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IMAGE-BASED TECHNIQUES FOR THE SURVEY OF MOSAICS IN THE ST MARK'S BASILICA IN VENICE

TÉCNICAS BASADAS EN IMÁGENES PARA EL LEVANTAMIENTO DE LOS MOSAICOS DE LA BASÍLICA DE SAN MARCOS EN VENECIA

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Highlights:

- Modern digital photogrammetric techniques enable the acquisition of very complex objects, not only in terms of form but also in terms of material.
- To obtain high resolution orthophotos, it is necessary to accurately take care of all the stages of the process: photographic acquisition, surveying, modelling and orthographic reprojection.
- High resolution images and detailed 3D models can benefit from a complex BIM system for the management of all data.

Abstract:

This article aims to critically examine the entire methodology of very large scale (1:1) surveying and documentation of mosaic surfaces. The term 'survey' should be read in its broadest and most complete and sense, including the phases of measurement and data processing as well as management and use of these data for the purposes of preservation and maintenance. The case study presented here took place at St Mark's Basilica (*Basilica di San Marco*), in Venice, where mosaic flooring, wall and vault decorations have been surveyed on two separate occasions. These two experiences shared a common goal (a full-scale survey of the mosaic decorations) but differed in terms of the methodologies used, chiefly due to the technological developments of recent years. All this, therefore, lends itself to a methodological reflection and critique of the ways in which surveying technology has evolved over time. It enables to conduct surveys that would, just a few years ago, have been inconceivable due to their size and complexity. This article describes in detail current surveying processes, which includes the use of a multi-scale "image-based" approach, "re-topology" methods such as non-uniform rational B-spline (NURBS) and a tailor-made Building Information Modeling (BIM) system. This system allows the direct use of a three-dimensional (3D) model of the Basilica within the maintenance process of the monument itself with the options to georeferencing information, extract basic metric data and catalogue all its mosaics.

Keywords: photogrammetry; 3D modelling; Building Information Modeling (BIM); 3D reconstruction; complex architecture; orthophotos

Resumen:

Este artículo examina de forma crítica la metodología completa de levantamiento y documentación a gran escala (1:1) de superficies con mosaicos. El término 'levantamiento' tiene que ser entendido en su significado más completo y amplio, que incluye tanto la fase de medición como el procesamiento de los datos y también la gestión y el uso de los propios datos para fines de conservación y de mantenimiento. El caso de estudio presentado es el de la Basílica de San Marcos (*Basilica di San Marco*) en Venecia, donde en dos fases temporales distintas se han levantado el piso de mosaico y todo el programa decorativo de las paredes y bóvedas. Las dos experiencias, aunque tienen un objetivo común (el levantamiento a escala real del mosaico), difieren en las metodologías utilizadas, principalmente debido a la evolución tecnológica de los últimos años. Todo esto se presta a una reflexión y una disertación crítica de tipo metodológico sobre cómo han evolucionando las tecnologías de medición a lo largo del tiempo y cómo han hecho posible levantamientos hace unos años impensables por extensión y complejidad. El artículo describe más detalladamente el actual proceso de medición que implica el uso de procedimiento "basado en imagen" multi-escala, métodos de "retopología" tipo B-splines racionales no uniformes (NURBS) y un sistema de Modelado de Información para la Construcción (BIM) creado *ad hoc*. Este sistema permite el uso directo del modelo tridimensional (3D) de la Basílica en el proceso de mantenimiento del monumento propiamente dicho con tal de georreferenciar información, extraer información métrica de base y catalogar todos los mosaicos.

Palabras clave: fotogrametría; modelado 3D; Modelado de Información para la Construcción (BIM); reconstrucción 3D; arquitectura compleja; ortofotos

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1. The St Mark's Basilica and its mosaics

When we think of St Mark's Basilica, we picture a great architectural work enriched by a complex iconographic programme and dominated, above all, by mosaics. Indeed, it is the latter that most influence the popular image of the Basilica, through the warm colours –particularly gold– that adorn this holy place. Surfaces consisting of millions of coloured tesserae cover approximately 8500 m^2 of walls, vaults and domes, depicting stories from the Bible (both the Old and New Testaments), allegorical figures, and events from the lives of Christ, the Virgin Mary, St Mark and other saints. Above all, however, they tell the story of the city, its power and its relationship with art, from the moment of its foundation until today.

Yet St Mark's is not merely a work of art but also a living monument, a lively church that hosts numerous liturgical, artistic, musical and cultural events. And, while they attract attention and interest, these activities are, in fact, a cause for concern with regard to the entire building. The passing of time, the huge influx of visitors, environmental conditions and human activity are contributing to damaging its immense heritage and, for this reason, the Basilica is governed by a Procuratoria that manages its preservation and ensures that the Basilica itself is always a busy workshop of restoration. The Basilica's history features such continual preservation and renovation work that it could be described as a constant maintenance site. This complex machine consists not only of the usual figures that generally revolve around a church but also teams of expert ebonists, carpenters, and joiners who, every day, look after the wellbeing of the Basilica and its immense body of art.

The Basilica's Studio Mosaico comprises a special team of five mosaicists who work every day to maintain the coloured tesserae. They take care of each individual tessera, cleaning and washing them. Any that are too deteriorated are replaced with new tesserae of the same material and colour. For tesserae made from vitreous glass, if the colour is no longer available, replacements can be obtained from the warehouse of pieces that have fallen off over the centuries. This process is possible provided that the mosaic is well-documented. A precise and accurate description of each individual tessera is therefore essential, and it is here that the value of this research lies; indeed, the aim of this study is to document the Basilica and its mosaics. An unusual feature of the work is that it supplements the geometric survey, and therefore the shape of the surfaces, by recording the colours at both high and very high resolution.

1.1. The mosaics, their history and their preservation

The mosaics found today in the Basilica date back to between the end of the 11th century and the second half of the 19th century. Their surfaces represent a complex combination of original parts and parts that have been altered over the years; up to the end of the 18th century, in fact, the practice was that of replacing the damaged parts, respecting their iconography but renewing them according to the taste and the aesthetic criteria of the time (see for example the mosaics realised on cartoons by Tiziano and Tintoretto). It will be necessary to reach the second half of the 19th century to witness the appearance of an approach aimed at their maintenance, thanks in particular to the action of Pietro Saccardo. Under his direction, more preservative and increasingly refined restorations were undertaken, consisting of the removal of the surfaces to be restored: it was him who invented the technique known as "lievo", which allows –thanks to the use of canvases glued on their surfaces– the separation of the mosaics, followed by the removal of deteriorated mortars, the integration of missing tiles and the relocation of deadlifts on lime and sand mixes.

The repositioning of the detached parts was preceded by plaster casts, or more frequently made in wet paper, pressed on the mosaics themselves to receive the imprint, then painted card by card; many of these casts, precious documentary evidence, are still preserved in Procuratoria, the institution that is dedicated to the conservation and restoration of the monument. Thanks to Saccardo, in the space of only a few years, the modalities of intervention on the mosaics changed from an attitude that considered the demolition and the remaking of the mosaic surfaces to be ineluctable, to respect them as a work of art.

Another fundamental step in mosaic restoration in St Mark's was the invention, in the first half of the 20th century, of the so-called "restoration from behind" technique: Luigi Marangoni, in dealing with the consolidation of the masonry vaults, experimented with a method of intervention aimed at avoiding the generalised separation of the mosaics laying on their intrados. Sturdy wooden ribs, able to withstand the entire load of the overlying brick masses, were cut and shaped to adhere to the mosaic surfaces, reinforced and protected by glued canvases. The vaults were then removed by sections and rebuilt element by element, while at the same time renewing the mortars for bedding the mosaics. The intent of Marangoni was to prevent the perception of the numerous joints of separation and reapplication of the mosaics, otherwise unavoidable.

A further, radical, technical and methodical evolution took place in the 80s of the 20th century, with the in-situ consolidation method. Experienced for the first time at a large scale on the mosaics of the Cathedral of Santa Maria Assunta di Torcello –and since then also applied to St Mark– the technique is based on the use of mortars based on aerial lime, injected clay and marble powders inserted in the voids below the mosaic surfaces. The main problem always suffered by the lagoon mosaics, in fact, is due to the progressive appearance of detachments between the supporting mortar and the masonry members, and/or between one and the other layer of mortar, which progressively worsens and finally leads to the fall of the mosaic surfaces. The primary cause of this degradation must be found in the change in water status at the interface surfaces between the masonry and the bedding layers. The water trapped in the walls, while passing from the bricks to the supporting mortar to reach the outside and be dispersed in the atmosphere, tends partly to change from the liquid to the gaseous state along the contact surfaces between the different materials. This change of state involves the crystallisation of the salts which are dissolved in the water (present in a strong concentration, both for the omnipresent phenomenon of capillary ascent, and for the contribution of marine aerosols) that gradually weakens the adhesion of the mortar to the walls, leading to their detachment. Consolidation by means of injections capable to restore the necessary adhesion of the mortars hosting the mosaics to the masonry support makes it possible to avoid, first of all, any loss of historical matter: the destruction of the support layers, including the sinopie and colour spreads that preceded the fixing of the mosaic tiles. The system also prevents any significant alteration of the faces of the work, since any operation of detachment and relocation of the mosaics inevitably produces a marked coplanarity in the surfaces of the tesserae, originally oriented in slightly different directions from one another, leading to an annoying and incongruous flattening of the mosaics.

2. Mosaic surveying as an opportunity

The survey of the mosaics in the St Mark's Basilica in Venice is an interesting example of how photogrammetric survey techniques have evolved over the last two decades (Manferdini, 2010). The survey in fact developed in two distinct phases: the survey of the mosaic themselves was undertaken between 2003 and 2008, while that of the walls and vaults has been carried out over the past four years and is currently in the completion phase. It is, therefore, a useful case study to synthetically look at the evolution of photogrammetric techniques over the past fifteen years. Relatively unusable in the world of Cultural Heritage until just a few years ago and which today, they have recently become a highly valid method to obtain complex objects that are difficult to digitalise through other methods, due to their complex materials.

