THE PHOTOGRAMMETRIC RECORD

The Photogrammetric Record 28(144): 375–395 (December 2013)
DOI: 10.1111/phor.12040

RECORDING COMPLEX STRUCTURES USING CLOSE RANGE PHOTOGRAMMETRY: THE CATHEDRAL OF SANTIAGO DE COMPOSTELA

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Abstract

This paper describes the photogrammetric 3D modelling of complex buildings using low-cost automatic image matching (AIM), consumer-grade digital cameras and low-altitude imagery. To verify the potential of this method, it was applied to the documentation of a specific case: the towers and roofs of the Cathedral of Santiago de Compostela in Spain, a UNESCO World Heritage Site. The design and development of a mechanism for coping with the elevation, based on telescopic masts, was essential. Models, orthophotos and plans have been obtained to determine and rigorously measure the geometry involved. Thereby it was possible to accurately record the materials and decorative elements based on the restitution of the granite stones. Furthermore, close range photogrammetry made the analysis and quantification of the inclination of the south tower possible.

Keywords: 3D image-based modelling, close range, cultural heritage, historic building, metric documentation, telescopic masts

Introduction

The Cathedral of Santiago de Compostela in Spain is an architectural prodigy of great technical and technological intelligence and is one of the most important religious sanctuaries in the world. It is unique in that it reputedly houses the tomb of the apostle Saint James (Santiago). Its historic buildings are of exceptional value and represent the history and cultural memory of a community (Pegón et al., 2004) so that its digital surveying for documentary and conservation objectives should be considered as necessary, beneficial and responsible.

The development plan for the cathedral defines it as an ideal subject for research, based on modern measurement techniques, given that the excellent state of conservation of the Romanesque building and sculpture allows for many multifaceted observations.

When preparing for a renovation or structural improvement, the original architectural plans may be inaccurate, if they exist at all (Arayici, 2007). Research aimed at planning conservation and/or restoration intervention of historic buildings must be based on up-to-date and precise documentation including geometric shape, architectural characteristics, materials and structural analysis (Genovese, 2005).

Grussenmeyer et al. (2008) describe the spatial data acquisition techniques currently used for cultural heritage documentation projects such as conventional surveying, photogrammetry and laser scanning.

The majority of technicians currently involved in heritage conservation still use traditional methods and techniques (Arias et al., 2007). Traditional manual methods are commonly employed for their simplicity of use and low cost, even though their application can mean the loss of information in the transmission of data from the original to the theoretical model (Yilmaz et al., 2008) and their accuracy is, in many cases, inadequate. Furthermore, as can be seen in Barazzetti et al. (2009), a complete geometric study of an element with irregular shapes is impossible to achieve with common topographic methods such as using a total station.

Photogrammetric methods (Remondino and El-Hakim, 2006), laser scanning methods (Beraldin et al., 2000) and their combination (Guidi et al., 2004) can currently generate high-resolution and accurate 3D models of historic buildings and can provide accurate measurements and objective documentation as well as different perspectives (Campana and Remondino, 2007). The 3D digitisation of architectural elements is important for continuous monitoring of the related spatial information at different time periods (Al-kheder et al., 2009). A typical output of these techniques is a point cloud, that is, a set of points of known X, Y, Z coordinates retrieved from the visible surface of the object under study. Three-dimensional point clouds obtained through laser scanning methods, which are required for the creation of the models, are faster to survey in the field than those generated by photogrammetry. However, the complexity and difficulty of access to specific work areas in addition to those considerations discussed in El-Hakim et al. (2005) and Chandler et al. (2005a) such as the high cost, limited portability and the need for a power supply (cameras use cheap batteries), limits the use of laser scanning in favour of photogrammetric methods in many applications.

The literature explains different approaches for the 3D documentation of complex structures that are the focus of this paper. Many of these studies apply methods based on images (Guidi et al., 2008; Pérez et al., 2011) and laser scanning (Núñez et al., 2012). Furthermore, some authors use multiple data sourcing techniques (combining the qualities and advantages of these different techniques) and have achieved very interesting results in these kinds of structures (Fassi et al., 2011).

Digital models have now generated derivative products such as precise 2D and even 3D drawings which are contributing extensively to the understanding of these complex and detailed surfaces (Yilmaz et al., 2008). In contrast to theoretical or idealised models, these models reproduce the true morphology of the object highlighting the differences between irregular elements or highly variable geometry (Riveiro et al., 2011).

This paper describes the process for the generation of 3D models, orthophotos and plans of the area around the Pórtico de la Gloria in the towers and roofs of the Cathedral of Santiago de Compostela using digital close range photogrammetry. The complexity of the element, the reduced working space in the inner façades of the structure, the height and difficult access, together with the architectural significance of the horizontal elements, required advanced and detailed planning and processing work.

Dense Photogrammetric Matching for 3D Modelling

The increased use of 3D image-based digitalisation methods in recent years is due to the appearance of user-friendly close range photogrammetric software packages such as Photosculpt, 3DSOM Pro, Shapecapture, Image Master, Photomodeler Scanner and 123D Catch. There is a growing professional demand for these products from a wide range of sectors. Proof of this is the extensive bibliography that presently exists covering a wide range of areas such as biology (Chiari et al., 2008), biomechanics (Camomilla et al., 2009), accident reconstruction (Du et al., 2009), geology (Fujii et al., 2009), structural analysis (Hampel and Maas, 2009; Riveiro et al., 2011), hydraulics (Wanek and Wu, 2006), microtopography (Abd Elbasit et al., 2009) and the possible surface modelling of Mars (Di et al., 2008). However, this increased use is most evident in the field of archaeology and cultural heritage with examples in rock and cave art (Chandler et al., 2007; Ortiz et al., 2010), buildings and monuments (Yilmaz et al., 2008; Barazzetti et al., 2011), town planning (Koutsoudis et al., 2007; Núñez and Pozuelo, 2009) and extensive archaeological areas (Chiabrando et al., 2011; di Giacomo et al., 2011; Hendrickx et al., 2011).

