NRC Publications Archive
Archives des publications du CNRC

Effective 3D Modeling of Heritage Sites

El-Hakim, Sabry; Beraldin, Jean-Angelo; Picard, Michel; Vettore, A.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. / La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

Publisher's version / Version de l'éditeur:

The 4th International Conference of 3D Imaging and Modeling (3DIM'03) [Proceedings], 2003

NRC Publications Archive Record / Notice des Archives des publications du CNRC :
https://nrc-publications.canada.ca/eng/view/object/?id=d6ae457d-11c0-4541-a214-0ac061dfc0bd
https://publications-cnrc.canada.ca/fra/voir/objet/?id=d6ae457d-11c0-4541-a214-0ac061dfc0bd

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
https://nrc-publications.canada.ca/eng/copyright
READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site
https://publications-cnrc.canada.ca/fra/droits
LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research Council Canada
Conseil national de recherches Canada

National Research
Council Canada

Institute for
Information Technology

Conseil national
de recherches Canada

Institut de technologie
de l'information

*Effective 3D Modeling of Heritage Sites **

El-Hakim, S.F., Beraldin, J.-A., Picard, M., and Vettore, A.
October 2003

* published in the 4th International Conference of 3D Imaging and Modeling (3DIM'03). Banff, Alberta, Canada. pp. 302-309. October 6-10, 2003. NRC 46553.

4th Int. Conf. 3-D Digital Imaging and Modeling, Banff, Canada, October 6-10, 2003, pp. 302-309.

Effective 3D Modeling Of Heritage Sites

Sabry F. El-Hakim, J.-Angelo Beraldin, Michel Picard
Visual Information Technology (VIT) Group, IIT
National Research Council Canada (NRC)
E-mail: {Sabry.El-Hakim; Angelo.Beraldin; Michel.Picard}@nrc-cnrc.gc.ca

Antonio Vettore
Research Center of Cartography, Photogrammetry, Remote Sensing, and GIS, Univ. Padova, Italy
E-mail: Antonio.vettore@unipd.it

Abstract

Over the past few years, remarkable increase has occurred in the demand for 3D models for cultural heritage applications. The techniques employed have evolved from surveying and CAD tools and/or traditional photogrammetry into laser scanning and more automated image-based techniques. However, selecting the most effective technique for a given project is not obvious. We will discuss each technique and point out its advantages and disadvantages. We will then present our approach, which is an integration of several technologies and is based on the experience we gained over more than a decade to accurately and completely model heritage monuments and sites. It was clear from our experience that using a single technique is not an effective approach. A highly detailed structure or site is best modeled at various levels of detail. Image-based modeling is used for the basic shape and structural elements, and high-precision laser scanning for fine details and sculpted surfaces. To present the site in its proper context, image-based rendering or panorama is used for landscapes and surroundings. We demonstrate our approach on two typical heritage sites in Italy: the Abbey of Pomposa near Ferrara and the Scrovegni Chapel in Padova.

1. Introduction

The most obvious motives for 3D modeling of heritage sites are documenting historic buildings and monuments for reconstruction or restoration if they are destroyed, and creating education resources for history and culture students and researchers. Other motives include visualization from viewpoints that are impossible in real world due to size or accessibility, interaction with objects without risk of damage and virtual tourism. Most applications specify a number of requirements, mainly: high geometric accuracy, capturing all details, and photo-realism. Other desirable features include full automation, low cost, portability, and optimum model size. The order of importance of these requirements depends on the objective of the application, for example whether it is documentation or virtual tourism, but as a rule all are significant. However, a single system that satisfies all requirements is still in the future. Specially, accurate and full automatic capture of all details for all types of objects and scenes remains elusive. For small and medium size objects, up to the size of human or a statue, range-based techniques such as laser scanners can provide accurate and complete details with high degree of automation, but being relatively new technology that is not produced in large quantities, they remain costly. They are also not portable enough for a single person to carry around and use in a manner similar to a video or digital camera. The resulting model can also be inefficient for interactive visualization for large-scale environments. Image based approaches entail widely available hardware and potentially the same system can be used for a wide range of objects and scenes. They are also capable of producing realistic looking models and those based on photogrammetry have high geometric accuracy. The issues that remain in image-based modeling are the capture of details on unmarked and sculpted surfaces and the full automatic creation of the 3D models. Image-based rendering [1], which do not need a geometric model, may suffice for virtual tourism but lack of geometric model makes them unsuitable for documentation purposes.

