

The 3D Model of St. Mark's Basilica in Venice



Luigi Fregonese and Andrea Adami

Abstract The San Marco 3D project had the ambitious goal of building a digital replica of the famous venetian basilica. Architectural surveying and modelling are very widespread procedures, but the complexity of the basilica, its decorative apparatus, in mosaic and marble, and its liveliness made this project a real challenge. Thanks to geomatics, from the most traditional topographic approach to cutting-edge methods of digital photogrammetry, it has been possible to build an information system of the basilica, a geometric database from which to continuously extract new and correct information. Even the mosaics, a main characteristic element of the basilica, have been documented through very high-resolution orthophotos, therefore providing useful and effective tools for the conservation of the basilica itself. Thus, the research project allowed for a better and deeper knowledge of the basilica, expressed through a very accurate 3D model where the geometry and the very rich decorative apparatus are merged into a single product.

Keywords Survey · Complex architectures · Photogrammetry · Orthophoto

1 Introduction

Many elements combine to constitute a research project: the innovativeness of methods, the use of the most advanced and recent technologies, the development of new software, the social impact, the applicability and many others. An element that is always present, but sometimes neglected, is the application case: the object (in this case the architecture) on which the objectives of the project are to be verified. For the San Marco 3D project, the exceptionality of the theme tackled strongly characterizes the research, to the point of becoming almost the theme itself; it is no longer just an application case, an occasion on which to make tests, but the element that determines the choices of the research itself.

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The construction of a 3D replica of an architecture is now a widespread activity because it lends itself to various activities and insights. It is the fundamental element of many specialized applications such as those that provide for the design, simulation and management in architectural and engineering of a building. 3D replication is also, however, a fundamental element for all communication and edutainment applications developed, for example in the field of cultural heritage. If therefore, 3D replication, from the survey of information to its geometric modelling, is a very widespread process, the same cannot be said of the methodology applied. As it is easy to understand, the different applications require 3D replicas with different characteristics, more or less detailed, more or less corresponding to reality in accordance with the purpose of the application itself.

In the context of the San Marco 3D project, the main need highlighted by the Procuratoria di San Marco, the managing body of the basilica and partner of the project, was to build a three-dimensional replica of the basilica, with very high resolution and precision, to be used for technical applications related to the knowledge and conservation of the building itself. This need, however, was not only linked to the shape of the basilica, but also to its appearance: golden mosaics and polychrome marbles cannot be overlooked in the phase of creating a 3D copy.

This article does not describe the technical aspects of the work, already described in Adami et al. (2018), Fregonese et al. (2017), but it highlights the choices made during the research and the reasons that led to those choices.

2 St. Mark's Basilica and Its Exceptionality

The uniqueness of St. Mark's Basilica lies without doubt in its historical vicissitudes and in its very high historical and cultural value. But for this research project, the elements that most determined the choices are linked to the use of the basilica and the construction techniques used.

The fruition of the basilica, in fact, means all the activities that take place in it: religious celebrations, concerts, cultural visits, tourist visits. It is estimated that tourists alone reach over 5.5 million each year and the basilica is open every day in fixed time periods. In this context, we should also consider all the activities necessary to ensure this enjoyment: in fact, the basilica always has a team of workers (electricians, cabinetmakers, mosaicists, stonemasons) engaged in ordinary and extraordinary conservation of the building. This intense programme of activities that takes place inside the basilica has caused many problems at the stage of architectural survey because, for obvious reasons, it was not possible to close the basilica to visitors and not even to work in the evening hours when the basilica was closed, so as not to weigh on the costs of management. All the measurement operations, therefore, were carried out during the normal period of opening of the church, with the tourists present and often with the need to move the work area to meet liturgical needs.

On the other hand, the construction techniques and materials that have guided the various choices are those of architectural surfaces generally decorated with mosaics

or marble slabs. The stone slabs, of different marbles and positioned in the lower part of the basilica, confirmed the difficulties, already known in the literature (Godin et al. 2001; Boehler and Marbs 2001) and also tackled in other cases by the authors (Fregonese et al. 2018), in the acquisition through range-based techniques where the emitted signal seems to 'penetrate' the object because of the characteristics of the material. At the same time, mosaics are often made of golden tiles and even in this case, all this has led to serious problems of reflection in the use of range-based techniques such as laser scanners at flight time or phase difference.

