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Geomatics for Cultural Heritage conservation: integrated survey and 3D modeling

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***Abstract* – Purpose of this paper is to illustrate the contribution of geomatics studies in management and protection of Cultural Heritage assets. Architectural surveys, carried out by integrating traditional survey techniques with more innovative instruments, are fundamental to guide the different actors involved in conservation and restoration processes, as they allow them to get a complete and extensive knowledge of the survey object, at different levels of detail and scales of representation. The integration and elaboration of the different survey techniques are illustrated in this paper with reference to the case study of the Calci Charterhouse, unique for its historical, artistic and environmental value. Among the different studies that are performed based on integrated geomatics tools, an innovative application is here discussed, which refers to the generation of informative parametric models starting from point clouds acquired through survey, as the pipeline of a Scan-to-HBIM process.**

I. INTRODUCTION

The paper illustrates the contributions of geomatic studies in applications of conservation, management, monitoring of Cultural Heritage (CH), bringing as a significant example the case study of the monumental complex of Calci Charterhouse, located in the surroundings of Pisa, Italy.

Nowadays, in order to manage the projects of conservation and restoration of heritage assets in a more efficient manner, it is necessary to rely on the integration of different survey techniques. By combining traditional topographic survey with Global Navigation Satellite Systems (GNSS), terrestrial laser scanning and ground-based photogrammetry, indoor and outdoor drone photogrammetry, a reliable restitution of architectures, shapes and 3D geometries can be provided, to be used in the different applications of CH studies and to describe each existing building in a refined and detailed way.

By deepening these issues related to integrated surveying and 3D modeling of CH assets, the paper is organized as follows: Section II displays the importance in the combination of different survey activities in view of conservation, restoration and maintenance of CH structures and discusses the current need to have 3D informative models where to add semantic information to the survey data. In Section III, the results of the several survey campaigns carried out on the Calci Charterhouse by the A.S.T.R.O. (Scientific and Topographic Applications for Operative Survey) Laboratory of the University of Pisa are presented, emphasizing how, over the years, the architectural survey has served as a supporting tool in the different restoration and management activities.

Moreover, amongst the studies performed thanks to the outputs of the integrated geomatics surveys, Section IV illustrates a novel procedure which concerns the creation of informative parametric models starting from point clouds acquired through surveys. The possibility to relate semantic information to the geometrical survey is here discussed considering the insertion of data related to the degradation levels of walls and surfaces.

Finally, Section V outlines the concluding remarks and the future developments of the work.

II. INTEGRATED SURVEY AND 3D INFORMATIVE MODELS

CH assets which, due to their own nature, are characterized by complex geometries and shapes, being the result of successive stratifications, increasingly require the application of integrated survey techniques. Recent studies have focused on the combination of traditional topographic survey with novel technologies of laser scanners and close-range or aerial photogrammetry, by underlying the need to define a common reference system to which the different acquisitions should be connected, for a shared data access and work interoperability [1][2][3]. The integrated geomatics survey techniques allow the different experts involved in the CH recovery process (from restorers, architects, civil and environmental engineers to specialists of hydraulics and geology studies) to gather metric documentation on the asset, to be used as a privileged instrument of knowledge for thematic analyses and diagnostic activities, in view of conservation and maintenance programs.

Integrated geomatics survey techniques, consolidated as eligible means for the representation of the shape and geometry of existing elements, thus constitute a fundamental resource to be used as a basis for the analyses of restoration, conservation and maintenance of CH [4] [5]. Today, the potentials of range-based and image-based techniques [6] in creating accurate and precise 3D representations of the real datum open the way to the possibility to create direct correspondences between the survey outputs and the results of the different researches on the heritage asset. In other words, one wonders now whether it is possible to create detailed 3D informative systems, in which the three-dimensional representation is related to an informative/semantic level, in such a way that each actor involved in the restoration and maintenance project can access, insert and modify in time the information on the heritage asset directly through the digital mockup [7] [8] [9].