Most documented projects on cultural heritage have used one method or another, whereas only some have used a combination of techniques. For example, a group from IBM [2] combined structured light 3D sensing and photometric stereo to model Michelangelo's Florentine Pietà. Combining laser scanning with image-based modeling and rendering [3] and image-based modeling with image-based rendering [4] have also been reported. There is however no set rules for which technology and hardware or software to use for a given application. With the availability of many new tools such as laser scanners and a growing assortment of image-based techniques, not to mention standard surveying and CAD tools, there is an urgent need for at least some guidelines. We will show in this paper that except for a simple object or structure, a single technique is inefficient, impractical, or inadequate to satisfy most requirements. Based on extensive experience, we propose a number of guidelines:

- Global shape, and basic elements like columns, steps, windows, doors, and arches, are constructed from high-resolution digital images. This is based on advanced photogrammetry with automated features that take advantage of properties found in classical architectures.

- Accurate close-range laser scanning captures fine geometric details, like sculpted and irregularly shaped surfaces. This is then integrated with the basic model.
- Visual details on the geometric model are obtained from image textures and reflectance models.
- For complex structures, multiple sets of image-based models are applied. Aerial images, if available, are used to combine multiple buildings and model the landscape.
- The need for surveying or direct measurement is not required except to establish a scale or, in some cases, fit the resulting model into a specific coordinate system.
- CAD or geometric modeling and rendering software tools remain necessary to fill the gabs that are not covered by imaging or scanning and to create complete representation for visualization.

The remainder of the paper is organized as follows. In section 2, an overview of 3D model capture techniques is presented. This leads to a discussion on combining multiple techniques in section 3. We then present the details of our approach in section 4. Modeling of the Abbey of Pomposa and the Scrovegni chapel follows. We finally conclude with a short discussion.

2. Overview Of 3D Model Capture

The classic approach to create a 3D model is to build it from scratch using CAD software, surveying data, direct measurements, or maps and engineering drawings. This is obviously time consuming, impractical, and costly. The created models look computer-generated, not photo-realistic, and also do not include fine details. Currently efforts are directed towards increasing automation and realism by starting with actual images of the object or directly digitizing it with a laser scanner. Here is a summary of recent techniques.

2.1. Image-Based Modeling

These methods involve widely available hardware and the same system can be used for a broad range of objects and scenes. They also produce realistic looking models and those based on photogrammetry have high geometric accuracy. On the other hand, 3D measurement from images requires visible interest points or features. This is often not possible either because a region is hidden or occluded, or because there is no mark, edge, or visual feature to extract. In monuments in their normal settings we are also faced with the restrictions of limited locations from which the images can be taken and the existence of other objects, shadows and uncontrolled illumination. Most methods also require significant human interaction. Efforts to increase the level of automation are essential in order to widen the use of the technology. However, approaches to completely automate the process from taking images to creating a 3D model, while promising, are thus far not always successful. Some of the steps, mainly the automation of camera pose estimation and computation of pixel 3D coordinates, have worked well in many cases. This procedure, which is now widely used in computer vision [5], starts with a sequence of images taken by an un-calibrated camera. The system extracts interest points, like corners, sequentially matches them across views, then computes camera parameters and 3D coordinates of the matched points using robust techniques. The first two images are typically used to initialize the sequence. This is done in a projective geometry basis and is usually followed by a bundle adjustment [6] in the projective space. Self-calibration to compute the intrinsic camera parameters, usually the focal length only, follows to obtain metric reconstruction, up to scale, from the projective one. Again, bundle adjustment should be applied to the metric construction to optimize the solution. The next step, creation of the 3D model, is difficult to automate and is typically done interactively to segment the points into separate objects and surfaces and also to edit the output. For large environments, since the technique may require a large number of images, model creation still necessitates significant human interaction, regardless of the fact that camera pose estimation and 3D point coordinates were computed fully automatically.

