DIGITAL PHOTOGRAMMETRY AND LASER SCANNING IN CULTURAL HERITAGE SURVEY

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ABSTRACT:

A joint project between the Interdept. Research Center of the University of Padova (CIRGEO), a research group of Istituto Tecnico per la Ricerca Scientifica e Tecnologica (IRST) of Trento and the Visual Information Technology group (VIT) of the NRC Canada, in Ottawa, has been undertaken, with the main aim to create a set of 3D models of an historical building by means of photogrammetry and laser scanning-based surveying techniques. Beside the investigation of their geometric accuracy, a photo-realistic representation suited for interactive navigation and manipulation in VR environment was a further objective of thie project. To this aim, the main room in the Aquila tower in Buonconsiglio castle (Trento, Italy) was choosen, as it featured a relative simple geometry along with artistically and historically very precious frescoed walls. In this paper a description of both surveying and modeling procedures adopted and results of a comparison test between employed techniques are presented.

1. INTRODUCTION

One of the major masterpieces of international Gothic art (1350-1450) is the Cycle of the Months, a fresco to be found in the Aquila tower in Buonconsiglio castle, Trento, Italy. The main room in the tower, completely frescoed with the Cycle of the Months, preserves a rare and most precious example of medieval painting on a nonreligious subject. A joint project, between CIRGEO (Interdept. Research Center of Geomatics) of the University of Padova, IRST (Istituto Tecnico per la Ricerca Scientifica e Tecnologica) of Trento and the Visual Information Technology group (VIT) of the NRC Ottawa, Canada, has been established, with the objective to acquire the most suitable data of the room by means of different survey techniques to generate corresponding 3D models. The geometric accuracy of each model will be assessed and compared with the other models. Another objective is the creation of textured photo-realistic models for interactive manipulation. To this aim we considered two different approaches based on photogrammetry and laser scanning. In the first case we addressed the 3D modeling of the room by *image-based modeling*, a technique suitable for regular geometric surfaces like architecture and monuments [El-Hakim, 2002]. The simple and regular shape of the room was therefore a good candidate. The photogrammetric survey and the subsequent modeling were performed using a high-resolution colour digital camera and a commercial modeling software.

The second kind of approach is a *Range-based modeling* by means of laser scanner, which allows to acquire a lot of small geometric details although the accuracy varies significantly from one scanner to another. Since scanners with integrated texture or colour acquisition do not provide the quality required for a room of this size and detailed frescos, textures have been acquired with a high-resolution digital camera. This means we separated acquiring geometry from acquiring texture. Obviously, digital images should be then properly calibrated and registered with the geometric data in order to perform the texturing of the 3D model by laser scanning. For this project the work has been arranged as follows: CIRGEO team created the models both from range data, whereas the IRST team and VIT provided the model from digital images and its texturing.

In following sections, the various kind of surveys will be described and concerns on both the modeling and rendering stages will be highlighted. Furthermore, results of a comparison test between the resulting models are presented along with some conclusions and future work.

2. INSTRUMENTS

In order to generate both photogrammetric- and laser scanner-based 3D models of the room, different instruments were employed. For the photogrammetric model, a 5 Mpixels digital camera, Olympus E20P (1920 x 2560 pixels), has been employed. The small size of the room yielded a limited coverage of each image (without using a fish-eye lens), therefore 16 images were needed to cover the walls, 8 for the ceiling, 2 for the entrance, and 5 for the tower. The average texture resolution was 2mm x 2 mm area of the wall per pixel. It should be noted however, that for texturing purposes it is advisable to limit as much as possible the number of required images in order to avoid changes of lighting conditions and subsequent effects of inconsistent illumination. Then, the *Riegl LMS-Z360* laser scanner [Riegl, 2004] was employed to create the second kind of model. Such scanning system is provided with a rotating head and two inner high speed rotating mirrors, which allow to acquire a scene with a large field of view (FOV = 360° H x 60° V), reducing therefore the need of several stations. Typically, accuracy such sensor is ranging between 3.2 mm (at 50 m distance) to 6 mm (at 100 m distance) with a beam diameter divergence of 3 mm at 50 m. Besides X, Y, and Z point coordinates, the laser is able to register the reflected beam intensity and RGB colors.

