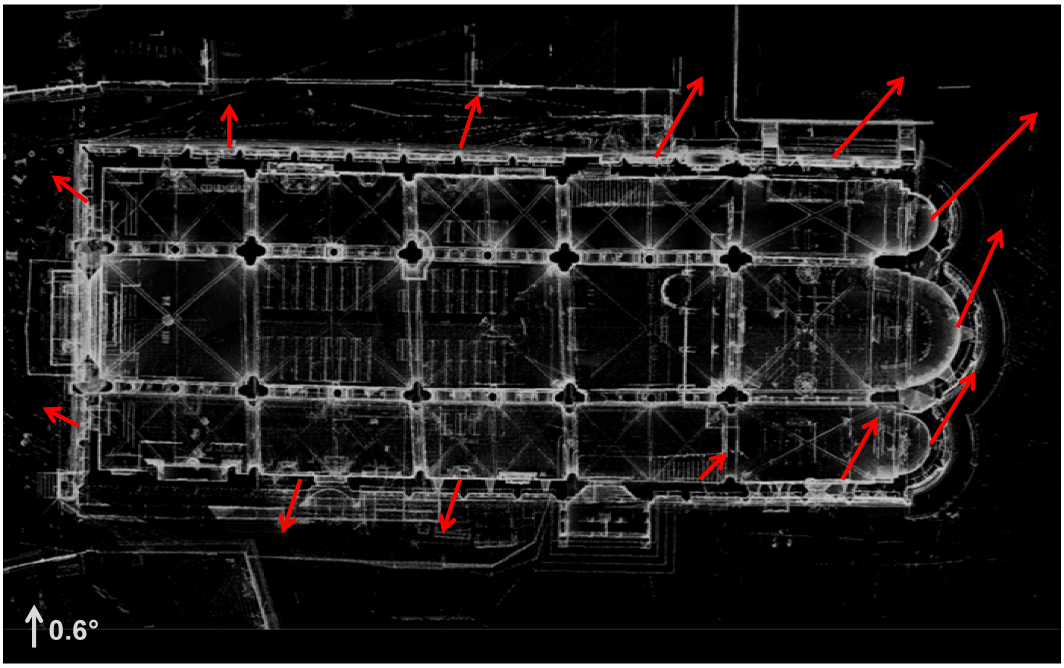

Figure 4. Summary of overhanging directions (red vectors) identified on external columns. Length of vectors is proportional to deflection angle value.

These analysis have also been performed on the apse and led to interesting results in relation to the subsequent steps of construction and restoration. This needs to be validated by comparison with art historians.

3.4 Results: identification of differential displacements by high precision leveling

The interesting results which have been obtained by analyzing laser scanner point clouds with a diagnostic approach, are particularly useful for structural engineers because irregularities and anomalies in the geometry of structures may improve results of numerical simulation models aiming to assess the static vulnerability of ancient artifacts. High precision leveling also gives a valuable contribution to this by providing information about vertical displacements. Differential movements, which are one of the most dangerous conditions able to endanger or cause collapse of a structure, are detected by periodically monitoring a network of benchmarks installed on investigated monuments. This approach is used for monitoring the Cathedral of Modena, the Ghirlandina tower and the whole complex of Piazza Grande since 1984. Left Figure 5 shows an example of differential movements affecting longitudinally the Cathedral: particularly, the apse and the front are characterized by major displacements if compared to the central portion of the structure. In addition front and apse show contrary displacements gradient. Furthermore, results obtained by high precision leveling confirm the overhanging directions identified by analysis of laser scanner point cloud. Indeed, the direction of differential movements is more clearly highlighted by investigating the gradient of displacements gradient. Such in-depth analysis is shown in right Figure 5 and confirm that the Cathedral is strongly affected by movements and anomalies towards North-East direction.

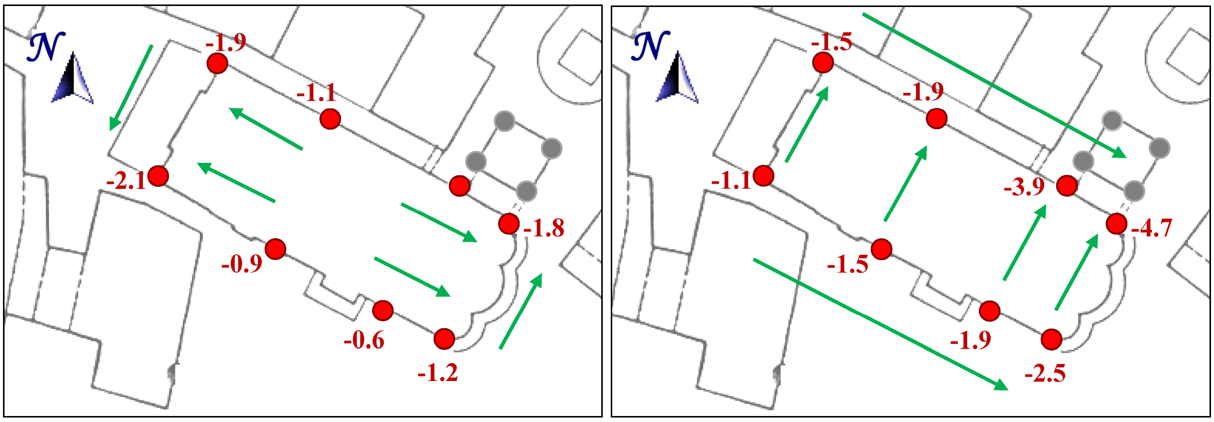

Figure 5. High precision leveling on the Cathedral of Modena: differential movements between central body and front/apse over four years (1985-1989) on the left; significant vertical displacements with major values towards North-East over four years (2007-2011) on the right. All values in [mm].