In this strand, the Architecture, Engineering and Construction domain has seen in latest years the spread of Building Information Modeling (BIM) techniques, based on the construction of parametric models enriched with information levels [10]. The application of BIM techniques to the domain of CH studies opens the way to further experimentations and researches [11]. In detail, a fundamental aspect concerns today the so-called Scan-to-BIM process, which indicates the shifting from the raw survey output, i.e. the point cloud, to parametric informative models of the heritage asset. Past studies on this aspect by [12] have underlined the problems of the process, that are mainly the lack of automation, the need to define controlled vocabularies for the construction of the digital database and the management of multi-temporal information inside the model.

As a matter of fact, even though great progress has been achieved in the development of innovative survey techniques, the research is still open for what concerns the possibility of creating a direct correlation between the raw output of survey acquisitions and the construction of digital models enriched through semantic information.

III. THE CHARTUSIAN MONASTERY OF PISA

The Charterhouse of Pisa in Calci (Fig. 1) represents an emblematic case study, on the one hand due to the historical and artistic importance it fulfils, and on the other hand due to the extension of the monumental complex itself, which requires the application of different survey methodologies and diverse scales of representation.

Located on the slopes of the Pisan mountains, the complex was founded in 1366 thanks to the support of noble Pisan families, and was further modified and enlarged between the 17^{th} and the 18^{th} century. The complex maintained its function of Charterhouse until 1969, when the last monks who resided there left; since 1972, it houses the National Museum of the Monumental Chartehouse of Calci, which is today part of the Tuscan Museal Pole, under the control of the Italian Ministry of Heritage and Cultural Activities and Tourism (*Ministero dei Beni e delle Attività Culturali e del Turismo* - MiBACT).

Between 1978 and 1979, the western side of the complex was granted to the University of Pisa, that transferred here the Museum of Natural History. The museum is placed today in the spaces once used for agricultural works and its collection has gradually been enlarged and improved.

Over the years, the creation of the two museums has opened the Charterhouse to the public, introducing visitors to the richness of the ancient complex, unique in its historical, architectural and scientific value. Today, most of the areas anciently used by the Carthusian monks in their daily religious activities can be visited: the church, the sacristy, the chapels, the great cloister, one of the Fathers' cells, the refectory, the chapter, the pharmacy, the noble guesthouse and the grand-ducal apartments [13] [14]. Starting from year 2018, the University of Pisa finances a multidisciplinary research project, involving several working groups of its institution -coming from different study domains, in view of a general project aimed at conservation, restoration and enhancement of the monumental complex.

Fig. 1. Calci Charterhouse (iltirreno.gelocal.it)

Among the several activities planned within this context, a complete architectural survey is required, in order to support the different working groups involved in this program providing them with reliable and metrically correct geometric information, so as to connect the precision of the metric survey with the various studies and analyses on the built asset. The extremely vast and complex scenario of the Charterhouse requires the integration of different survey methodologies: total station, GNSS, laser scanner, ground-based photogrammetry, indoor and outdoor drone photogrammetry, to be used alongside the traditional topographic survey techniques. The choice on the type of survey depends on the type of analysis to be performed, in the general context of the conservation and management studies of the architectural heritage of the Charterhouse.

A. Definition of the 'Charterhouse Reference System'

A fundamental aspect of the survey campaigns carried out by the A.S.T.R.O. Laboratory is represented by the need to put all the survey acquisitions in a same reference system, in order to homogenize the coordinates of the documents produced by the various working groups involved in the project.

For this purpose, a network of benchmarks is realized, to capillary define a 'Charterhouse Reference System'. In a first acquisition phase, physically existing elements are used as temporary reference points, the stability over time of these existing physical elements being evaluated based on historical-structural knowledge. As a future improvement of this aspect, it is planned to materialize a certain number of benchmarks characterized by stability and durability over time, in order to use them as a reference for monitoring operations requested by other working groups.

Besides, in order to make this system compliant with existing cartographic and urban planning tools, the defined 'Charterhouse Reference System' is geo-referenced in the UTM-ETRS2000 and Gauss Boaga systems. This georeferencing is performed through the GNSS survey in static-differential mode of 24 points of the network.

