# BIM Application for the Basilica of San Marco in Venice: Procedures and Methodologies for the Study of Complex Architectures

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**Abstract:** The BIM (Building Information Model) of the Basilica of San Marco contains the solutions to the many problems encountered during its acquisition and modelling stage. The complexity of the church and the variety of its materials (golden mosaics, capitals of different styles and origins, statues and decorations in many different marble types), the large and continuous stream of visitors, and the request for high-resolution models and orthophotos forced us to devise a strategy for the digitization process: a multiscale photogrammetric approach allowed us to acquire all materials and decorations of the basilica and, according to the use of a reference topographic network, we could split the whole work into smaller parts. Later, in the modelling stage, the decision to use a non-commercial BIM software allowed us to use NURBS (non-uniform rational B-spline) for a more accurate restitution of architectural elements and decorations and to integrate high-resolution orthophotos for the description of all surfaces (both marbles and golden mosaics). The established workflow started with the initial acquisition of images and resulted in both final models and high-quality orthophotos, so we were able to obtain different outcomes to answer the specific needs of the church, its managers, and its users.

**Keywords:** HBIM; modelling; cultural heritage**;** complex architecture

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## 1. Introduction

The Basilica of San Marco is certainly one of the most visited monuments in Italy, probably all over the world, and for many justified reasons: the eventful history of its constructions, the provenance of its artistic elements, the richness of the decoration, and the opulence of materials, not to forget the uniqueness of the position in San Marco square in central Venice. All these characteristics combined make this church one of the most important masterpieces of Cultural Heritage.

However, the Basilica of San Marco also has a special feature which relates to its liveliness. In the cultural heritage field, many monuments became museums of themselves, independently of their function, and their architecture seems to be frozen, suspended in an ideal state. This behavior, which has the aim of preserving the monument from damage, also involves the risk of changing the nature of the place and of the building. The condition is very different in San Marco, because the church hosts many activities every day. It is open for both simple visitors and worshippers who either visit the church or follow the religious activities. It is also a high-value location for the very famous evening concerts which take place occasionally inside the Basilica. The liveliness of this architectural complex involves not only the aforementioned public activities, but also the ones carried out behind closed doors. The church itself is a large and animated construction site: a team of construction workers, carpenters, electricians, marble workers, and mosaicists work every day to maintain the building in the best possible conditions. Even in this sense, this cultural heritage artifact shows a peculiarity of its own: although it underwent some major restoration works during the centuries, the maintenance carried out daily by this team of different specialists is what makes San Marco a unique example of intervention in the conservation scene.

Such a complex management effort requires the Procuratoria (the institution which oversees all the activities) to be provided all the instruments and tools that can optimize this massive work. The knowledge of the architecture and its state of preservation cannot be demanded of only one responsible (the "proto della fabbrica", the architect who has the responsibility of the architecture of San Marco), but must be managed and shared between all the participants in the process. This approach can be helped drastically by providing a BIM (Building Information Model) which allows each single intervention on the Basilica to be observed, managed, and evaluated together. For this reason, in 2013 the Procuratoria of San Marco asked the Politecnico of Milano to produce a 3D volumetric model to be used as the base for a subsequent BIM.

This work is only part of the collaborative activities carried out between the Politecnico di Milano and the Procuratoria of San Marco which led, over the years, for the monitoring of the Basilica, the survey of the entire mosaic floor, up to the detailed survey and modelling of the volumes between the vaults and the roofs.

### *1.1. A BIM for the Basilica*

Although the theme of the BIM is starting to be of great relevance in the Italian heritage scene, the transition from the theoretical approach to practical operations is always fairly complex.

The possible uses of BIMs are a new trendy topic for professionals who deal with Cultural Heritage, because its advantages are relevant and noticeable. Firstly, it ensures the coordination between the various interventions in the building and the different experts involved during the processes. Moreover, a model designed according to BIM criteria allows you to collect different types of data in one single database: drawings and historical maps, archival documentation concerning the evolution of the artifact, its material, the state of preservation, the previous interventions which regarded the building, and CAD drawings related to more or less recent surveys.

The model is also an excellent knowledge tool and starting point for further investigation and tests to be made by experts in the field. In addition, it is potentially interoperable with different software systems; for example, for structural analysis. Therefore, the insertion of the model in structural calculation software provides information on the state of conservation of the building, and it allows projections to be made of its behavior in the short- and long-term, with or without the prevision of consolidating interventions.

It is not wrong to think that BIMs could be used for educational purposes. A BIM can provide a 3D image that gives a general idea of the architectural complex you are visiting, or more specifically, it can illustrate—for each element of molded material—construction characteristics and period of construction, to give an overall picture of the building's evolution over time.

Moreover, from the point of view of the administration, a BIM-oriented model can facilitate the management of the building, ensuring the ability to extract from the model itself documents related to security, such as evacuation plans, management previsions, and maintenance cost summaries.

Unfortunately, all these benefits collide with some issues which cannot be completely solved when the aim of the BIM project is to build a correct 3D model to be used for restoration and conservation purposes (Fai et al., 2001; Murphy, McGovern, 2009). There are many possibilities and different strategies to arrive at the aforementioned 3D model, but it is very difficult—quite impossible—to find only one ultimate solution.

Before delving into all the possible options to reach a choice, it is necessary to understand and define exactly which are the main objectives of the BIM. As the use of BIM in Italy is still limited and the procedure for BIM adoption—if it even exists—is not applied and intended for private institutions, the identification of the requirements from the customer and the definition of possible uses and future perspectives are a necessary first step to designing an efficient BIM.