Most of the work in these applications employs dense automatic image matching (AIM) on oriented image networks. The technique allows for the automatic creation of dense point clouds from stereoscopic pairs of photographs taken with conventional cameras. This means that the program can record, from oriented photographs, the physical 3D coordinates of the points of the surface under study and store each one of these with its red, green and blue (RGB) chromatic information. To do this it is necessary to identify and reference each pixel (or group of pixels) of an image with its homologue in the second image. A description of these algorithms is available in Remondino and El-Hakim (2006), Caballo (2009) and Orteu (2009). Until recently, the software that allowed the creation of point clouds comprised photogrammetric products for complex work such as the Z/I Imaging SSK ImageStation from Intergraph (used by Aguilar et al. (2005) for mapping small areas) or Leica Photogrammetric Suite (used by Chandler et al. (2007) for recording rock art), both designed for specialised aerial photogrammetric applications and consequently very expensive (Chandler et al., 2005b).

The inclusion of AIM in close range photogrammetric software has raised the status of photogrammetry to that of other techniques such as the use of laser scanning. Examples of comparative studies of both techniques (Kadobayashi et al., 2004; Rizzi et al., 2007; Sturzenegger and Stead, 2009) and their combined use (El-Omari and Moselhi, 2008; Al-kheder et al., 2009; Lerma et al., 2010) confirm this. Multi-image-based matching techniques have also been developed and have been effectively applied to historical buildings (Koutsoudis et al., 2013). AIM now allows for the recording of X, Y, Z coordinates of several hundred-thousand points per minute, which substantially improves on the thousand points per minute in Chandler et al. (2005b); it can digitally represent, with great detail and accuracy, the irregular surfaces of highly complex elements.

The final quality of the 3D model is directly related to the point clouds generated through AIM and this, in turn, depends on the quality of the photographs and imaging geometry. A realistic and uniform dense point cloud without holes and noise is achieved with frontal images (with the axis camera perpendicular to the object's surface), which means having a stereopair for practically each face to be modelled. With this in mind, it is clear that to survey vertical elements of low height such as walls or façades, it suffices to take photographs at ground level. This does not apply, however, when modelling elements, or parts of elements, that are more horizontally inclined irrespective of whether they are at ground level or in a more elevated position such as cornices or wall crowns. In these cases, therefore, it is necessary to take the photographs from the air, or from an elevated platform, with the camera in a nadir-looking position. Visibility occlusions and double projection problems are discussed in Al-kheder et al. (2009) where only ground-level perspectives are used.

The fundamental question is to decide at what height to elevate the camera to acquire the point clouds; for this it is necessary to establish the required spatial resolution and accuracy, both vertically and horizontally. The most logical way to augment the resolution and precision of the spatial information is to move the sensor closer to the object (Smith et al., 2009). However, the higher the camera, the greater the surface area covered by the photographs and so the more efficient the work. The height of the camera is, therefore, a balance between the requisites of accuracy/resolution and efficiency. Archaeology, for example, requires centimetre resolution which limits the altitude to below 200 m (low-altitude photography). In many cases, the excessive rental costs of planes and helicopters, the impracticability of the target zone or flight altitude restrictions limit their use as a platform for photography (Smith et al., 2009). Alternatively, a wide variety of devices are used to elevate the camera: paramotors, cranes, scaffolds, masts, wires, balloons, kites or unmanned aerial vehicles (UAVs) which include radio-controlled model helicopters or aircraft. These can elevate consumer-grade (non-metric) digital cameras to obtain stereo photography suitable for AIM (Chandler et al., 2005a).

Case Study: Towers and Roofs of the Pórtico de la Gloria in the Cathedral of Santiago de Compostela

The cathedral is located in the old town of Santiago de Compostela in Galicia, north-west Spain (Fig. 1). The old town, with its Romanesque, gothic and baroque buildings, is one of the world's most valuable architectural heritage areas and a famous pilgrimage site. The basilica, constructed following the discovery of the bones of the apostle Saint James (Santiago) in approximately AD 818, was completely destroyed, together with the city, by

Fig. 1. Location of the Cathedral of Santiago de Compostela. (A) Obradoiro façade of the cathedral. (B) Survey area of the roofs of the cathedral.

the Muslims at the end of the 10th century. The city was rebuilt during the 11th century around the apostle's tomb, which had not been plundered.

The main body of the cathedral possesses a Romanesque structure: its plan is in the form of a Latin cross, with choir, deambulatory (cloisters) and radiating chapels; the interior space is magnified by a great number of galleries. Building continued throughout the 12th century and drew to a close in 1188 with the erection of the Pórtico de la Gloria at the main façade.

After the consecration of the basilica in 1211, the shape of the cathedral has continued to change with the construction of adjacent spaces and new façades, during the renaissance, baroque and neoclassical periods. Minor alterations have continued ever since leading to the present 21st-century cathedral.

The moisture found in the sculptured area around the Pórtico de la Gloria and caused by water ingress from the roofs, has instigated the implementation of an emergency restoration project. The aim of the renovation of the roofs is to eliminate this damaging infiltration (of water and salt efflorescence) into the granite stone. The emergency restoration project team is in possession of a photogrammetric plot (carried out in 1989 by the Spanish Ministry of Culture), and another showing the planimetry (developed by the School of Architecture at A Coruña, Spain). However, these studies are not considered adequate for the analysis of water damage as they do not include the restoration project area and are not sufficiently detailed and accurate for the purposes of the project team.

The work presented in this paper falls within the remit of the emergency project and is intended to record the present condition of the monument prior to the commencement of restoration work. The area to be modelled comprises part of the two towers of the cathedral (the bell tower (south tower) and the "Carraca" (north tower)), together with the tribune gallery and adjoining areas. The aim of this work is, therefore, to acquire, process, record and present the necessary data to determine the position and the existing form, shape and size of the aforementioned parts of the towers and roofs of the Pórtico de la Gloria. The created 3D models will permit the creation of stone-by-stone plans of the elevation of the façades and different floors to the degree of detail necessary to represent the perimeter or boundary of each stone with a minimum of 30 points. This high-resolution digital planimetry is essential for an understanding of the building and it will serve as a solid and reliable base from which to determine the renovation and maintenance activities to follow. This graphical information will allow architects to plan the renovation and test various construction options (Huber, 2002).