From an altimetric point of view, in addition to the use of the tools made available by the Italian Military Geographical Institute (IGM) for the conversion of the ellipsoidal heights detected with GNSS systems, a connection is planned to be made to the benchmarks of the nearest national levelling network.

B. UAVs for orthophotos

Survey techniques based on the use of Unmanned Aerial Vehicles (UAVs) are carried out, in order to supplement ground-level acquisitions [15] [16].

In detail, two flights are performed with a DJI FC6310 camera (CMOS sensor, 13.2 x 8.8mm, 4000x3000 pixels, 8.8mm focal lenght), at different altitudes of 35 meters and 80 meters respectively. The UAV-based photogrammetric process allowed to obtain extensive information on the state of roofs, inaccessible courtyards and perimeter walls -data that could not be acquired through terrestrial surveys, and also provides two orthophotos at different scales of representation. The flight plan and the characteristics of the camera, in fact, make it possible to obtain frames with a Ground Sampling Distance value that is compliant with the 1:50 scale for the 35-meters flight and with the 1:200 scale for the 80-meters flight respectively (Fig. 2).

Such a survey, co-registered with the three-dimensional models of the exterior and interior of the complex, has revealed to be fundamental also for the analysis of the complex historical hydraulic system of the Charterhouse.

Fig. 2. UAV-borne orthophotos at different levels of detail

C. Image-based and range-based surveys

For a wider and more accurate documentation of elevation walls, plans and sections, ground measurements are performed with integrated laser scanner (Fig. 3-4) and close-range photogrammetry, besides traditional topographic survey techniques. The laser scanner is a Leica ScanStation C10, while for photogrammetric survey campaigns a Nikon D700 (full frame sensor 4256x2832 pixels, 20 and 50mm focal length lens) and a GoPro Hero 4 (sensor: 6.16x4.6mm, 4000x3000 pixels, 1.5mm focal lenght lens) are used.

Such an integrated method is used for the graphical and geometrical restitution of plans, sections, elevations of the entire complex of the Charterhouse on a 1:100 scale and of some significant portions on a 1:50 scale. In some cases, architectural and decorative elements, which require to be further documented due to their artistic value or to their excessive state of degradation, are also returned in a scale of greater detail (1:10 and 1:5). The combination of image-based and range-based surveys allows to obtain 3D models which are characterized by the metric rigor of the laser scanner and by the radiometric quality of a high-definition photographic campaign. In general, the potential of this combined techniques to provide a complete description, beyond the geometric characteristics of the complex, of the material characteristics and shape and visual appearance of surfaces is exploited so as to get extensive documentation of frescoed areas, stuccoes and decay maps (Fig. 5-6).

A last remark in this section is related to the performance of photogrammetric acquisitions and deals with the use of UAVs: an indoor UAV-based survey campaign, in fact, was also carried out, aimed at delineating the geometry of large underground tanks and other areas that could not be directly inspected or surveyed by the operators. For this purpose, the devices were equipped with protective cages, which implied problems related to the post-processing of the acquired images, as already discussed in [17].

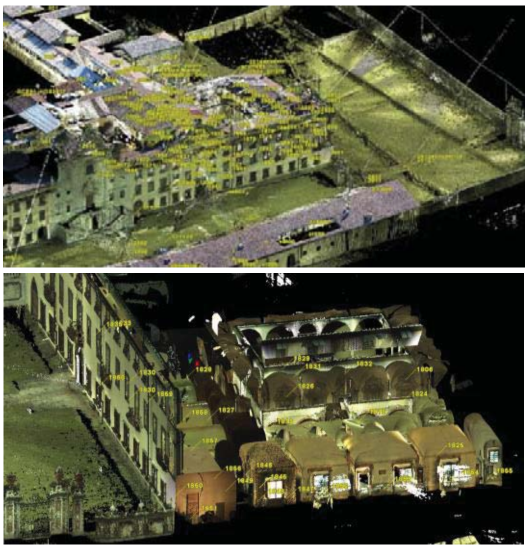

Fig. 3-4. Laser scanner point cloud.

Fig. 5-6. Photogrammetric survey outputs.