The layout of the Basilica of San Marco is quite unique; consequently, its BIM cannot be considered in the same way as other case-study buildings. In the Basilica, the most urgent necessity was the knowledge of the geometry of the building. It could have been very difficult to set some single sections and plans to survey because, as we said, the conservation process is continuous and repeatedly treats each section of the church. The possibility of having a 3D model of the entire volume allows to put off the choice: the BIM system in fact is intended for the extraction of infinite drawings simply by defining the position of the cutting plane.

The efforts of survey and modelling are concentrated in one single stage, whilst the outcomes can be computed whenever necessary, theoretically until the building suffers some new changes.

However, the interest of the Procuratoria was not only focused on the geometrical layout: they also wanted detailed information about the decorated surfaces, covered with mosaic and stone. About ten years ago, the Politecnico di Milano realized the complete survey and modelling of the pavement of the Basilica to extract an orthophoto at a scale of approximately 1:1. The intention was to give the restorers a document which they could use for their activity of mosaic conservation and renovation: they could use the printed 1:1 scaled orthophoto as a reference to reassemble the tesserae of the mosaics (Fregonese et al., 2006). Likewise, the Procuratoria asked for a very similar outcome for all the surfaces of the church, be them mosaic or marble tiles.

These requirements which we had to meet demonstrate that the BIM for the Basilica of San Marco can be considered exceptional not only for the richness, importance, and complexity of the building itself, but also for the necessity of managing high-resolution images (orthophotos). Therefore, the main discussion about the design of the BIM regarded the choice of the best solution capable of guaranteeing these results. Initially, the choice was between the use of commercial BIM software or a self-implemented one. For a review of both systems, see Logothetis et al., (2015).

On one side, the approach through commercial BIM authoring software such as Revit, Archicad, or Allplan guaranteed a good level of integration with many other software and a high level of spread. This meant that the management of the model could have been quite easy and widespread, and that it would have been possible to count on a large community of users. Some doubts were connected with the geometric complexity of the church. As that kind of software operates on the concept of standardization, through the concept of parametric families, it was very difficult to translate each element of the Basilica in a dictionary of elements, each one precisely defined in all its parts. This behavioral model was fighting not only with the concept of Cultural Heritage, where each element should be considered unique (and modelled as such), but especially with the history of the Basilica itself. The architectural complex we see today is the result of the addition of many different pieces, all coming from different places of the Venetian supremacy and therefore with different characteristics, and it was unconceivable to reduce all this complexity into defined classes. Another problem was concerned with the management of high-resolution orthophotos. Even if it is given that each BIM software allows different kinds of information (including images) to be linked, the problem was the quality of the connections. Because high-resolution orthophotos reach very large dimensions (in terms of number of pixels) and memory demand (megabytes or even gigabytes each), the commercial software could barely manage those attributes. Moreover, it was required to develop a more user-friendly system to allow the employees of the Procuratoria to deal with it easily.

On the other hand, a self-implemented software required many efforts assemble all the necessary aspects which characterize a BIM environment. From modelling and data visualization to content sharing and database connection, all these elements needed to be merged in a single system. The risk connected with this self-implemented approach was the complexity of use: many open source systems, even if very efficient in terms of calculations and outcomes, are disadvantaged because of their interface.

The solution to this dilemma came with the experience of the 3D Survey Group of Politecnico di Milano on the Main Spire of Milano Cathedral (Fassi et al., 2015). They implemented a specific solution for the Cathedral of Milano which allowed the realization of a highly customizable system, able to easily adapt itself to the different cases and to work with different types of objects, different representation scales and resolutions, also showing different types of information. The system can visualize huge dimensions and high numbers of different 3D models which can be realized in any external software (in their case, Rhinoceros software of Robert McNeel and Associates). The advantages of this systems are on several levels. The system can in fact be implemented to manage high-resolution images and, in a second phase, to project the database according to the requirements and needs of the Procuratoria. Another positive element is that the modelling stage is disconnected from the BIM environment: this means that we could decide which is the best software to realize the model, only after importing the model in the BIM system. This is convenient not only during the first steps of modelling, when the model is created by specialists in the field of geomatics and architecture, but also in a following phase when the 3D is to be managed by the architects of the Basilica. Lastly, the database of the whole system can be installed on a remote server or on the cloud, in order to be accessible by more workstations. However, if needed, the database can be both local or placed within a local network.

This research discusses the construction of the BIM for the Basilica of San Marco, considering different aspects. The entire activity is split into survey stage and modelling stage, although this subdivision is quite fleeting and it is very difficult to exactly set the domain of survey and the one of modelling. We include in the survey the stage of data acquisition (both photogrammetric and topographic), the registration of all data in a single reference system, and the data processing to obtain the point-clouds. Together with the description of the techniques used, there is also a discussion about the logistic and technical problems which characterized the entire work.

The following step—3D modelling—regards the modelling workflow from point-cloud to the final 3D model. In particular, it concerns the approaches used for modelling different items which characterize the church (walls, arches, vaults) and the enriching decorative elements such as moldings, capitals, and statues.

The last step of the process discusses the method used to obtain the orthophoto.

## 2. The Basilica of San Marco in Venice

### *2.1. Characteristics and Complexities*

The current structure is the result of more than 12 centuries of transformations, and it is evident in its structure and its decoration. The Basilica has a floor plan in the shape of a Greek cross, with a main dome over the crossing and another dome on each of the four arms. The nave and the transept have a central aisle and two side aisles divided by an arcade. The nave of the upper arm corresponds to the presbytery, raised by a few steps, below which there is the crypt. To the sides of the presbytery there are two chapels. The area of the presbytery is separated from the rest of the Basilica by the iconostasis, which itself is divided into three distinct sections: the central one, right in front of the presbytery, and the two lateral parts, in front of the chapels. The upper inner perimeter of the entire Basilica, except for the apse, is crossed by the women's galleries. A narthex wrapped around the west end disguises the cross shape, but creates a wider surface for the main facade.

