3-D RECONSTRUCTION OF COMPLEX ARCHITECTURES FROM MULTIPLE DATA

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ABSTRACT:

In this paper we developed an approach to 3D modeling of complex architecture such as medieval castles using multiple types of data. The method creates independent models from each type then assembles and integrates them to form one complete model of the site. The advantage of this technique is the flexibility it provides to handle complex and difficult-to-access sites where a single technique is largely inadequate. Two main research issues had to be addressed: (1) since image-based modeling will be required in most parts, the level of automation must be increased without compromising accuracy and robustness, (2) the seamless and accurate integration of models created independently from different sets of data of different accuracy and levels of detail. We provide new contributions to each of these areas and apply them to modeling the Stenico castle in the Trentino province, Italy.

1. INTRODUCTION

Many heritage structures were built and reconstructed or restored over different periods and follow no conventional architectural design. Castles in particular were built for defensive purposes and had to make the most of readily available natural protective settings like hilltops and ridges. They were fortified with multiple rings of high walls, gates, and towers. As a result, data acquisition and modeling of such structures are complicated. We initiated a complex-structures digital documentation and visualization project (named 3D-Arch) jointly between ITC in Trento and NRC in Canada. The goal of the project is to accurately and completely model several of Trentino castles, beginning with the Stenico castle. The castle is one of the oldest and most important medieval castles in the region, and is an interesting mixture of styles of buildings added over several centuries. A view of the castle is depicted in the January panel of the "cycle of months" frescoes (figure 1) in Aquila Tower at Buonconsiglio castle in Trento, which we modeled in another project [El-Hakim et al, 2003b].

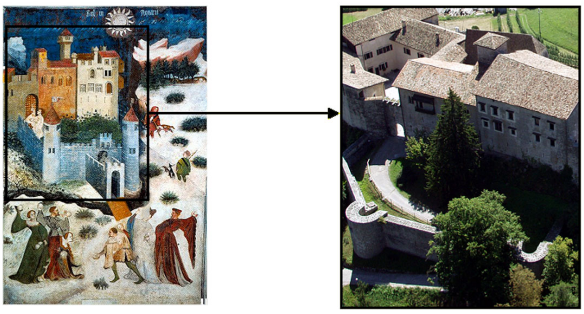

Figure 1: The Stenico castle in a 1350 fresco and now.

We needed to reconstruct all castle buildings, courtyards, protective walls, and interiors particularly frescoed rooms. The cost and data collection time must fit the limited budget and granted access time, noting that comparable projects took years to finish. The planning phase of the project [El-Hakim et al, 2004] revealed several problems in 3-D reconstruction of castles. Mainly, due to typical castle locations (figure 2), it is hard to find an adequate number of places from which to capture images or scans. Also, the assumptions made on standard architecture to obtain 3D data and increase automation, such as parallelism, perpendicularity, or symmetry, are not applicable. Complexity and variety of the architecture make it difficult to capture all details without extensive manual interaction. Previous work suggested that combination of Photogrammetry, surveying, and other data such as maps or floor plans, are all needed to model the main elements of large complex sites [El-Hakim, 2001]. Laser scanning and automated image-based techniques can be used to add fine details.

Figure 2: Castle location and setting

In addition to castles, the techniques developed for this project can be applied to other complex heritage structures. The results presented in this paper focus on image-based techniques since they entail the most economical and portable sensors and the shortest on-site data collection time. Laser scanning data acquisition is still in preliminary stage and will be integrated in the future. The objective of this paper is to address the main problems in creating accurate and photo-realistic models of complex architectures using mainly image-based techniques. We must also develop a technique to combine image-based models together, and with models from other sources such as floor plans and laser scanning. The technique must remove overlaps and fill gaps between models to create a model suitable for 3D reconstruction and visualization.

This paper updates and builds on our previously published work in El-Hakim et al, 2004. In the remainder of the paper we give an overview and analysis of methods being used for modeling similar sites or structures in section 2. This is followed by the details of our approach in section 3. Results of modeling the Stenico castle are given and evaluated in section 4, followed by conclusions.

2. OVERVIEW OF 3D MODELING TECHNIQUES

Techniques and related work of modeling complex architectures like castles is reviewed in this section. The effectiveness of the techniques to modeling such architectures will be argued. Problems associated with each will also be discussed and, when possible, a solution will be proposed.