Methodology

The complexity of the project can be explained by four factors: height, accessibility, time restrictions and weather conditions. Height is the most challenging aspect given that it is necessary to capture, at close range, those elements that are to be found at higher levels such as cornices, baroque terraces and the Romanesque trays of both towers, the latter being one of the principal elements for analysis in this study. The limited space available in some areas, such as those situated between the north tower and the tribune, the latter and the south tower, or the hollows in the central gable, means that the photographs have to be taken, in some cases, within 3 m of the object. Another restriction related to the project's timeline; as an emergency project, the time available for taking the photographs was conditioned, from the start, by the subsequent erection of scaffolding and a provisional protective covering to allow conservation work to proceed (A in Fig. 2). Had the scaffolding been erected prior to photography, this would have obscured certain areas and impeded the possibility of the 3D modelling process. In addition to these obstacles, the need

FIG. 2. Taking photos on the roofs. A shows the scaffolding. B, C and D depict the consumer-grade camera and tripod, E shows lifting the telescopic mast and the aerial poppet-head.

to protect the equipment being used from the rain must be mentioned as it rained for a total of 20 days during the month in which the survey took place.

With these considerations in mind, close range photogrammetry was selected to develop the plans and to model, with the required resolution, the highest zones or upward-facing surfaces, with the resulting financial and time costs. When it was necessary to speed up data recovery, because of weather conditions, the 3D photogrammetric survey, contrary to what might be supposed, allowed for the rapid completion of fieldwork, photography and post-processing record analysis.

The cost of a complete photogrammetric set of equipment (including software, camera, PC and accessories) did not exceed €6000 (purchased in 2011). The existence of flush-jointed stones, which are only identifiable for restitution through photography, also makes close range photogrammetry a particularly suitable technique for this purpose. Laser scanner technology, given its high cost, transport difficulties, time investment and the complexity of its data management, gives rise to problems of implementation when applied to certain areas of fieldwork (Campana and Remondino, 2007).

EQUIPMENT

The software used in the present work was Photomodeler Scanner 2011, version 6.3.3 (Eos Systems, Vancouver, Canada). The photographs were taken with a Canon EOS 550D camera with a CMOS sensor of 18 megapixels (5184 × 3456 pixels; 22·3 mm × 14·9 mm). This non-metric digital camera was used in conjunction with a Canon EF 20 mm 1:2·8 objective lens. The pixel size was 4·3 μm × 4·3 μm.

Alternative systems to elevate the camera were considered. Kites are the most economic and are appropriate for a range of applications because they can be launched quickly from the ground (Aber et al., 2002). However, the need for suitable wind speed conditions, limited manoeuvrability and the presence of vertical elements invalidate their use in this project. Balloons and dirigibles are also economically attractive but, like kites, are susceptible to wind conditions (Johnson et al., 1990) which can compromise the photographic equipment and data quality. UAVs are, generally, much more expensive and their rental requires the assistance of a trained operator (Eisenbeiss, 2009). A telescopic camera mount (or mast), like kites, balloons and dirigibles, is inexpensive but is much less susceptible to wind conditions. Their use is common in the professional world of photography as a result of their portability and manoeuvrability in the field, although the latter consideration depends on the height at which one is working. An example of the use of a mast in photogrammetry, applied to monitoring streams, can be seen in Bird et al. (2010). Other devices often successfully used in photogrammetry, such as scissor lifts, articulating booms or telescopic booms, cannot be employed in this study because of ground features and accessibility in the project area.

The mast was selected as the most suitable device for this study because of the need to generate plans from a 3D model with high resolution and accuracy in a complex environment (in terms of its geometry and location), the adverse weather conditions and considerable spatial limitations. The elevation device designed comprises three principal parts: the lift telescopic mast (LTM), the aerial poppet-head (APH) and the ground control unit (GCU). The LTM is a commercial manually extendible device and is constructed of lightweight materials (aluminium and plastic). The working length of the mast is set at 5 m and the APH is mounted on the top of the LTM. The APH is of two types: when the LTM is positioned vertically, a simple APH (s-APH) is selected with movement about the vertical axis (only) and operated manually (E in Fig. 2). However, when the LTM is positioned horizontally, a complex APH (c-APH), with movement about both the vertical and horizontal axes, is used and operated by remote control. In both cases, the APH has a remotely controlled trigger and wireless video transmitter. The GCU comprises multimedia glasses and a wireless video receiver which allows for the instantaneous visualisation of the camera view; it is equipped with a live-view function and a hand-held radio-controlled device for controlling the camera rotations (azimuth and tilt) and the shutter. The s-APH substitutes the radio-controlled device with a simple system of cords and a trigger operated at a distance by a cable. The device is designed to be operated by either one person (LTM in a vertical position with a s-APH) or two people (LTM in a horizontal position with a c-APH).

Additional metric instruments included a Pentax R-326EX total station with a mini prism and a 5 m long steel tape measure, with a maximum error of 1·3 mm, which are used in order to georeference the model and check the accuracy. Targets, a PC, a computer-aided design (CAD) program for the restitution, a tripod and a folding ladder complete the necessary equipment to develop this methodology.