This architectural structure of the church and its ornaments are byzantine, but we can also find Gothic and Romanesque styles in the decorations. These are indeed the result of a continuous addition and re-use of ornaments, sculpture, and precious marbles acquired during travels and exhibited as a symbol of power. A certain repetition of similar shapes and dimensions can commonly be noted in complex architectures such as this, but in San Marco it practically never happens.

One of the main distinctive features of the Basilica is definitely its ornamentation; composed of marble slabs, sculpture, and golden mosaics, it completely hides the sight—from both inside and outside—of the main brick structure of the church.

Inside, due to the impressive gilded mosaics cover, the upper structure, composed of vaults and domes, looks like a continuous surface without edges, while the lower part of the building is completely enclosed by marble slabs and columns, in the same way as the exteriors. This is contrary to common architecture, where the break lines are the most important elements to be represented.

Moreover, the entire building presents some huge irregularity in shape, because of the constant addiction of architectural structure and decorations over the centuries, such as the heavy wooden and lead domes overlapping the original ones or the gothic spires of the façade.

The complexity of the shape is accompanied by the degradation which the church is subjected to daily due to the continuous presence of visitors and the salty air, considering its location (Figure 1). The high water and its salinity have been deteriorating surfaces and decorations for a long time now and, today again, in the narthex, the high water due to floods is very frequent and it continues to cause damages. Together with these surface degradations, we also found geometric deformations due, for example, to the instability of the soil: the effects are particularly evident in the pavement of the central nave, where the deformations have great values and can be perceived by the naked eye.

All these characteristics—even if they define the absolute value of the Basilica of San Marco—caused many challenges for both the survey and modelling stages. Apart from the difficulties in surveying particularly reflective materials, such as marble and mosaics, many problems were connected to the logistical aspects.

The Basilica was open to the public every day, some sections were just for praying and others purely for touristic purpose; many liturgical functions, even special ones, were being carried on and this made the church constantly busy with people during the day. We also had to consider that we could not enter at all in some of the construction sites inside the church and the narthex for the survey activities. All these aspects made it difficult to completely isolate an area and work freely. Additionally, night work sessions were not allowed because of safety and economic reasons.

**Figure 1.** The interior of the Basilica with many of the difficulties that were encountered: tourists, high water, light, degradation.

Apart from these aspects, we also had to face some problems connected with the lighting inside the church. Of course, one of the main interests of the church's administration was to guarantee the best possible visitor experience, so they set up a system of lights of different intensity and color to create a certain "atmosphere". Together with the sunlight coming in through the rose-windows of the main and south façade, these lights made the acquisition operations very difficult, being almost impossible to achieve the diffuse illumination which is more suitable for the survey.

### *2.2. Previous Works and Data Reuse*

During the last century, several survey campaigns have been conducted because of the necessity of monitoring the Basilica's structural situation, given its particular location. All this information has been georeferenced in the same reference system, such that a huge database for the Basilica has been created.

The decennial campaign of 1983–1993, entrusted to a private company, led to the complete geometrical representation of the interior of the Basilica, with plants, sections, and facades, and external parts (narthex, lateral side, and facades). The drawings produced on different scales (1:20, 1:50, 1:100) made it possible to carry out the following diagnostic surveys of the 1990s, and to create a mathematical model of the structure.

In fact, the plans have been used for floor-to-floor chemistry, static studies, and plant design, as well as having been the graphic support for the performance of monitoring results.

Since 2000, the collaboration with the Politecnico di Milano has allowed the implementation and improvement of the quality of the Basilica surveys needed for a correct approach to the planned conservation of the building. In 2001–2002, a laser scanner approach was tested on the internal side of the dome of the "Ascensione", a part of the mosaic floor (including some of the narthex) and for the detection of the external facade of the Basilica.

Since 2003, a collaboration project with the San Marco Procuratoria has been signed and we have acquired about 1,700 photogrammetric shots of the entire floor of the Basilica for a total of 2,600 $m^2$, with the aim of obtaining an overall geometric model of the pavement and an orthophoto representing each part of the mosaic. The final product has been a representation that provides information on various levels, all important for both direct application and accurate study of the mosaic, its degradation, iconography, and more specific geometric and material information (Fregonese et al., 2006).

Subsequently, in the years 2005–2008, the necessity of placing the roof systems under fire-protection has led to the survey of the crawl spaces of the Basilica. This survey also had the important aim of understanding the complexity of the structure and the irregularity of its morphology. In fact, it highlighted the profile and thickness of the masonry to the level of the cover and defined the actual conformation of the vaults.

During the same years, the geometric information regarding the dome of Pentecoste and of the Profeti was surveyed (Fregonese et al., 2012). During 2010, the areas of the Sacristy and the Chapel of St. Leonard were added to the large database of the whole Basilica.

## 3. Survey Stage

### *3.1. The Architectural Survey*

The last few years have not seen any major innovation in the architectural survey scene, particularly in terms of data acquisition instruments and techniques. After the apparent prevalence of laser scanners on photogrammetry, and vice versa, we are now heading towards a more mature phase, where these two main methods are studied and compared in terms of efforts, data processing, achievable results, costs, and processing times.

