3D VIRTUAL RECONSTRUCTION AND VISUALIZATION OF COMPLEX ARCHITECTURES – THE "3D-ARCH" PROJECT

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ABSTRACT:

The 3D Virtual Reconstruction and Visualization of Complex Architectures (3D-Arch) project started in 2005 and is now completed. It proposes an integrated approach based upon a combination of different 3D measurement techniques for the virtual reconstruction of complex architectures like those found in medieval castles. This paper summarizes the work done in this project, consolidates incremental work published earlier, and details the latest developments and results. Since no established procedure has been available to model and visualize this type of architectures, the project resulted in several new contributions: an effective workflow for castle 3D modelling, increasing the level of automation, the seamless integration of models created independently from different data sets, integration of 3D models and GIS data, and developing useful visualization tools. We tested the approach on various castles in Northern Italy and the results demonstrated that it is effective, accurate and creates complete and highly detailed models suitable for many purposes such as documentation to track changes for future restoration, education, and tourism.

Figure 1: Typical castles of the Trentino's valleys (northern Italy) from aerial views (above). Images of various castle parts (below).

1. INTRODUCTION

The 3D-Arch project started in 2005 to capture and model complete geometric and colour details on exterior and interior of castles in Trentino province (northern Italy) for accurate documentation and photo-realistic visualization. It is a joint project between FBK (formerly ITC) in Trento, Italy, and the NRC in Canada. Our own earlier work on castle and large architecture modelling [El-Hakim et al., 2004a and b] showed that due to typical castle size, complexity and setting, it is hard to find sufficient number of places from which to acquire images or scans. Castles are usually located at protective settings like hilltops and ridges, and are fortified with rings of high walls, strong gates, moats, and towers (Figure 1). Complexity, occlusions, structures variety and inaccessible locations are serious problems that will affect capturing all the geometric details of such structures. This makes it necessary to collect large amount of data from various positions that must be accurately registered and integrated together. Multiple sensors and techniques such as laser scanning, photogrammetry and modelling from floor plans must be used, each where best

suited [El-Hakim, 2001]. This requires developing methods able to seamlessly combine different models together and remove overlaps and fill gaps between them to create one model suitable for documentation and visualization. When possible, surveyed targets are used to assist data registration and geo-referencing. Those targets will also serve as ground truth for accuracy evaluation. Preliminary results at different stages of development have been published [Voltolini et al, 2006, El-Hakim et al, 2007]. We give a more complete account and the final results in this paper.

Each of the castles modelled in the project presented different challenges, which gave us an opportunity to develop a general approach that can be applied to most other castles and complex architectures. All the castles in general included buildings and towers of mixed styles added over different times and have undergone damage and restoration. Courtyards, inner and outer tall thick walls and large gates are also found in most castles, which adds to the complexity and increases the amount of data that must to be collected. Some of the castles have unique

elements. The Buonconsiglio castle has the Romanino loggia with rich ceiling frescos and the well-known "Cycle of the months" medieval frescos in one of its towers. Some castles, such as the Valer and Avio, have chapels with vibrant frescos. Many castles, such as Avio and Beseno, have extensively destroyed buildings and ruins, which complicates data collection and processing due to the fact that no surface constraints or relationships can be enforced.

2. RELATED WORK

3D modelling can be either *from reality* (photogrammetry, surveying, laser scanning) or from *computer graphic, CAAD or procedural* methods, but all can be integrated to achieve more complete and photo-realistic results. Since there is a large body of work relevant to our project, only a small selection focusing on modelling large architectures is discussed here.

Many castles have architectural drawings created from direct measurements or surveying techniques. Converting existing 2D architectural drawings to 3D models may be done interactively from simple floor plans using commercial software. However, for complex drawings automated techniques have been developed [see Yi et al, 2009 for recent survey].