The mosaics, in particular, highlighted another problem, only partially solved. In literature, there are many studies on colour and acquisition methods to be as faithful as possible to reality. All these studies, however, envisage working on small objects and being able to operate in controlled environments such as a laboratory. The case of San Marco is completely different because the architecture with mosaic cladding is very large (the upper part of the whole basilica measuring about 64 m in width and 78 m in height) and above all it is not possible to guarantee a constant lighting condition due to the fact that there are fixed times for the lights (to facilitate the visit of tourists) and the large openings on the south and west side allow a different light to enter (in colour, intensity and angle) depending on the time of day and season.

The decorative richness of the basilica, which can also be seen in the sculptural and moulding parts, as well as the deterioration due to time, also constituted a challenge in the field of modelling.

The last exceptional element of the Basilica is linked to the amount of data. The data collected (images and, after processing, point clouds), the geometric model, with and without texture, and the orthophotos represent a huge amount of data that must not only be stored but also used, thus opening new themes related to organization and accessibility of the data.

3 The Choices of the Project

The exceptional nature of the basilica has brought to light, as described, a series of issues to be addressed and which were encountered, in various respects, in the different phases of the work that, developed according to a shared approach, includes a phase of project survey, data acquisition, processing up to the moment of modelling and structuring of the data.

3.1 The Survey Project

The objectives of the project were known from the outset, so it was possible to define the quality of the final deliverables from the outset. The planned scale of return, 1:50, requires accuracy of 1 cm, but given the complexity and richness of the basilica, it is increased to 5 mm to be able to describe all the architectural details of value. The less

obvious choice, however, concerned the survey techniques. The possibilities included the use of range-based (laser scanner) and image-based (photogrammetry) methods. The characteristics of the materials (marbles and golden tiles) led to a preference for photogrammetry as it was less affected by systematic errors. And it also responded to the need to acquire not only the geometry of the factory but also its surface finish (Chiabrando et al. 2015; Remondino et al. 2014). In this way, it was possible to obtain metrically correct and valid data both for the modelling of the geometries and for the construction of the orthophotos and the texturization of the models.

Once the photogrammetric approach has been chosen, the question to be answered was linked to the richness of detail of the basilica, an element to be considered, however, also in relation to the real need for the data to avoid falling into the risk of an 'unconditional' acquisition with the subsequent effect of exponentially increasing the amount of unnecessary data. In this way, we have operated with a multiscale principle, choosing to build different models, all georeferenced, but with different resolutions. Thanks to the use of different lenses (and consequently different quantities of images), general models and detailed models have been created by photogrammetry of the same area.

3.2 *Data Acquisition*

In data acquisition, the greatest difficulties were encountered in relation to lighting conditions and the need to work flexibly throughout the factory to comply with opening hours and the different activities that take place within.

To meet this need, the most efficient solution was to divide the entire factory into small areas and to conduct the survey area by area. This method also partly reflects the operating conditions of multi-image photogrammetry, which benefits from operating on closed and well-defined areas, as is the case with a topographic polygonal: the closure of the ring allows for a greater control over errors. Referring back to the Basilica, you can imagine the survey as a series of closed rings, connected together. The function of the topography, in this case, is precisely that of connecting the individual rings (referring to the individual areas or single elements) in a single reference system. The presence of an existing topographic network, with points well distributed and already compensated for previous works of survey carried out in the basilica (Fregonese et al. 2006), has therefore made it possible to make a non-linear process operational and thus meet the different needs encountered.

To solve, on the other hand, the problem of lighting, a number of tricks were used that have not allowed to completely solve the problem, but only reduce it. The need would have been to have a homogeneous light, for colour, intensity and time, but this is virtually impossible in the hypothesis of working during normal business hours of the basilica. For this reason, three Airstar lighting balloons were used to provide a homogeneous light. In addition to the balloons, four adjustable LED lamps (more manageable than the large balloons described above) were also used.