2.1 CAD and Architectural Drawings

Traditional 3-D CAD techniques using architectural drawings remain the most common [Forte et al, 1998, Haval, 2000]. Many use synthetic textures, which yield a computer-generated look. Some projects used textures from images, which offer a more realistic appearance [DeLeon, 1999, Foni, et al, 2002]. The approaches typically lack automation, although one technique [Dikaiakou et al, 2003] modeled heritage buildings in Nicosia using an automatic building generation method based on a library of predefined 3D building blocks.

In the case of drawings created directly in digital form from surveying data, file formats such as AutoCAD or DXF allow the information to be arranged in separate layers, each containing different type of elements. Some adjustments to obtain consistent local geometry and layout topology are needed. Commercial CAD software does not address the situation where a floor plan drawing already exists. Therefore, significant research has been devoted to convert such drawings to CAD representation. This can be difficult due to the complexity and variety of drawing notations and the necessity to handle noise and unwanted features. Kernighan and Van Wyk, 1996, developed a technique that can extract lines and poly-lines from digitized floor plans and remove any information not needed for 3-D modeling. Creating 3-D models may be done interactively on simple floor plans: closed poly lines are used to define solid portions of the model, differentiating between walls and interior space. These areas are then extruded to the desired wall height. However, this method can be time consuming and error prone on complex buildings. Thus, some semi-automatic techniques were developed to create 3-D models from floor plans [Lewis and Sequin, 1998].

2.2 Photogrammetry

Many successful interactive photogrammetric and image-based techniques are available [Debevec et al ,1996, Liebowitz et al, 1999]. Also several commercial software products are available and were successfully used in many projects over the past few years. The medieval fortress Kufstein, Austria, was modeled using images taken from a helicopter by metric film camera, ground images by non-metric camera, and surveying [Hanke and Oberschneider, 2002]. CAD software was used to fill in missing parts. A similar approach was used to model several German castles [Kersten et al, 2004]. Photogrammetry and surveying was used to model medieval castles in Western Sicily [Bacigalupo and Cessari, 2003]. The methods are still labor intensive and the projects may take several years to complete.

2.3 Laser Scanning

Laser scanning is increasingly being used for large site digitization [Allen et al, 2003, Cain et al, 2003, Frueh and Zakhor, 2003]. A large complex model of imperial Rome was digitized and modeled with highly accurate laser radar [Guidi et al, 2005]. Laser scanners promise to provide highly detailed and accurate representation of any shape [Blais, 2004]. Combined with color information, either from the scanner itself or from a digital camera, a realistic-looking model can be created. The accuracy at a given range varies significantly from one scanner to another. Also, due to object size, shape, and occlusions, it is usually necessary to use multiple scans from different locations to cover every surface. Aligning and integrating the different scans will affect the final accuracy of the 3-D model. The generated data can also be too large in size to be practical for a large complex site without significant simplification.

2.4 Automated Image-Based Techniques

Most of the efforts of current techniques are focused on the automatic recovery of internal and external camera parameters and the stereo matching of extracted points. On the other hand, acquiring points suitable for modeling and creating the model itself, which involves segmenting the point clouds into topologically meaningful groups, remain interactive [Gibson et al, 2003]. To our knowledge, no large complex site model was completed based purely on fully automated image-based techniques. Only small sections of large structures have been modeled automatically [e.g. Pollefeys et al, 1999]. Closely spaced images, like low-resolution videos, are required for robust matching. This may be difficult to acquire for a large complex structure. Even if accessibility is not an issue, covering a large site with closely spaced image sequences is time consuming. Also, accuracy becomes an issue on long image sequences due to error propagation since points are only tracked in two or three images. However, the technique can be useful on parts of the site, like stonewalls with well-defined features. Many techniques attempting full automation of the modeling process [Werner and Zisserman, 2002, Wilczkowiak et al, 2003], or improving the final model accuracy [Cantzler, 2003], were developed. Such techniques rely on constraints of surface shapes and assumed relationships between surfaces, or require vanishing points from sets of parallel lines. However, in many complex heritage structures these assumptions do not apply, which makes fully automated techniques ineffective. A possible solution is to incorporate a limited interaction on regular shapes such as arches, columns, doors and windows [El-Hakim, 2002]. With a small number of interactively measured seed points, the remaining points defining the model of those elements can be added automatically.