Image-based methods [e.g. Hanke and Oberschneider, 2002; Bacigalupo and Cessari, 2003; Debevec, 2003; Kersten et al., 2004] use aerial or ground images and require some interaction during the modelling phases. Indeed acquiring points suitable for modelling and segmenting the point clouds into topologically meaningful surface groups remain an interactive procedure. Fine details are usually added from dense matching (stereo or multi-photo) after the determination of the camera parameters. Most fully automated image-based methods [e.g. Pollefeys et al, 2008] are based on video or closely spaced image sequence, which may be difficult for castle settings. Also, accuracy becomes an issue on long image sequences due to short base-to-depth (B/D) ratio and error propagation unless points are tracked in many images [Voltolini et al., 2006]. To solve this problem, wide baseline stereo matching has been attempted [Strecha et al., 2004] but no practical results on full structure like a castle are yet available. To our knowledge, no entire castle model was completed based purely on fully automated techniques, although small sections have been demonstrated. For structured scenes like architectures, techniques attempting full automation of the modelling process [e.g. Zissermann et al., 2002] rely on constraints of surface shapes and assumed relationships between surfaces and many require vanishing points from sets of parallel lines. Since in most castles these assumptions do not apply, such techniques will be ineffective. A practical solution is to incorporate limited interaction on regular shapes such as arches, columns, doors and windows and use those as constraints for fully automated dense stereo [El-Hakim, 2002 and 2006].

Active sensors like laser scanners are increasingly being used for digitising large site and complex architectures [e.g. Bano, et al, 2008, El-Hakim et al., 2008, Stamos et al., 2008]. However, these sensors are not very portable and may not be easy to place in many parts of a castle grounds. Systems used and results vary widely from one published work to another and in many projects it is combined with other techniques. For example, Beraldin et al. [2002] combined photogrammetry and high-resolution range data for the 3D modelling of a Byzantine crypt; Stumpfel et al. [2003] used laser scanners, structured light systems, photogrammetry and photometric stereo for the digital reunification of the Parthenon's structures; El-Hakim et al. [2004b] used photogrammetry for outlines and main shapes while laser scanning was used for the fine geometric details.

Yastikli [2007] also employed both photogrammetry and laser scanning to model large heritage structures. Klette and Scheibe [2005] reconstructed a castle hall by combining panoramic images and laser scanning. Bahmutove et al. [2006] modelled interiors of architectures with specially designed active system, while Brusco et al. [2006] used a multi-spectral system to model large frescoed rooms.
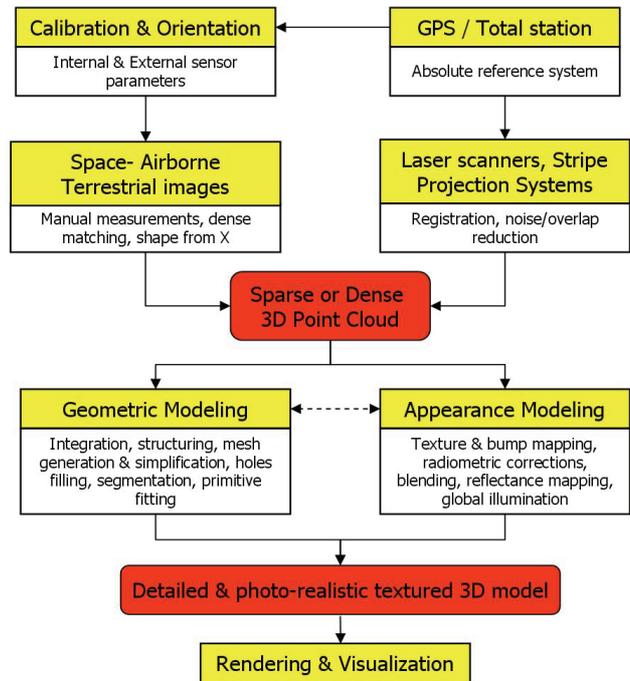
Figure 2: 3D modelling pipeline for site documentation.

3. THE APPROACH

Our methodology to accurately model complex architectures like castles combines active and passive sensors exploiting the intrinsic advantages of each technique (Figure 2).

The approach is summarized as follows:

1. Use existing floor plans to create a non-detailed less accurate model with approximate extruded heights;
2. Survey (total station and GPS) selected well defined features or targets to define the reference coordinate system, scale and connect independently-created models;
3. Accurately calibrate digital cameras in the lab at all the various settings used on the field;
4. Take images from a helicopter and create an overall model of building exteriors, walls, courtyards and main grounds. This model will integrate with or substitute most of the model created in step 1;
5. Take ground images to model parts not visible from aerial images;
6. Add fine geometric details of relieves or sculptures using advanced dense stereo or multi-image matching;
7. Use rectified ground images to derive high-resolution details of windows, portals or other important architectural elements of interest (horizontal extrusion);
8. Use medium-range (1m-50m) laser scanner to capture details of selected interiors that are less suited for image-based modelling;
9. Assemble and integrate all models together and with the surrounding landscape.