The most recent innovations in laser scanner techniques concern, above all, the development of new instruments customizable to the necessities of the customers (with increasing acquisition speed) and optimized to allow an easier and more efficient acquisition process, paying particular attention to the costs. Another issue is the one concerning the automation in the acquisition workflow, whose aim is to avoid the use of a topographic network (surveyed by a total station), in favor of an automatic algorithm for registration in order to minimize the acquisition time (Vosselman, Maas, 2010). The topic of automation also deals with the research of methods for point-clouds segmentations, in order to provide 3D data with meaningful attributes (Grilli et al., 2017).

The last applications of digital photogrammetry—especially the ones about dense image matching, based on many algorithms (global or semi-global matching) (Szeliski, 2010) according to the different stages of the photogrammetric process—are geared to process optimization and software validation (Remondino et al., 2014). The attention is focused on new algorithms that can refine the results, from the image processing to a better dense matching (Gaiani et al., 2016) and to the use of particular sets of images such as the oblique images (Remondino et al., 2014) or wide-angle images (Perfetti et al., 2017, Barazzetti et al., 2017).

Although each of the two techniques have specific features that allow you to prevail in different areas, it has been clear that there is no real winner in this competition. In the practice of architectural surveying, for some years now, we have been witnesses of the stabilization of laser scanners and photogrammetry, and the integration of the two methods. When possible, the integration of a laser scanner (to acquire geometry) and photogrammetry (to acquire appearance) seems to be the most effective solution.

In the case of the Basilica of San Marco, the integrated approach cannot be used, as the materials of the church—especially its mosaics made of gilded glass tessera and marble—cause some geometric errors in laser scanner point-clouds. As described in (Godin et al., 2001), there is a cause–effect relationship between the laser spot diameter and the estimated noise levels in the geometric measurements. A bias in the depth measurement can be observed, and it is supposed to be the result of scattering on the surface of small crystals near the surface.

Therefore, the entire acquisition necessary to the model (both the general architecture and the details) has been conducted by using only the photogrammetric approach, integrated with the traditional topographic survey.

Moreover, complete automation in the field of architectural surveying is very difficult to achieve. The latest pieces of software try to avoid the specialist's intervention in favor of an automatic point-cloud registration (as Autodesk Recap does when importing new point-clouds) or by using black-box solutions which can make serious mistakes. As we will see, mostly in the next chapter, the automation is completely defeated in the further step, where the intervention of the architect—as the person who knows extensively about the architecture and its construction—is fundamental.

### *3.2. Survey Activity*

As described before, the survey of the Basilica of San Marco was conducted using the photogrammetric method based on dense image matching. While on one hand it was clear from the beginning which method to use for that, we cannot say the same about the process of data acquisition.

Because of the above-mentioned logistical issues, the most relevant problem was the impossibility of conducting the survey in a single and continuous work session. Because of the touristic and religious activities, the presence of some construction sites in some areas of the church, and the special events which were scheduled in the Basilica's calendar, the survey had to be broken down into smaller campaigns. Moreover, the sequence of areas to be surveyed did not allow a unique linear development to be followed, but it had to be studied, discussed, and agreed upon day-by-day with the technical office. These constraints not only influenced the schedule of the work, but its overall methodology as well: we developed a program based on the photogrammetry and the topographic survey which answered to all these requirements. We worked with a multiscale approach in order to obtain different levels of detail according to the characteristics, dimensions, and complexity of the object. We used three high-resolution cameras (2 Canon EOS 5D mark III and 1 Canon EOS 5DS R), which enabled simultaneous work in different areas, and we used different lenses (24 mm – 35 mm – 85 mm – 200 mm) as shown in Figure 2. The choice of the lens was done according to the elements to be acquired, the distance from the object to survey, and the pixel-size needed for the processing. The result was a multiscale project in which the same elements were surveyed with different density of points. Usually, we realized several photogrammetric models for each area where we worked. The main model—the one obtained with the 24 or 35 mm lenses—was used to render the overall dimensions of the space, its geometry, and its shape. It was noted later that the architectural details and decorations could not be correctly extracted from this main model because of the point density—not accurate enough to describe these smaller details. In order to avoid this problem, some other models were computed for the same area. With the 85 mm lens, we obtained denser point-clouds of the details such as capitals and decorations. The upper mosaic surfaces needed a very high-resolution image acquisition for the creation of the final orthophotos, given the high distance from there (the dome's height reaches about 28 m above the ground floor). In those cases, we went so far as to use tele-lenses (up to 200 mm) in order to acquire the most distant mosaics. All images were acquired with the help of the tripod and according to the poor lighting conditions.

Additionally, we applied two different strategies in georeferencing the photogrammetric models (Figure 2). The main models—made with the 24 or 35 mm lenses—were georeferenced in the reference system we materialized, and adjusted for the survey of the pavement which occurred in 2004–2010 (Fregonese, 2004). This choice had many advantages: besides the re-use of the topographic network, after the necessary validation, each new point-cloud was integrated into the previous survey by using a single reference system. The result is an upgradable database over time, georeferenced to the same general topographic network. This allowed, for example, to avoid the survey of the pavement and to use (both for modelling and texturing) the previously acquired high-resolution images. The general photogrammetric models were geo-referenced thanks to a topographic survey by a total station (Leica TS30) and an automatic recognition of code targets (to minimize the selection errors). The use of the topographic network has also allowed the control of the georeferencing to be maintained, avoiding the propagation of any errors in the images' alignment.

**Figure 2.** Images of two models at different resolutions, according to the needs of modelling and orthophoto. From the left: model of the whole area with 35 mm, model of a capital with 85 mm, model of the dome with 200 mm for orthophoto.