2.1. Metric representation of the mosaics

The classic "representation methods" useful in rendering objects such as mosaics have always been line renderings, rectified images and orthophotos.

Line drafting may be carried out using direct or manual measurements or based on stereophotographic images. This method is used in cartography and permits measurement based on photographic images. Through this method, it is possible to digitalise all planar views, both horizontal and vertical, based on a stereo-photogrammetric pair. The resulting product is normally a drawing in 2D CAD format. In this case, the images are merely an intermediary tool for the extraction of simplified 2D geometric and metric information, producing general 3D representations on rare occasions if the shape of the object is sufficiently simple. In rendering, however, we lose the qualitative information on the object, in terms of both its colour and its level of conservation; information that past surveyors of the mosaic flooring of St Mark's transferred to often brightly-coloured panels at large (1:33) or very large (1:10) scale (Fig. 1).

Nowadays, with digital photography being of everyday use, there are two methods that could be better employed for surveying of these objects: rectified images and orthophotos. Both products are "metric images" –the end result of photogrammetric processing– and are orthographic views of an object projected onto a specially-selected projection plane, normally the plane that best interpolates the shape of the surveyed object. Due to this feature, these images may be measured using distance measurements but only on the selected

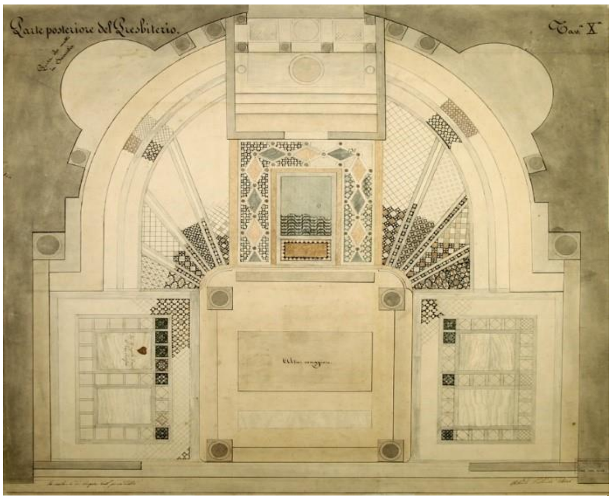


Figure 1: Survey of the Pellanda (1860) original design in Indian ink and watercolour, on paper.

reference plane. Conceptually, these products are like traditional architectural representations. However, rather than being drawn, re-worked, interpreted and simplified by the operator, they represent the object photographically, with all its features, therefore not only their geometry (which can be measured) but also their shape and quality, expressing, for example, information on their colour, material and state of conservation. To describe the concept in highly simplistic terms, both products are based on the principle of projection of images, once oriented, onto a 3D model of the object and, subsequently, the projection of the latter onto the plane that best approximates it. A rectified image is a simplified orthophoto and can only be used when the object itself is flat or is used as such; in other words, when any architectural protrusions are negligible. This hypothesis permits simplification of the mathematical photogrammetric model of the collinearity equation since it disregards the depth of the object and assumes that it is perfectly flat. This means that rendering requires only a photo and that an image may be rectified, if only geometrically, by applying a homographic transformation (Fregonese, 2004). For this reason, this method can easily be used to represent flat architectural elements such as the façades of a building or even a floor. The advantage of this technique lies in the extremely quick and simple process involved, which requires non-specific skills as it is not actually a complete or complex photogrammetric process. Moreover, it normally eliminates the need to conduct a topographic survey of the support due to the very fact that the problem can be resolved geometrically and not necessarily through analysis. By working directly on individual photos, manually mosaicking them once rectified in order to compose the entire object, it is possible to produce a final image of good photographic quality and an apparently continuous representation (free from areas of shadow) (Monti et al., 2004). Nonetheless, it should be emphasised that only the area which is on the reference projection plane will be metrically correct and will have the correct perspective correction. All other parts, which are outside of the plane, will not be metrically correct, and thus should not be used for measuring. For this reason, it is essential to note that this technique cannot be used in the case of the mosaic decorations of St Mark's Basilica. Indeed, both the floor and the walls of the Basilica present significant irregularities which cannot be assimilated into a plane, especially in view of the vast restitution scale required. It is therefore essential to use the orthophoto, this being a more accurate method of metric representation.

Indeed, orthophotos are “true and correct orthogonally projected” photographic images; they are the final product of the photogrammetric process. For this process, it is indispensable to have access to an accurate and complete 3D model (Digital Terrain Model, DTM; or Digital Surface Model, DSM) of the object in question, and the more closely the model adheres to these characteristics the better the geometric accuracy of the final orthophoto will be. The real challenge of the entire process lies in creating a 3D model of the object. Indeed, creating a complete, high-resolution, high-quality 3D model of a complex architectural object is, in general, not an easy task and requires skills, many hours of work and high-performance hardware. It is for this reason that, for years, it was impossible to create a high-resolution 3D model of objects and complex architecture through photogrammetric methods and orthophotos were, for a long time, matters and methods used only in cartography. A DTM is simpler to create; indeed, it can have lower resolutions, it is easier to interpolate and approximate numerically and, furthermore, it is easier to build as it is actually in 2.5D and not a true 3D virtual object. In the world of architecture and cultural heritage, the wealth of detail that must be acquired and represented requires high-resolution images and labour-intensive 3D modelling procedures. The complex nature of free and artistic forms necessitates acquisition and processing of a very large number of photographs. Use of manual or semi-manual photogrammetric methods therefore discouraged or severely restricted the creation of a complex 3D survey, as the processing of a large number of images constituted a real bottleneck in the process. This continued over time, not only with the use of analytical photogrammetry but also with the advent of digital photography, since photogrammetric processing operations have always, in one way or another, been mainly manual.

For highly complex objects, this operation could even be considered impossible, due not only to the quantity of data to be processed, but also to the effort of manually or semi-automatically identifying connecting points between the images that are sufficient in number and uniformly arranged in the images in order to guarantee correct construction of the projection beam, a key factor in the initial process of photogrammetric orientation.

A further problem concerned calibration of the camera, another essential step in the photogrammetric process and in high-precision modelling. Indeed, it was complicated and expensive to use precisely pre-calibrated instruments such as the well-known metric or semi-metric still video/single-lens reflex cameras used until a few years ago, and this limited the use of photogrammetric techniques to a few expert operators. Later, with the advent of digital technology, it became possible to perform field pre-calibration more simply, thus permitting the use of commercial digital cameras. This was the first step in making photogrammetry more accessible, expanding the number of users and dramatically reducing costs and operating restrictions.

2.2. Photogrammetry and laser scanning

A large number of images and pre-calibration of the camera were, therefore, two key factors that negatively influenced the use of “close-range photogrammetry” due to its long processing times and, in some cases, its practical unfeasibility. This favoured the use of TLS (terrestrial laser scanning) techniques which, from the early 2000s, promised to be truly revolutionary. Several years later, in 2007, Karl Kraus, the father of modern photogrammetry, wrote: "photogrammetry makes it possible to reconstruct the position, orientation, shape and size of objects from images. These images may originate from photochemical images (conventional photos) or from photoelectric photos (digital photography). Laser scanner images, a third group, have arrived on the scene in recent years. These images include information on distance associated with each image element" (Kraus, 2007). It is interesting that Kraus defined the laser scanner as a photogrammetric technique and not a topographic technique, as is commonly thought. This highlights that, in 2007, the laser scanner was the “rescue” of photogrammetry as it permitted automatic, high-resolution acquisition of 3D objects. Despite being much more expensive, this technique is simpler and quicker at the acquisition phase and permits real-time, 3D, geometric analysis even of extensive environments featuring highly complex architecture (Boehler & Marbs, 2001).

As we know, its product is a point cloud which is a discreet 3D scene composed of an enormous quantity of points that describe the scanned surface. This type of instrumentation is capable of measuring an object’s geometry at high resolution and in an automatic and systematically-structured way in real time. However, it has two defects which cannot be ignored, particularly in relation to the case study in question. The first is the fact that laser scanners alone do not capture colour unless external apparatus is used. While the usage of integrated digital cameras, mounted inside or outside of the instrument, permit colouring of the cloud in order to make it more readable, thus far neither the level of accuracy in projecting colour onto the 3D point cloud acquired nor the quality of the colour itself is particularly high. The second, and most important, the defect is that the metric quality of the acquisition depends on the physical and chemical characteristics of the material surveyed.

It was therefore clear that integrating these two technologies –laser scanning and photogrammetry– (Lerma et al., 2010) was the only way to use the high-resolution 3D geometry provided by the scanner as the geometric base within the photogrammetric process from which to create a precise orthophoto (Barazzetti et al., 2010). However, noisy data in the presence of different materials and colours, the presence of numerous edges (yielding mixed edge problem effects) and an inevitably imperfect shooting geometry taken from an angle insufficiently orthogonal to the object have impeded the use of laser scanners in mosaic flooring surveys, requiring –as we will see in the following paragraphs– the use of photogrammetric techniques alone.

2.3. The revolution

In recent years, the union of photogrammetry and computer vision (CV) –also known as photogrammetric computer vision– has revolutionised the way in which 3D objects are surveyed, particularly in the world of cultural heritage. This type of method functions along the standard lines of photogrammetry, while also using automatic image analysis methods at both phases, orientation and 3D modelling. The substantial difference lies in the complete automation of each step. In extreme cases, the entire process can be performed automatically by the software with no intervention by the human operator, so much so that, today, we no longer talk about an “automatic process”, but about a completely autonomous process.

