Digital documentation of complex architectures by integration of multiple techniques – The case study of Valer Castle

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ABSTRACT

The digital documentation of monuments and architectures is an important field of application of the 3D modeling where both visual quality and precise 3D measurement are important. This paper proposes an integrated approach based upon the combination of different 3D modeling techniques for the virtual reconstruction of complex architectures like those found in medieval castles. The need of combining multiple techniques, like terrestrial laser scanning, photogrammetry and digital surveying comes from the complexity of some structures and by the lack of a single technique capable of giving satisfactory results in all measuring conditions. This paper will address modeling issues related to the automation of photogrammetric methods and to the fusion of 3D models acquired with different techniques, at different point densities and measurement accuracies. The test bench is a medieval castle placed in Trentino A.A., a tiny region in Northern Italy.

Keywords: 3D modeling, Image-based modeling, Laser scanner, Cultural heritage

1. INTRODUCTION

Digital documentation of cultural heritage sites and objects is becoming a very important field of application for 3D modeling. In many cases, the use of a single modeling technique can't give the required results, in particular when we are working on complex objects or when the 3D model requires different levels of detail. Although in the last few years many investigations were conducted in the field of the 3D modeling of complex objects, there isn't a single technique that can be considered the best for all applications. Techniques also vary in accuracy, reliability, ability to capture details, and their level of automation. Therefore, for the modeling of complex architectures it is often very useful to combine data obtained by different technologies. Image-based approaches [1] are generally complementary to range-based methods [2]. In [3, 4] the key features of different laser scanner technologies and photogrammetry-based systems are analyzed. Each method has its advantages at different working environments and distances and the ability to capture different levels of detail.

The objective of this work is to explain a methodology for virtual reconstruction of cultural heritage complex objects by integrating multiple techniques. An interactive 3D model incorporating all the models created from different data sets will also be produced. One final result of the work is also a walkthrough movie outside and inside the heritage. Geometrically accurate and detailed photorealistic models are essential for cultural heritage documentation. The aim is to combine image-based and range-based modeling in order to have a good trade-off between the level of detail and the size of the model [5]. In this work a medieval castle is used as test bench (Figure 1). It is an example of complex architecture with internal complex courtyards and narrow alleys. The complex architecture is reconstructed by using different techniques, mainly close-range and aerial photogrammetry and laser scanning. A digital terrain model of the surroundings is realized in order to put the heritage building in its correct environment. In the choice of the modeling techniques we considered different factors, as for example the required level of detail occlusions, and the place for data acquisitions. At the end of the 3D reconstruction, the models obtained from different sources are unified in the same reference system by means of surveying Total Station and GPS.

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Figure 1. Aerial views of Valer Castle, located in Tassullo, Trento (Italy).

2. THE METHODOLOGY

In this section the proposed methodology is explained in detail. The modeling process is divided into five steps: project planning and data acquisition, surveying, image-based modeling, terrestrial laser scanning and integration. Image-based modeling and terrestrial laser scanning can run parallel while all the others have to be performed sequentially (Figure 2).

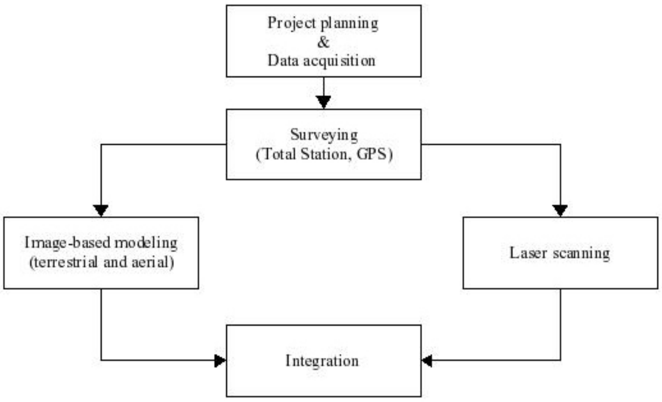

Figure 2. The proposed 3D modeling methodology.