2.5 Combination of Multiple Techniques

Mayer et al, 2004, modeled the Wartburg castle using automated image-based techniques for camera orientation and calibration and interactive photogrammetric techniques, using commercial software, for model creation. Tourist slides, existing engineering drawings, and geodetic measurements were used to model the church of Holy Sepulchre in Jerusalem [Georgopoulos and Modatsos, 2002]. Bundle adjustment with self-calibration on the digitized slides, with geodetic and engineering drawings measurements as control, was used in that 7-years-long project. Aerial and terrestrial images were utilized for the main shapes, and laser scanning for fine geometric details to model the abbey of Pomposa in Italy [El-Hakim et al, 2003a]. Borg et al, 2002, modeled parts of a temple in Malta using Photogrammetry for outlines and laser scans for details, plus surveying to register the data.

Tools to assemble models created by various techniques are required to create one model suitable for documentation and visualization. [Flack et al, 2001]. In addition to differences in coordinate systems and scale, the models will also not perfectly match at joint primitives such as surfaces, edges, and vertices. Some of those will overlap or intersect and some will be disjointed, which is unacceptable. Again, commercial CAD and rendering software do not address these problems therefore special tools must be developed for this purpose.

3. THE APPROACH

The proposed procedure is hierarchical, depending on the data source, where the details, accuracy and reliability increase as we advance from one data type level to the next. Therefore, data in one level overrides the data in previous levels.

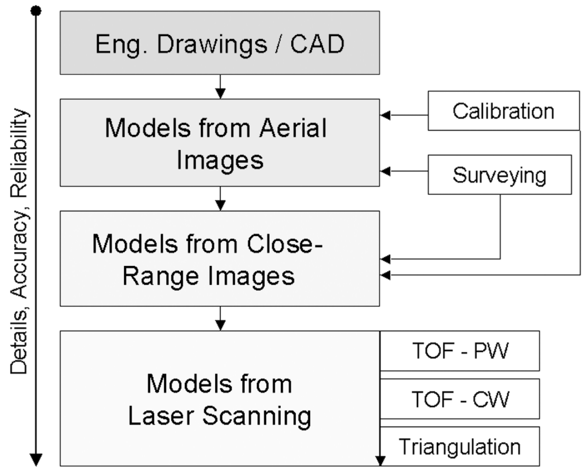

Figure 3: Hierarchy of model assembly.

Figure 3 summarizes the currently existing data sources implemented in this approach. The engineering drawings provide the least detailed or accurate level. They are also the least reliable since they may not reflect changes that took place since their completion. Accuracy, details and reliability are better with models from aerial images, and increase for models from close-range images. A relative accuracy improvement and higher level of details can be achieved by Time-Of-Flight (TOF) – Pulsed Wave (PW) laser scanners, and more improvement by the TOF- Continuous Wave (CW) scanners. Triangulation-based laser scanners, if used at close range, provide the most detailed, accurate and reliable source of data.

The following steps provide a general outline of the approach to fully model a complex site. Note that the first six steps can be performed in any order or simultaneously:

1- Calibrate the digital camera for its internal parameters.
2- Survey some points, for example with a total station.
3- Acquire a floor plan in digital form and create rough 3-D model. This model will lack most of the details.
4- Acquire aerial images and create the overall model.
5- Acquire terrestrial images and create detailed models.
6- Acquire data from a high-accuracy laser scanner if available and create fine detailed models.
7- Register and integrate the models created from sensor data.
8- Parts without data exposure are completed from floor plans. Missing sensor data can be intentional for uninteresting parts, or inevitable due to lack of access or improper coverage.
9- Additional sources of data may be needed to reconstruct lost parts of the castle. Those are usually drawings, sketches, paintings, or frescos. They will usually be incorrect as a source of 3D reconstruction, but they can be calibrated if some elements in the drawings still exist now. For example, parts of the Stenico castle towers as depicted in the January panel of the “cycle of months” frescoes in Aquila Tower at Buonconsiglio castle in Trento, are now destroyed. We will use the frescos to reconstruct those parts.

We detail some of the steps in the following sub-sections.