Photogrammetric 3D Modelling Process

The methodology involved is based on images derived from AIM and is composed of the four simple steps outlined by Remondino and El-Hakim (2006): design; 3D measurement; structuring and modelling; and texturing and visualisation. The methodology in this paper includes a fifth step: the evaluation of the accuracy of the acquired 3D

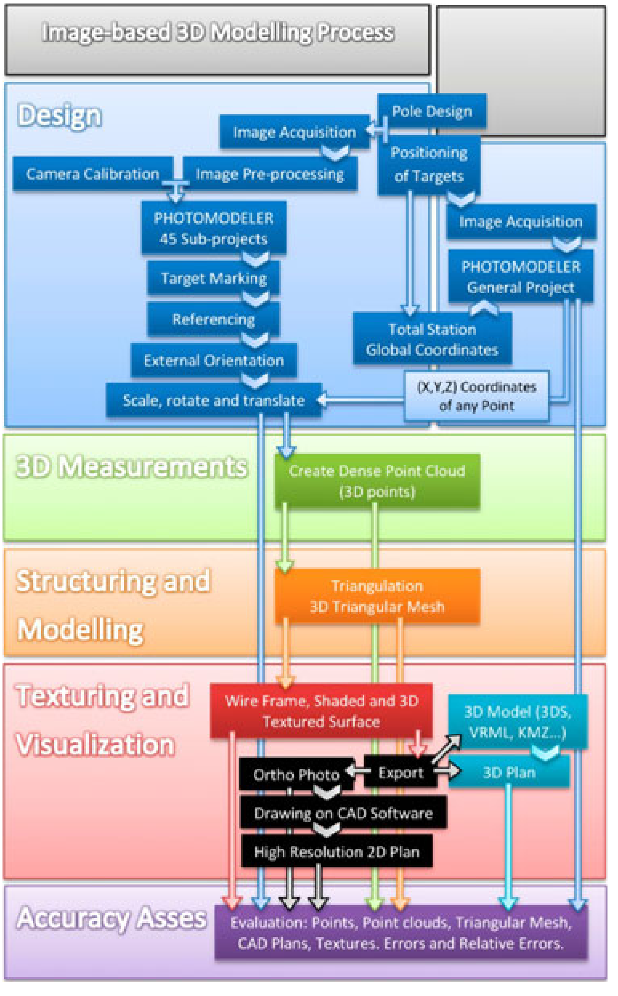

FIG. 3. Image-based modelling process.

photogrammetric models (Ortiz et al., 2010). Its application to historic buildings can be seen in Fig. 3. The five steps in this methodology are described below.

Design

The design includes all the steps required for the photo shoot and their subsequent preparation: calibration file assignment; target marking; ground photo recording; and exterior orientation.

Calibration File Assignment. Calibration (interior orientation) is necessary to resolve the interior parameters of the camera and is achieved using Photomodeler calibration software.

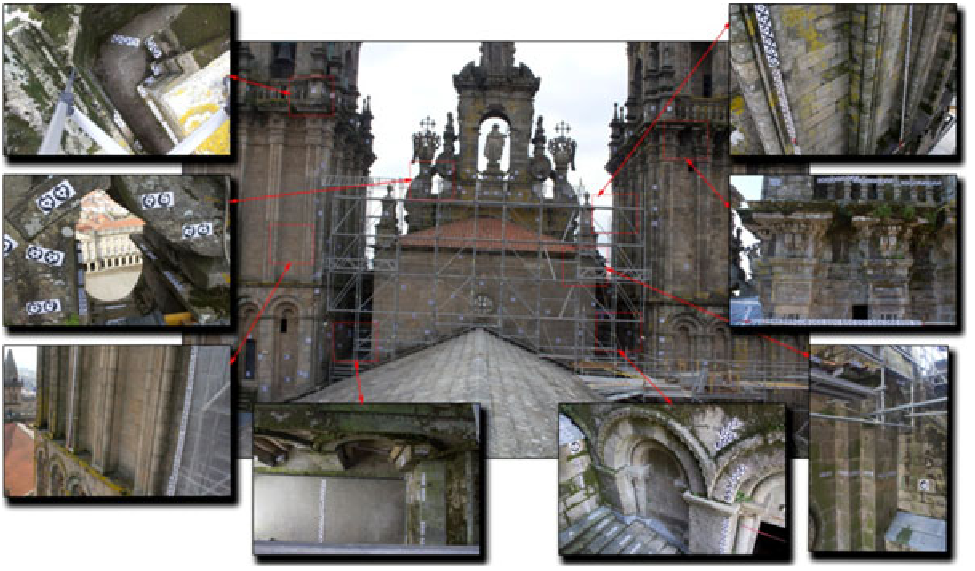

FIG. 4. Examples of camera capture geometry: general photogrammetric survey (central larger photograph) and detailed sub-project surveys (eight peripheral images).

Target Marking. The next step involves the positioning of targets on the monument. The coded targets are predefined markers highlighting the location of a point and carry information that is easily recognised by the photogrammetric software. Photomodeler recognises, marks, codes (according to the ring code) and automatically references those targets for each photograph. In this project 300 lineally printed coded targets on foam board panels were used. The targets were arranged in a line to provide placement on mobile structures. They can be seen in Figs. 2 and 4.

Ground Photo Recording. To prepare for the image acquisition stage, a detailed study and reconnaissance of the work area was carried out. To achieve a complete photogrammetric model of both towers and the tribune, it was decided to carry out two different photogrammetric surveys: the first one divided the work area into 45 sub-projects in order to attain the detail required; the second one, covering the complete working area, is a general photogrammetric survey to fit the pieces of the sub-projects together. Because of the narrowness of certain areas, many of the sub-projects had to be subdivided to include targets (so that they would not appear in the final model) and also to work with sets of a high number of photographs to model each sub-project with accuracy (about 65 images for each one). In those cases where support targets had to be used, they were attached to the element with removable putty. Ground photo recording is used in those areas immediately affected by the scaffolding and, to do this, the work had to be closely coordinated with the scaffolding company. The parameters of the configuration remained constant for all the photographs: raw format, fixed zoom, focus ring adjusted to infinity, exposure time 1/250 s with an automatic aperture and ISO 400. In total, 3000 photographs were taken at distances of between 2 and 7 m for the detailed sub-projects, and up to 30 m for the general photogrammetric survey. Consequently, the object pixel size varied between 0·4 mm × 0·4 mm and 1·5 mm × 1·5 mm (Fig. 4).