The second strategy relates to the detailed models made with the tele-lens (from 85 to 200 mm). Obviously, we could not use coded targets for different reasons: the detailed models would have required too many targets. Moreover, the models often incorporated inaccessible parts (domes, vaults) where it was not physically possible to put some targets. In these cases, we decided to georeference the models using the Iterative Closest Point (ICP) algorithm (Zhang, 1994) which is implemented in the software we used for the photogrammetric alignment and dense image matching (Agisoft Photoscan).

The automatic multi-image photogrammetry required us to take images with large overlap between consecutive shots and to use a homogeneous illumination to acquire realistic photos without shadow areas or flash effects. This was surely quite a big issue, given that the lights used inside the Basilica came from various sources and we were not allowed to work at night. To minimize the effects of artificial lighting (and also of the sun), we used some large lighting balloons equipped with a discharge lamp that generated neutral light, and some adjustable LED spotlights which were more manageable than the former (Figure 3). As a general rule, the balloons were used in larger spaces, where it was easier to manage them and possible to illuminate high surfaces; as a matter of fact, they were provided by telescopic tripods that permitted regulation of the height up to 8 m. On the other hand, the smaller LED spotlights were used in complex areas within small spaces (e.g., the galleries' level), and where it was necessary to correct the illumination coming from different directions to obtain a more homogeneous condition. On the contrary, the problem of contrasting the natural light coming from the rose windows was not solved in any other way than organizing the acquisition according to the hours of the day in order to avoid the naturally sun-lit areas.

All the methods described in this paragraph were validated beforehand in a test area. The Baptistery of the Basilica represented a very suitable test bed to try the complete photogrammetric approach, and there we set the survey workflow to use for the entire church. This area was optimal for test acquisition: the Baptistery is independent of the rest of the church, but concurrently it is constituted by the same architectural elements that are present in the whole building: domes, arches, vaults, columns, capitals, sculptures, etc., so that the problems faced in this test area were going to substantially be the same in the rest of the church. Technically, in the other spaces we had to adjust the survey process and the instruments according to the specific case, but the sequence of actions for surveying (and modelling) was the same. More precisely, the dimension of the main church is greater than the one of the Baptistery, and this required different lenses for the acquisition phases to obtain the most suitable resolution, but the method was exactly the same.

After the validation of the workflow through practice, the same method was applied to the whole church. The entire complex was split into smaller spaces considered independently (even if they were not so). For each of them, we realized photogrammetric models at different resolutions, but included in the same reference system, according to the increasing necessity of information for details.

**Figure 3.** Images of the interior of the Basilica with the large balloons and LED lights to set the best lighting conditions.

The data processing which followed the acquisition step is well known. The images were oriented and georeferenced in Photoscan by using the previously described methods. Then, we calculated the point-clouds that were merged in a single point-cloud model of the interior, as in Figure 4.

## 4. Modelling Stage

### *4.1. BIM Modelling of Cultural Heritage: State of the Art*

3D modelling in the field of Cultural Heritage is currently a topic of great relevance. In a sense, we could affirm that the research has moved its interest towards data modelling rather than data acquisition, and there are several reasons for that. Firstly, there has been a greater integration of research areas that, until a few years ago, worked autonomously: an example is the combined effort of geomatics with computer sciences such as computer graphics. Another reason should be searched in the outbreak of low-cost methods for obtaining 3D point-clouds, both using laser scanner and, mainly, photogrammetry. However, after the acquisition stage, the primary question remains how to use the amount of data, and how it can be applied for the valorization of Cultural Heritage. The first answer has been, of course, representation: to describe, to imagine, to virtually reconstruct a cultural asset. The figures who tried to give first-hand answers have come from the computer science community, as highlighted before.

However, now that 3D models started being used for other purposes, the situation has grown increasingly complex, and the case of BIM modelling is an example in this sense. In fact, many problems arise when the goal is to be very accurate and fitting to reality, to attach many kinds of information to a 3D object, and to deal with different software (to be used by both experts and non-experts) to follow the changes over time. The BIM approach has not caused these problems, but it has enhanced their appearance.

Practically, the difficulties connected to 3D modelling can be grouped into different levels. The first challenge is the choice of the most suitable approach for modelling. As described in Tommasi et al. (2016), different approaches can be used from direct modelling to parametric object-oriented modelling. The main method of modelling inside the BIM environment should be the parametric one, which allows objects to be modified with the use of simple parameters. This approach applies very well to new building projects, but its use is more complex in Cultural Heritage because it requires the use of previously-built libraries (i.e., Revit, ArchiCAD, etc.) or to work with a complex series of commands (i.e., Grasshopper).

For the Basilica of San Marco, we chose the direct modelling approach, which allowed us to be very accurate in fitting the point-cloud model. This method is quite time consuming, but it allows to the exceptional elements (variations in the moldings, relevant damages, etc.) to be modeled whenever necessary.

**Figure 4.** The result after merging all the point-clouds of the interior.

Particularly, we adopted non-uniform rational B-spline (NURBS) modelling with Rhinoceros software to describe the complex elements which could not have been represented with other methods. We considered surface modelling as the most flexible and effective method to describe the complexity of the Basilica.

Moreover, this choice allowed us to complete and make available blocks of the model without necessarily having the whole survey of the adjacent area of the building. This peculiarity allowed us to test the realization process from the survey to the texturing of the modelled object, individuating the guide-lines for the successive areas, like in the case of the baptistery. This method also responded to the necessity of integrating the model in a complex system for data management; as a matter of fact, the plugin to import a Rhino model into BIM3DGS already existed.