3.1 Camera Calibration

The camera can be calibrated using the same project images (self-calibration) [Fraser, 1997] or calibrated separately at a different location such as a laboratory [Faig, 1975]. Self-calibration is necessary if camera settings are unknown and vary between images. But to achieve accurate and reliable self-calibration, certain geometric configurations of images are needed. Since this is not guaranteed at the project site, and makes imaging more restrictive, it is sensible to employ a high-quality camera and take the images at fixed known settings. Many modern digital cameras can save a number of settings. We then calibrate in the lab at those settings using surveyed points (figure 4). All camera distortion parameters such as lens distortion and pixel scale factor are determined in this process.

Figure 4: Calibration targets.

3.2 Three-Dimensional Information from Floor Plans

Floor plans can serve two main purposes: to add sections missed by imaging or scanning, and to support the modeling process by verifying surface shapes and the relationships between surfaces, such as parallelism and perpendicularity. To convert the floor plans into a 3-D model we semantic information is necessary such as room identities and connecting openings followed by walls extrusion to given heights. The heights will be known from the sensor-based models. Window and door insertions are carried out where needed.

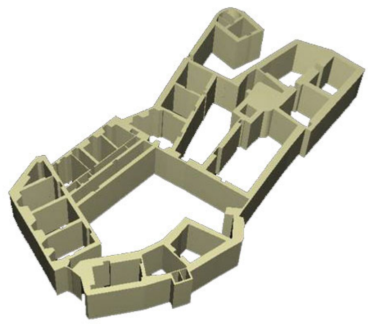

Figure 5: 3-D building model extruded from floor plans.

3.3 The Overall Model from Aerial Images

The roofs, outside of buildings, courtyards, surrounding walls, and close-by grounds are very difficult to fully capture from ground-based images. Therefore, images from a low-flying helicopter at various viewing angles are best suited to create the overall model of a large complex site. The images should have strong geometric configurations - being convergent with large base-to-height ratio. Photogrammetric bundle adjustment is applied, sometimes using some surveyed points to define the reference coordinate system and the scale. The semi-automatic modeling technique described in El-Hakim, 2002, is applied to create the model.

3.4 Detailed Models from Ground Images

The façades detail and the inside of rooms will obviously require close up images taken from the ground level. These images are used to semi-automatically create detailed models of selected elements such as sections occluded from the aerial views, entrances, and indoor spaces. We start by manually creating a less-detailed model with selected seed points using bundle adjustment. Then, we select two images with the best geometric configuration, and apply our hierarchical matching procedure [El-Hakim, 1989] (similar idea is also proposed in [Ferrari et al, 2003]). Corners are automatically extracted followed by stereo matching, constrained by the epipolar line and disparity-range determined automatically from the seed points (examples are shown in figure 6). Other constraints such as color and point ordering are also used. Finally, 3-D points on regular shapes like columns, arches, doors, and windows are created semi-automatically using selected seed points [El-Hakim, 2002].

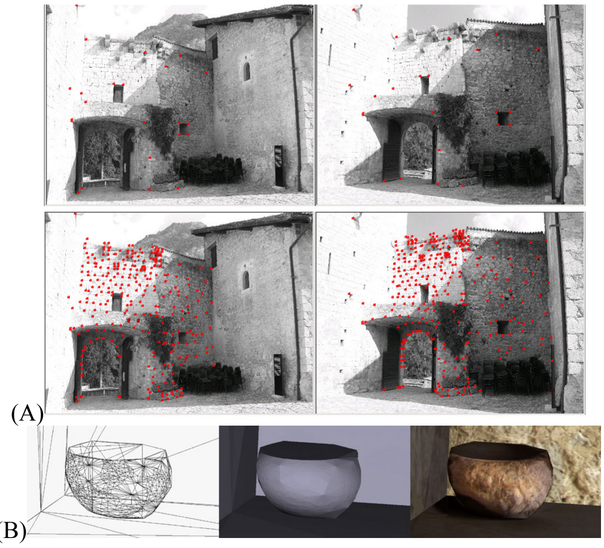

Figure 6: (A) Top pair with manually picked seed points, bottom pair with automatically matched points on a castle entrance. (B) Detailed model where matching was applied.

Ground images can also be used to approximate surface geometry on areas where exact dimensions are not necessary. Modeling software such as *3ds max*® provides displace modifiers that automatically extract surface contours from the texture map based on shading. This is particularly effective in stonewalls where there is no decoration, and shading represents cast shadows (figure 7).