2.1 Project planning and data acquisition

The project planning is one of the most important phases in the 3D modeling process. The shape of the complex architecture can be studied by using available floor plans and it can be divided into some parts that have to be modeled in different stages. In this way it is possible to choose which places have to be modeled by means of image-based modeling using terrestrial or aerial images and which ones have to be modeled using a terrestrial laser scanner. In order to decide which method has to be used, it is important to consider the location of the object/room, its size, occlusions, shape and the demanded level of detail. In our work, the overall 3D model of the castle is done by using image-based modeling. Also some internal courtyards are modeled with the same technique as there are many occlusions hard to handle with a range sensor. On the other hand, in those situations where it is difficult to acquire images with good network and reasonable overlaps [6], a range sensor is preferred. In the image-based modeling technique the same images used for the geometric reconstruction are used for texture mapping. For the range-based technique, additional digital images have to be taken for texture mapping to produce photo-realistic results.

2.2 Surveying

In order to create the models with the correct scale and have a check on the final accuracy of the results, some control and check points are generally acquired with a Total Station. For wide and complex structures, these points can also be used to register all the individual models in the same reference system since it is not always possible to find common points between these models. Generally a closed polygonal surveying line is used around the object of interest, but in some cases internal stations are also placed. Considering as final aim the combination of the whole terrestrial model with a digital terrain model of the surroundings, some surveying stations can acquire GPS data to place the structure in the global coordinate system.

2.3 Image-based modeling

Image data can be acquired from ground level or at different altitude and with different sensors. Considering a complex and large architecture, it is hard to take ground images from viewpoints that cover the entire object. Therefore, aerial images from a helicopter are taken to cover the whole object's surface in order to model the overall castle (including the roofs). Furthermore, in a complex architecture there can be many parts of the building occluded by walls, roof or some other obstructing objects, as well as narrow paths. For these reasons, some pieces of the structure, not visible from the helicopter, or some others that require more details, must be modeled using terrestrial close-range images. A good network configuration is often difficult to be achieved, in particular for internal rooms or courtyards. Therefore the image registration step becomes very complex and robust procedures must be used for the orientation phase. As also reported in [7], in practical 3D modeling cases, it is difficult to work under an optimal image network (good B/D ratio and image distribution), mainly due to constraints in the image acquisition, leading to accuracy degradation of the results. The image-based modeling technique has to be preferred in those cases where occlusions are the major obstacles. In those cases a technique to obtain 3D information from a single image, by recurring to geometric constrains, were used. To achieve optimal and accurate results, the employed camera has to be calibrated. Generally the images acquired for the scene reconstruction do not allow a successful self-calibration procedure. Therefore, in practical cases, rather than simultaneously calibrate the internal camera parameters and reconstruct the object, it may be better first to pre-calibrate at a given setting using the most appropriate network and then recover the object geometry using those calibration parameters at the same camera setting.

2.4 Terrestrial laser scanning

As explained in the previous section it is sometimes impossible to create an accurate highly detailed 3D model through image-based modeling and for this reason the use of 3D laser scanner is necessary. One of the reasons that lead up to use terrestrial laser scanner instead of image-based modeling is the impossibility of acquiring images with good angles and good overlaps to create the 3D model; moreover in some situations it's necessary to reach a high level of detail in short time. Both triangulation and time-of-flight systems can be used to acquire data, depending on the distance and on the level of detail demanded. Range scanners based on triangulation work on short distance and with a very high accuracy while range scanners based on time-of-flight work on longer distances (e.g. 300 – 1000 m) but they are usually less accurate than close-range triangulation systems. Details of the acquisition and modeling process can be found in [8]. In addition to geometric information, digital images have to be used (and generally separately acquired) for the texture mapping [9].

2.5 Integration

A key step in the 3D modeling process is the integration of the different models generated with different source data and techniques. In this phase, all the models must be transformed into the same reference system. First the models created by image-based modeling have to be assembled together and then registered with those generated using range sensors. The registration is done either with common points or with control points, or both. The registration of the terrain model with the overall object model is done with some control points and the GPS data.