3.3 Geometric Modelling

The phase of geometric modelling also involved numerous choices, linked to the characteristics of the basilica, in this case, its decorative richness.

The decorative apparatus is very varied: San Marco, in fact, can be seen as a collection of pieces of art from the entire domain of Venice in the Mediterranean basin. Very often capitals, decorations and statues come from different areas of the world and different historical periods; each element has specific characteristics in terms of shape, size, position and geometric complexity. Therefore, each individual object has required specific modelling devices. The most evident example is the erosion of the bases of the columns of the central nave, for which it is difficult to lighten the original moulding.

Finally, the basilica is characterized, unusually for European architecture, by connected curved surfaces (for example, the connection between the domes and the arches of the aisles): so it is not always possible to identify the breaklines that generally 'build' the architecture (Fig. 1).

Considering all these difficulties, it was decided to use a modelling approach based on NURBS. This system combines the possibility to have a reliable representation of reality and easy to manage processes, at least in terms of memory occupation. Other alternatives such as parametric or mesh modelling, widely used in the industry, have in fact proved to be particularly effective only in one of the two areas (model accuracy, ease of use), but very weak in the other. The negative factor of the NURBS approach is the very low level of automation: all operations require a strong manual intervention of the operator and, therefore, make the entire construction phase of the model very expensive in terms of time. The work pipeline has provided researchers to start from the point clouds, obtained by photogrammetry, and then build basic and generating profiles for sweeping, extrusion and loft operations (Fig. 4). In some specific cases, such as domes or more complex elements, profiles were extracted at close range and then modelled using commands such as 'loft' or 'network of curves'. Even the most



Fig. 1 Example of modelling by NURBS. From the left: pointcloud, geometric model and final result with a single element highlighted. *Source* He.Su.Tech. group



Fig. 2 Examples of sculptural elements modelled by mesh approach. *Source* He.Su.Tech. group

complex elements, such as capitals, where possible were represented as NURBS (Fig. 4).

Only a few elements, usually of a sculptural type such as statues, bas-reliefs, were represented as meshes (Fig. 2).

3.4 Texture and Colour Mapping

A fundamental element of the research was the management of colour, understood as the need to provide not only a geometric representation of the Basilica but also, and above all, an accurate description of its appearance. This aim stems from the project's conservative objective: the Procuratoria wanted to equip itself, as with the pavement (Fregonese et al. 2006), with an effective tool for the restoration of mosaics. With this objective in mind, but without neglecting the need to navigate through the model, we worked on the texturization of the NURBS model by reprojecting the photographs oriented on the surfaces. This operation was carried out in the Agisoft Photoscan software. In order to proceed with the projection of the photographs, the working pipeline planned never to modify the reference system or to translate the object. The result of this procedure is that the geometric model, modelled by a manual process with the photogrammetric model previously developed in Photoscan, coincides completely. The result of the texturization phase is a three-dimensional model mapped with the real texture, in which the position of every single tile is topologically correct. It is, therefore, a mapping not only obtained for the purpose of immersive representation but guarantees the metricity of the result (Figs. 3 and 4).

Still, with regard to the treatment of colour, but with the aim of obtaining the most useful outcome for conservative purposes, the orthophoto, the next step was the projection of images oriented on a plane of reference. In this case, the resolution of the result is very high: the covering of the single pixel on the real surface is 0.5 mm



Fig. 3 The same object represented only with geometric information (left) and with texture extracted from georeferenced images (right). *Source* He.Su.Tech. group