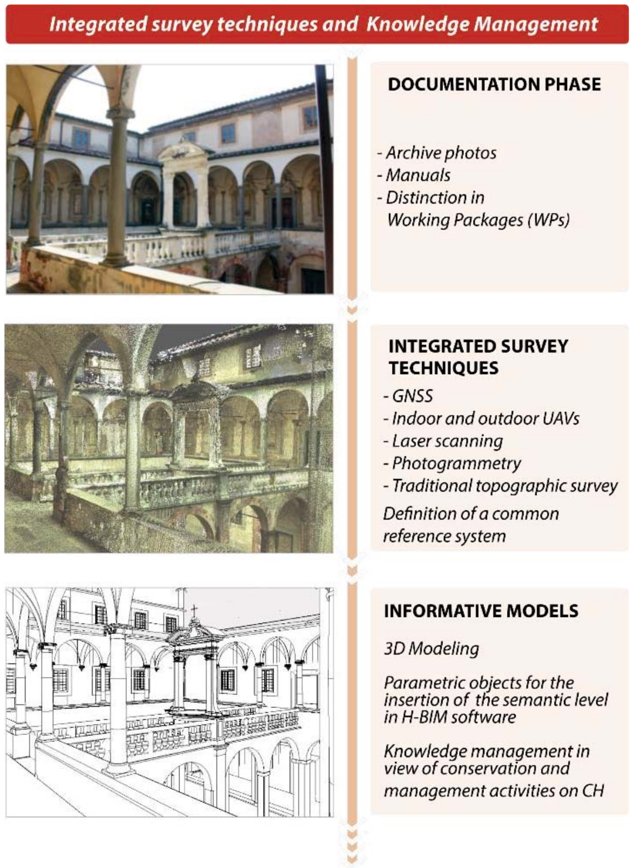

Fig. 7. Phases of the creation of informative models based on integrated survey techniques and prior knowledge.

IV. SURVEY DATA AS A BASIS FOR CONSERVATION STUDIES

The combined use of the several afore-mentioned survey techniques allowed to achieve, on different scales of representation:

- A precise geometric survey, from which important geometric elements such as plans, sections and elevations, but also additional information on thicknesses of walls and slabs, can be derived;
- A survey of the state-of-the-art, with radiometric information on the surfaces, to document decorative elements such as frescoes, stuccoes, moldings;
- A survey of the surface degradation, with precise documentation of the presence of decay levels and their respective extension.

These different kinds of survey made available through the survey campaigns carried out by the A.S.T.R.O. Laboratory served in the past and serve today as a reference for different analyses on the CH asset, ranging from geological and hydraulic investigations to structural and seismic assessments, from archaeological and historical studies to conservation activities.

In this section, the instance of a possible application related to the use of the material provided through integrated geomatics survey is presented, and it deals with the study of wall paintings, ancient plaster and decorative apparatuses of the grand-ducal apartments and cloister.

For this area, in fact, the existing survey data acquired through photogrammetry and laser scanning are used as a basis for the creation of a parametric model in a H-BIM platform and for the subsequent insertion of information levels on the state of degradation of walls and surfaces, for the semantic enrichment of the model (Fig. 7).

The whole process consists of different working phases: firstly, the area of interest is isolated from the rest of the survey by using the Leica Cyclone software for the elaboration of laser-scanned point clouds. This allows to work with a reduced section of the overall point cloud, thus gaining a greater speed in the data processing phases.

Then, the true Scan to BIM process is performed, aimed at the realization of the parametric 3D model: in this regard, the integration between EdgeWise, a software designed to automatically extract features from point clouds, and Autodesk ReVIT, designed for the management of BIM processes, is tested. The EdgeWise software is used only for the semi-automatic realization of parametric objects of elevation walls and for simple architectural structures, achieving acceptable results.

However, the Scan-to-BIM process provided through EdgeWise reveals not to be satisfactory in the case of more complex architectural elements such as vaults, capitals and corbels, that are characteristics of CH assets; in these cases, in fact, it is necessary to proceed with long elaboration phases, involving a non-automatic process of parametric modeling starting from point cloud data and providing for each object to be modeled manually as a single ReVIT family (Fig. 8).