The most impressive results remain to be those achieved with highly interactive approaches. Rather than full automation, an easy to use hybrid system known as Façade has been developed [4]. The method's main goal is the realistic creation of 3D models of architectures from small number of photographs. The basic geometric shape of the structure is first recovered interactively using models of polyhedral elements. In this step, the actual size of the elements and camera pose are captured assuming that the camera intrinsic parameters are known. The second step is an automated matching procedure, constrained by the now known basic model, to add geometric details. The approach proved to be effective in creating geometrically accurate and realistic-looking models of architectures. The drawback is the high level of interaction and the restrictions to certain shapes. Also since assumed shapes determine all 3D points and camera poses, the results are as accurate as the underlying assumption that the structure elements match those shapes. Façade has inspired several research activities to automate it. For example, Werner and Zisserman [7], proposed a fully automated Façade-like approach. Instead of the basic shapes, the principal planes of the scene are created automatically to assemble a coarse model that guides a more refined model of details such as windows, doors, and wedge blocks. Since this is a fully automated approach, it works best with closely spaced images to assure correct correspondence.

Our method, although similar in philosophy to Façade, replaces basic shapes with a small number of seed points for more flexibility. To achieve higher geometric accuracy, camera poses and 3D coordinates of points are determined without any assumption about shapes but instead by a full bundle adjustment, with or without self-calibration depending on the given configuration.

2.2. Range-Based Modeling

As mentioned above, Image-based modeling requires visible interest points or features and is affected by illumination problems. Active range sensors avoid these limitations by creating features on the surface by controlled projection of light. Advances in laser, CCD technology, and electronics made possible detailed shape measurements with accuracy better than 1 part per 5000 at rates exceeding 10,000 points per second. Most produce organized points, in the form of array or range image, suitable for automatic modeling. A single range image is usually not sufficient to cover an object. The amount of necessary images depends on the shape of the object, amount of self-occlusion and obstacles, and the object size compared to the sensor range. The 3D data must then be registered in one coordinate system. Most registration techniques are based on the iterative closest point (ICP) approach [8]. For the approach to converge to the correct solution, it needs to start with the images approximately registered. Once all data is registered, it can be used for modeling. This step reduces the large number of 3D points into triangular mesh that preserves the geometric details and at the same time suitable for fast rendering [9]. Also the areas where scans overlap must be integrated into a non-redundant mesh. Other requirements include filling of holes and removal of outliers.

There are two main types of range sensors. The first is triangulation-based that projects light from a known position and direction, and measures the direction of the returning light through its detected position. Obviously, the accuracy of measurements depends on the triangle base relative to its height. Since, for practical reasons, the triangle base is rather short, triangulation-based systems have a limited range (most are less than 2 meters). The second type is based on the time-of-flight principle. They measure the delay between emission and detection of the reflected light, and thus the accuracy does not deteriorate rapidly as the range increases. This allows measurements in the kilometer range.

Notwithstanding the advantages of range sensors, we should mention some drawbacks. At the moment accurate systems are costly and bulky, and those that do not use lasers are affected by surface reflective properties and ambient light. They may also be complex to operate and calibrate. Also a range sensor is intended for a specific range, thus one designed for close range is not suitable for long range, and vise versa. For large-scale environments, if a range sensor is to be used to model the entire scene, the amount of data can be huge and requires considerable effort to register the large number of scans.

2.3. Image-Based Rendering

Although not a modeling technique, we include it as a useful visualization tool. In image-based rendering [1] (IBR), images are used directly to generate new views for rendering without explicit geometric representation. This has the advantage of creating realistic looking virtual environment at speeds independent of scene complexity. The technique relies on either accurately knowing the camera positions or automatic stereo matching. Object occlusions and discontinuities particularly in large-scale and geometrically complex environments will affect the output. The ability to move freely into the scene and viewing objects from any position may be limited depending on the method used. It is therefore unlikely that IBR will be the approach of choice for purposes other than limited visualization. For tourists where general visualization is enough, this approach may be adequate, but for historians and researchers, and of course for documentation, correct geometric details are needed.

3. Combining Multiple Techniques

From the above summary of current techniques, it is obvious that none by itself can satisfy all the requirements of culture heritage applications. Given that:

- Even though laser scanning captures most details, it is usually not practical to implement as the only technique for every object and structure. Large buildings for example will require either a large number of scans or scanning at long range at low resolution. They also produce huge number of points even on flat surfaces.
- Image-based modeling alone will have difficulty with irregular and sculpted surfaces. Automated techniques require large number of closely separated images and still require human interaction for complete modeling. Techniques using small number of widely separated views do not offer a high level of automation and have problems with occluded and unmarked surfaces.