Details of some steps are given in the next sections.

3.1. Basic model from floor plans

Floor plans are used to add sections missed by imaging or scanning and for model assembly (section 3.5). To convert floor plans to 3D models, semantic information, such as room identities and connecting openings, is necessary followed by walls extrusion to known heights or heights from sensor-based models. Window and doors are inserted where appropriate.

3.2. Basic Image-based models

For most castle architectures, image-based methods are the ideal choice. Images can be taken much faster and manoeuvred easier than the slower bulkier laser scanners, and both geometry and texture are acquired from the same images. However, considering a complex and large architecture surrounded by narrow spaces, it is hard to take ground images from viewpoints that cover an entire surface. Therefore, images from a low-flying helicopter are preferred to model exteriors, walls, courtyards, roofs and main grounds. These models substitute most of the models created by means of floor plans and add correct heights and details. On the other hand, for façade details, occluded spaces and room interiors, ground close-range images are used (Figure 3).

Figure 3: Examples of models generated from aerial and ground images.

Unfortunately, it is often difficult to achieve a good network configuration (good B/D ratio and image configuration), in particular for narrow sections, which may reduce accuracy. In other cases where occlusions are a major problem, a technique to obtain 3D information from a single image, using geometric constrains, is employed [El-Hakim, 2002].

3.3. Detailed image-based models

In steps 3.1 and 3.2, basic models without fine geometric details are generated. For simple and fast visualization purposes, the details might not be necessary but for architectural studies, conservation issues, and visualisation at close-up, fine details are often necessary. Some features (e.g. relieves) require high-resolution meshes to achieve accurate documentation (Figure 4). Other features (e.g. windows) need detailed geometry for more realistic visualisation (Figure 5). Therefore the following techniques are used, each where appropriate, to add fine geometric details and create suitable LOD visualisation of the architecture [Remondino et al., 2008]:

- For patches with regular shape, implicit function (e.g. plane, cylinder or quadric) is fitted using seed points and applying a relative stereo matching technique [El-Hakim, 2006];
- For more complex or irregular segments with unknown shape function, an absolute multi-image matching technique is used (Figure 4A and B) [Remondino et al., 2008];
- For segments unsuited for image matching, Depth from Shading (DFS) is applied [El-Hakim, 2006] (Figure 4C);
- For repeated and common architectural features (windows, portals, balconies) with known dimensions, rectified images are used to derive high-resolution and precise details applying a horizontal extrusion (Figure 5).
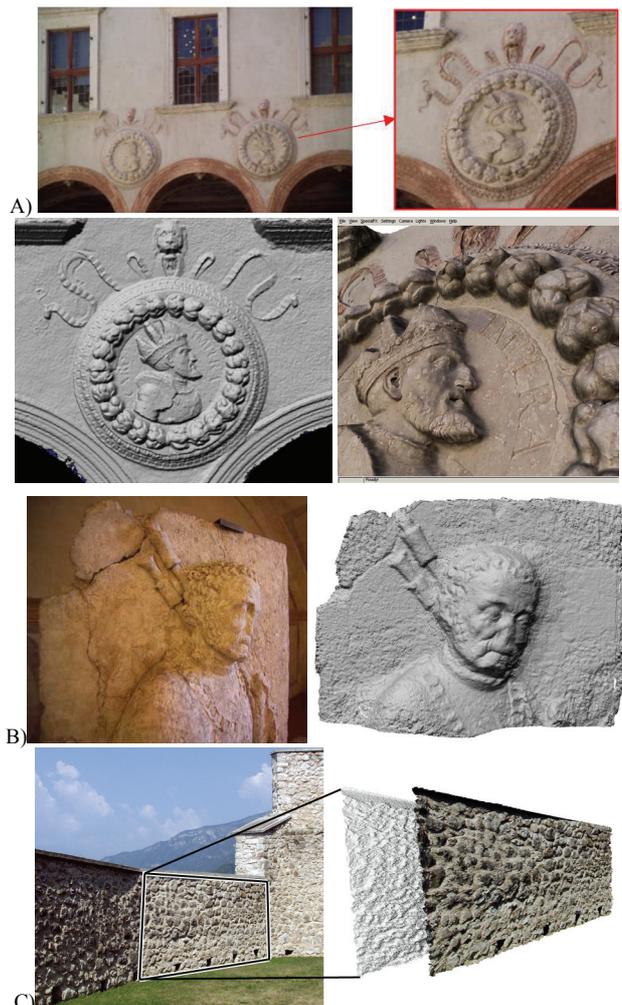

Figure 4: Detailed models achieved with multi-photo matching (A and B) or Depth from Shading (C).

