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DIGITAL TWIN MODEL OF AN EARLY MEDIEVAL CHURCH: ENTANGLEMENT OF HISTORICAL STUDIES AND MATHEMATICAL METHODS

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Summary. Interest in digital twins has grown rapidly in recent years, both in science and industry. Moreover, due to their inherent ability to preserve fragile information, i.e., exposed to the risk of loss, digital twins have become relatively common in archeology. However, far from being just digital copies that allow one to learn about, share, preserve or even just enjoy an artifact without the need to be at the location of the original physical entity, a digital twin is a dataset that can evolve as new information becomes available or as the reference object changes. With this idea in mind, the present work focuses on a multidisciplinary research activity devoted to modeling the early medieval church of Santa Sofia in Benevento, Italy, which has undergone alterations in its geometric and structural layout several times throughout its long history. To track these modifications, a model was constructed combining data from a laser scanner survey of the church in its current state and research sources documenting past configurations. The model includes five main archeological and architectural phases backwards in time. The virtualization process made use of both open source and proprietary software. In addition, to upload the complex vault system of the church into the model, a specific computer code was developed to reconstruct the surfaces from the point cloud making use of Coons patches based on Hermitian cubics.

1 INTRODUCTION

The concept of *digital twin* has gained increasing interest in recent years, despite the fact that its formalization has a rather short history of just over two decades [1]. Such interest is testified also in the scientific literature where a fast-growing number of papers related to the topic can be found [2]. Basically, a digital twin includes real space, virtual space, and links for data flow between them, in a bi-directional fashion. Essentially, the digital twin acts as a virtual counterpart of a physical object or system, relying on data collection through a variety of sources as simulations, sensors and graphical documentation. As a comprehensive approach, it aids in visualization, control, analysis, and decision-making and allows to enhance product lifecycle management. As digital twin technology improves the understanding of physical entities, it clearly represents a complex of tools with a wide field of applicability in industry and related engineering fields, such as aerospace, automotive, buildings, communication, power plants, smart cities, to cite a few [3]. The name "digital twin" itself is currently applied in a wide variety of ways with variations from a sector to another or even with definitions that can vary significantly within the same field. While the basic components of a digital twin are generally well established, there are still many open questions connected to data, reliability and uncertainty, or to dynamic model updating [4].

Digital twins have also become increasingly common in the field of cultural heritage and, in particular, in archeology due to their inherent ability to preserve fragile information, i.e., exposed to the risk of loss. Beginning with digital reconstructions that enable the interaction and study of heritage sites or artifacts that are damaged, lost, or simply difficult or impossible to visit in person due to restrictions of any kind, digital twins can also be used for real-time monitoring of the conditions and environmental factors, such as temperature, humidity, etc., of the physical entities they duplicate, if these are properly instrumented [5]. Building a digital twin in archeology also means creating a model that can be exploited to verify hypotheses on the historical and architectural phases of a monument or a site. Starting from visible traces, it is possible to virtually fill in negative stratigraphic units, that is, surfaces with obvious signs of material removal or collapse [6], and propose a reconstruction to match the gap. Conversely, it is also possible to dismantle stratigraphic units that covered or modified previous structures in order to re-expose the original shapes. Such operations are supported by careful analysis of the sources and accurate mapping of the stratigraphies of the monument or the site. The virtual twin becomes therefore the synthesis of the research, expressed visually, and is much more flexible than traditional representational methods, because it allows for easy modifications. For example, as more archeological sources or data are found, new information can be added and results updated.

In addition, the virtual twin is a valid way of heritage dissemination. In fact, besides to the scientific and technical knowledge restricted to the specialist community, direct forms of communication through which it is possible to trigger a cultural process that involves the public of non-experts have been experimented. Indeed, in recent years, the role of communication, with its multimedia features, has become important in a *public archeology* perspective [7]. Through new technologies, it is possible to observe, consult and preserve cultural heritage, overcoming physicality, in open and shared databases, accessible through personal computers, smartphones, video installations, etc. Increasingly popular are interactive museum routes, three-dimensional (3D) models, referenced systems, as the geographic information system (GIS), that allow the collection and representation of landscape and site data, based on laser technology. Such data can represent the current state or its evolution in a diachronic sense and make it possible to virtually visit sites of interest in terms of art, archeology, and history, also allowing to understand their value and fragility [8, 9].