Coordinates of ground control points, as common points for the comparison between the two models, were measured with a *Leica TCR 705* total station, featuring a EDM with two laser beams: one, invisible, for conventional measurements to prism and a second one, visible, for reflectorless surveys. About 70 control points were measured with the total station with an accuracy of about 5 mm. In order to compare the geo-referencing of the laser scanner model using both natural and artificial targets, part of the control points (50) were chosen as easily recognizable features on the frescoes, whereas further 20 retro-reflective targets were placed mainly at the bottom of the walls of the room to avoid any damage of the frescoes, and were surveyed in reflectorless mode (see figure 1). For an exhaustive overview of both the Leica total station and the Riegl laser scanner specifications see Tables 1 and 2.

Table 1. Leica Total Station specifications

MANUFACTURER	Leica
PRODUCT	TCR 705
Angle measurement	5",1.5 mgon
Distance measurement	3000m (with reflector); 2mm + 2ppm 170m (w/o reflector); 3mm± 2ppm
Measuring time	<1s (with reflector) typical 3-6s (w/o reflector)
Recording	>8000 measurements and coordinates 232 interface for external connection
Magnification	30 x
Plummet	Laser: located in alidade, turning with the instrument, accuracy ± 0.8mm at 1.5 m

Table 2. Riegl laser scanner specifications

MANUFACTURER	Riegl USA
PRODUCT	LMS Z360
Laser Wavelength (in nm)	904
Laser Power (in W, mW)	1 mW
FDA Laser Classification (Class)	1
Beam Diameter at Specified Distance (0.Y ft at X ft/Ymm at X m)	20 mm at 50 m
Measurement Technique	LiDAR
Average Data Acquisition Rate (pps)	8,000
Maximum Data Acquisition Rate (pps)	12,000
Distance Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)	6 mm at 200 m
Position Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)	6 mm at 100 m
Angular Accuracy (degrees-min-sec)	0.002
Minimum Range (feet/m)	1 m
Maximum Range (feet/m)	300 m
Field of View (vertical angle) (degrees-min-sec)	90
Field of View (horizontal angle) (degrees-min-sec)	360
Minimum Vertical Scan Increment (degrees-min-sec)	0.002
Minimum Horizontal Scan Increment (degrees-min-sec)	0.002

3. IMAGE-BASED MODELING

The modeling approach adopted at this stage is based on a semi-automatic technique described in [El-Hakim et al, 2003] and implemented in ShapeCapture commercial software [ShapeQuest, 2004]. The bundle adjustment in the software was done with free network, i.e. no control points were used at this stage and the model scales were determined from a small number of linear measurements (such as window dimensions) collected while taking the images. The resulting geometric models are shown in figure 2.
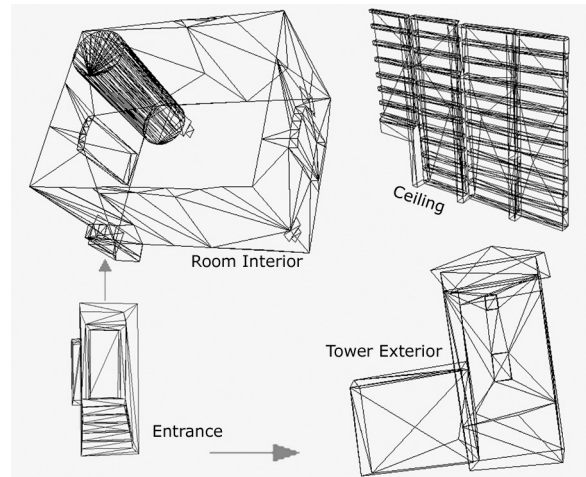

Figure 1. View of a frescoed wall in the room

Figure 2: Wire-frame models by image-based method.