3.4. Detailed models from laser scanners

Indoor rooms with interesting geometric and texture details are good candidates for laser scanning since the scanner can be better set up in an indoor environment and they can survey the interesting features with millions of points faster than image-based techniques. One of the most important issues is to determine the spatial resolution to be used. This depends on the desired level of details, the type of scanner and the scene's size. The number of scans is affected by the spatial resolution, surface shape complexity and occlusions. Examples of such range-based models for some castle rooms are shown in Figure 6 and Figure 7.
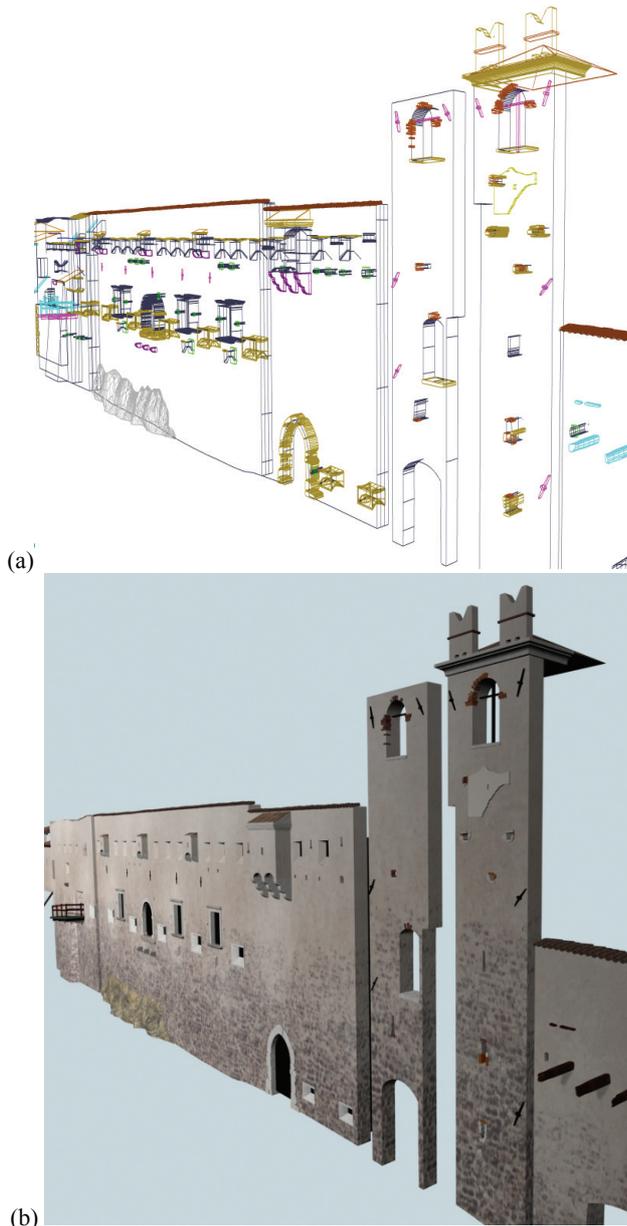

(a)

(b)

Figure 5: Architectural elements extruded from rectified images with CAAD tools (a); the final texture model of the façade (b).