Bringing these different aspects together, we understand that, in a broad sense, a digital twin can be seen as a data collection that can evolve dynamically when new information becomes available or when the reference object changes, a property that can be exploited in cultural heritage learning and protection processes.

With this idea in mind, the present work summarizes a multidisciplinary research activity [10] devoted to modeling the early medieval church of Santa Sofia in Benevento, Italy, which has undergone alterations in its geometric and structural layout several times throughout its long history. Therefore, the current layout is the product and the stratification of all those different configurations. To track them, a virtual twin was constructed based on data coming from a laser scanner survey of the church in its current state and from the representations of the monument in the past, through the consultation of documentary sources (archive maps, cadastral maps, artistic reproductions) as well as archeological sources.

The reconstruction process made use of both open source and proprietary software and presented different levels of difficulty, with some parts requiring specialized geometric analysis [10]. In particular, to upload the complex vault system of the church into the model, a specific computer code was developed. The code [11] is aimed at reconstructing surfaces from the point cloud making use of Coons patches based on Hermitian cubics.

The present contribution is organized as follows: Sect. 2 gives some details about the church concerning its history and architecture, Sect. 3 summarizes the workflow of the virtual reconstruction and digital twin assembly and, finally, Sect. 4 reports some concluding remarks.

2 FEW DETAILS ABOUT THE CHURCH

The church of Santa Sofia was founded in 758 AD by Duke of Benevento, future Prince, Arechis II soon after his election and was dedicated to the Divine Wisdom, in the likeness of the Justinian's church Haghía Sophía in Constantinople. It was built with the function of a national temple of the Lombard people [12], also known as Longobards in agreement with the Latin name *Longobardi*, a Germanic people who moved from Northern Europe towards South about 1st century BC and finally, in 568 AD, started to conquer the Italian Peninsula [13].

The church of Santa Sofia has had a very intricate history, due to the damages produced by various seismic events or changes in style due to architectural trends. In fact, research based on material remains and other documents has made it possible to recognize a series of renovations corresponding to different archeological phases, five of which are the most relevant, hereafter simply referred to as first to fifth, the latter being the current one.

The first phase starts from the foundation of the church and the pertinent data about it relies on (i) the masonry texture and wall stratigraphies, (ii) an excavation in the square in front of the church conducted by the local Archeological Superintendency in the early 2000s, which revealed the remains of masonry structures that can be interpreted as the foundation of a forceps narthex, and (iii) few details of a miniature in the *Chronicon Sanctae Sophiae* [14]. Further details were deduced through analogy with late antique, early medieval, and Byzantine architectural monuments, according to well established techniques of archeological research.

The construction of a Romanesque bell tower in between 1038 and 1056 [15, 16] marks the end of the first and the beginning of the second phase. Information about such a phase comes from (i) the wall stratigraphies and (ii) historical and epigraphical reports about the works of Abbots Gregorio junior [16] and Giovanni IV [17]. The phase is the longest of the five identified because the event that marks its end is an earthquake that occurred in 1688. As a consequence of the seismic event, the bell tower collapsed and also the church was deeply damaged.

Therefore, the third phase was characterized by a profound restoration, at the behest of the Archbishop Orsini, who wanted to adapt the original layout of the church to the Baroque style.

Other notable changes include the construction of a façade, with the space in front enclosed in a masonry fence and a new bell tower built in 1703 outside it, for safety reasons. The demolition of the masonry fence that took place in 1809 corresponds to the end of the third phase and the beginning of the fourth.

The documentation about the fourth phase is quite rich and varied and is based on historical, archival, and artistic records as well as wall stratigraphies [18–20]. The phase culminates in the mid-20th century, giving way to the fifth phase, in effect the contemporary one.

Indeed, between 1951 and 1957, the church was subjected to a restoration conducted by Rusconi [21] which is documented by some technical records. Finally, since 2011 the church has been listed as a UNESCO World Heritage Site [22].