3. DATA ACQUISITION AND INTEGRATION

In this section all the results obtained by applying the described methodology to the Valer castle are presented. Both laser scanner and image–based modeling have been used to create the 3D model of the complex architecture which is approximately 35 m high (the tower) and has a base of ca 40 x 70 m.

First the floor plans were analyzed to study the shape of the castle. The complex architecture was divided into parts and decisions were made on which ones needed to be modeled with terrestrial or aerial images and which ones needed to be modeled by a range sensor.

As the castle is located on a small hill, it was hard to find an adequate number of places where to capture images for the overall modeling of the architecture. Therefore 16 aerial photographs acquired from a helicopter (with an average flight height of 65 m) were used to model external walls and roofs. The used camera is a Kodak DCS SLR/n pre-calibrated in our laboratories at a focal length setting of 66 mm. The camera positions are recovered with a bundle-adjustment. The overall network of camera positions with the 3D model of the castle is shown from two views in Figure 3.

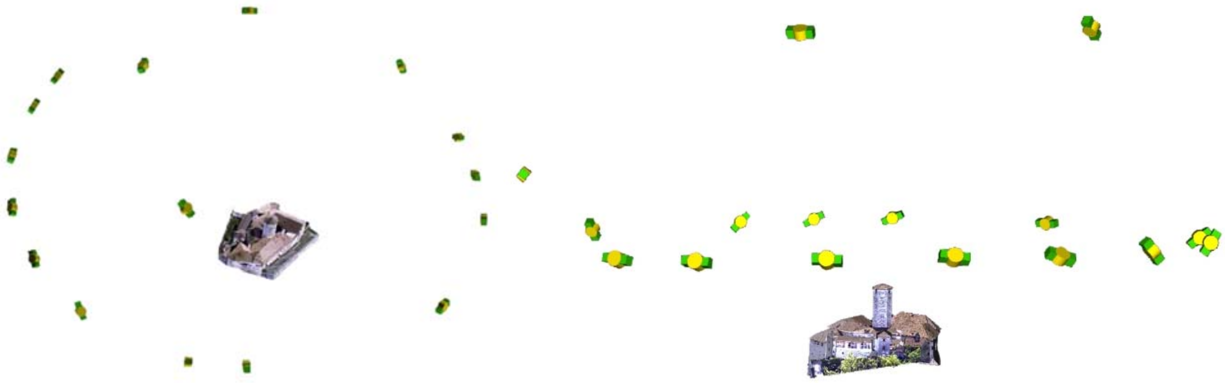

Figure 3. Recovered camera positions for the modeling of the overall castle from the 16 helicopter images.

For the internal courtyards and paths, terrestrial images (acquired with the same camera but with a focal length set at 18 mm) were used. Different examples are displayed in Figure 4, 5 and 6.

(a)  (b)

Figure 4. Image (a) and generated 3D model (b) of an internal courtyards.

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

Figure 5. An internal courtyard (a) and a narrow pathway (c) and the related 3D models (b and d respectively).

Figure 6. Images (a and b) and recovered 3D model (c and d) of a very complex internal courtyards.

For the interior part of the castle, many difficulties were encountered in the image acquisition step due to occlusions and narrow spaces. Range sensors were also excluded for these reasons. In some configurations there was a very small baseline between the images but this was overcome with good image redundancy. The image registration became very complex and robust procedures joined with very precise tie points measurements were necessary in the orientation phase. Geometric constraints, together with image invariants, were used to retrieve 3D information of occluded objects from single images.

In the open courtyard of Figure 5 (approximately 10 m high with a base of 4 x 9 m) the vegetation on the walls could not be removed or geometrically modeled in details, thus affecting the visual quality of the 3D model. Some methods published to overcome this problem [10, 11] could be employed, even if they are based on statistical image analysis and require a large number of different images to remove the occlusions. In this case we couldn't use these methods because we didn't reach a high redundancy due to the narrow area.

For other areas of the castle, a time-of-flight laser scanner was used to recover the required 3D model. In particular, the internal chapel of the castle was scanned with a Leica HDS3000 and a resolution of 1 cm. Furthermore, for the texturing of the model, images acquired with a Kodak DCS Pro SLR/n and a focal length of 18 mm, were used. Figure 7 shows the results of the modeling and Figure 8 shows an internal view of the 3D model of the chapel.