3.5. Registering and integrating all models

Since the different models created by different techniques vary significantly in accuracy and resolution, or LOD, this difference must be taken into account when integrating the models together. Engineering drawings provide the least accuracy and detail level. They are also less reliable since they may also not

include changes that happened since their completion. Accuracy, details and reliability are better with models from aerial images and even better from ground image or range sensors. To combine models from different data sets into one model appropriate for reconstruction and visualization the following rules should be fulfilled:

- The models must have the correct scale and orientation.
- Joint primitives, surfaces, edges and vertices from adjacent models must match perfectly.
- No gaps, redundant surfaces or intersecting edges are acceptable.
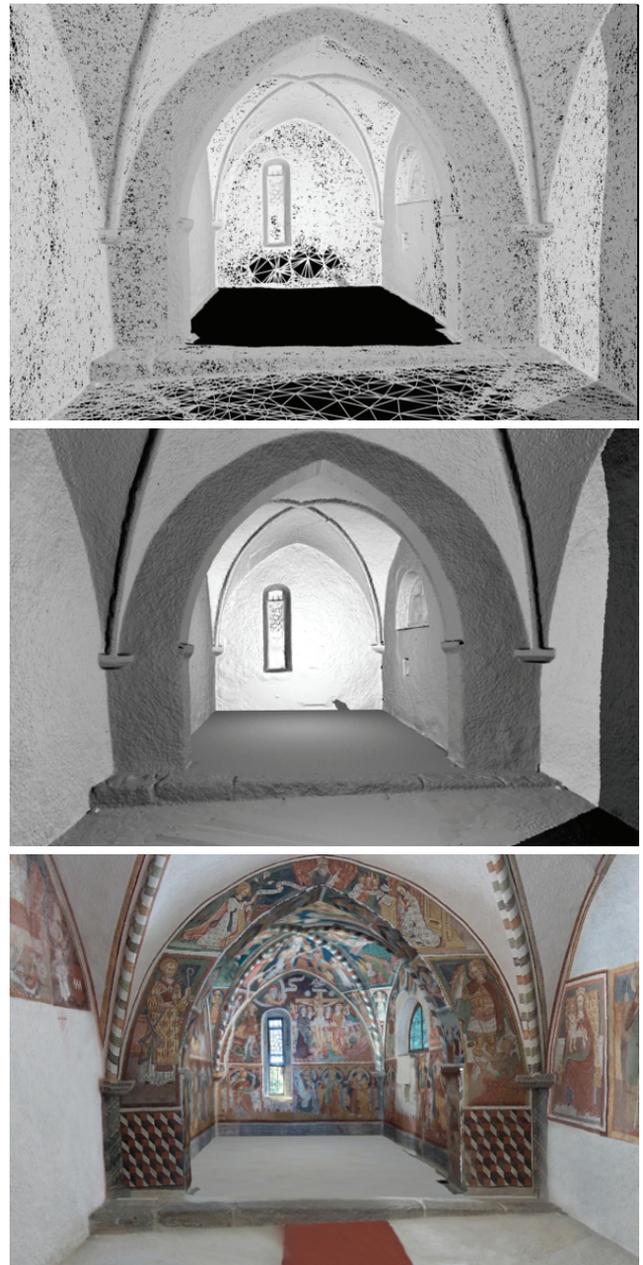- Textures on adjacent models should integrate seamlessly.

Figure 6: Wire-frame, shaded, and textured model of an interior chapel altar in the Valer castle.

Some of these issues are not dealt with in commercial software, thus we had to develop our own techniques and software tools. The models are registered manually in modelling software such as 3ds max® using common points or portals (Figure 8a). Registration will be unnecessary if the individual models were

directly created in the same coordinate system or if common (surveyed) points were visible. When models have no visible common points with other models or no surveyed points, floor plans are used for positioning those models. Any remaining gap between models is filled also from the floor plans (Figure 8b).
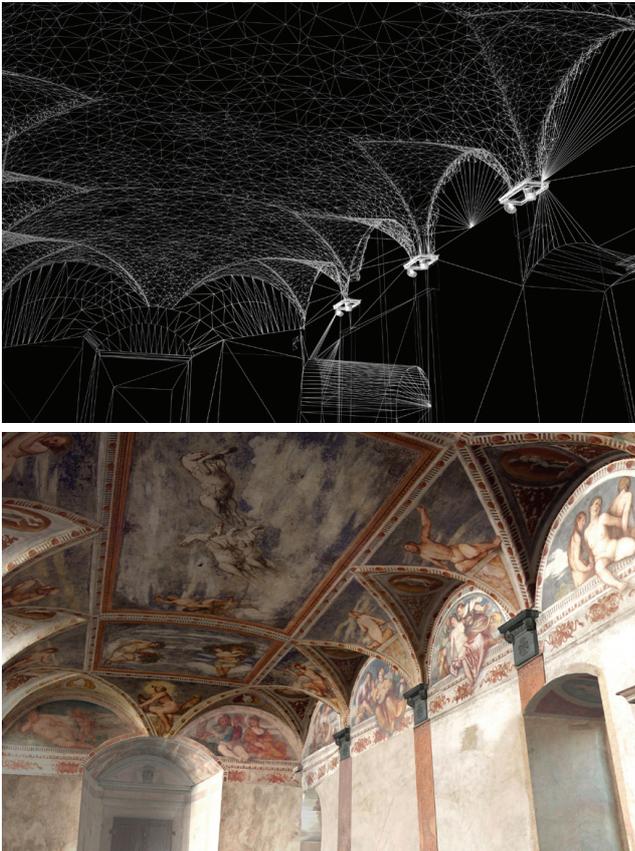