The accuracy of the model was a relevant and complex task. The literature and the regulations already gave some instructions, mainly related to the concepts of level of development and level of detail (the same acronym—LOD—for different concepts, as explained in Ciribini, 2013). However, it is not equally clear how these suggestions can deal with the traditional—and diffusely adopted—concept of scale of representation. In the modelling of the architecture of San Marco, the principles we applied derive from traditional architectural drawing, where the scale of representation gives information not only about the relationship between the object and its representation, but also about the amount of detail, and define the smallest element that can be represented. In this case, at a scale of 1:50, the smallest element to be modelled had to be larger than 1 cm.

The last level of complexity refers to the possibility of being able to manage the model. The large amount of survey data—even if processed and strongly reduced—could produce models which are quite large (in terms of memory occupation), which cannot be easily used in navigation and exploration. Parametric modelling produces very efficient models, but it has the same limitations we described before. On the contrary, the NURBS modelling allows an optimal file dimension, as well as a very accurate description of cultural heritage assets.

### *4.2. Modelling of the Basilica of San Marco*

The amount of data related to the interior of the Basilica is enormous and, of course, it was not possible to use all those points together. As we did for the survey stage, we subdivided the work into smaller areas to be modelled independently. This subdivision was very suitable for the acquisition stage, but it showed some problems in the modelling stage, as each part could not be considered as completely independent. In fact, to model the borders of the area, it was necessary to use the next model as a reference. The main pillars in the church, which support the main dome, were a typical example of this problem: they are located at the conjunction point of the central and the lateral nave with the transept, and each one of them belongs to at least three or four of the areas, and the number even grows if we consider the union with the second level of the Basilica with the matroneum (the women’s gallery on the first floor). Therefore, the work went from modelling each single area to refining the borders and the conjunctions between areas in a second step. This approach has highlighted another technical problem. In fact, to refine the borders it was necessary to open at least two models (in some cases more than two models, as in the case of the connection between the pavement and the wall) in the same file, with obvious problems of calculation and of shared work. We solved this problem by using a feature of Rhinoceros (the software selected for modelling) called "work session". It allows the work to be shared between all participants in the working group: it is a base file which manages a series of 3D models and allows multiple users to navigate and work on them like it were a unique one, avoiding that the dimension (byte) of the original files make the process more demanding.

Apart from the technical problems of managing such a huge amount of data, the modelling stage presented some other difficulties. As we saw before, the variety of elements and their characteristics did not permit the creation of "standard" objects, but some of them with similar features could be grouped, and a standard modelling methodology was decided for each group. The method was based on the fundamental concept of the extraction and generation of sections of the object from the photogrammetric point-cloud. To do this, the point-clouds extracted from the photogrammetric models were converted into Pointools file format (.pod) and then imported into Rhinoceros. The Pointools plugin allowed the extraction of new views and slices from the point-clouds directly in the Rhinoceros environment, to build the generating curves.

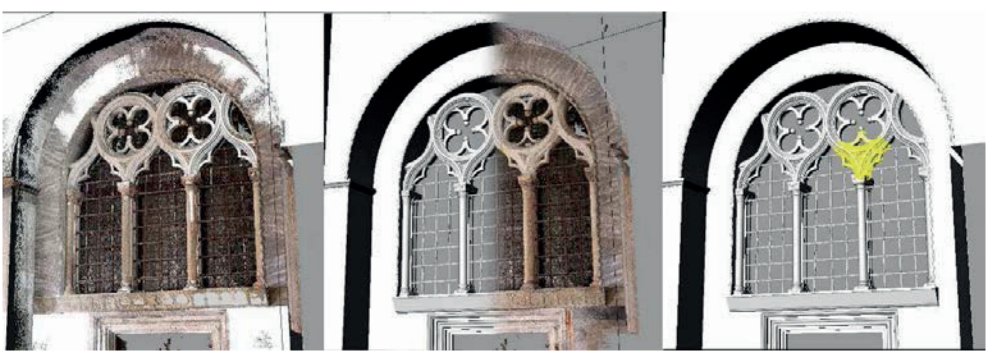

**Figure 5.** Example of modelling of a complex architectural element (gothic window) from a point-cloud to a non-uniform rational B-spline (NURBS) model.

For the main structure of the walls, the aim was to obtain a simple surface which could describe the complex shape of the object, by the extraction of some control curves in strategic points such as the junction of the marble slabs or the connection with cornices, columns, and other decorations. The same approach was used for the construction of smaller objects consisting of simple surfaces or objects with constant geometric profiles (Figure 5). We included the marble cornices in this category, even if they have a refined sculptural decoration. This choice helped both to avoid a large use of meshes and to respect the representation scale chosen for the 3D model (1:50). In fact, at this scale, some of the tiny decorations (smaller than 0.01 m) could be omitted from the model. This information is given by the applied textures and the orthophotos, rather than from the aspect of the object. Additionally, the large use of mesh model did not allow simple navigation of the model, being too heavy to manage.

Therefore, for each of the aforementioned objects we extracted a geometric construction section, which was modified in terms of dimension, rotation, and distortion to fit the point-cloud (Figure 5). The modifications were applied with a frequency based on the extension of the object, its deformations, and the presence of key points like corners, fractures, and junctions. As for most of the operations of the modelling stage, an automatic approach was very difficult to use, as each element had to be considered as unique. So, we could not set, for example, a predefined number of sections to be used to model a molding: it depended on the length, the direction, the presence of discontinuities, and the state of preservation.