Exterior Orientation. Once the photographs are taken, it is necessary to reference them and to proceed with the exterior orientation to scale, translate and rotate the 3D digital model of each of the 45 sub-projects. These three steps were achieved on the basis of the coordinates of three points in each sub-project, which were obtained with another general photogrammetric survey which was previously carried out using targets, total station and the same photogrammetric equipment. A system of general coordinates was applied based on two existing survey control marks located on the ridges of the cathedral. This general survey, based on these coordinates, can accurately determine the X, Y, Z coordinates of any indentation, discolouration, crack, target and other feature, existing in the work area and so scale, move and rotate the 3D model of each sub-project to generate the complete model. The topographic surveying was performed basically from one station placed on one of the known marks of the ridge, but in order to register certain details of the working area, two new stations were located beside each tower (in the places shown in the two lower photographs in Fig. 4). Their positions were fixed by using the intersection method.

3D Measurements

The referenced dense point cloud is automatically created from a stereopair with a known external orientation. The 3D surface is measured in a routine procedure integrated in the software which correlates textured areas of stereoscopic pairs using AIM for a cloud of coloured points which represents the morphology of the surface of the element.

This means that the program is capable of registering the coordinates of the surface of an object at more than 250 000 points per minute together with its RGB colour information. Its density is calculated according to the degree of likeness to the real object and the authenticity required and this results in the final number of points; therefore 4 points per cm^2 were established in an attempt to balance the quality, degree of realism and the impact on computer resources (Fig. 5). To be viewed together, the final number of points for each sub-project was diminished through a reduction stage.

FIG. 5. Point cloud example of 4 points per cm^2 in colour. A shows the face, and B an arcade, of the north tower.

Structuring and Modelling

Once the point cloud was obtained, it was transformed onto a polygonal surface. Polygons, in this case triangles, are usually the most flexible way to accurately represent the results of 3D measurements and provide an optimal surface description (Remondino and El-Hakim, 2006). This step involves the triangulation of all points to obtain a 3D triangulated irregular network (TIN). Every sub-project is constructed of between 200 000 and 500 000 triangles.

Texturing, Visualisation and Photogrammetric Restitution

Following the creation of the polygonal grid, the results can be visualised in wire-frame form, using a shaded and/or textured mode. Once the internal and external orientations of the images are known, their corresponding coordinates are calculated for each vertex of each triangle on the 3D surface. The RGB colour values of each triangle in the project are then linked to the surface (Remondino and El-Hakim, 2006). In this work, textures have been assigned manually; even though the program can do this automatically, it cannot process criteria such as light quality, focusing or the presence of objects extraneous to the building (such as scaffolding). In complex structures such as this one, the aesthetic results are often inadequate if the texture assignment is not performed manually. A high-quality 3D model with photorealistic texture is obtained for each sub-project. An orthophoto is then created with Photomodeler and can be exported to any CAD program for the photogrammetric restitution to plot the plan.

Accuracy Assessment

In order to evaluate the success of the project output, it is necessary to review the accuracy of the photogrammetric work and the validity of the 3D model output. It is important to achieve a good finish in the models at an aesthetic level and to determine to what extent the dimensions of the model correspond with reality; accuracy therefore has to be assessed. As can be seen in the sequence in Fig. 6, photogrammetry allows for the

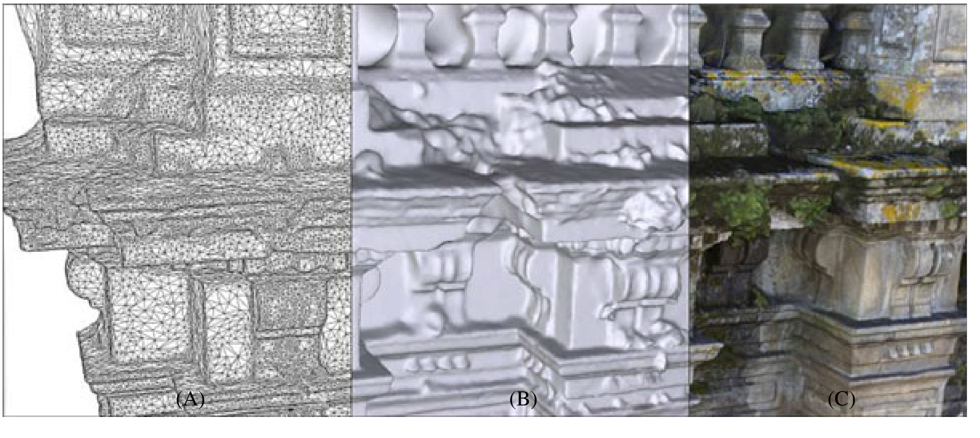

FIG. 6. Triangulation (A), shadowing (B) and texturing (C) of the cornice and baroque terrace of the north tower.

analysis of errors at diverse stages of the modelling process: point clouds, triangular mesh or plan development. It is also possible to establish if the textures are correctly positioned or not. As the plan is developed on the basis of an orthophoto and this, in turn, is based on the 3D model, errors will have accumulated so that, by studying the accuracy of the final product, it is possible to determine the maximum error in the plans and whether it is acceptable or not. An accurate control system, depending on the 3D model application, has to be established. In fact with some applications, such as virtual tourism, precise geometry is not as critical as the photometric accuracy (Huber, 2002), but in other cases, including the current Santiago Cathedral work, this aspect is crucial.

The quality of the measurements, carried out with Photomodeler, is determined by the metric quality of 20 distances between 40 check points randomly distributed throughout the project. The distances between check points were measured with a steel tape, valid for checking accuracy at this scale. The check points were identified in the plans and the distances between them were directly calculated in the CAD application used for the restitution. The error recorded in these measurements between check points was then analysed.

The metric quality of the method was tested using some descriptive statistics of the error and a *t*-test paired two samples for means. The *t*-test was run in Microsoft Office by comparing the tape measurements with the transformed distance value obtained on the final plan.

With regard to the accuracy of the photogrammetry, the mean error of the 20 observations is below 1·3 mm with a maximum absolute error value of 10 mm. Table I shows the descriptive statistics of the accuracy assessment on the final plan of the cathedral. Based on these statistics, the photogrammetric method shows a high metric quality.

TABLE I. Results obtained at the accuracy assessment stage for 20 check distances.