Therefore, combining techniques where the basic shapes are determined by image-based methods and fine details by laser scanning is the logical solution. For example in figure 1 the main structure is easy to model by image-based techniques. However, parts of the surface contain fine geometric details that will be very difficult or impractical to model from images, such as the enlarged section shown. A laser scanner best acquires those parts.

This involves matching and integrating local 3D points obtained by the scanner with the global model. We measure several features, usually 8-10 points, using the images then extract the 3D coordinates of the same features from the scanned data. This is done interactively using a display of the image and the 3D model. The resulting parameters are then used to register the two data sets in one coordinate system. Details of each approach and the combined approach will be described next.

Figure 1: A scanned section (shown enlarged) on the façade the abbey of Pomposa.

4. Details Of The Integrated Techniques

In the following sections we will describe each of the techniques that we developed to create models from digital images, range data, and the integration of both.

4.1. Semi-Automatic Image-Based Modeling

This approach is designed mainly for man-made objects such as classical architectures, which are divided into elements logically and hierarchically organized in space. For example, a columnar element consists of: 1) capital, a horizontal member on top, 2) column, a long vertical tapered cylinder, 3) pedestal, a base on which the column rests. In addition to columns, other elements include pillars, pilasters, banisters, windows, doors, arches, and steps. Each is constructed with a few seed points from which the rest of the element is built. Our approach is Photogrammetry-based and provides enough level of automation to assist the user without sacrificing accuracy or level of details. Figure 2 summarizes the procedure and indicates which step is interactive and which is automatic (interactive operations are light gray). The figure also shows an option of taking closely spaced sequence of images, if conditions allow, increasing the level of automation. Here, we will discuss only the option of widely separated views, which is more practical for large-scale environments.

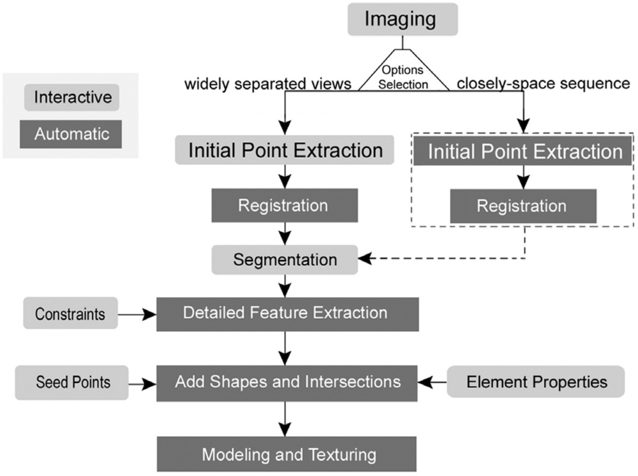

Figure 2. Procedure for image-based modeling

Images are taken, with known camera set ups, from suitable positions. There should be a reasonable baseline between images to ensure strong geometric configuration. Few points, usually 10-12 per image, in multiple images are interactively extracted. The user points to a corner and labels it with a unique number and the system extracts the corner. Image registration and 3D coordinate computation are based on bundle adjustment for its effectiveness, accuracy, and flexibility compared to other structure from motion techniques [6]. Other key aspects for high accuracy such as camera calibration with full distortion corrections have long been successfully tackled in Photogrammetry and will not be discussed here. Next we divide the scene into connected segments suitable for modeling. This is followed by corner extraction and matching procedure to add points into each of the segmented regions. The matching is constrained in a segment by the epipolar condition and disparity range computed from the 3D coordinates of the initial points.

In addition to using multiple images, an approach to obtain 3D coordinates from a single image is essential since some parts of the scene may appear in one image only, for example due to occlusion. It is also needed to cope with lack of features. Our approach uses several types of constraints for surface shapes like planes and cylinders, and relations like parallelism, perpendicularity and symmetry. The equations of some of the planes can be determined from seed points interactively measured. The equations of the remaining planes are determined using the knowledge that they are either perpendicular or parallel to the planes already determined. The equations of all the planes on the structure are then computed. From those and the known camera internal and external parameters, we can determine 3D coordinates of any point or pixel from a single image even if there was no marking on the surface. When some plane boundaries are not visible, they are computed by plane intersections.

This is also applied to surfaces like quadrics or cylinders whose equations are computed from seed points. Other constraints, like symmetry and points with same depth or height are also used. The general rule for adding points on an element and for generating points in occluded parts is to do the work in the 3D space to add points to complete the shape then project them on the images using the known camera parameters. The main steps are shown in figure 3 (with column and window examples).