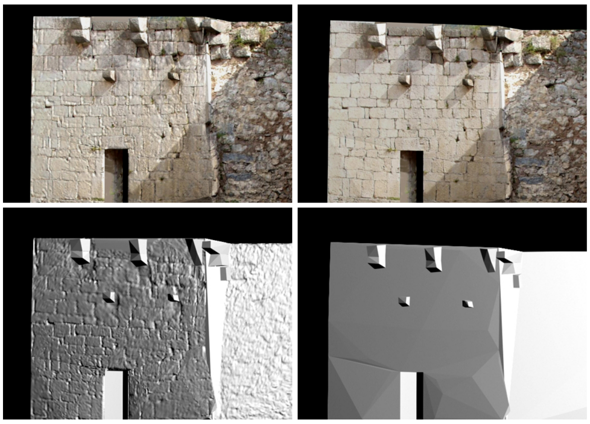

Figure 7: Left pair with displace modifier approximating stone surface geometry. Right pair has flat surfaces.

3.5 Modeling of Complex Un-Textured Surfaces

Lack of geometric constraints is particularly problematic when modeling complex un-textured surfaces. For example ceilings in many medieval chapels resemble groin vault structures and are undecorated. Hence there are no well-defined features for extracting 3-D points with image-based techniques. Likewise, floor plans are insufficient since they provide only 2-D information. Two possible alternatives are to determine a mathematical description of the geometry, or model the ceiling manually with available software as shown in figure 8.

Figure 8: Left: Groin vaulted ceiling modeled with *3ds max*®. Right: Two arches extruded at right angles form a mould for the ceiling model.

3.6 Model assembly

Many issues must be addressed in order to combine models created by different data sets into a single model appropriate for 3-D reconstruction and visualization:

1. Relative scale and orientation must be correct.
2. Joint primitives, specifically surfaces, edges, and vertices, from adjacent models must match perfectly. However, it is unlikely that we have the same primitives between the adjacent models. For example an arch may have 500 vertices in a detailed model but only 50 in a general model. Additionally, extruded floor plans produce walls as solids (with thickness), whereas image-based models produce walls as planes.
3. No gaps, redundant surfaces or intersecting edges are acceptable. This can easily happen if the floor plans do not reflect the "as built" conditions. There is no clear solution to this apart from a significant post processing of the integrated models.
4. Sensor-based techniques produce actual wall surfaces rather than perfect planes. In contrast, wall surfaces from

floor plans are extruded with user provided heights, thus they are exactly planes. This can be visible at seams between the two types of model.

5. After the assembly phase it may still be necessary to update the sub-models. Two methods, neither is ideal, are possible: 1) Update the sub-model in its original co-ordinate system then manually reapply transformations involved in assembly. This process is both tedious and error prone. 2) Update the sub-model in the new co-ordinate system by exporting from the assembled model. In this case, the exported VRML file will be cluttered with transformations.
6. Textures on both types of model should integrate seamlessly [El-Hakim et al, 2003].

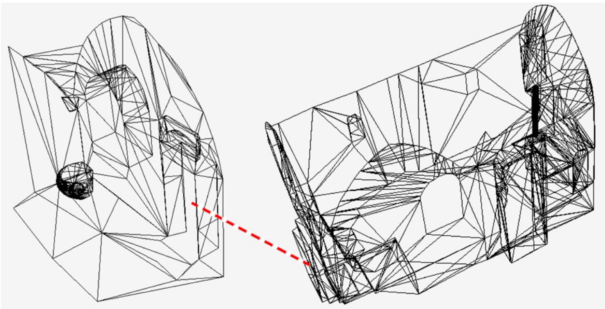

Figure 9: Two adjacent models connected by a portal.

Commercial modeling tools do not deal with these issues, thus special techniques and software tools were needed. The models can be registered manually in modeling software such as *3ds max*® using common points between them (figure 9). The process will be unnecessary if the individual models were directly created in the same coordinate system using control points. But some models have no visible common points with other models or have any control points. In this case the floor plans can be used for positioning those models (figure 10).

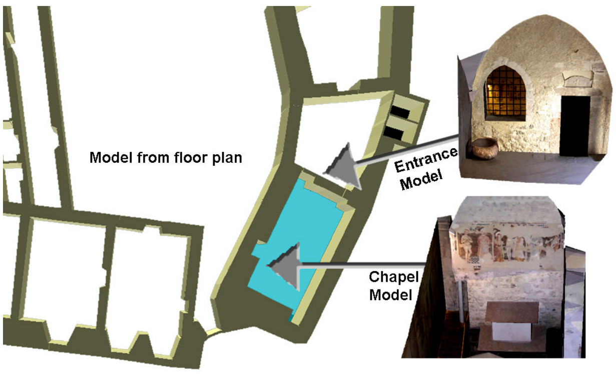

Figure 10: Position detailed models using floor plans.