True distance (m)	*Plan distance (m)*	*Error (m)*	*Absolute error value (mm)*
2·783	2·783	0·000	0·000
3·015	3·017	−0·002	0·002
1·470	1·477	−0·007	0·007
0·794	0·794	0·000	0·000
3·029	3·025	0·004	0·004
3·573	3·573	0·000	0·000
1·606	1·607	−0·001	0·001
3·492	3·485	0·007	0·007
2·631	2·638	−0·007	0·007
3·330	3·324	0·006	0·006
2·923	2·933	−0·010	0·010
0·946	0·951	−0·005	0·005
4·661	4·663	−0·002	0·002
3·025	3·031	−0·006	0·006
1·285	1·280	0·005	0·005
1·486	1·487	−0·001	0·001
1·133	1·132	0·001	0·001
0·709	0·707	0·002	0·002
2·155	2·162	−0·007	0·007
2·126	2·128	−0·002	0·002
Mean (m)		−0·001	0·004
Standard deviation (m)		0·005	0·003
Minimum value (m)		−0·010	0·000
Maximum value (m)		0·007	0·010
RMS (m)		0·005	

Results and Discussion

The 3D surveying of this monument has been a challenge because of its complexity. First, the need to acquire high-quality photographs requires a very good knowledge of digital photography. Second, the planning of such a project requires significant experience in photogrammetry, given that this is the key to success in any complex project. Third, the required use of targets to obtain a high degree of accuracy is an additional difficulty with the technique.

With regard to simplicity and cost-effectiveness, only one team of two people using a single camera were required to meet the deadlines; the cost of equipment, approximately €6000, includes the camera, software, mast and PC. The entire project was completed by two people over a period of 22 weeks: the photography took 8 weeks; the orthophotos and 3D models were obtained over a period of 6 weeks while the stone-by-stone photogrammetric restitution lasted 8 weeks.

The use of a mast to take "aerial" photographs can capture details in the highest areas such as the Romanesque trays or the horizontal platforms in baroque decoration, and avoids the visibility occlusions and double projection problems when only ground-level perspectives are used. In the latter case, the computer program extrapolates the occluded area which clearly means a loss of realism and objectivity in the shaded 3D model and results in errors in the designation of the texture. This, in turn, affects the quality of the orthophotos and the plans. The use of the elevated camera mount system is decisive in obtaining photographs at close range in the highest and most inaccessible areas and achieving viewpoints essential for obtaining 3D models with the degree of detail and definition required.

The 3D modelling process resulted in a cloud of several hundreds of thousands of points for each sub-project and the corresponding surface, once structured and modelled, was formed by thousands of triangles. All sub-projects were merged together: the 3D models were joined with Photomodeler in a single file employing the coordinates of the general photogrammetric survey to create the complete 3D model of the project (Fig. 7). In addition, all sub-projects were merged with CAD software following the photogrammetric restitution of each sub-project (Fig. 8). The degree of detail achieved in the modelling of the various complex elements, such as the rose windows, can be seen in Fig. 9. Detailed photo-textured and shaded 3D visualisations and a 3D model of accessible parts can be seen in Fig. 10. It should be pointed out that these models are complete and include all the surfaces in the work area, whatever their orientation and irrespective of the complexity of the various façades and elements. The 3D models generated are then exported in various digital formats (such as 3DS, 3DM, VRML and KMZ).

All areas were modelled to the required resolution (4 points/cm^2). The density of the point clouds is very regular throughout the project. The generated orthophoto (Fig. 11) has a very high resolution given that the photographs were taken at close range to allow for the high level of detail (Fig. 12). The high-resolution orthophotos, obtained through close range photogrammetry, allowed complex details to be easily drawn and with a precision in the order of millimetres irrespective of the size of the structure. This degree of precision can be achieved thanks to the high quality of the 3D model, the high-resolution orthophoto and the high number of points per restituted stone. The use of targets during the exterior orientation step automated the process which again contributed to the high level of precision. The use of an algorithm capable of determining these points without targets under different viewing conditions, included in Photomodeler Scanner, was experimented with. However, the results

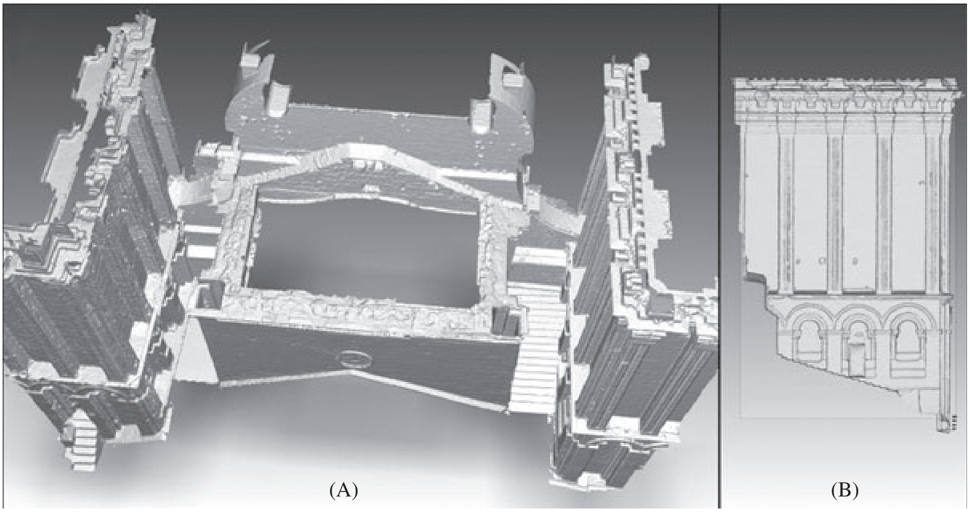

FIG. 7. Complete 3D model of the working area. A shows a general top perspective and B the north tower façade.

obtained were worse and demonstrate that targets are necessary to assemble multiple sub-projects in highly complex elements of this type.

It is also possible to digitise directly on the record of very dense point clouds, taking advantage of the fact that each point contains RGB information as if it were a photograph (using a screenshot). This system is accurate and fast with clouds of very high density and it is effective when used in the restitution process of elements of small dimensions, but it is impracticable to proceed with it when the structure is too large.