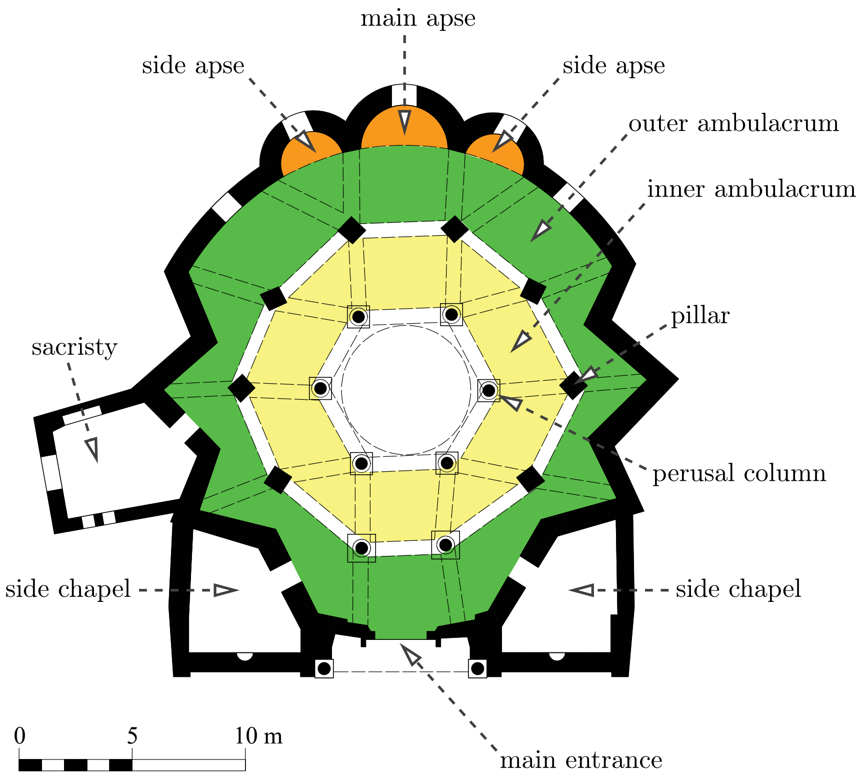

Figure 1: The church floor plan as it appears today (modified from [10]).

The current layout of the church (Fig. 1) mostly follows the original one dating back to the eighth century, as discovered by Rusconi, but also contains relevant parts that were added in the baroque period (as the façade [18, 19, 21]) or after, and saved during the mid-20th century restoration.

Starting from the baroque façade and moving along the left and right sides of the church, the eighth-century boundary wall has a star-shaped profile, with a face visible in its entirety from the interior of the church. The other face is partially visible from outside the church and partially from the interior of the two 18th-century side chapels and a sacristy added in the 19th century. The star-shaped profile ends in a circular wall, in which three apses, of two different radii, open. This mixed profile strongly defines the interior space, which is organized in a concentric fashion.

From a geometric point of view, there is a hexagon within a decagon within the mixed profile.

It is interesting to observe that the space inside the eighth-century part is punctuated only by perusal columns and pillars made of reused bricks and stones, with no other walls. The hexagonal space in the center is marked by six columns and covered by a dome. Then there are two ambulacra, one inside the other, from the center towards the wall, covered by a system of vaults, bounded by arches set on columns and pillars. Noteworthy, the apses present traces of early medieval frescoes [21, 23].

3 THE VIRTUALIZATION OF THE CHURCH

Here, we briefly report about the virtualization of the church of Santa Sofia and refer to [10] for further details.

The process started from the current configuration, i.e. the fifth phase, that was surveyed by using Leica BLK360 Laser Scanner at a resolution of 20 mm at 10 m and an approximate scan size of 3 million points per setup [24]. The survey consisted of 32 setups and the corresponding point clouds were merged in a bundle cloud of about 3.8×10^7 points by means of Cyclone Register 360 [25].

Exploiting the bundle cloud and aerial and ground photographs, the solid modeling of the church was performed mainly within AutoCAD® [26]. However, since the system of vaults presents a complex geometry that is not easy to trace back to graphical primitives, we elaborated a workflow based on several tools and steps:

i. the parts containing only the vaults were extracted from the bundle point cloud with 3DF Zephyr Free [27];
ii. the coordinates of points were exported on an ASCII `dat` file organized as 22 lists, one for each vault;
iii. to approximate the vault surfaces, the `dat` file was loaded into *Mathematica*® [28], in which a specific code [11] based on Coons patches [29] was developed. The analytical form of the patches was written using Hermitian cubics;
iv. the obtained surfaces were exported in a DXF™ file;
v. the latter was inserted into the 3D solid model of the current phase of the church using AutoCAD®.