Figure 7: Wire-frame and textured model of the Romanino loggia vaults in the Buonconsiglio castle.

Once all models are registered and integrated according to a predefined hierarchical order, the meshes are adjusted to remove redundant surfaces from the lower level models (Figure 9). Lower level models are re-triangulated to account for point changes and to create holes where detailed models are inserted and in some cases Boolean operations are required to create these holes.

3.6. Visualization with the surrounding landscape

The generated 3D models of the castles are finally visualized within their surrounding landscape (Figure 10 and 12) using various DTM and DSM resolutions (1x1, 2x2 and 10x10m) and orthophotos (0.5m and 5m resolution). GoogleEarth and Autodesk LandXplorer are used for this.

DTMs and building 3D models are also utilized for further analysis in GIS environments (ESRI ArcGis) to perform visibility analyses of the castles (Figure 11) as well as line of sights between the various castles. The use of GIS in heritage management has been also underlined by the UNESCO [www.unescobkk.org/culture/gis/index.html] as GIS allows: (1) historical and physical site documentation, (2) the assessment of current physical condition, cultural significance and administrative context, (3) the preparation of conservation and management strategies, (4) the implementation, monitoring and evaluation of management policies. Furthermore, a GIS tool generates permanent records of heritage sites, including text documentation, virtual flight-over and 3D models.
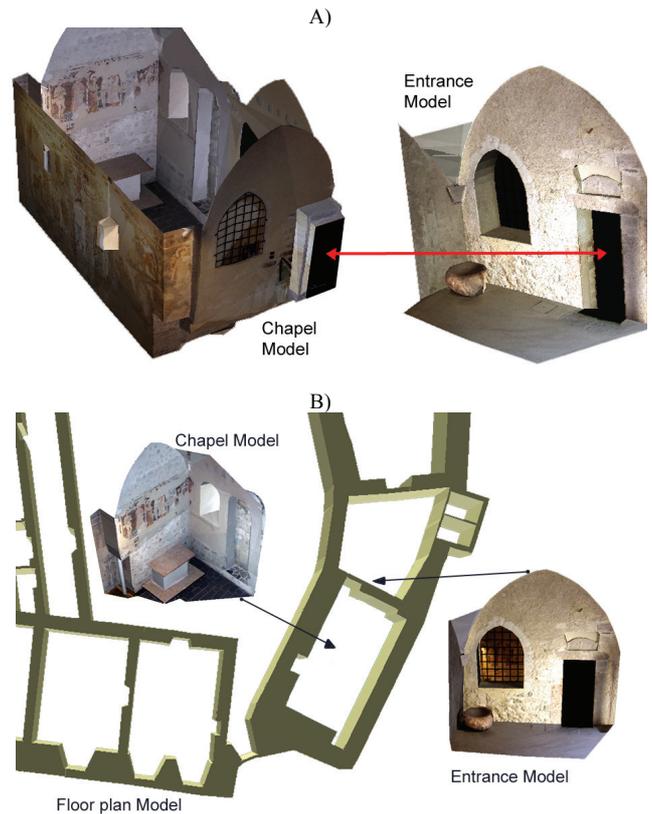

Figure 8: Model registration with common portal (A) or using floor plans (B).

Figure 9 Final assembled models (Beseno and Avio) with buildings, walls and ground.