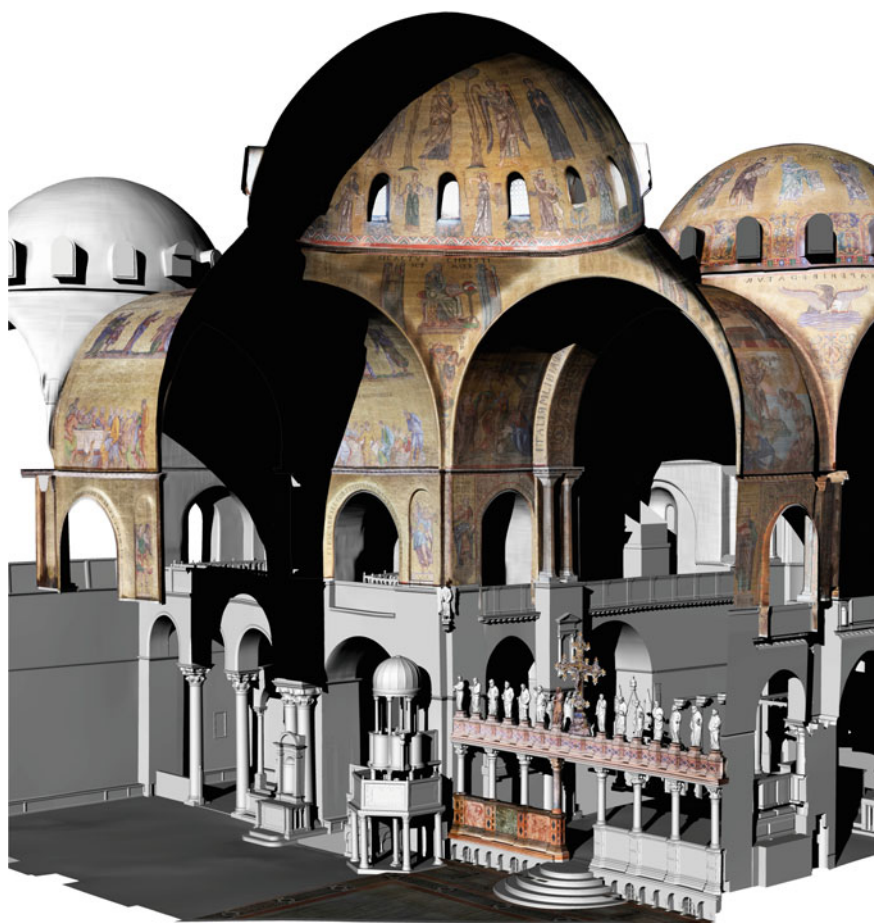


Fig. 4 The area of the Ascension, in the centre of the Basilica, with the overlapping of textured areas. *Source* He.Su.Tech. group

(Fig. 5). This very small value is linked to the need to accurately represent the single card. To recognize the single tessera, it was necessary to set a pixel size smaller than the gap between two different tiles, to be able to display it in the final result.

In the most complex areas, domes, vaults and connecting elements, it was decided to use simplified reference planes.



Fig. 5 The orthophoto of the dome of Baptistery, (top), with some details (bottom) where it is possible to see the smallest details of the golden tessera in the orthophoto (pixel size of 0.5 mm)

3.5 *Data Management*

The exceptionality of the study, even in data management, is linked to several aspects. First of all, the very aim of the study was to elaborate a three-dimensional model from which to extract a lot of other information. This means that it is not necessary to decide in advance on the necessary sections but to postpone the choice to a later stage according to the different needs. In addition, the research project immediately involved not only surveying and modelling the geometry of the basilica, but also its image—the finishing of the surfaces. All this translates into the need to manage various types of data (geometry and images), to be able to organize them in such a way that access to the data is effective and immediate and, above all, to provide for different types of use linked to the operators involved.

The answer to all these needs came through the BIM systems. Designed for new buildings, they allow the design to be shared by the various operators of the building process, from the conception phase to the realization and management. The attempt made within the research project was to identify a system that could apply the same method to the existing heritage. The HBIMs differ from the BIMs precisely because they concern objects that are already made, in which the knowledge phase is not determined by a design choice, but implemented by a series of analyses, surveys and subsequent observations. The HBIM logic highlights many problems such as the construction time of three-dimensional models, which serve as a three-dimensional index of all information, the cost of realization and the difficulty in building reliable models of reality.

A step in solving these problems has been taken with the use of the BIM3DSG system, developed by the 3DSurveyGroup of the ABC Department of the Politecnico di Milano, already tested on the Duomo di Milano and in other cases (Fassi et al. 2015).