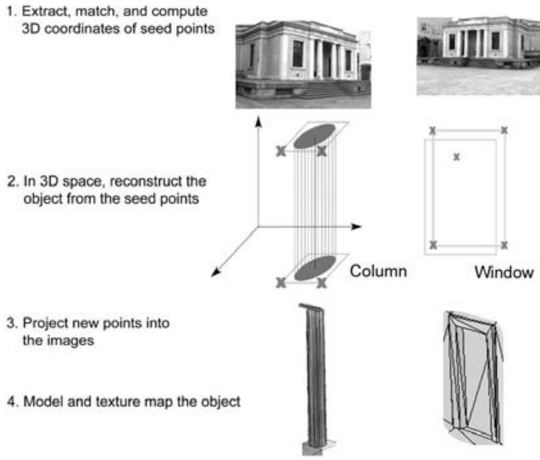

Figure 3. Main steps for modeling architectural elements semi-automatically.

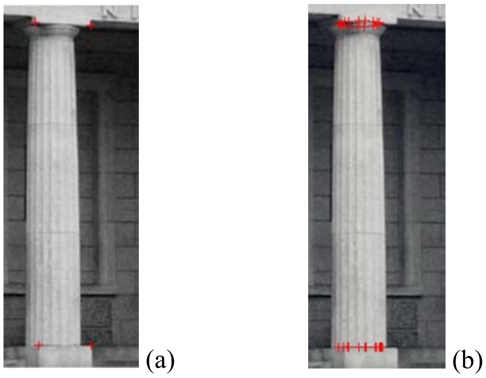
(a) (b)

Figure 4. (a) 4 seed points on the base and crown, (b) automatically added points.

A cylinder is constructed after its direction, radius, and position have been automatically determined from four seed points (figure 4-a). The ratio between the upper and the lower circle can be set in advance. It is set to less than 1.0 (about 0.85) to create a tapered column. From this information, points on the top and bottom circle of the column (figure 4-b) can be automatically generated in 3D resulting in a complete model. For windows and doors we use four corner points and one point on the main surface (figure 3). We complete the model by fitting a plane to the corner points, and a parallel plane at the surface point.

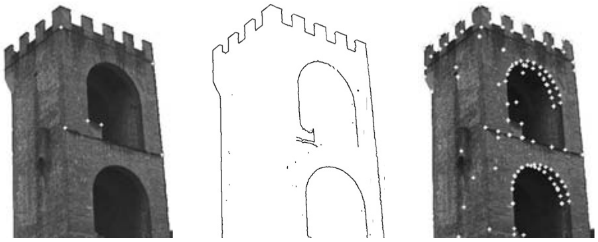
(a) (b) (c)

Figure 5. Automatic 3D points on Arches (a) Seed points, (b) detected edge, (c) arch points.

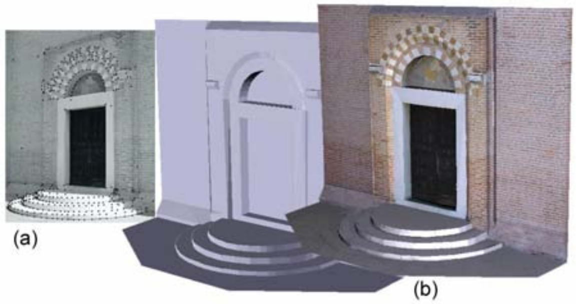

Figure 6: Entrance to the Scrovegni chapel.

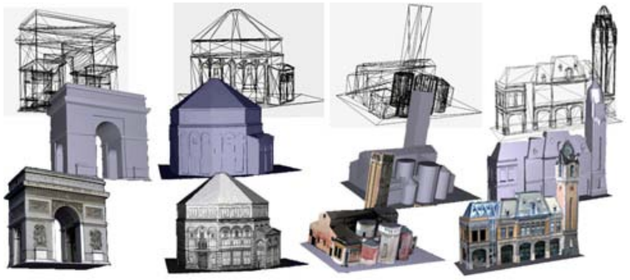

Figure 7. Sample models of structures in wire-frame, shaded solid, and textured solid.