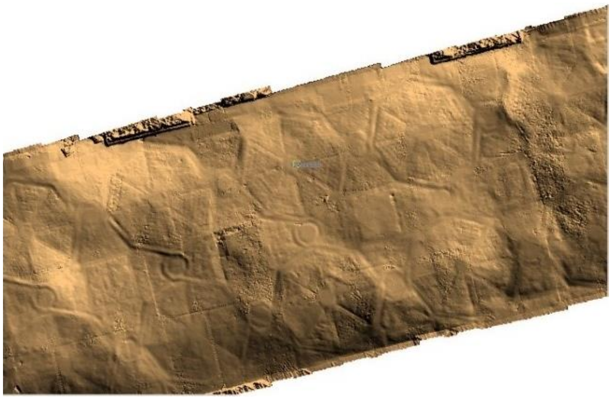
These two disciplines, when integrated, give rise to a revolutionary way of working that combines the accuracy of the photogrammetric process with the typical automation of CV. This method may be referred to as an “image-based” modelling approach. It offers the possibility of orienting a significant number of images quickly with no waste of “human time”, thus permitting the survey even of very extensive environments and highly complex objects. In addition, automatic identification of a huge number of connecting points (matching features) permits self-calibration of cameras, thereby eliminating complex pre-calibration procedures. In this way, the photographic acquisition is freed (but only up to a certain point!) from the complex photogrammetric acquisition rules of the past and regains the feature of great flexibility and “easy acquisition” characteristic of photography as it allows freedom of movement around the object (Fassi & Campanella, 2017).

The product of this type of processing is the so-called “dense point cloud” generated by the “image-matching” process which permits the creation of a complete and accurate 3D reconstruction of an object based on stereo images depicting it (Remondino, Spera, Nocerino, Menna, & Nex, 2014). Thus, even the photogrammetric restitution phase is completely automatic and generates a 3D point cloud comparable –if not superior– in terms of density and achievable resolution to those achieved using a laser scanner (Remondino et al., 2017).

The problem of creating the high-resolution 3D model required for the creation of a precise orthophoto would, therefore, appear resolved (Piatti & Lerma, 2014). Furthermore, and last but not least, the point cloud obtained photogrammetrically also contains metrically accurate information on the colour of the object, thus permitting the creation of high-resolution, metrically correct, texturised 3D models (Stylianidis et al., 2016).

For these reasons, particularly in the world of architecture, we are witnessing the return of photogrammetry because it is extremely flexible (Martinez et al., 2013): it can be applied to large architectural buildings or small decorations, in large- and small-scale surveys, and permits accurate and high-quality rendering in terms of both geometry and colour (Remondino et al., 2016) as for the flooring of the St Mark’s Basilica in Figure 2.

All these features have, in effect, made it possible to carry out the project that we are about to describe, which is still challenging today, due to the size and scale of the representation achieved, but would, just a few years ago, have been impossible in a reasonable time and with reasonable costs.



(a)

(b)

Figure 2: Narthex area: a) DSM; and b) orthophoto. Note how, from the DSM, it is possible, even with the naked eye, to identify the macro-movement in the floor and the discontinuity due to the individual mosaic representations.

3. Photogrammetrical survey

3.1. The mosaic floor (2003-2008)

The mosaic flooring of St Mark’s falls within the category of 2.5D objects: it is generally flat but with marked undulations and significant changes in height due to movements in the substrata over the centuries.

This means that it cannot be simplified with a rectified image, but that its shape may be interpolated photogrammetrically and represented with excellent approximation, even without pushing the modelling to millimetric resolutions, while ensuring extremely high resolution and accuracy in the construction of the orthophoto at “near 1 to 1” scale. This is the main reason why photogrammetric surveying of the floor mosaic between 2003 and 2008 was possible. In fact, while pioneering in terms of the restitution scale required and the dimension, and requiring enormous manual work that took several years, the “geometric simplicity of the flooring” was an advantage, permitting the generation through matching of its DSM at centimetric resolution (a regular mesh of 1.5 cm), impossible to extract in any other way (Fig. 3).

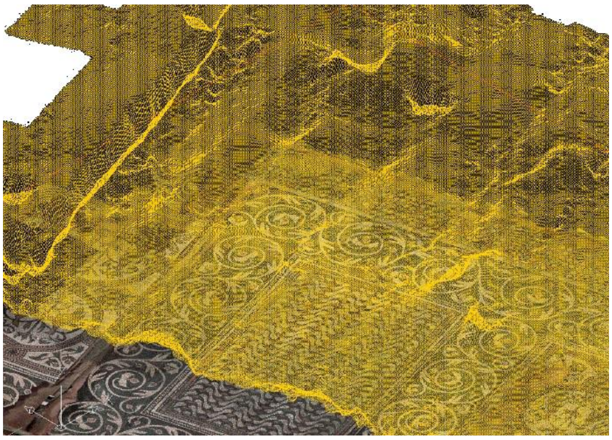


Figure 3: DSM at 1.5 cm resolution and relative orthophoto of a part of the flooring.

3.1.1. Mosaic surveying: the classical method

The survey was conducted using a Rollei DB44 Metric, a semi-metric camera with CCD Phaseone sensor with a physical pixel size of 9 µm and a resolution of 4080 x 4076 pixels. A Zeiss 40 mm F4 focal camera lens was used. The shooting geometry adopted was equivalent to the classic aerial photogrammetry, positioning the camera at a height of approximately 2.3 m with its optical axis perpendicular to the ground and creating longitudinal strips with the classic overlap of 60% between frames (endlap) and 20% between strips (sidelap). The resulting Ground Sampling Distance (GSD) achieved was equal to 0.5 mm. A total of just over 2000 frames were taken (Fregonese & Taffurelli, 2004 and Fregonese et al., 2006).
To facilitate manual recognition of the tie points, these were formed on the ground with some small sights in order to provide at least 9 connecting points per image that could be easily identified by the operator. All these points (approx. 3800 in total) were topographically surveyed using a Leica TCRA 1103 motorised reflectorless total station and levelled using a Leica NA 1203 high-precision digital level. This made it possible to limit the planimetric positioning error to a couple of millimetres and the height positioning error to less than half a millimetre.

The software used was SOCET SET v5.2.0, normally used for photogrammetric plotting of aeroplane flights. The software was, therefore, able to orient only images nadiral to the ground, impeding restitution of some areas in which it was necessary to acquire the photos in a convergent way and forcing the operators to temporarily change the reference systems in order to complete the work. The entire photogrammetric process –from the importation of the images, calibration parameters and Ground Control Points (GCPs) to bundle adjustment, the creation of the autocorrelated DSM and creation of the orthophoto– was performed using the largely manual software. Processing times were very long, both for manual selection of the GCPs/tie points and for the automatic stage of matching and creation of the DSM at resolutions ranging from 10 to 15 mm. The average DSM uncertainty, referenced to the GCPs, was kept below 1 mm, thanks, in part, to the huge number of points surveyed on the ground. The orthophotos were created with a resolution of 0.5 mm through the subsequent manual blending of the various parts to obtain an overall image of uniformly-balanced colour and exposure. A visualisation system based on image pyramid generation was specially created using what was then known as ZoomifyTM, which permitted navigation of the flooring at various viewing scales up to full scale. The final orthophoto of the whole Basilica was created at 0.5 mm resolution (Fig. 4).

3.2. Dome and walls (2013-2018)

3.2.1. The surrounding conditions

As is well known, the boundary conditions determine the methodological choices of a survey as well as the technical/organisational ones relating to conducting field operations. In the case of St Mark's Basilica, two different types of factors influenced the surveying of the elevations: i) the physical and geometrical characteristics of the objects to be surveyed, and ii) the environmental characteristics (Figure 5)

Generally, the architecture of St Mark's Basilica is rather expansive and complex: it consists of three naves, a transept and a number of chapels and apses arranged over two levels, with arches, vaults and domes of various and irregular shapes. These characteristics favour measurement using a laser scanner, which would appear to be the ideal instrument for the acquisition of such large and complex spaces. However, it must be considered that the materials covering the Basilica vary greatly: glass and coloured (often golden) tesserae for the wall mosaics and various types of marble for the flooring or lower parts of the vertical walls.

These materials prove problematic in range-based acquisition as, due to their reflective nature and chemical and physical structure, the data acquired is not accurate (Fassi et al, 2011). During the preparatory phase, it was attempted to verify the effect of the mosaics and marble surfaces on the laser scanner acquisitions. To this end, two laser scanners were used (Leica HDS7000 and Leica C10) which have different data acquisition methods (phase shift for the former and time-of-flight for the latter), and therefore different resolutions, speeds and signal characteristics. Scans were taken for both the mosaic walls and the multi-coloured marble walls, attempting to simulate normal operating conditions. With regard to the mosaics, the two laser scanners provided very different data, as clearly demonstrated in Figure 6, yet neither proved usable for high-resolution surveying of the mosaic. In the time-of-flight laser scan, the point cloud was noisier, with a homogeneous noise level of around 1 cm, while the scan obtained using the phase shift instrument proved less noisy, but contained some localised errors that were more serious in metric terms.

Regarding the mosaics, the two laser scanners provided two very different pieces of data as clearly shown in Figure 6, but nonetheless, neither proved usable for a high resolution survey of the mosaic. In the time-of-flight laser scan, the point cloud was also noisier, with a homogeneous noise level –around 1 cm– while the scan obtained with the phase shift tool proved less noisy, but contained some localised errors that were more serious metrically speaking.

The same trial, conducted on the marble wall and using a sheet of white paper as a reference, clearly confirms (Godin et al., 2001) the penetration of the laser signal into the crystalline structure of the marble.