4. ACCURACY EVALUATION

Surveyed targets and points on the buildings façades provided ground truth accuracy evaluation of individual models and the complete integrated models. Results from the Stenico castle (Figure 1-top right and Figure 3-top) are given here as a typical example. The castle buildings extend over about 100 meters by 64 meters area and have up to 35 meters height. The aerial images were taken from a range of 65 meters to 120 meters. The image average field of view was 160 meters wide. One pixel in the image corresponds to about 8 cm when using 9mm focal length. The accuracy is assessed by the variance-covariance matrix of the measured 3D points, and validated by the surveyed points that had 3mm accuracy. The achieved accuracy averaged to 17mm (X), 15mm (Y) and 16mm (Z). This is one part in 10,000 and represents to 0.2 pixels. For the ground-level models, we achieved accuracies of: 1mm to 2mm, 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 tight spaces around most buildings and inside rooms. Results from other castles were similar, except for Valer castle which had less accuracy on ground models (2mm to 3mm) due to its tighter spaces which resulted in fewer images and less favourable configurations.

The procedures to derive detailed surface models from images were tested on several test objects, in a lab environment and on several castle carvings. For ground truth, the objects were surveyed with a triangulation-based and TOF scanners. The average differences between the scanned model and the image-based model demonstrated that there are no significant differences between image- and range-based approaches. This suggests that laser scanners are no longer superior in accuracy or level of details, at least in most of the terrestrial applications. [El-Hakim et al., 2007; Rizzi et al., 2007; Remondino et al., 2008].
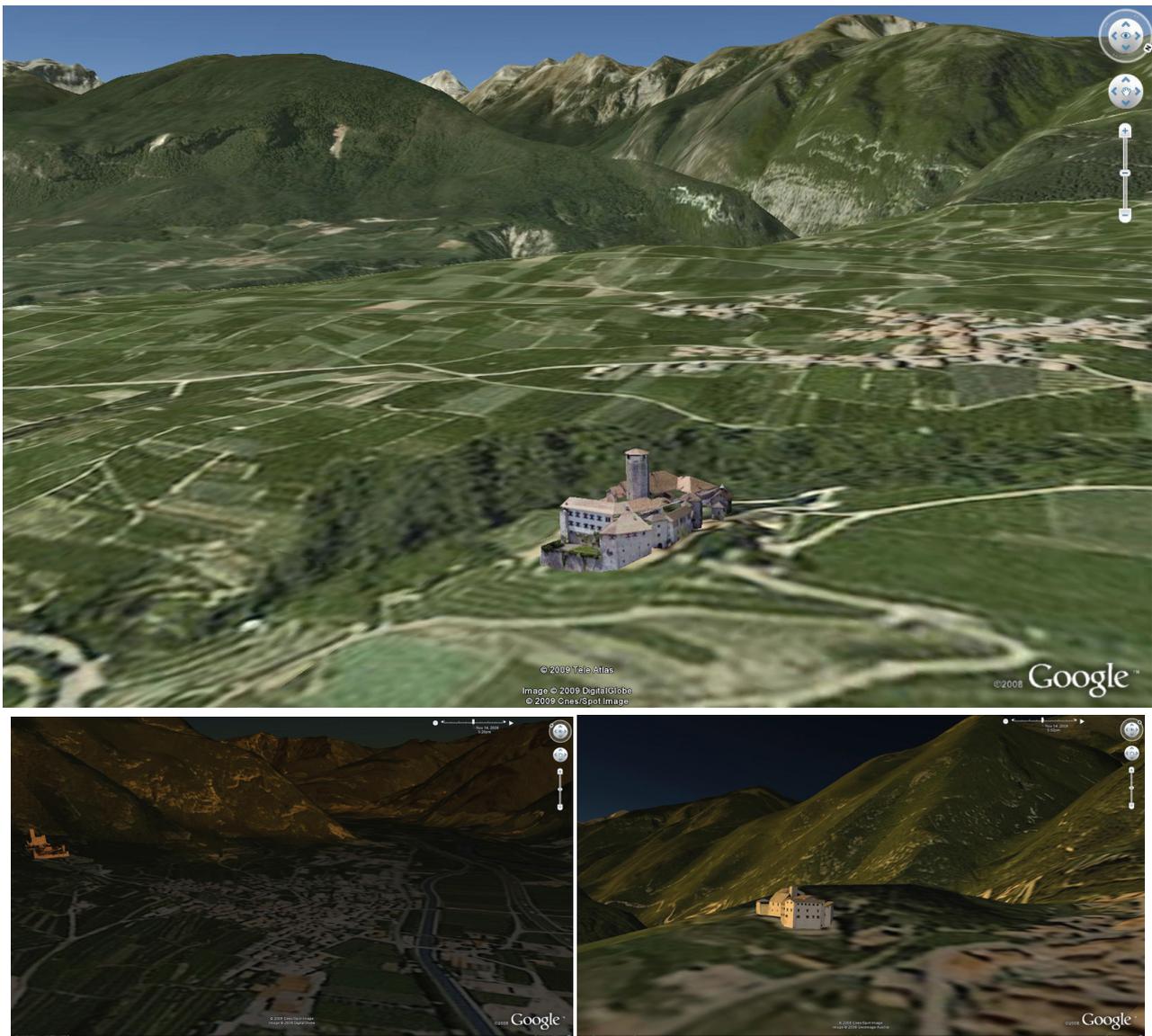