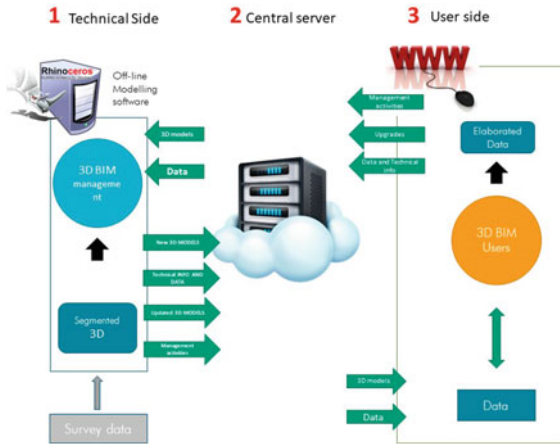
To allow for the greatest adaptability to the case studies, the system has not provided its own modelling environment but relies on external software of a commercial and non-commercial nature. This guarantees, therefore, that it can be integrated into an existing work process and avoids a very steep initial learning curve.

In the case of San Marco, for example, the use of the NURBS model made with Rhinoceros allows for the extraction of infinite plants and sections, where necessary, without having to choose them a priori. At the same time, the three-dimensional model is also the three-dimensional element (or rather the sum of the 3D objects) to which all the information can be linked.

Among this information, in particular, the orthophotos that constitute the most reliable and effective elaborate in the representation of the mosaic and stone surfaces are also included.

Finally, the third type of data is stored in the archive and that is the textured model. The latter, generated to offer a more immersive visualization of the entire basilica, is built through the import of the NURBS model into Photoscan (then with the transformation from NURBS to MESH) and the texturization through the reprojection of photographs on the model.

Fig. 6 Scheme of BIM3DSG system. *Source* Fassi, Rechichi



The system is structured in three parts that reflect three different actors of the operational process (Fassi et al. 2017): the modeller, the user and the data manager (Fig. 6).

The first part of the system provides the interface with a modelling software chosen by the user (in this case, the software used was Rhinoceros). The separation of this phase from the general BIM process responds to the need for specialized figures in data modelling starting from reality-based data and relieves users from the BIM and also from the heavy construction load and/or management of the three-dimensional model. The modeller can load the model, element by element, and eventually also load subsequent versions, which allow for keeping the initial ones.

The second part of the system, on the user’s side, provides a simplified interface so that you can easily and directly access the georeferenced data on the 3D model. This part of the system is responsible for both data entry and querying the system through a database that can be adapted according to existing needs. This is done on a web-based basis and therefore does not require the use of any specific software. This aspect should not be underestimated as it ensures the multi-platform use of the system: you can access, enter data and perform queries from both desktop and mobile systems that can then be used directly on site (e.g. via tablet).

In this phase, the user can load all the objects of interest through a selection menu and, in addition, define the level of detail. The user can also decide whether to see the geometric or textured model. After loading the model, if you select an element of the model, a window will open containing all the files linked to the element itself: in the case of San Marco, the orthophotos of the individual elements will be linked, but other types of images could also be linked.

The third part of the system, transparent with respect to the other phases, is the true heart of the system: the central server, where all the information, both geometric and logical, reside, dedicated to the management of data through a database Postgres.

4 Conclusions

As it emerges from the critical issues discussed, the San Marco 3D project has highlighted how the characteristics of the object affect the choices of the survey, both in the design phase and in the phase of data processing and management. In cases of applied research, such as the project described here, the objective is precisely to bend the standards and guidelines, often defined in a theoretical way, to the concrete operational needs. This operation, however, is only possible if, behind the choices to be made, lies the awareness of the operations to be performed, the results to be obtained and especially the knowledge of methods and tools and their operation.

In the case of photogrammetry, which in recent years has reached a very high level of diffusion, the need for a basic theoretical knowledge is a particularly burning issue: the development of increasingly automatic software seems to go in the opposite direction—that of a total ‘democratization’ of the system, but it is actually an attitude that shows its limits especially when the object to be detected is complex and therefore not suitable for an automatic approach.

Finally, the research has shown the need for a multidisciplinary approach to the problem: the collaboration between the field of surveying, the computer world and that of conservation, final users of the system, has allowed those involved to focus on the results from the beginning with a certain degree of clarity.

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