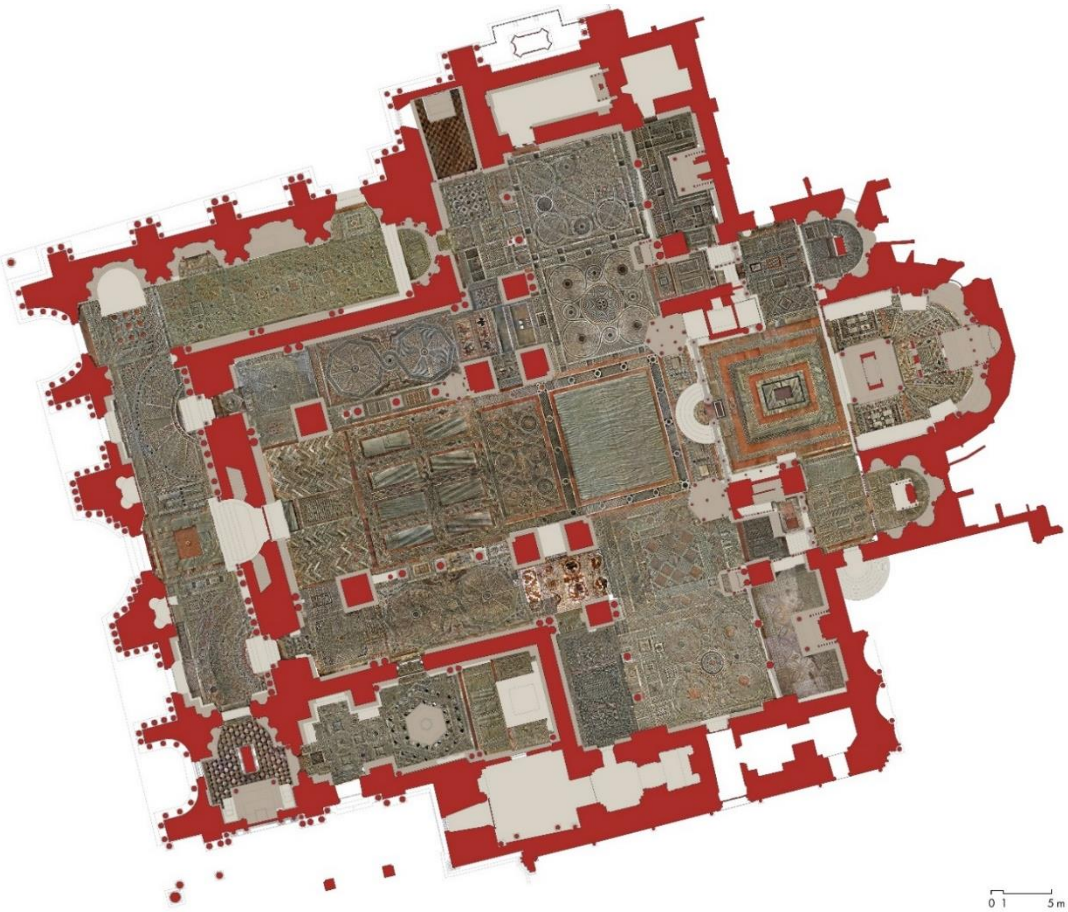


Figure 4: Plan of St Mark's Basilica with the whole orthophoto of the flooring.

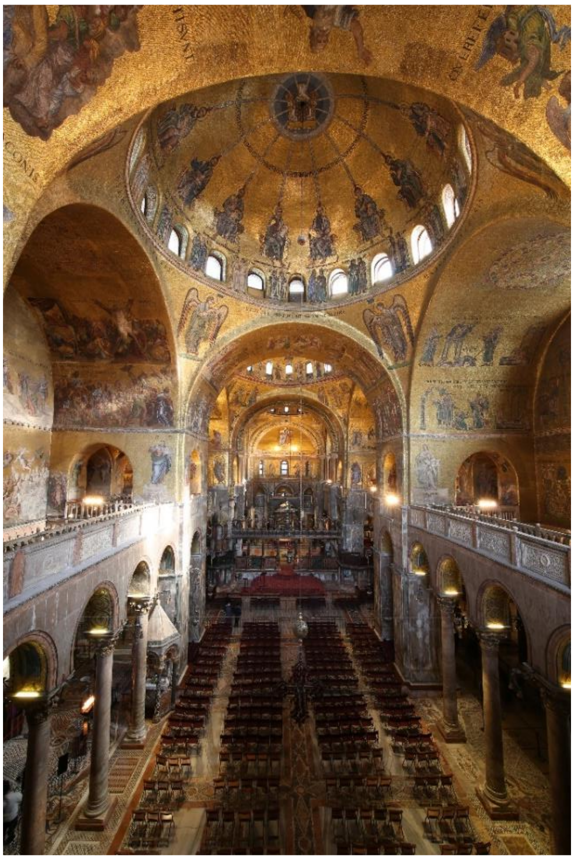


Figure 5: View of the interior of the St Mark's Basilica. Note the mosaics on the walls and the dome and the natural and artificial lighting conditions that characterise the Basilica.

(a) (b) (c) (d)

Figure 6: Analysis of the point cloud resulting from the laser scanning survey: comparison between the scanner and the photogrammetric survey: a) detail of the mosaic surface; b) profile extracted from the photogrammetric cloud; c) profile extracted from the Leica C10; and d) profile extracted from the Leica HDS7000.

Another geometric characteristic that conditions the operating choices –in this case, 3D modelling– is linked to the continuous surfaces that characterise the Basilica. Architecture is generally defined by sharp corners, for example where vertical surfaces, vaults and domes meet, and it is from these corners, in 2D and 3D representations, that architectural designs and models take their form. In this case, however, these are almost entirely absent and the mosaic surface seems to continuously envelop the architecture in its entirety. This means that, especially in the upper, mosaicked part of the Basilica, there are no clear boundary elements: the architecture appears to be "a single object formed from a single piece", and it is very difficult or even impossible to understand where one object ends and another begins.

This entails great difficulty at the modelling phase and little freedom in simplification of objects and, above all, requires complex logical and iconographic division of the elements, particularly for creation and cataloguing of the orthophotos.

Another aspect that complicates the survey phase lies in its history. St Mark's may, indeed, be considered the most important and significant art collection in the entire Venetian dominion of the Mediterranean Basin. In many cases, the capitals, decorations and statues originating from different areas of the world and different historical periods, each with its own specific characteristics in terms of form, size, position and geometric complexity. Moreover, it is very difficult to establish, in advance, a rule and a standard method of proceeding, both for the acquisition phase and for the modelling phase. This makes it impossible to create a standardised library of objects and forms applicable to the entire Basilica.

3.2.2. Contextual features

One of the features for which St Mark's Basilica is famous is the golden light that bathes and characterises it. This light, of great pathos, is a reflection of the ambient light which, entering the large openings and windows of the dome, shines on the golden mosaics and is then diffused throughout the entire space. The artificial lighting, too, was designed to emphasise this effect using a system of warm lights that are reflected in the golden surfaces. The dramatic effect of this light, however, proves problematic when it comes to surveying the object and all its surfaces in an accurate and scientific way to create a product with real colours free from the environmental lighting effects. The colours produced by this light clearly tend towards warm tones and are not compatible with a description of the mosaics using orthophotos. The large windows that illuminate the Basilica also have a negative effect on the survey procedure in that they cause the light (and its reflections) to vary continually within the church, resulting in a lack of uniform exposure in the images acquired. Furthermore, as in all churches, there are many alternative sources of lighting in different positions with different directions, intensities and colours. All this makes it very difficult to achieve well-distributed light and correctly position the camera in order to accurately record the colour and ensure a final uniform exposure (Verhoeven, 2016). It was therefore necessary to shoot images with controlled lighting, taking into account that the natural light from the windows and the existing lighting cannot be eliminated in any way but merely reduced and that the golden and glass surfaces of the tesserae, being extremely reflective, impede the use of spotlights such as those of photographic flashes. For this reason, three Airstar lighting balloons were used: two Sirocco 2500W HMI Hot Restrike ones for use as a pair in large spaces and a small Sirocco 575W for use in narrow spaces or for decorations (Fig. 7). These provide highly uniform 360° lighting with a colour temperature calibrated at 5600°K. Mounted on special stands, they can be adjusted to a height of 8 m and are therefore useful in illuminating even the highest parts of the Basilica or for "blocking" the natural light that shines in. Since it is impossible to work at night, as would be advisable, the problem of combatting the natural light coming from the rose windows cannot be resolved definitively except by choosing the best hours of the day in order to avoid direct sunlight.

Figure 7: Lighting of the baptistery with Airstar balloons.

In addition to the balloons, four adjustable LED lamps (more manageable than the large balloons described above) were also used. These panels were used in surveying the narrower areas, such as the galleries, and where it was necessary to correct the lighting coming from different directions, and were extremely useful for the shadow-free lighting of decorations and ornamentations.

Another factor that caused significant problems during the survey campaign was the continual flow of visitors through the cathedral and the constant presence of restoration workers. The Basilica is open to the public every day for tourist visits and religious services and, naturally, the presence of people does not aid an intensive and wide-ranging survey. Moreover, St Mark's is a great working site on which restorers, carpenters, electricians and marble workers all contribute, at the same time and in different areas, to maintain the building. This practical problem is obviously common when dealing with such important constructions and significantly complicates the organisation of the work. Not only that; it may also invalidate the quality of the work. The need to interrupt and resume work –be it surveying or modelling– requires modification of procedures and practices. It is essential that this problem is considered at the scheduling phase as well as during planning of the methodological and technological procedures.

3.3. Image-based survey

For data acquisition, the technique chosen was that of photogrammetric computer vision which, as previously mentioned, is more correctly referred to today as "image-based" technology. This choice was essentially made obligatory by the impossibility of using the laser scanner due to the characteristics of the materials as described above. In reality, however, it provides an opportunity to work directly with the photos, thus optimising the survey pipeline whose end goals include the creation of 1:1 scale orthophotos of each individual element (Chiabrando et al., 2015).