Reconstructing arches uses 3-4 seed points and the arch points are extracted automatically. First a plane is fitted to seed points on the wall (figure 5-a). An edge detector is applied to the region (figure 5-b) and points at constant interval along the arch are automatically sampled. Using image coordinates of these points (in one image), the known image parameters, and the equation of the plane, the 3D coordinates are computed and projected on the images (figure 5-c). Steps are constructed by using 3-4 seed points on one step, to establish a plane, then one seed point on each other step to establish the planes of those steps. Figure 6 shows a model containing arches, door, and steps. A total of 70 seed points were measured manually while 440 points were added automatically (figure 6-a) to create a detailed model (figure 6-b). More details of the approach are given in [10]. Examples of models created by this approach are shown in figure 7.

Each is reconstructed in 1-2 person-days with less than 20% of the total points measured interactively.

4.2. Range-Based Modeling and Texturing

The procedure for creating a triangular-mesh model from 3D images is summarized in figure 8. If the 3D data is presented as a set of registered images it is easy to create a triangular mesh by simply triangulating each image. However, since there is often sizeable overlap between the images from different views, a mesh created this way will have many redundant faces. It is desirable to create a non-redundant mesh with no overlapping faces. The adopted technique has been developed partly at our laboratory and at Innovmetric Software Inc. [9] and implemented in Polyworks^{TM} commercial software.

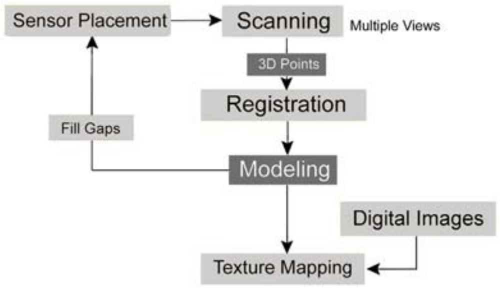

Figure 8: Procedure for range-based modeling

Most laser scanners provide only a monochrome intensity value for each pixel as sensed by the laser. To acquire realistic look, texture maps obtained from high-resolution color camera is necessary. Some scanners have a color camera attached to the scanner at a known configuration so that the acquired texture is always registered with the geometry. However, this approach may not provide the best results since the ideal conditions for taking the images may not coincide with those for scanning. For example a complex pattern or fresco on a surface can only be fully captured with high-resolution images taken at close range. Our approach [11] allows taking the images independently from scanning and at locations and lighting conditions that are best for texture.

4.3. Combining the Models

First the model of the whole structure, except for the fine details, is modeled using the semi-automatic image-based approach. The sections that require scanning will be modeled separately. Common points between image-based models and the range-based models are used to register them in one coordinate system. This is done interactively with software that can display and interact with images from various types of sensors and cameras. The next step is to automatically sample points from the range-based model along its perimeter and insert those into the image-based model. The triangulated mesh of the image-based model will be adjusted based on those new points to create a hole in which the range-based model is added so that there will be no overlapping triangles.

4.4. Landscape Visualization

When images of the scene taken at long distances, such as aerial images, are available, the landscape can be represented and integrated with the structures model to increase the level of realism. The elevation of ground points between the main structures are determined from aerial images while the remainder of the landscapes and far objects like mountains are represented by panoramas. A few 3D points common between the structures and the grounds are used to register the grounds elevation model and landscape panorama with the structures. The procedure is similar to the approach applied in [3].

5. Modeling The Abbey Of Pomposa

This is one of the most appealing Italian churches of the Romanesque period. It is a complex made of several architecturally simple buildings with mostly planar surfaces. There are also three arches decorated with brick and stonework. The main façade is ornamented with several relief works of art carved in marble.

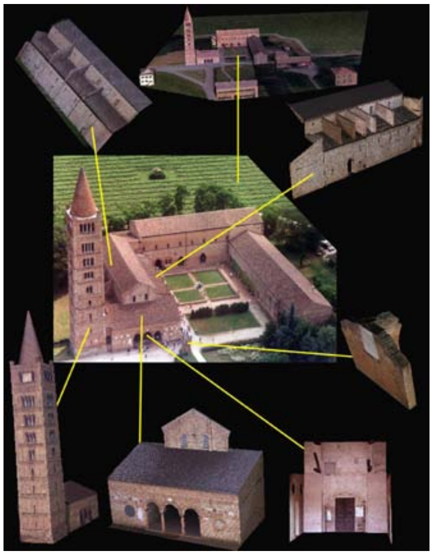

Figure 9: The image-based models

Except for the relief works, all the structures have been completely modeled using a 4 mega-pixel digital camera. Seven different sets of images were acquired including one from low altitude airplane and one inside the entrance hall of the church. The resulting seven models are shown in figure 9. Details like the left wheel and the peacock carvings (figure 10) were scanned with our sub-millimeter Biris 3D sensor. A close up wire-frame model of the wheel is shown in figure 11. The level of details of the scanned sections, which was acquired at 0.5 mm resolution, is clearly much higher than the other regions. It is more convincing when viewing these sections up close while navigating through the model.