Figure 7. An image of the internal chapel and the generated 3D model by means of a triangulation laser scanner.

Figure 8. Different visualization of the recovered 3D model of the chapel.

As in the near future we plan to model some other castles in the same area, the modeling of the surroundings is necessary to put all the castles in the correct geographic location and within their natural environment. For this reason, two aerial images were used to generate the DSM of the landscape around the castle. The images have a scale of 1:40,000, a pixel size of 21 μm and a foot-print of approximately 1 m. The stereo images were oriented using some control points acquired with a GPS and placed in the UTM-WGS84 reference system. Afterwards a DSM with a resolution of 3 m was automatically created by means of an "in house" software (at ETH) developed for the automated 3D modeling from terrestrial, aerial and satellite images. The derived digital model textured with the related ortho-photo is shown in Figure 9.

Figure 9. DSM of the surrounding area of the Valer castle.

Finally all the recovered 3D data were merged together. Considering the big dimensions of the structure it was important to survey some reference points on the external walls of the castle with a Total Station. In this way a polygonal line was traced around the castle and some control points were surveyed from the vertices of the polygonal line. The polygonal line was extended to some internal parts in order to assemble all the internal 3D models. In some cases, as for example for the castle's bridge, we didn't need points surveyed with the Total Station because there were sufficient common points. The positions of the stations used to survey the control points were acquired with a GPS in order to put the castle in the UTM-WGS84 reference system as the DSM.

4. ANALYSIS OF THE RESULTS

In this section we report on the accuracy of the obtained 3D models. In the image-based modeling projects we rely on the results achieved in the main castle model and in the complex internal courtyard model shown in Figure 6. The results of the others inner parts are similar to those of the courtyard. The value of σ_0 obtained after the bundle adjustment is 1.42 pixels for the overall castle and 2.67 pixels for the internal courtyard. As far as the courtyard concerns, the σ_0 is not very good and this is due to the weak image network, dictated by the very narrow acquisition space. In order to have more realistic information about the precision of the models, we compared the coordinates of some points in the 3D models with the same points surveyed with the total station. The obtained root mean square errors (RMSE) are reported in Table 1. As far as the interior of the chapel concerns, the computed root mean square errors (RMSE) of the scanned points presents better results and they are reported in Table 1 too.

	$RMSE_x$	$RMSE_y$	$RMSE_z$
Overall 3D model	8.8 cm	7.6 cm	6.0 cm
Internal courtyard	1.9 cm	2.3 cm	3.1 cm
Internal chapel	7.0 mm	6.0 mm	9.0 mm

Table 1. RMSE of the overall 3D model, the internal courtyard and the chapel.

5. CONCLUSIONS

In this paper we have reported some issues about 3D modeling of complex architectures and shown a typical methodology that can be applied in the reconstruction of various heritage architectures. Using a practical example, we have described the 3D modeling pipeline and the integration of multiple measuring techniques. The image-based modeling allows to perform 3D models at low cost but with generally high manual interaction while with the laser scanner we can perform detailed 3D models with fast acquisition but often a lot of editing time. The right way, according to our experiences, is the merging of the two techniques as no one is appropriate in all the possible modeling projects. The choice of the reconstruction technique has to consider the demanded level of detail, time and effort to invest in the modeling, occlusions and the surrounding spaces to take images.

As final result a photorealistic 3D model of the exterior walls of the castle and some internal courtyards are realized and used to create a flying through movie which shows all the complex parts of this architecture and its surrounding landscape. In addition to the model of the castle, we have created a Digital Surface Model (DSM) of the surroundings in order to visualize the castle within its environment. In this way the 3D model can be visualized from all the viewpoints and virtual flights can be realized to show the entire structure and environment.

As future work, we plan to integrate other heritages in the recovered surface model and to generate a GIS of the area's heritages.

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Figure 10: Some more screenshots of the recovered 3D models of the castle. From the top, the overall heritage, two courtyards and the interior of the chapel modeled with a laser scanner.