In terms of the utility of the 3D model output for the analysis of historic buildings, the way conservation specialists (architects, restorers, archaeologists, cultural heritage conservationists and so on) document and analyse panels is likely to improve considerably with current 3D data following the described methodology. Digital photography, in addition to allowing a high-resolution and photo-realistic 3D model of an object, provides 2D and 3D information in different formats and media.

The photographic set, created by the project, can also be used to analyse and study the element in conjunction with the model itself and the 2D and 3D restitutions. In a monument which is the size and complexity of a cathedral, the development of the plans defining its construction is expensive but essential for an understanding of the building and as a solid basis for future developmental activity. Thus, the greater the quality of these plans, the more effective and reliable the subsequent development will be. For example, in the current study 3D recording using close range photogrammetry has permitted the analysis and quantification of the inclination of the south tower of the cathedral (approximately 2%) as can be appreciated in Fig. 8 (left side). (It should be pointed out that an inclination of the south tower was detected and rectified between 1667 and 1670 (Navascués and Sarthou, 1997).)

The inclination of the pilasters can be easily seen when observing the tower between the lower roof and the baroque cornices of the balcony. Analysing the plan from bottom to top, the lower stairs that give access to the door of the façade are horizontal. The pilasters and rows of stone between the roof and the intermediate tray are inclined at 2% with respect to the vertical. The pilasters between the intermediate tray and the upper cornice have two clear sections; a

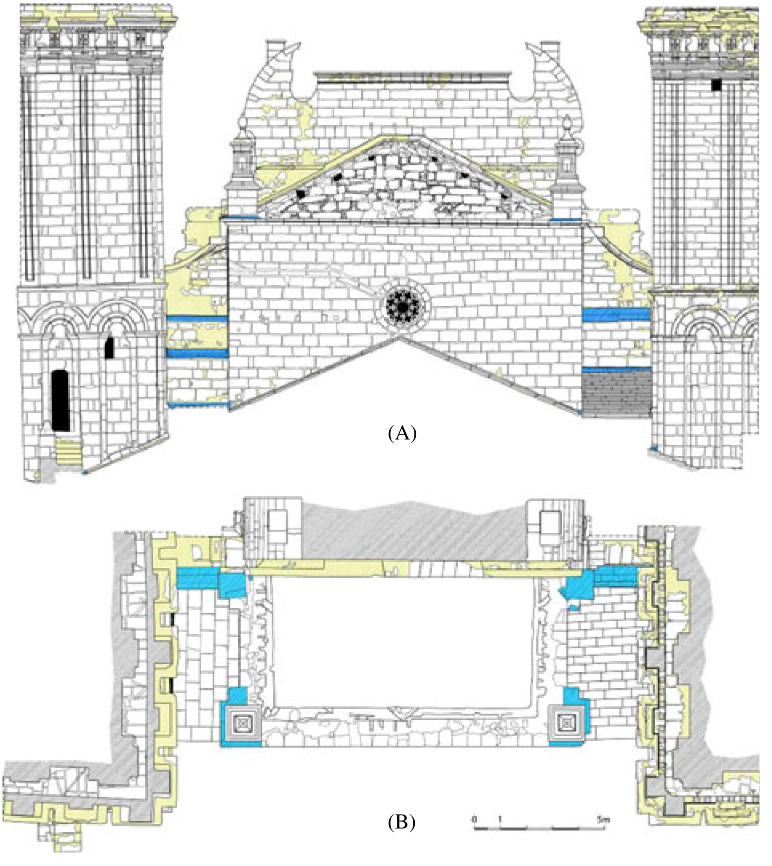

FIG. 8. Complete photogrammetric restitution of the working area on the roofs of the cathedral. A shows the elevation and B the floor plans. The south tower is on the left and the north tower on the right.

FIG. 9. Detail of one of the rose windows of the tribune. A shows the shaded model, B the textured model and C the photogrammetric restitution.

lower part which is inclined at 2% and an upper part, about 1·5 m long, which is almost vertical. The intermediate tray is also inclined at 2% while the upper cornice is practically horizontal. The distortion is also reflected in the floor level of the balcony which corresponds

FIG. 10. Detail of an arcade of the north tower. A is an example of a section of the shaded model. B shows the corresponding textured model and C the complete 3D shaded model.

FIG. 11. A is an orthophoto of the south façade of the north tower. B indicates the level of high resolution detail in the inset box in A. C shows the resulting photogrammetric restitution of the same inset area.

to the baroque cornices. It can be seen from the plan that the passages are not orthogonal in contrast to those in the north tower.

SUMMARY AND CONCLUSION

This paper has presented the methodology used to establish a documentation system for complex historic buildings using digital photogrammetry. The use of relatively low-cost commercial software (Photomodeler Scanner), consumer-grade digital cameras, a mast as an elevation system and a total station for georeferencing have been used to produce dense point clouds. The paper has also described the process for producing high-quality CAD plans on the basis of orthophotos created from the model itself. The documentation generated is fundamental to the comprehensive monitoring, protection and maintenance planning for historic buildings which, given their exposure to the elements, are slowly deteriorating. The 3D digital model of a historic building represents a permanent record and a reference for posterity. This work demonstrates the potential of this technique for the development of highly

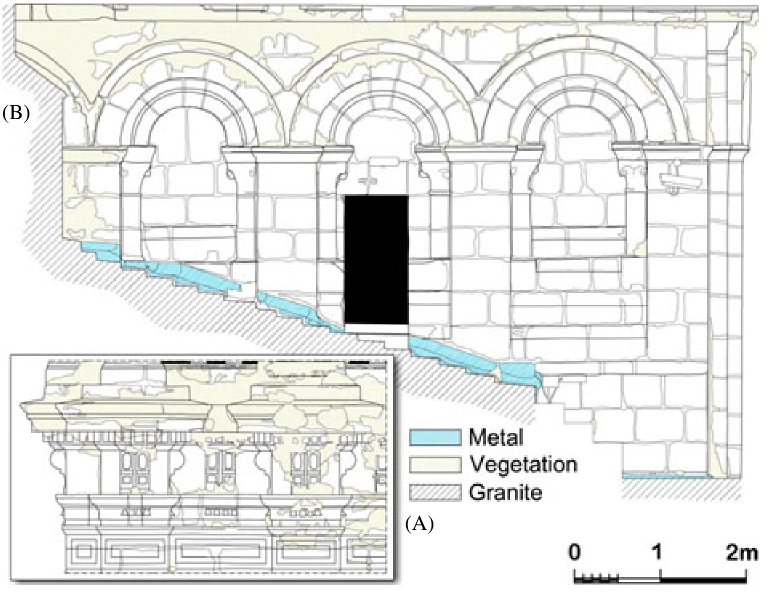

FIG. 12. A shows the detail of the photogrammetric restitution of the arcades and B of the baroque cornice of the north tower.