We emphasize that each step of the sequence involved different single operations. In particular, the third one called for the implementation of a trial-and-error loop-based approach [10].

From the model of the current phase, earlier phases were reconstructed by going neatly backward in time to the eighth-century phase, and moving from a more recent to an older phase parts were added or removed according to the relevant documentation, following a stratigraphic logic. Indeed, such a reconstruction process should serve to uncover the relationships between what still exists and what has been lost or deeply modified, as the unfolding of an archeological stratigraphic sequence [6]. In fact, as already stated in Sect. 1, a virtual reconstruction for cultural heritage preservation and for archeological aims is not only the reproduction of the geometry of the object, in terms of overall dimensions, sizes and collocation of the single existing parts, surface textures and colors, materials, and so on.

In this sense, the reconstruction of the five phases of Santa Sofia, gathering information on the current and past configurations, is a digital twin of the church. Of course, accuracy and reliability, which are key features in virtual reconstructions for scientific aims, may vary from a

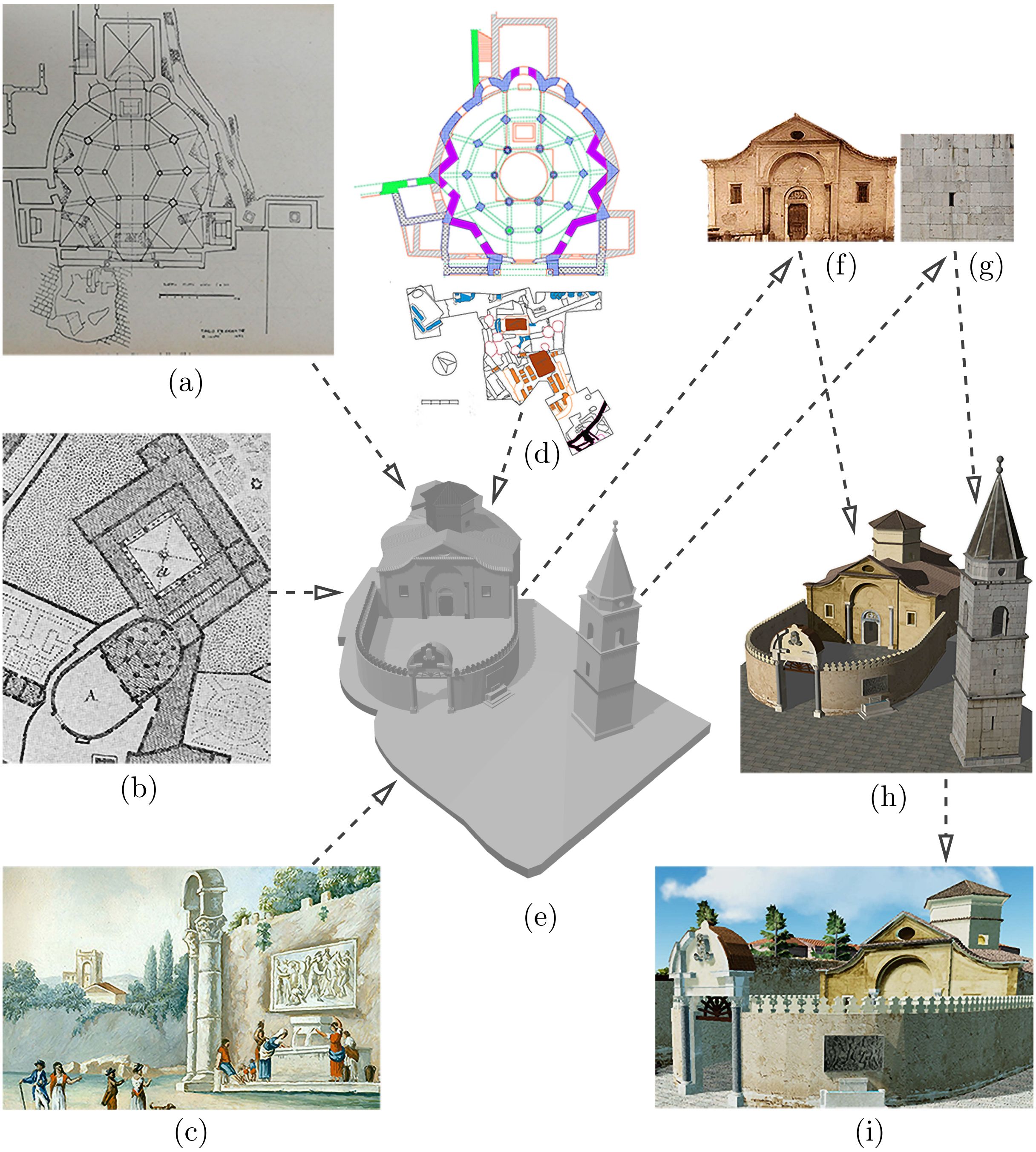

Figure 2: A sketch of the virtualization of the third phase, starting from the collection of data: (a) technical drawings, (b) details taken from city maps of Benevento, (c) paintings or (d) information from archeological excavations; (e) the solid model; textures of (f) the church plaster and (g) the bell tower surface; (h) textured model; (i) rendered model.

phase to another. In fact, while virtual reconstruction of *what is still there* is as precise as the adopted tools allow, the credibility of reconstructions of lost or deeply altered parts strongly depends on the quality of the data and records on which the modeling assumptions are grounded.

Indeed, the assembly of a digital twin for archeological purposes is the entanglement and collection of very different scientific approaches. For example, in reconstructing the geometry of the vaults, a major role was played by modeling and mathematical methods, but understanding the relationships between the parts that make up the church and how and when they underwent changes would be impossible without a research approach belonging to the humanities and archeology, specifically.

In particular, the search and analysis of sources (usually divided into archeological, archival, bibliographic, epigraphical, and photographic) and the formulation of reconstruction hypotheses on the lost parts must be organized following approaches typical in archeological research, which exploits the sources, but also makes use of comparative studies and analogy with similar coeval structures.