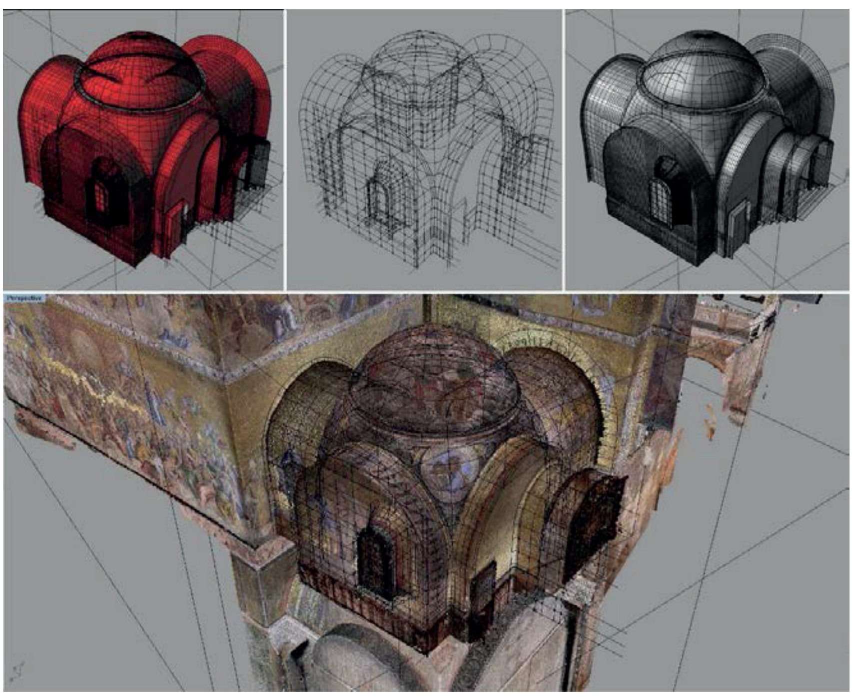

**Figure 6.** Different steps in the constructions of domes.

With the same method, we also modelled the many vaults, domes, and arches in the Basilica. The complex surface of the vaults was obtained by an interpolation of sections extracted from the data using a reference grid (Figure 6). This method was selected after several attempts. Firstly, we tried to obtain the dome directly from the point-cloud as a mesh model. Of course, the 3D model was actually fitting the real surface, but it was very heavy for usage. We also tried to convert the mesh into a NURBS curve, with an automatic algorithm allowed by Rapidform and Geomagic, but the problem was the presence of some missing areas (because of the shadows due to the eaves of the moldings) and the difficulty in filling them. Instead, the method of interpolation of sections has allowed us to be very accurate and, at the same time, to close some of the holes in the vaults.

The outline and the pace of the grid depended on the dimension, geometrical features, and complexity of the shape that had to be obtained. For example, a simple and quite smooth barrel vault required a regular square grid with a 0.5 m step, whereas the small dome within the pillar (each pillar has a structure like the nave's, with a small dome and four smaller pillars) with its pendentive, required a radial pattern grid in a single direction, and a close series of horizontal sections that can reach a 0.2 m or smaller distance.

A completely different approach was employed for sculptural objects like capitals and statues, which cannot be represented by simple geometric shapes (Figure 7). In these cases, we went slightly beyond the limits that the scale of representation imposed on the rest of the model, both because these kinds of objects needed a particular attention and for the extreme complexity of their shape, which did not allow a geometric simplification. Those were the cases where the NURBS model gave way to a mesh model directly extracted from the dense point-cloud and triangulated and processed in Rapidform. If this kind of model was really fitting the surface and very much accurate, its problem resided in its memory occupation. Then, we noticed a second problem with this mesh model: the impossibility of using it in Rhinoceros for the automatic extraction of sections. One of the advantages of the geometric NURBS modelling of the Basilica was the possibility of extracting infinite sections from the model—a function present in all types of commercial BIM, and not a difficult one to use (compared with the mesh model, which made it impossible). Right now, we are defining the best workflow for converting the mesh models of statues and capitals into NURBS: of course, the problem of this conversion is the level of accuracy.

As the extraction of the model was finished, the 3D model obtained needed to be divided into singular elements, which had to be classified with a code and assigned to a layer to be used in the BIM3DSURVEY system. The classification was made according to the typology of architectural components; for example: vault, arch, dome, wall, cornice, column, floor, and windows.

**Figure 7.** Two capitals modelled in different ways according to their complexity. Above, a simpler capital modelled with NURBS, below the complex one, modelled with mesh.

## 5. Orthophotos

### *5.1. The Orthophotos for Architecture*

In recent years, orthophotos have increased in terms of diffusion and use. The reason is quite evident, and it is related to the latest innovations in digital photogrammetry—Structure-from-Motion in particular (Chiabrando et al., 2015). The availability of systems that similarly, in a quasi-automatic way, allow a 3D model to be built, solved one of the problems of the process necessary to obtain orthophotos. This workflow is well-known, and it requires three elements: a DTM (digital terrain model) as detailed as possible, according to the scale of the orthophoto), the images oriented in the same reference system, and a reference plane where to project the object. Today, digital photogrammetry allows us to orient images and to obtain 3D models quite easily, and that has increased the diffusion of orthophoto usage.

In architecture, orthophotos represent a very important and valid tool, even if they are sometimes still not completely understood. The possibility of simultaneously acquiring measurements and qualitative information about an object is very advantageous in terms of time—not only in the survey stage, but also, for example, in the evaluation of the state of preservation.

*5.2. The Orthophoto of San Marco Decorated Surfaces*

As described before, in the Basilica of San Marco, the use of orthophotos was intended above all for the monitoring and the eventual restoration or reconstruction of mosaics. With this purpose, the orthophoto had to be of very high-resolution: for instance, the orthophoto should present not only the single tessera but also the grout lines. In practical terms, this means that we should also be able to recognize the elements with a dimension of about 1 mm.

This requirement influenced the acquisition stage: in fact, we created some photogrammetric models dedicated specifically to orthophotos: we used the 200 mm tele-lens in order to acquire these high-resolution images.