Figure 10: 3D models of castles (respectively Valer, Avio and Stenico) integrated in the surrounding 3D environment and visualized within GoogleEarth.
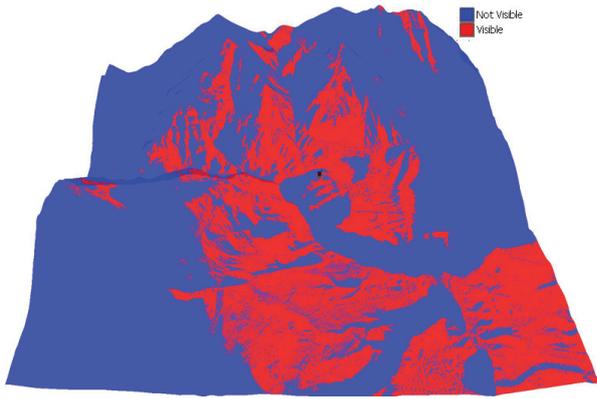
Figure 11: Visibility analysis results for Stenico castle, with a surrounding area of ca 15 x 15 km. In red the areas from where the heritage is visible.

5. CONCLUSIONS

Despite of the challenges related to size and complexity, we have achieved the 3D-Arch project objectives of modelling and visualizing of complex architectures and created detailed 3D models of several different castles. A successful workflow has been established, integrating different methodologies and technologies, each one where best suited. Using images taken from a low-flying helicopter and from ground, combined with surveying, laser scanning and existing floor plans, a complex castle with realistic details and different LOD can be completely modeled. Semi-automated modelling and model assembly techniques were developed as for such complex architectures fully automated approaches are ineffective. The time required to collect the data was only 2-3 days per castle and the data processing and modelling averaged 1-2 months, which is much less than reported similar works. To capture fine geometric details from images, the developed procedure starts with basic model of surface elements then adds details with relative stereo matching, absolute multi-image matching and depth from shading, each on the most appropriate surface. The results have shown that our semi-automated approach creates highly detailed models with high accuracy and at low cost.

The research in this field is still open, in particular to increase the automation in the different modelling steps and develop smart and efficient techniques to reliably orient widely separated images, seamlessly combine different 3D models together, remove overlaps and fill gaps or holes with no or minimum human intervention.

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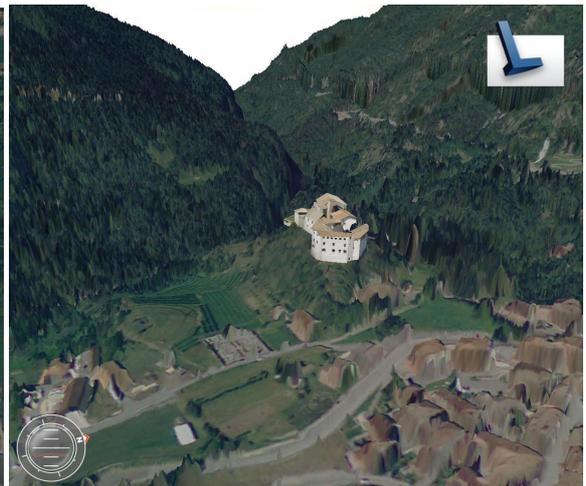
Figure 12: The modeled castles (respectively Valer, Beseno and Stenico) inserted in the LiDAR DSM (1 m geometric resolution) of the surrounding landscape and visualized with Autodesk LandXplorer.

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