detailed models, orthophotos and complete plans of historic buildings in complex conditions and with limited space. Close range photogrammetry allows for the creation of accurate 3D models using the same equipment and irrespective of the size of the element; there is no need to invest in multiple items of equipment depending on the size of the structures surveyed.

It is important to note that highly detailed digital models are usually applied to architectural monuments of great value, as in the present case of the Cathedral of Santiago de Compostela. However, their use in less significant projects can be excessive for reasons of time and cost. Nevertheless, one of the most attractive aspects of photogrammetry is the possibility to adjust the level of detail in the same set of photographs and work with models of less dense point clouds. The prospect also exists, with advances in technology, of being able to improve on the results using photographs that have already been taken. Such photographs, taken with simple photogrammetric criteria, become documentation that is capable, in the future, of being transformed into a three-dimensional model with greater precision.

The application of close range photogrammetry in combination with a mast allows high-quality 3D models to be obtained at an accessible price which transforms it into a very competitive methodology. As a result, close range photogrammetry has been presented as a 3D documentation system that is accurate and capable of competing with other modern techniques such as the laser scanner, which is also widely used with these structures.

With this documentation, the areas requiring intervention can be established and it can function as a basis for derived maps for other specialist areas such as humidity detection, micro-organism research, salt deposits, identification of anthropic damage, fissures and general damage. The graphical documentation obtained provides the medium from which the structural behaviour of the monument can be studied as, fundamentally, it depends on its geometry. Accordingly, it has permitted the detection of the inclination of the south tower of the cathedral. The vertical alignment of the higher sections of the pilasters and the horizontal inclination of the higher cornice are probably due to the restoration work carried out between 1667 and 1670.

The 3D model created can be used for other purposes such as education or so-called "musealisation" (a virtual museum) and will allow scientists to view and study the target object in new ways and from different perspectives. Virtual tourism, for example, will allow "visitors" to interact and explore monuments without physical travel. In addition, the possibility of interacting with, and studying, 3D models remotely will contribute to their cultural diffusion. By demonstrating the benefits of the technique, it is hoped to encourage conservationists to test it out in their work.

Further studies in the field of photogrammetry could lead towards fully automating the process of desk-based 3D modelling without a loss of accuracy. The majority of the sub-processes are, at present, automatic, but some of them, such as the creation of a 3D surface model (with or without photo-texture), require a manual approach. Photomodeler Scanner uses algorithms that currently work on only two images and it is necessary to manually select each stereopair to create point clouds and, in many cases, manually edit them once they are generated.

Nowadays, digital multi-view 3D reconstruction algorithms allow for the production of 3D models of high precision and photorealistic quality based on a collection of disordered images of a scene or object, taken from different points of view. Use of this multi-image approach in combination with UAVs could be a starting point for future work.

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Résumé

Cet article décrit la modélisation 3D par photogrammétrie d'édifices complexes par des techniques bon marché de corrélation automatique d'images, des appareils photo du marché et des images acquises à basse altitude. Le potentiel de cette méthode a été étudié en l'appliquant à la documentation d'un cas spécifique: les tours et les toits de la cathédrale de St Jacques de Compostelle (Espagne), un site inscrit au patrimoine mondial de l'UNESCO. La conception et le développement d'un mécanisme permettant des prises de vues aériennes depuis un mât télescopique se sont avérés essentiels. Des modèles, des orthophotos et des plans ont permis de déterminer la géométrie du lieu et ainsi de restituer précisément les structures de pierre et les éléments décoratifs à partir du dessin de chaque bloc taillé. Par ailleurs, la photogrammétrie rapprochée a permis l'analyse et la quantification de l'inclinaison de la tour sud.

Zusammenfassung

Dieser Beitrag beschreibt die photogrammetrische 3D-Modellierung komplexer Gebäude mit kostengünstiger automatischer Bildzuordnung (AIM), digitalen Konsumenten Kameras und Aufnahmen aus geringer Höhe mit Teleskopmasten. Die Methode wurde bei der Dokumentation der Türme und Dächer der Kathedrale von Santiago de Compostela in Spanien, einem UNESCO Weltkulturerbe, getestet. Besondere Aufmerksamkeit wurde auf den Einsatz der Teleskopmasten gerichtet. Es wurden Modelle, Orthophotos und Pläne abgeleitet, um die Geometrie präzise zu bestimmen. Dabei konnten auch die Materialien und dekorativen Elemente der Granitsteine für eine spätere Wiederherstellung ermittelt werden. Ebenso konnte eine Analyse und Quantifizierung der Neigung des Südturmes durchgeführt werden.

Resumen

Este trabajo describe el proceso de modelado 3D fotogramétrico de edificios de gran complejidad mediante técnicas de correlación automática de imágenes de bajo coste, cámaras digitales convencionales e imágenes de baja altitud. Para verificar el potencial de este método, ha sido aplicado en la documentación de un caso real: las torres y las cubiertas de la Catedral de Santiago de Compostela (España), Patrimonio de la Humanidad de la UNESCO. El diseño y desarrollo de un mecanismo de elevación basado en mástiles telescópicos resultó esencial. Los modelos, ortofotos y planos obtenidos han sido usados para determinar y medir rigurosamente de la geometría del objeto. A través de ellos fue posible registrar con exactitud el estado de la cantería y de sus elementos decorativos. Además, la fotogrametría de objeto cercano hizo posible el análisis y cuantificación de la inclinación de la torre sur.