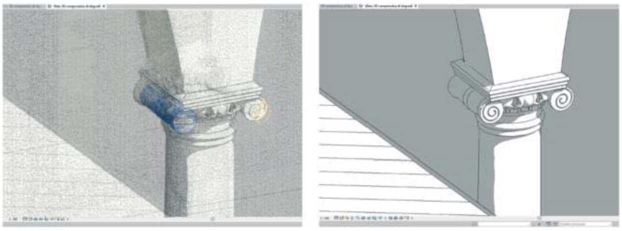

Fig. 8. Scan-to-BIM reconstruction of a capital.

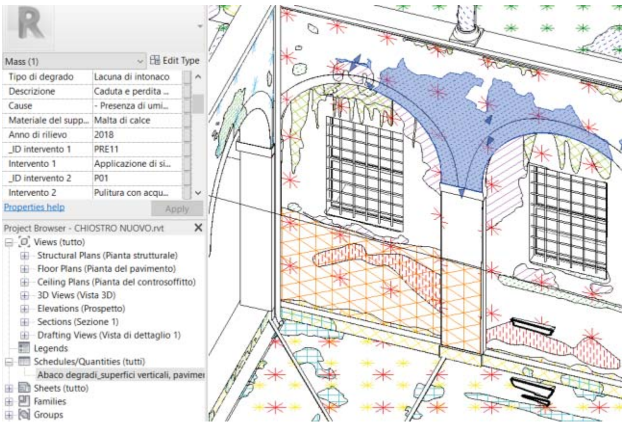

Fig. 9. Information on degradation maps inserted directly on the parametric model.

Anyway, the result of this process, providing for the integration of semi-automated and non-automated phases of point-clouds elaboration, is the acquisition of a parametric model of the area of the grand-ducal cloister and apartments.

For the implementation of the model through the insertion of semantic information, the studies of degradation phenomena and decay maps are considered. In particular, the surfaces of the parametric models are enriched with information relating to the degradation level of surfaces and materials, following the classification provided by the 'Illustrated glossary on stone deterioration patterns' of the International Council on Monuments and Sites ICOMOS [18]. An example of three-dimensional mapping of the degradation elements is illustrated in Fig. 9; in this way, within the resulting parametric model, each degradation phenomena has a precise spatial reference and its dimensions and extensions can be geometrically localized.

This case of application, related here to the insertion of degradation maps within the parametric model, is provided to demonstrate how, with such procedures based on prior survey acquisitions, interoperable parametric objects can be generated, and associated with semantic information on the built asset, to be used for management of knowledge related to the survey object and in view of conservation, restoration and monitoring activities. In this sense, the H-BIM model is conceived as a database of 3D objects, in which each three-dimensional object is linked to certain metadata, containing semantic information and being constantly enriched through controlled vocabularies.

V. CONCLUSIONS

Cultural Heritage assets, being often characterized by complex shapes and stratified surfaces, by their very nature require the use of different survey techniques at different scales of representation. The application of a working methodology based on the integration of geomatics techniques and on the adoption of common reference systems is of paramount importance for a clear understanding of the survey object.

The Scan-to-BIM techniques, allowing the transition from point clouds to parametric models, although not yet fully automated, show the potential of integrating the geometric information on the building with analytical data, for a complete knowledge management. This paper presents a prime example of the creation of informative digital mockups, by referring to the enrichment of the parametric model through the insertion of spatial information related to the degradation level of walls and surfaces. However, a subsequent phase of the model implementation could deal with the insertion of spatial data concerning the type of intervention to be performed, the degree of priority and the temporal state of each intervention. In such a way, the different studies on conservation and management activities for Cultural Heritage could be connected one another, each one being related to the same reference system and with a precise time reference. Through such informative models, each actor involved in the restoration activities could access, edit and update in every moment the information related to the built environment, so as to handle more efficiently the process of conservation and management of historical built heritage. Further studies on the creation of informative models could allow to get a complete knowledge management and to access in every moment the information related to the heritage asset.

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