This may be due to the strong interaction that links the Cathedral together with the Tower. In order to strengthen this aspect, the cumulative displacements map of the whole area over 27 years of monitoring is represented in Figure 6: major vertical displacements are detected in correspondence of the two ancient structures, with values increasing as soon as getting closer to the tower. More complex analysis is required to describe and properly explain their behavior; a multidisciplinary approach is essential because geotechnical characteristics of ground substrates have a strong influence (*i.e.* micro-subsidence effects).

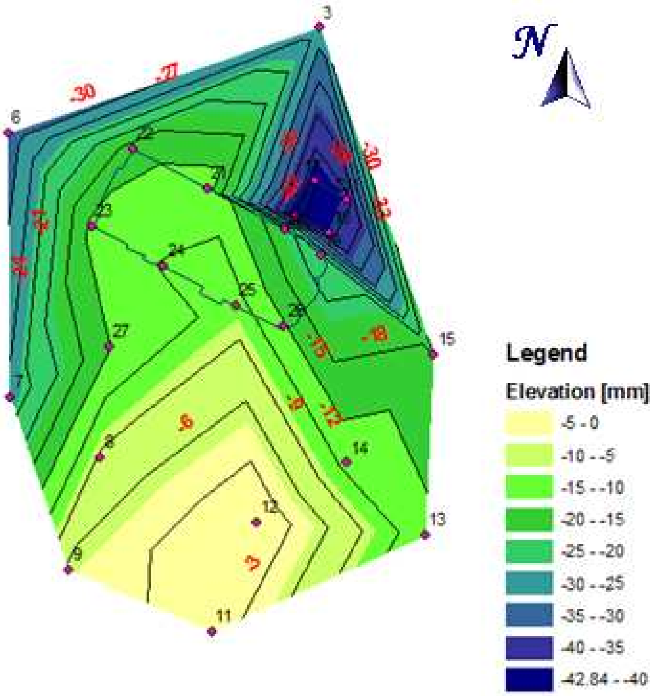

Figure 6. Vertical displacements of Modena UNESCO World Heritage area: cumulative map with contours obtained by high precision leveling over 27 years (1984-2011).

4. CONCLUSIONS

The described research proposes a new and innovative use of laser scanning technique for cultural heritage applications: attention is not paid to artistic and architectonic elements and the aim is not only to return the three-dimensional surface model of the investigated structure for qualitative assessments (traditional approach). The basic idea aims at approaching laser scanner data with a critical point of view in order to analyze the complexity of structures as well as their geometry. The attention moves to constituent elements as well as any evidence of cracking or warping, which are critical for the effective stability of the structure. Three-dimensional point clouds can be valuable sources of information for extracting measurements and parameters which are helpful to foresee the structural behavior, for highlighting whether differential displacements and deformations occur or not and for making hypothesis about any additional load that increases imposed stresses. These results are fundamental to plan interventions for strengthening and securing the structure. This confirms the usefulness of laser scanning as a diagnostic tool for structural analysis. As a consequence, the research may conclude by asserting that laser scanning is a sufficiently complete and accurate technique to be considered as the basis for geometric investigations. The above discussion confirms that the analysis allowed to extract lot of information about the structure as well as its status. It is worth to underline that it is not possible to interpret results and identified anomalies without integrating and comparing with information about the history of the structure. The research is a work in progress and further steps will focus on multidisciplinary approach in order to provide a comprehensive methodology for studying cultural heritage.

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BIOGRAPHICAL NOTES

Cristina Castagnetti successfully completed her PhD in March 2010 at the University of Modena and Reggio Emilia. She took her degree in Environmental Engineering studying kinematic positioning by means of GNSS. Her PhD dissertation focused on land-based navigation with particular attention to the design of a low-cost integrated system for precision farming application. Since few years she is also involved in archeaology and cultural heritage applications with the purpose of surveying and monitoring ancient structures.

Eleonora Bertacchini was born in Reggio Emilia (Italy) the 18th January 1982. She graduated in 2007 at University of Modena and Reggio Emilia in Environmental Engineering with a thesis about the orthorettification of very high resolution satellite images. Now she is going to discuss her PhD dissertation about GB-InSAR for identifying landslide displacements. She is involved in surveying, mapping, remote sensing and topographical monitoring systems.

Alessandro Capra took his degree in Mining Engineering at the University of Bologna (Italy). He is Full Professor of Geodetic Sciences, Surveying and Mapping at the Engineering Faculty of University of Modena and Reggio Emilia. He also is Chief officer of Geosciences group of SCAR (Scientific Committee on Antarctic Research), President of SIFET (Italian Society of Photogrammetry and Surveying) and Editor-in-chief of *Applied Geomatics* journal.

Marco Dubbini was born in Ravenna (Italy) the 2nd May 1967. He took his degree in Civil Engineering at University of Bologna in 1998. He finished his PhD in Geodetic and Topographical Sciences at University of Bologna in 2002. At the moment he works at University of Bologna. He is involved in surveying, mapping, data processing related to all geography applications. Number of scientific publications: 23.

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