Figure 10: Scanned regions.

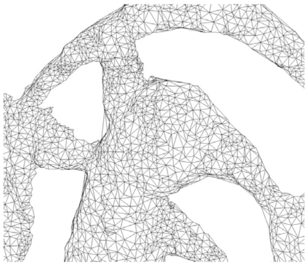

Figure 11: Wire-frame model - part of the wheel.

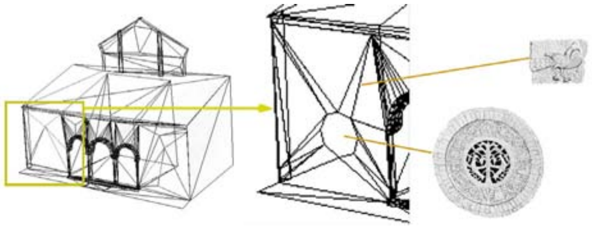

Figure 12: Integrating the models.

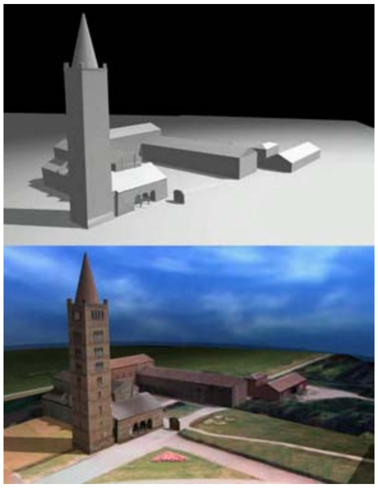

Figure 13: Full model (shaded and textured).

Figure 12 shows the general model of the church building with added 8 new points from the trim of the wheel and the re-triangulated mesh. The hole shown is where the model of the scanned wheel will fit. The peacock model does not require a hole in the main model since it is completely solid and can simply be attached to the back plane. Snap shots, one shaded and one textured, from the complete model are shown in figure 13.

6. Modeling The Scrovegni Chapel

This Chapel, built in 1303-1305, was once part of the Scrovegni Palace in Padova. We took images all around the chapel with 5-mega-pixel digital camera. We also took close up images at the entrance and the bell tower at the back. Unlike the Abby of Pomposa where we used a high-resolution close-range scanner, here we used a med-range scanner to scan the whole building. The scanner has a 25 mm resolution, but after combining all the scans the final accuracy was worse than this resolution. Figure 15 shows the model of the front façade from the scanner data. The results are noisy and did not capture all fine geometric details. The front fence and the trees around the chapel also caused missing and erroneous batches. In fact the image-based model was clearly more realistic and geometrically complete. Thus it is apparent that such scanner is not an effective tool for this type of structure. Figure 16 shows three image-based models: one of the main building from far images, one of the entrance from close up images (see also figure 6), and one of the back including the bell tower. These models were put together using common points to create a detailed and realistic model of the whole chapel.

Figure 14: The Scrovegni Chapel.

Figure 15: Part of the model from range data.