The acquisition was organised by subdividing the entire space into smaller, identitary parts that could potentially be surveyed independently of one another. This necessitated the use of a suitable, well-materialised and stable topographic grid within the Basilica permitting final georeferencing of all these surveys. It is a classical method, somewhat overlooked today in favour of new automatic and "real-time" 3D technologies, but essential where the architecture is extremely large and complex, survey accuracy is required to be high, and a project taking place over several years must be divided into various phases. The topographic grid also ensures correct verticality of the reference system and overall monitoring of the precision of the photogrammetric phases of processing, point cloud registration and, in general, the entire survey process. The topographic grid used during the current modelling phase is the same one used in previous surveys managed by the Politecnico in St Mark's Basilica (surveys of the flooring, some specific areas, etc.). Following necessary testing of the grid, the possibility of acquiring the information in the pre-existing reference system made it possible to recover the data and manage many surveys carried out previously together with the recent ones.

The acquisition was organised at multiple scales, for two reasons. The first was the need to construct the 3D geometry of the Basilica's general architecture, i.e. a 3D model permitting automatic extraction of measurements (plans, sections and elevations) at a traditional architectural scale (normally between 1:50 and 1:100). The second was to represent the characteristics of the smallest details, according to the requirements of the representation for maintenance purposes.

For the model of the Basilica and its mosaics, the architectural areas were surveyed at a typical scale of 1:20 or, rather, with a GSD around 4 mm, according to the accuracy of the total station. The statuary has a resolution suitable to a scale of between 1:5 and 1:10, or rather with a GSD around 2 mm, according to the necessity of recording a high level of detail (LoD). The entire mosaic apparatus, represented through orthoimages, is represented at the almost real scale with a GSD no higher than 0.5 mm. For the mosaic, the choice was to represent it at a very high resolution according to the necessity to distinguish each single tessera, even if the geometric accuracy is the same as the whole 3D model.

For each individual space, various photogrammetric acquisitions were performed at different scales (Fig. 8). A number of different cameras were used, all full-frame (Canon 5D Mark II, Canon 5D Mark III and Canon 5D DsR) but with different resolutions. This was in order to achieve not only the correct choice of the camera lens, but also high and extremely high resolutions even in the most inaccessible places. In this regard, it should be remembered that the use of fixed or mobile elevators or scaffolding towers was prohibited for acquisition due to tourist management requirements within the Basilica.

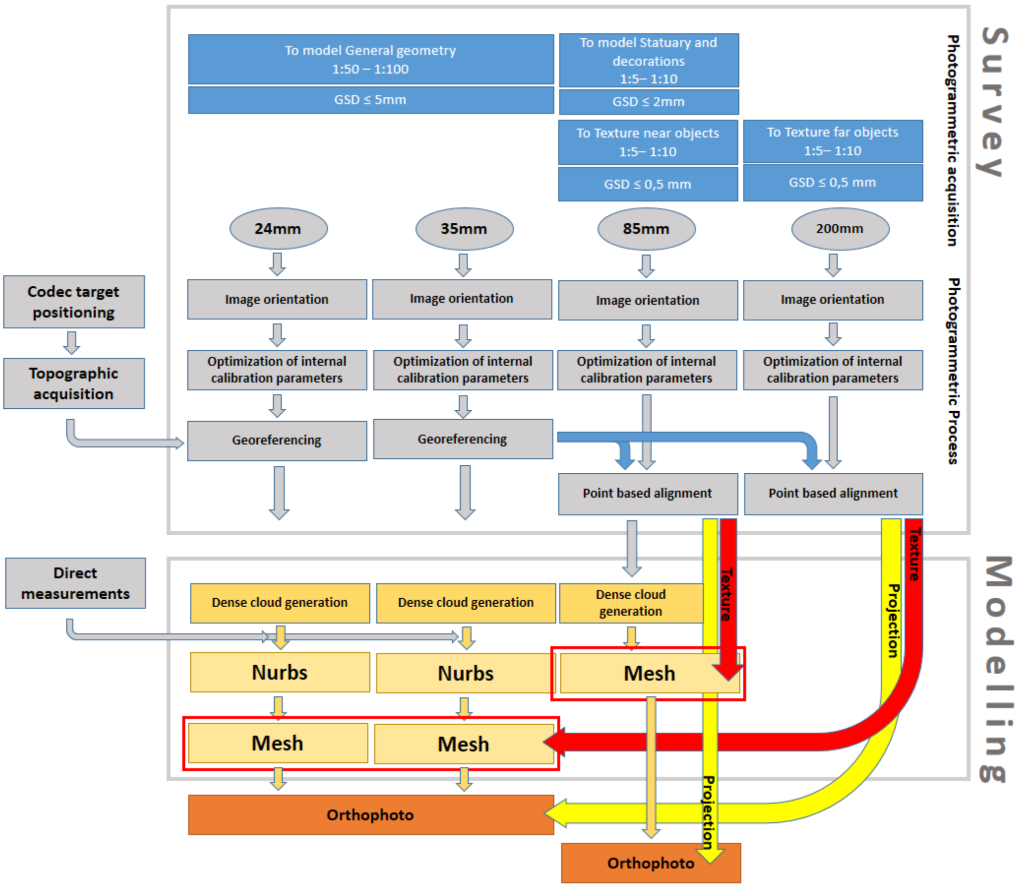


Figure 8: Diagram of the survey and modelling phase.

All acquisitions were therefore carried out from the ground or by making use of the existing architecture (terraces, galleries, women's galleries, etc.) to reach the necessary heights. Small-scale acquisitions performed using 24 mm or 35 mm lenses made it possible to obtain the overall geometry of the space, with sufficient resolution and accuracy to achieve 3D reconstruction of the object and extraction of flat representations at a minimum scale of representation of 1:50. A further acquisition was performed for each space at a higher resolution, usually with an 85 mm lens, in order to obtain further details on the statuary and the mosaic decorations based on texture and orthomosaicking operations. In some cases, depending on the distance of the object to be surveyed, a 200 mm lens was used (sometimes with a 2x converter to achieve 400 mm) in order to ensure a very high resolution sufficient to create orthophotos of the most distant parts. This was the case in the main vaults and the large arches of the lateral naves. The various lenses used to construct the model permitted the achievement of dense point clouds with millimetric resolutions. In this way, we have at least two acquisitions per area acquired: one for the small-scale 3D reconstruction and another to project the texture and generate the orthophoto.

The photogrammetric survey was conducted in accordance with the rules dictated by the algorithms of automatic "image alignment" and "image matching", therefore creating a dense image network with a minimum overlap between frames of 80% and using superimposed imaged schemas nadiral to the object and inclined images to better bind the shooting geometry (Arias et al., 2011). For completely round objects, such as pillars and columns, classic shooting geometry was used with acquisition around the object, taking a shot every 10 degrees.

By adhering to a redundant and rigid shooting geometry, it was possible to position few markers on the scene while still ensuring good reliability of the automatic process. The usage of coded targets was, in any case, necessary and obligatory both for the automatic optimisation phase of the orientation process and for checking the accuracy achieved. During the acquisition phase, certain fundamental rules were abided by in order to optimise the quality and accuracy of the photographs (Menna et al., 2015; Fassi et al., 2015):

- Setting of the camera to manual mode before acquisition so that the focus would remain the same during the acquisition phase.
- Raw shooting of all photos to ensure maximum editing possibilities during post-processing (mainly white balance and colour correction) and to permit correct image blending at the texturing and orthophoto mosaicking phase.
- Maintenance of the same acquisition distance, where possible depending on the space, to avoid having to continually change the camera and to ensure the correct depth of field.
- For data acquisition with long focal lengths, use of a tripod to prevent blurred or micro-blurred photos.

All acquisitions were individually oriented (to individual focal length) using Agisoft Photoscan software. General, small-scale acquisitions, corresponding to more extensive survey areas, were georeferenced in the global reference system through the topographic acquisition of some of the targets positioned on the scene. These photogrammetric blocks then served as a reference for positioning of blocks acquired at a larger scale. In this case, georeferencing was performed using "point based" alignment, available within the Agisoft software, which permits a kind of "cloud-to-cloud registration" but using tie points extracted from the images (and not among the dense point models) between different pre-oriented blocks. This process, which uses the principle of "scale invariance" of the Scale-Invariant Feature Transform (SIFT) algorithm, is more accurate than cloud-to-cloud between dense point clouds and, most importantly, permits registration between two photogrammetric blocks precisely by avoiding the generation of dense clouds, and thus saving a considerable amount of processing time.

The next step, once the various photogrammetric and georeferenced blocks have been oriented in the correct reference system, is the modelling phase, which begins with the creation of a dense point model (through image dense matching) (Remondino et al., 2014). Image matching was always calculated in high mode, i.e. by reducing the original resolution by a factor of four, and image redundancy and abundant overlap ensured a final point cloud density of at least 5 mm.

The first result of the survey was, therefore, a large set of high-resolution point clouds, registered in a single reference system (Fig. 9). This provides a complete discrete point model of the Basilica, which can be viewed and navigated and from which all kinds of metric information can be extracted. This can be done within the modelling software or in any external point cloud viewer. This product is, in fact, an important step in itself since it provides a complete, high-definition survey of all public and private areas of the Basilica.

3.4. The modelling phase

The final objectives of the project were that modelling should have the following three functions: i) to create a 3D model that could be measured at architectural scale for automatic extraction of two-dimensional representations; ii) to be an atlas and a means of cataloguing of all the mosaic decorations in the Basilica but also, at the same time; iii) the metric basis upon which to construct very high-definition orthophotos which will then support all conservation of the mosaics.