Once all models are registered, the integration procedure begins. The models are organized in a hierarchical manner where the top model contains the least details (Figure 3): We begin with the general model that consists of the entire structure from aerial images. Detailed models are then imported along common edges and vertices, using the floor plans to ensure accurate scale and positioning. The mesh for the general model is then adjusted to remove redundant surfaces, and in some cases Boolean operations are required to create holes for portals and windows. Any remaining gap between models is filled from the floor plans. Then points from adjacent models on the borders of the gap are used to re-triangulate it so that we have realistic surfaces rather than perfect planes in the filled gap.

4. CASE STUDY: THE STENICO CASTLE

A good example of an architecturally complex site is the Stenico castle, in Trentino, Italy. The castle consists of several buildings of mixed styles, built over several centuries (figure 11) and arranged around 4 courtyards. There are also several towers, a Renaissance loggia, many ramps and staircases, and inner and outer tall thick walls with arched gates. Some of the castle rooms have painted frescos from different time periods. Of particular interest is the 13th century San Martino's chapel with medieval frescos on the walls.

Figure 11: Sample project images of some castle elements.

4.1 Data Acquisition from Different Sources

Aerial and ground images were taken with the *Olympus*® *E-20* 5-mega-pixels digital camera. Figure 12 shows the computed camera positions from the helicopter over the castle. The imaging, both aerial and terrestrial, took a total of 4 hours in two visits to the site. Two camera settings were used during the project, one at 9mm and one at 36mm focal length depending on the available space around the object. The camera was calibrated at both settings using the targets shown in figure 4. One day was spent in surveying of 115 points on the castle outside walls with a *Leica*® total station. We have also obtained all existing detailed floor plans of the castle, in AutoCAD DWG format, from the castle director. This format made it easy to remove any unwanted information, such as notations, fire escape routes, and symbols since they were placed in different layers.

Figure 12: Actual locations of the used aerial images.

4.2 Site Reconstruction

The image-based modeling technique described in this paper has been implemented in the *ShapeCapture*® software, version 5.5 [http://www.shapecapture.com]. The software was also used for calibration and bundle adjustment. Different software was developed for the automatic feature extraction and matching. A general model was created from the aerial images, and 17 detailed models were created using different sets of ground images, including models of the St. Martin's chapel, the towers, the loggia, the entrances, and details of the walls enclosing the courtyards. Figures 13-15 show snapshots of some models, both as wire frame and solid with textures. The semi-automatic procedure, which needs about 10% of the points to be measured interactively, required an average of 1-2 days of work by one person for each model. *AutoCAD*® software was used for modeling from the floor plans.

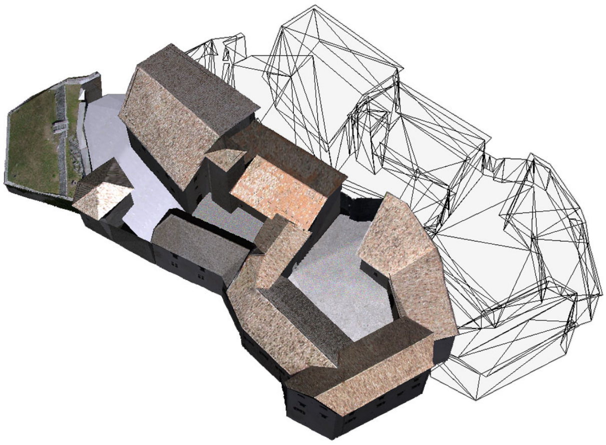

Figure 13: General model of castle buildings.

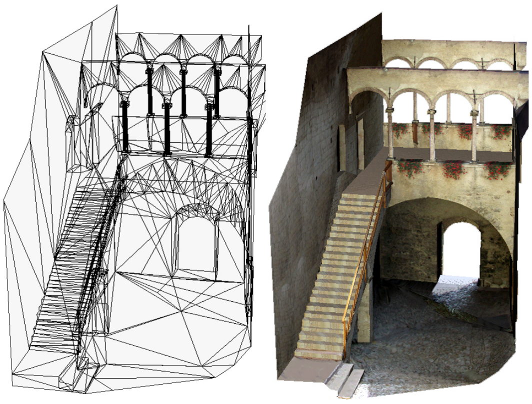

Figure 14: Detailed model of the loggia.