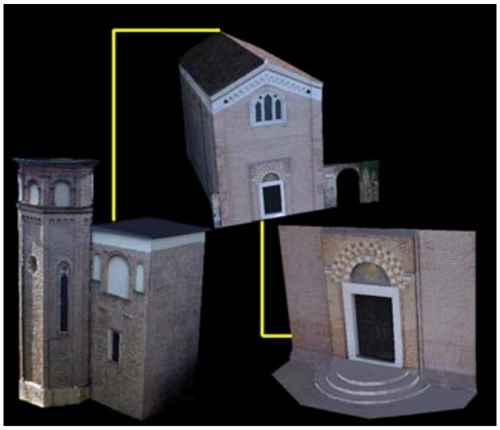

Figure 16: The chapel image-based models

7. Discussion and Concluding Remarks

A multi-technique approach to creating detailed large-scale 3D models of cultural heritage sites and monuments was presented. It combines image-based and range-based modeling, each where it is best suited. The image-based modeling is a semi-automatic approach that takes advantage of properties and arrangements common to such objects. Parts of the process that can easily be performed by humans, mainly registration, seed point extraction, and objects segmentation, remain interactive. Numerous details plus the occluded and the un-textured parts are added automatically by imposing realistic assumptions about elements shapes and the relations between them. Modeling of columns, windows, doors, arches, steps, and other architecture elements are made from a minimum number of seed points. Fine geometric details and sculpted surfaces are best captured with high-resolution laser scanner. Modeling of the scanned sections is carried out fully automatically while its registration with the image-based model is interactive. The high geometric accuracy of our approach guarantees that models acquired at different time periods with different sensors can be integrated seamlessly. We used the method to model several heritage sites all over the world. The Abbey of Pomposa and Scrovegni chapel were presented in this paper as examples. The results supported our approach in that it produced realistic and geometrically correct detailed models. Combining image-based modeling with high-resolution close-range scanners was more effective than using a med-range scanner to model the whole structure, particularly those scanners with resolution and accuracy of several centimeters. The approach's weakness is that an amount of human interaction still remains. Thus, near future research activities focus on increasing the level of automation and ease of use of the tools involved.

8. Acknowledgements

For the Abbey of Pomposa project, we thank Prof. Marco Gaiani and architects Francesca Pozzi, Anna Maria Iannucci and Andrea Alberti. Alberto Guarnieri helped us with the Scrovegni chapel work.

9. References

[1] H.-Y. Shum, S.B. Kang, "A Review of Image-based Rendering Techniques", IEEE/SPIE Visual Communications and Image Processing (VCIP) 2000, Perth, pp. 2-13.

[2] F. Bernardini, H. Rushmeier, I.M. Martin, J. Mittleman, G. Taubin, "Building a digital model of Michelangelo's Florentine Pieta." *IEEE CG & A*, 22(1), 2002, pp.59-67.

[3] V. Sequeira, E. Wolfart, E. Bovisio, E. Biotti, J. Goncalves, "Hybrid 3D reconstruction and image-based rendering techniques for reality modeling." SPIE Vol. 4309, 2001, pp. 126-136.

[4] P. Debevec, C.J. Taylor, J. Malik. "Modeling and rendering architecture from photographs: A hybrid geometry and image-based approach." SIGGRAPH'96, pp. 11–20.

[5] R. Hartley, A. Zisserman. *Multiple View Geometry in Computer Vision.* Cambridge Univ. Press, 2000.

[6] W. Triggs, P. McLauchlan, R. Hartley, A. Fitzgibbon, "Bundle Adjustment for Structure from Motion." In *Vision Algorithms: Theory and Practice*, Springer-Verlag, 2000, pp. 298-372.

[7] T. Werner, A. Zisserman, "New technique for automated architectural reconstruction from photographs." Proc. 7th Europe. Conf. Computer Vision, May 2002, vol. 2, pp. 541-555.

[8] Besl, P.J., McKay, N.D., "A method for registration of 3-d shapes". IEEE Transaction PAMI, 14(2), 1992, pp. 239-256.

[9] M. Soucy, G. Godin, R. Baribeau, F. Blais, M. Rioux, "Sensors and algorithms for the construction of digital 3-D colour models of real objects." Proceedings of the IEEE International Conference on Image Processing, Lausanne, Suisse. September 16-19, 1996. Volume II. pp. 409-412.

[10] S.F. El-Hakim, "Semi-automatic 3d reconstruction of occluded and unmarked surfaces from widely separated views." Proc. ISPSRS Symp., Corfu, Greece, Sept. 2002, pp. 143-148.

[11] J.-A. Beraldin, M. Picard, S.F. El-Hakim, G. Godin, V. Valzano, A. Bandiera, D. Latouche, "Virtualizing a Byzantine Crypt by Combining High-Resolution Textures with Laser Scanner 3D Data." Proc. VSMM, Korea, 25-27 Sept. 2002.

[12] S.F. El-Hakim, J.-A. Beraldin, M. Picard, "Detailed 3D reconstruction of monuments using multiple techniques". ISPRS-CIPA Workshop, Corfu, Sept. 1-2, 2002, pp. 13-18.