To achieve this, there are clearly two options: a) to separately create three types of model of different scales and accuracies, or b) to create a single model capable of performing all three desired functions. The latter option was chosen, which is more difficult to achieve but more convenient from the perspective of time and future updating of the system. The approach adopted was, therefore, that of creating a 3D model of the external surfaces of the walls, serving as both an informative catalogue and a metric model, and also as a model supporting the creation of orthoimages. The modelling phase varied, however, depending on the objects and the LoD and complexity that they presented. Two strategies were therefore pursued. For modelling of the simpler and more linear architectural elements, a NURBS retopology approach was adopted which permitted simplification of the object and provided the opportunity for modification and better manageability within the modelling software. The dense clouds

Figure 9: Point cloud of the whole interior space of the Basilica.

generated photogrammetrically were used to create the final 3D model using the direct modelling approach within the Rhinoceros software. Modelling of the decorations and ornaments, on the other hand, was performed using the classical modelling process starting with a point cloud and, therefore, the creation of a texturised mesh. All these operations were performed entirely within the Agisoft Photoscan software. During the modelling phase, the main difficulty was the impossibility of defining, in advance, groups of objects repeated throughout the church and consequently, the impossibility of simplifying the structure and therefore speeding up the modelling phase (Fassi et al., 2011). This is a very common problem when dealing with cultural heritage and reflects the problem with the BIM approach precisely when dealing with cultural heritage (Nieto et al., 2016): it is not always possible to identify common construction rules for architectural elements without overly simplifying the objects. The modelling choices, in other words whether to follow a BIM approach (Logothetis et al., 2016) or a classical modelling approach (manual modelling from slices extracted from the point cloud), depend on the final objective of the project and the complexity of the architecture (Volk et al., 2014).

Certainly, the relevance/importance of the object in question and the economic burden that one is willing to sustain are two equally important parameters that sway the methodological decision one way or another. For this reason, the idea of constructing the 3D model using a NURBS modelling software, such as Rhinoceros, instead of the more common BIM programs on the market today (such as Revit or ArchiCAD) is completely justified, in that it provides the opportunity to achieve highly complex models that adhere as closely as possible to the actual forms with controlled simplifications that respect the modelling scale required, and in that it is not obligatory (by contract) to perform volumetric modelling. Indeed, for the purposes of the project, the model to be used is not of the walls, but of the exterior surfaces that cover the walls and vaults. Furthermore, the choice to manage the model in NURBS offers a reduced file size –an aspect that is not of secondary importance when dealing with large, complex structures– and the possibilities of integrating different objects within the model and of modifying the object not only during the modelling phase but also in the future in the event of subsequent alterations. This type of approach –direct modelling– is based on the extraction of the object geometry (corners or sections of corners) and the generation of functions from the point cloud. This is a manual operation which can be performed directly in Rhinoceros using the photogrammetric point cloud as a reference and using support plug-ins such as, for example, Pointools for Rhinoceros or Arena4D, programs which can visualise one or more point clouds, including large ones, and use them in the background (in the software itself) to extract new views and sections from the point clouds.

This approach was used for various elements such as walls, mouldings and decorations. In any case, the number and position of the sections are not fixed but must be determined based on the characteristics and state of the object itself. If an object has some deteriorated parts, more sections in that position are required in order to describe those effects.

Subdivision of the survey into smaller parts is achieved, from a practical and organisational perspective using the "work session" function in Rhinoceros, which makes it possible to share the work between all the group's modellers. This sharing method includes the creation of an index that manages the entire series of 3D models and enables more users to navigate and work on them as though in a single space. In this way, the modellers can work in different areas while sharing their own models at the same time.

Figure 10: 3D model of the Basilica, the perspective view is seen from the bottom.

3.4.1. Twofold use of the NURBS model

The 3D model created within Rhinoceros (Fig. 10) is a group of open NURBS surfaces functionally segmented into parts, therefore the following subdivision by objects and architectural categories or by historical/artistic criteria, in other words subdividing the model based on its iconographic representation. This is the case, for example, with large, vaulted surfaces that are subdivided into smaller parts by subdividing the various subjects of the mosaic.

The different architectural models now follow two separate paths depending on their intended use. The original NURBS models are still used within the modelling software itself and are used to automatically extract information, such as plans, sections and 2D views. They are also, however, exported in mesh form, re-imported into the Agisoft Photoscan software, and used as DSMs to create individual orthophotos. Even if the model, as previously mentioned, is simplified, it is, however, more than optimal for these both purposes. The corners and noteworthy geometric characteristics are modelled to the correct resolution and are in the correct position. Simplification causes only a general smoothing of the surfaces and elimination of some irregularities due to external objects such as, for example, built-in furniture or electrical power lines and boxes. The main reason for performing this twofold step (the dense point cloud is exported from the photogrammetric software and re-modelled in NURBS to then be re-imported into the same software as a basis of projection for the orthophoto) is that any imperfections found in the various 3D models created photogrammetrically in the different parts of the 3D model must be corrected, with removal of imperfections and completion of areas of shadow, simplified to lighten the structure and merged with adjoining parts with respect to the topology between them and their continuity. All these operations are much more manageable if performed on NURBS surfaces rather than on mesh surfaces. Conversely, final management of the model, its visualisation in the web catalogue as described below and, above all, the entire procedure of model texturisation and creation of the final orthophotos can only be managed individually or, preferably, using mesh models. Hence the twofold step in the modelling software for the creation of a continuous, mathematical and topologically-correct model and re-transformation into mesh surfaces, which is necessary for particular colour management.

3.4.2. Creating the orthophoto

Before creating the orthophoto using Agisoft Photoscan, the images are carefully selected so that only those with high/very high resolution and those taken from the correct angle are used. All images whose colours are altered too much by light from the windows or which are taken from a bad convergence angle are deleted, and only those considered most chromatically correct and most orthogonal to the surface are kept. For this reason, photos taken using long focal lengths (85 mm and 200 mm) are chosen. These shots did not contribute to the creation of the model, except in exceptional circumstances, but merely serve for the creation of the orthomosaic and for high-resolution texturisation of the surfaces.

On completion of the process, the orthophoto is created with a GSD of 0.5 mm using the best interpolating planes of the architecture as projection planes, manually identified each time in order to obtain the best approximation (Figure 11).

To facilitate the usage of the orthophoto, the entire catalogue was organised into small areas according to restoration needs, the iconography of the contents and the characteristics of the individual architectural elements. This is the case, for example, for the main arches: their intrados is decorated with mosaics and therefore needed to be opened up to achieve a planar representation (Webb et al., 2017). A different operation was required for the domes, where it was not possible to correctly open up the surface into a single plane. The decision was made on a case-to-case basis in agreement with the Procuratoria di San Marco, selecting the part subject to maintenance and choosing the best projection plane (Fig. 12).

Figure 11: Orthophoto of the right transept, west wall, lower register. "The oratio and invention of the body of St Mark". The mosaic is of the first decade of the 13th century. It is one of the first representations with two sections of the Basilica. On the right some details where we can see all tessera, each one with its different dimension.

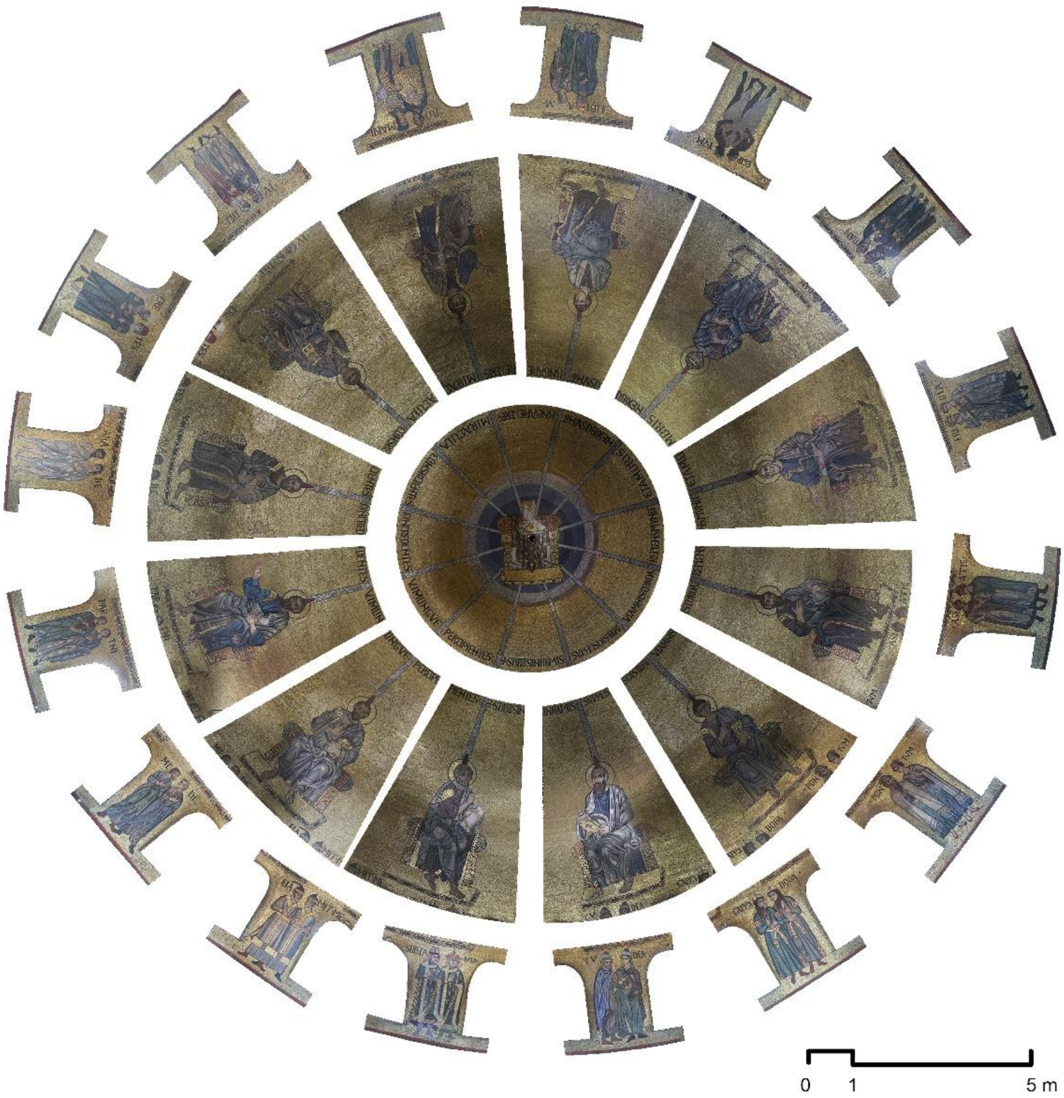


Figure 12: The Dome of Pentecost, subdivided into smaller orthophoto details.