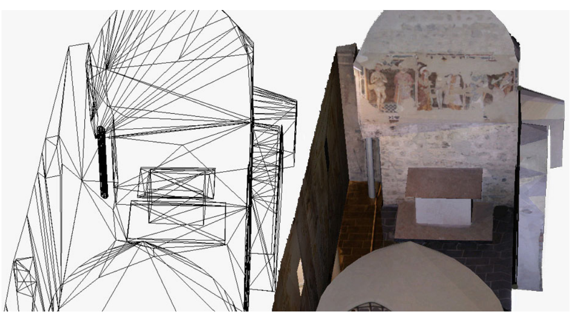

Figure 15: Part of the model of St. Martin's chapel.

4.3 Accuracy Assessment

The castle structures extend over an area of about 100 meters by 64 meters and have up to 35 meters height. The castle grounds are elevated by over 30 meters above the road approaching it. The aerial images were taken from an average range of 120 meters and average vertical distance of 65 meters above the castle. The field of view of each image usually covered all buildings, with an average view width of about 160 meters. One pixel in the image corresponds to about 8 cm when using the 9mm focal length. The accuracy is assessed by the variance-covariance matrix of the least-squares-computed 3-D points, and validated by surveyed checkpoints that had 3 mm accuracy. The achieved accuracy was in fact homogeneous in the three coordinates and averaged: **17***mm* (X), **15***mm* (Y), and **16***mm* (Z). This is one part in 10,000 and represents 0.2 pixels. For the ground-level models, we achieved accuracies of: **1***mm* to **2***mm*, which give average relative accuracy of one part in 6,000 and represents 0.3 pixels. The superior relative accuracy reached from aerial images, even though they were taken from much longer ranges, is attributed to the better geometric configuration compared to ground images. Ground images had less than ideal locations due to obstructions and tight spaces around most buildings and inside the rooms.

4.4 Combining Models from Different Data

Applying the procedure presented in section 3.6, we started by superimposing the general model on the floor plan. Using the floor plan as a guide, detailed models such as the loggia in figure 14, and indoor models such as the chapel in figure 15, were then inserted. Detailed models such as gates and parts of the courtyards are connected to the general model using common regions. Points along those regions were first used to register the two models. Then only points along the boundaries of the regions were kept in the general model, and new points were imported from the detailed model. The general model was then re-triangulated to account for the point changes and to create a hole where the detailed model was inserted (figure 16). Finally, sections still missing from the general model were added from the floor plan using known wall heights.

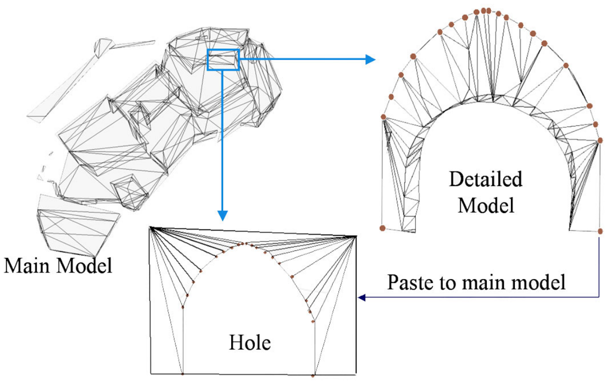

Figure 16: Combining detailed models with main model.

5. CONCLUDING REMARKS

Using images taken from a low-flying helicopter and from ground levels, combined with existing floor plans and limited surveying, it is feasible to completely model a complex castle such as the Stenico castle at high accuracy and with realistic details. Semi-automated modeling and model assembly techniques were developed. On average, about 10% of all 3-D points were created interactively while about 90% were created automatically. The cost and time required was much less than reported work of modeling structures similar in dimension.

Many sculpted shapes and un-textured surfaces, such as the groin-vaulted ceiling in the San Martino's Chapel, are better suited for modeling with laser scanning. In the future, we will use an accurate laser scanner on some parts of the castles being modeled in our 3D-Arch project to add higher levels of detail to the model.

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