To give a rough idea of the logical procedure, we refer to Fig. 2, which sketches the reconstruction of the third phase. Recalling that in the backward-in-time process the reconstruction of this phase occurred after that of the fourth, which in turn took place after that of the fifth, a significant amount of geometric and material data was already available in the model.

The transformation from the fourth to the third phase had to be driven by the sources, as those schematically summarized in Fig. 2: (a) technical drawings [30], (b) details taken from city maps of Benevento [31], (c) paintings [32] or (d) data coming from archeological excavations [33].

Collecting data allowed to obtain the solid model of the phase shown in Fig. 2(e), which was operated in AutoCAD®, as stated before.

For the next steps aimed at rendering the solid, textures were made from photographs. Panels (f) and (g) in Fig. 2 show the texture of the church plaster and the texture of the bell tower surface, respectively, which were applied to the solid model, Fig. 2(h), taking advantage of the UV mapping available in SketchUp [34].

Finally, the model was rendered and immersed in realistic settings, Fig. 2(i), with OneRay-RT [35] to make it also usable to the general non-expert public.

4 CONCLUSIONS

Digital twins have become increasingly common in the field of cultural heritage and, in particular, in archeology. This is certainly due to the inherent ability of digital twins to preserve fragile information. In addition, digital twins of instrumented monuments or sites can be used for real-time monitoring, as tracking changes in environmental factors. However, a digital twin in archeology can also be seen as a database collecting information as in an archeological stratigraphic sequence, allowing to show the diverse configurations a building, an artifact or a site took over time. The present contribution briefly summarized the assembly of a digital twin of the early medieval church of Santa Sofia in Benevento, Italy, for which five different main archeological phases have been identified. In order to have as accurate as possible reconstructions, the reliability of the sources was verified and, in some cases, the interpretation was also improved with respect to the previous archeological knowledge. We finally emphasize that this research work can be also seen as experimental archeology which combines digital survey tools, programming languages, humanities and engineering.

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