The choice to avoid a "cartographic projection" to describe the dome was due to the necessity, by the restorer, to use the orthophoto as a reference for their analysis. Moreover, the domes are deformed, and therefore very hard to be accurately represented on a single plane.

Once the orthophoto has been automatically created, Agisoft Photoscan post-processing makes it possible to operate on it manually, choosing the most correct images, at the most critical points of the object, to be re-projected. This is an extremely useful process in further improving the final orthophoto at the local level.

3.4.3. Projecting the texture

In order to create an atlas of all the Basilica's mosaics (on the internet, as we will see in the next paragraph), all the mesh models were texturised in Agisoft Photoscan (Fig. 13).

The requirement is to recognise even the smallest details of the object, which means that the texture must be created at high resolution. In order to achieve this, the resolution of the texture atlas and the number of textures necessary to texturise each individual object are calculated based on its size, ensuring a minimum texture resolution of at least 1 mm. It should be noted that the visualisation system, made to measure and described below, visualises textures no bigger than 4096 x 4096 pixels, in order to optimise memory use during the visualisation phase. In order to achieve this, the information and dissemination system was equipped with the possibility of visualising the object in multi-texture mode.

The texturing re-projection operation is metrically accurate since the texture itself is calculated photogrammetrically. It is therefore very useful not only for representation purposes, in other words for visualising the 3D model in a more "realistic" way and navigating within the model like a true 3D catalogue of the mosaics, but also, in particular, for taking measurements directly in 3D using colour points as a measurement reference, for geotagging and including hotspots, and for estimative metric computation.

4. BIM3DSG data management system

The management system used for all the project's data, from the point cloud to the NURBS model, the texturised mesh model and the orthophotos (as in the lower part of the scheme of Figure 14), is an implementation, created especially for St Mark's Basilica, of the BIM3DSG system (realised by 3D Survey Group, Politecnico di Milano) introduced in Rechichi et al. (2016). It is an updated version of the WebBIMDuomo system (Fassi et al., 2015) with which it shares the objective of creating a computer system dedicated to the cultural heritage and developed in consideration of this sector's specific characteristics and needs.

(a)

(b)

Figure 13: Views of the model inside the Basilica, texturized: a) View of the north nave with the columns moulded in the foreground and the surface textured in the background; b) View of the first floor in the north-west area.

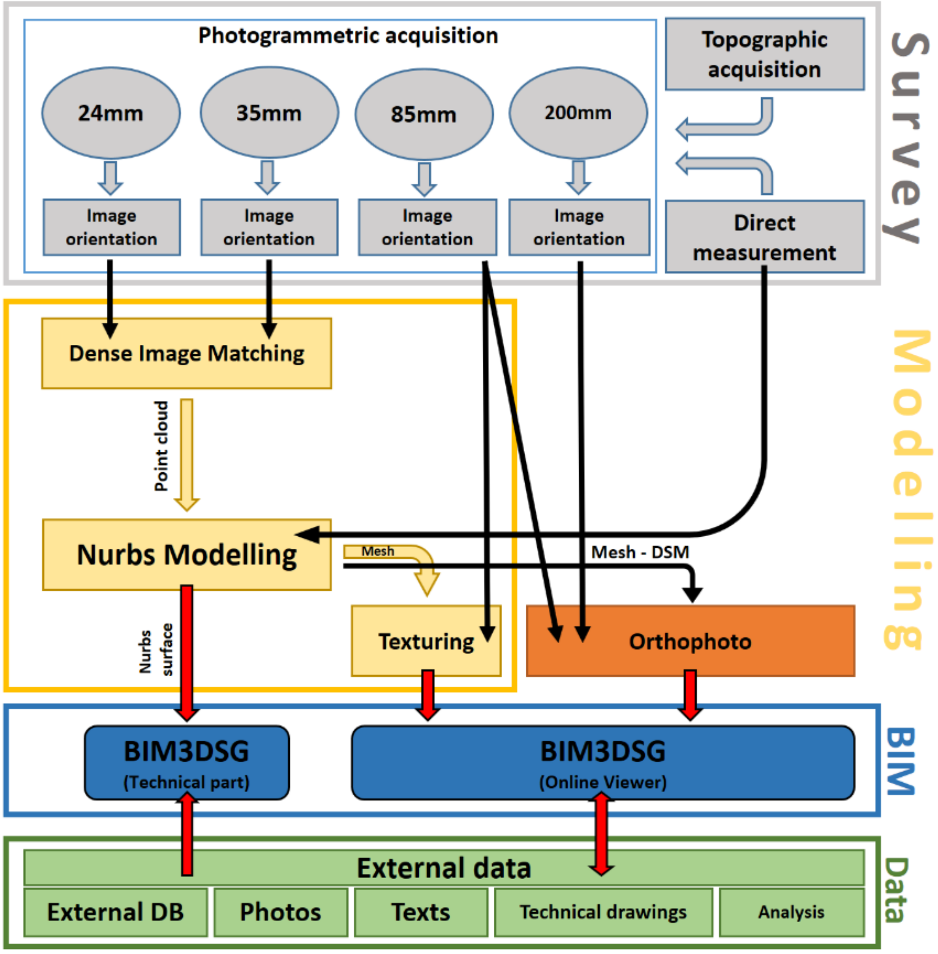


Figure 14: General diagram of the work undertaken, from the survey conducted photogrammetrically using different optics and resolutions to the modelling phase which led to the creation of two types of models.

It is of prime importance to provide some introductory considerations explaining the philosophy of the system. The first consideration is that, despite being very difficult to standardise a computer system in order to obtain a single universal version, the computer system created is able to adapt to the changing needs which are partly linked to the item of cultural heritage and partly to the type of operation and approach planned. In this way, a software system's general architecture may have various versions, each with its own specific characteristics. However, this complexity of conceptual and design has a very simple basic approach that builds all its architecture on the 3D model which acts as a 3D index for all the different types of information connected to it (geometric, diagnostic, design, etc.). For greater adaptability to case studies, the system does not require an external modeller but, rather, manages a model created using external software, both commercial and non-commercial. This ensures, therefore, that any pre-existing workflow will not be interrupted and also avoids the initial difficulties of learning to use it. Currently, as we have seen, the 3D model is created in Rhinoceros using all the power of the software in handling irregularly curved surfaces, but it could be replaced by any other software with the sole requirement of changing the system's interface.

Today, the system is divided into three parts corresponding to a division of the workflow and the various contributions that make up the final system: the modelling side, the user side and data management.

As previously mentioned, the first part of the system (modelling) involves interfacing with a modelling software chosen by the user. Separation of this phase from the general BIM process has removed the need for specialists in data modelling using reality-based data and also saves BIM users from the onerous task of building and/or managing the 3D model.

The second part of the system (the user side) involves a simplified interface for easy and direct access to data georeferenced on the 3D model. This part of the system includes both data entry and system enquiries via a database that may be adapted based on actual needs. All this is web-based and there is, therefore, no need to use specific software (Scopigno et al., 2017). This feature should not be undervalued as it provides multi-platform use of the system so that it is possible to access and enter data and make queries from both desktop and mobile points, thus facilitating its use directly from the working site (for example, using a tablet).

The third part, which is more transparent than the other phases and constitutes the core of the system, is the central server containing all the geometric and logical information, which is dedicated to data management using a PostgreSQL database.

With reference to the specific handling already mentioned (Rechichi et al., 2016), below is a brief summary of the some of the functions of the BIM3DSG system:

a) Real-time viewing and navigation of the model;

b) Loading of the model with various LoD (automatically calculated by the system);

c) Management of NURBS and mesh models;

d) Dynamic database for data management (in input and output);

e) Option of giving the model a theme with specific information;

f) Optimised management of the cache memory to favour access to the model.

4.1. Implementation for the St Mark's Basilica

For the St Mark's Basilica, the starting point was the original architecture of the system (Fassi et al., 2015). From the initial version, a system of functions associated with model visualisation and image management was implemented. In fact, this involved adapting a system conceived for stereometry of the structure (a subdivision of the elements into 3D blocks) to a system focussing on the visible surface of the architecture.

Specifically, the research concentrated on the possibility of:

1) Visualising high-resolution texturised models on the web in real time, thereby implementing the model's texture import and export functions;

2) Connecting, managing, visualising and navigating the high-resolution orthophoto based on the 3D model;

3) Managing and synchronising the NURBS model created in the Rhinoceros environment using the structured mesh provided by the subsequent move to Agisoft Photoscan.

The system's new functions are also based, however, on the renewed management of the modelled 3D data. In order to optimise the work, the BIM model must be segmented to permit efficient data management. Generally, this phase only takes place based on construction considerations, so that vertical walls are subdivided by ceilings and, more specifically, capitals are subdivided by column shafts. In the case in point, in addition to this principle, the model must also be subdivided based on the iconographic content represented on the surface. For this reason, for example, a vertical wall may correspond to a number of orthophotos each of which represents a different mosaic. The model is then segmented manually, and it is the modelling phase specialist who divides the model into individual units in accordance with the end requirements. Each individual unit is imported independently into the system using the BIM3DSG plug-in for Rhinoceros.