Regarding the process for orthophoto construction, after the dense point-cloud calculation, we decided to use (as 3D model for the orthophoto) the model we realized in Rhinoceros. This choice avoided the construction of high-resolution mesh models and the use of the NURBS models.

To achieve this, the NURBS objects were converted into a polygonal model and were used in the photogrammetric software Agisoft Photoscan.

The so-obtained polygonal object was imported in the original photogrammetric model and used. The texture of the object was given by the projection of the original oriented images used for the construction of the dense point-cloud on the object surface.

This passage was not essential to obtain the orthophoto, but it permitted the mesh to be colored enough to obtain a textured model for navigation purposes. In fact, in this procedure (which was initially planned for representation), we have no metric control of texture resolution on images, and it is only possible to set the final dimension of the texture atlas (typically in power of two to better interact in computer graphic application). If the object to be represented is not planar, the software constructs an atlas of pieces of the orthophoto, and it is difficult to deal with it for any photographic correction.

For the construction of the real orthophoto, after the choice of the projection plane, we had to select the best images to use. Not all cameras were necessary to realize the final orthophoto. So, we made a first selection by checking the quality of the images, to keep the best ones and to control the predetermined pixel-size, according to the analysis of Photoscan in terms of image quality and a direct review by the operator. Once the best-quality images were selected, we decided to use only the most nadir-positioned cameras in order to avoid an excessive stretching of pixels. Finally, the pictures that showed inhomogeneous light conditions were discarded to achieve the best possible radiometric information, which affected the general quality of the orthophoto.

Following this workflow, the orthophotos were produced with a pixel-size of 0.0005 m, which allowed the border of the tiniest mosaic tiles to be seen clearly, permitting use for restoration or analysis (Figure 8).

**Figure 8.** Unwrapped orthophoto of one of the main arches inner mosaic (**top**). Detail view of the same area, where we can recognize each single tessera and grout line (**bottom**).

## 6. Results for BIM Application

At the end of the process, we obtained three different results that could be used in the BIM environment with different purposes. In particular:

(a) a geometric NURBS model for the subsequent insertion into the BIM environment, with the possibility of extracting two-dimensional drawings such as plans and sections;
(b) a mesh model with low-resolution textures for online navigation;
(c) a high-resolution orthophoto.

These three results represent the overall answer to the requirements of the customer.

The NURBS model will be used especially in the BIM application to link the database (about history, restoration, planned conservation). It guarantees a good accuracy of the model, but at the same time, it is not so difficult to manage in terms of memory occupation and file size. In Rhinoceros, it is possible—as in other BIM software—to extract plans and elevations directly from the 3D model. This is a very relevant function for the management offices of the Basilica, as it allows innumerable sections and plans of each part and element of the architecture. The whole model can be uploaded in different parts according to the necessity of working on a particular area, as implemented in BIM3DSURVEY software.

The mesh model can be considered as a by-product of the workflow. To obtain the orthophoto, it was necessary to use a mesh model in Agisoft. This allows a realistic navigation inside the church, and can be used to see the mosaics in their real position in the 3D of the church.

Finally, the orthophoto represents the other request of the Procuratoria of San Marco. The high-resolution allows recognition of each individual tessera of the mosaic, but they are not easy to manage because of their file size.

To handle these three kinds of results (Figure 9), strictly connected but independent from each other, we selected the BIM system BIM3DSURVEY, developed by Politecnico di Milano for the main spire of the Duomo of Milano (Rechichi et al., 2016). It allows easy management of large-dimension 3D models, so it was particularly suitable for the architecture of San Marco. It maintains a strict relationship with the original Rhinoceros model, so it is possible to update the final model or add new parts not involved in this work. Furthermore, it allows the uploaded model to be linked to many other pieces of information. For this application, the system has been implemented with a function which allows the use of the model as a 3D spatial index for the orthophoto. The user can select an element and then it is possible to view and download the orthophoto of that element.

**Figure 9.** The three results of the previously described workflow which can be used in BIM environment. From left to right: 3D NURBS model, texturized mesh model, detail of orthophoto.

## 7. Conclusions

This research concerns the modelling of the Basilica of San Marco in Venice for a BIM environment. The characteristics of the church itself and the expected future use of the BIM make this case study a very particular one in the context of BIM applied to Cultural Heritage (HBIM). The BIM will be used to extract geometric and dimensional information and as an index for the orthophoto of mosaic and marble surfaces.

Both the acquisition and modelling stages were influenced not only by the material and geometrical features of the church, but also by its liveliness (considering the countless streams of visitors and continuous conservation activities that were being carried on). With regards to the survey, the experience of digital acquisition of the Basilica showed that digital photogrammetry—especially dense-image matching—is a very effective and flexible tool for architectural surveyors, especially if the project is referenced to a well-defined topographic network. The possibility of having photogrammetric models with different levels of point-density according to the complexity of the church was a very relevant issue, and allowed organization of the entire work and management of all data non-linearly. It also satisfied all the requirements of the customer and, at the same time, did not stop the entire working process.

The 3D model extracted from the point-clouds confirmed that, in the context of Cultural Heritage, we are quite far away from automation. Actually, automation in the field of dense point-cloud production requires an important human intervention, necessary to understand each architectural element, its role, and how it can be represented. NURBS modelling is a very effective tool, but only when used by specialists—experts not only in the field of survey, but also with a good knowledge of the architecture.

Some problems were not solved at all, but only faced to find a temporary solution. This is the case of the lighting set-up in the church for image acquisition: the spatial configuration of the Basilica with large rose windows and the system of light for architecture enhancement and touristic visit made it very difficult to delete all the reflections and color dominants that affect the images.

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