In the original software, during export of the model from Rhinoceros to BIM3DSG, each individual element is exported in .3DM format and also converted into .JSON format for online viewing. However, due to requirements of representing marble and mosaic surfaces, it was necessary to use another system since this system does not manage the texturised NURBS model. Export operations can, therefore, follow two separate procedures: in addition to the one described above (to obtain the .3DM format), which provides a non-texturized NURBS model, a second option, created especially for web-based viewing, was added. Indeed, the corresponding .JSON version, required for all LoD of each object, is automatically generated for each individual model.

The two models (.3DM and .JSON) are connected to one another and to the individual object but may be modified independently. Any synchronisation of the two parts is obviously performed manually.

4.2. The texture function

The texture is applied to the model by loading the map (Mullen, 2009), using the UV coordinates that are saved within the JSON file. The system permits the use of JPG and PNG texture images and saves them directly in the database. Textures follow the same procedure as models for optimal access and memory management: the images are saved in a private cache memory which gives almost instantaneous loading times after the first time, even with low-speed connections.

The maximum resolution supported for texturing is 4096x4096 pixels and, where the texture provided by the user is larger, it is automatically reduced during export.

When uploading the model to the internet viewer, it is also possible to choose the LoD of the texture. The maximum level corresponds to the original texture while, for lower LoDs, the image is resized using the pixel resizing technique, halving the size of the pixels at each step.

The choice of LoD for the image is independent of the LoD of the 3D model, for which it is possible, for example, to load a simplified model and a maximum-resolution texture to make the best use of the graphics resources and the available memory in order to achieve the best resolution results. The LoD may be selected while the model is being uploaded and may also be modified in real time, at any moment. This is an extremely useful feature of it and should be decided, once the entire model has been loaded at a low level, to focus on a specific element for more detailed viewing. The various options provided by the system include the option of switching texture viewing on or off at any time.

4.2.1. The orthophoto functions

Management of the orthophoto in the BIM3DSG system is more complex since it is not possible to define a maximum resolution in advance, as is the case for texture. Indeed, it is necessary to maintain the initial resolution in order to ensure the metricity of the orthophoto.

It was therefore decided to integrate open source software into the system permitting the import and management of images without maximum resolution.

Orthophotos (even large ones) can be imported into the system using Ajax File Uploader which divides them during the uploading phase, due to their size, and then reassembles them remotely using PHP. Once uploading is complete, the system automatically processes the image to create a compressed pyramidal TIFF. TIFF is a standard extension, supported by the majority of image processing applications, and is simply a mosaicked image in several pages with each resolution saved as a separate level within the same

TIFF file. Conversion is performed using VIPS. This is a free image processing system performed on the server using PHP. Following conversion, the resulting mosaicked TIFF is automatically moved to the dedicated file (one for each BIM3DSG project) and renamed using a specific convention that makes it possible to associate each file with the specific connected object.

For visualisation, BIM3DSG integrates IIPMooViewer, a high-performance HTML5 JavaScript element. This viewer permits streaming and zooming of very high-resolution images. It is compatible with almost all web browsers and mobile device browsers and provides the option of enlarging, navigating and rotating images. IIPMooViewer is open source and was specifically designed to function with the IIPImage server. It is a CGI open source module written in C ++ which was designed to be incorporated into a web host server such as Apache, used by the BIM3DSG system.

This system, designed for orthophotos, also permits management of all other types of image, making it possible to link other information to the individual object, always represented by images which can be viewed even at high resolution (Mandelli et al. 2017). Operators can manage orthophotos during both input and output processes. After creating the orthophoto using the above method, they can load the image to the BIM system using a simple plug-in which also activates the process of constructing the pyramidal TIFF.

On the client side, once again through the web browser, the user can access orthophotos by selecting an individual object and observing all the linked images in the special interface. At this point, having selected the orthophoto to view, a simple system permits visualisation of the orthophoto and zooming within it, using a navigator to aid understanding of the detail being viewed and a graphic reference that shows the actual size of the image (Fig. 15).

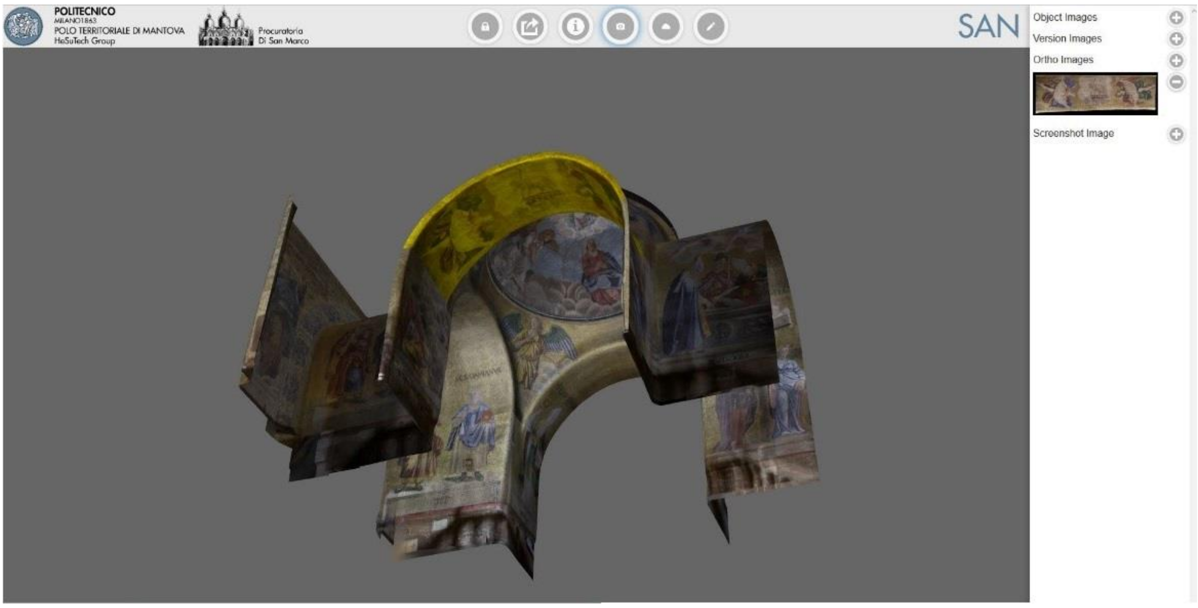
5. Conclusions

The challenge undertaken through this research concerned the possibility of creating high-precision documentation for the decorated marble or mosaic surfaces of St Mark's Basilica (Fregonese et al., 2017). Orthophotos being the most suitable tool to describe a surface that is not flat either geometrically or radiometrically (and all other observations that may be deduced from the colour), the intention was to survey and manage both photographic and metric data.

The experience with the Basilica highlighted a number of very important aspects of the practice of surveying cultural heritage. Firstly, the role of new technology which makes possible to achieve results that were virtually impossible ten years ago. One example of this is the work carried out on the flooring mosaics, compared to that performed today on all other surfaces which have a much higher level of 3D complexity. It should be underlined, however, that the process described in this paper still has some rather complex aspects yet to be fully resolved. The first difficulty is associated with the automation of the software. Indeed, on one hand, making processes more automatic and independent of the human factor is an undeniable advantage. However, experience has shown that software automation fails in the most complex contexts, where the contribution of specialist operators actually contributes to finding the correct resolution of the problem. The most critical phase is undoubtedly the acquisition of images, in which shooting geometry and photographic quality are obstacles difficult to overcome without experience. Other problems remain unresolved, such as the need to control colour during acquisition: in photographs of small objects or very limited spaces, it is possible to control the aspects of exposure, colour, and uniformity and intensity of the light. However, when the dimensions are changed and one moves from a controlled environment such as a photographic studio to any real environment, colour control is an area yet to be developed.

This observation also highlights the way in which applied research complements the theoretical research phase. While, in theoretical terms, this work would not have presented particularly problematic elements, the practical aspect has revealed the true difficulties involved, namely working in crowded places open to the public, the need to modify the survey project (in terms of time and space) based on parameters that are difficult to parameterise (the presence of people, improvised activities, etc.).

Furthermore, there is another significant problem which still remains the bottleneck in many survey processes and, in particular, in restitution of the acquired data. Indeed, 3D data modelling continues to require considerable manual input. Unfortunately, modelling systems of varying degrees of automation that result in mesh solutions do not provide model segmentation that proves functional for architecture. This means that the model, while it may be relatively realistic, cannot be easily used in normal applications. The attempts of almost automatic segmentation are also at odds with the fact that items of cultural heritage are unique and non-standardisable objects. Finally, let us briefly describe the web-based data management system which was designed as a smart computer system for maintenance of the mosaics of St Mark's Basilica in Venice. This system is intended to be a 3D catalogue of all the mosaics, which can be viewed and navigated both in 3D and in 2D at very high resolution. All data collected and created during the course of the project, as well as 3D mesh surfaces, 3D NURBS surfaces and orthoimages, is memorised and interconnected within the BIM3DSG system. The system permits navigation of the 3D model, measurement of linear dimensions and individual point coordinates, adding or updating of information and notes, and connection of external files to the system. Each object is linked to one or more high-resolution orthophotos which can be viewed in full-resolution on a separate web page. This process, implemented for orthophoto management, works for each type of image and is, therefore, a way to bring together many different types of data connected to the individual element (historical images, state of conservation, description of deterioration, mapping drawings, etc.). The BIM3DSG system is used as a data repository, for collection and sharing of information between all users working in some capacity with the mosaics of the Basilica. It is a way to simply but actively use all the data acquired during surveying, that allows the sharing of information with internal operators and also, in the future, with a wider audience.



(a)

(b)

(c)

Figure 15: Screenshot of the orthophoto functions. From the top: a) selection of the element from the 3D textured model; b) view of orthophoto and navigator system; c) maximum detail of the orthophoto.

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