4. TEXTURE MAPPING

Achieving high level of photorealism was another goal of the project, in order to create extremely realistic visual experiences. Due to the nature of this frescoed room, in this stage of the project, effort has been spent to identify the main factors affecting the visual quality of the models and the performance of interactive visualization and to select the most appropriate technology. Basically, the modelling and rendering approaches used for this project can be summarized as follows:

1. Create geometrically accurate model with an image-based photogrammetric technique.
2. Divide the model into efficient size groups of triangles.
3. Select best image for each group.
4. Compute texture coordinates of vertices using internal and external camera parameters.

5. Compute radiance images of all texture-images from a calibrated response curve.
6. Re-sample pixels within each triangles based on projective transformation between triangle plane and image plane.
7. Apply filtering and radiometric corrections to the textures.
8. Create MIP maps; a sequence of textures each of which is progressively lower resolution (by a factor of 2) of the original image. This is used to solve aliasing problems and also for texture size management.
9. Create bump maps on smooth surfaces, like walls, by introducing small variations in surface normals thus adding roughness and more realistic look to surfaces when lighted.
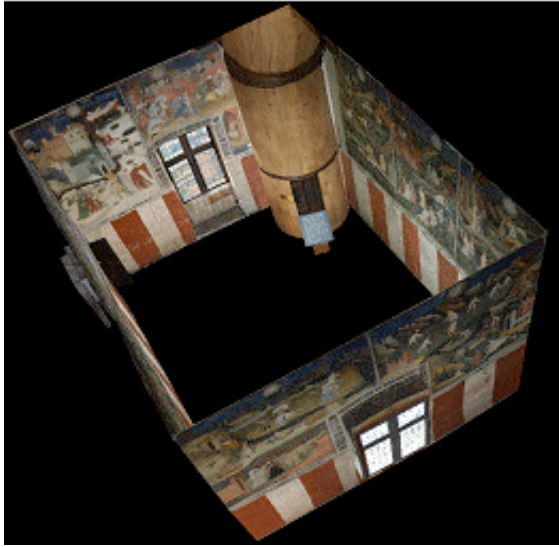10. Rendering with efficient rendering software.

Figure 3: Textured 3D model.

Figure 3 shows the final textured model of the frescos. Here a brief overview of the different kind of approaches adopted for texture mapping and texture correction is reported. More details can be found in [El-Hakim et al, 2003].

Selecting most appropriate image to texture: With sufficient image overlap, the texture of a triangle can be obtained from a number of different images. As a rule, the image that has the largest texture should be selected, however in order to avoid multiple assignments of many different images to adjacent triangles, local re-assignment of triangle patches to images was employed. In this way the number of triangle edges where adjacent triangles are mapped from different images is reduced.

Texture perspective: The employed method defines a local Texel coordinate system for each 3D triangle. Projective transformation between the plane of the triangle and image plane is determined and used to resample the texture within each triangle. This is followed by low pass filter to remove high frequency noise introduced by this re-sampling. The geometric accuracy of projective transformation was ensured by proper camera calibration, image registration and bundle adjustment, which were carried out by TexCapture software.

Radiometric distortions: Radiometric distortions result along common edges of adjacent triangles mapped from different images. Though corrections to this problem are still experimental, some solutions were adopted for this project. Firstly, the response function of the digital camera was determined. In this way the non-linear mapping between the digitised brightness value for a pixel and the scene radiance could be estimated. Such a knowledge allows to merge images taken at different exposure setting, different angles, or even different imaging devices. Secondly, color corrections between adjacent textures obtained from different images are applied to minimized the differences.

Rendering: in order to achieve the desired performance, the software for interactive visualisation has been developed at VIT [Paquet and Peters, 2002] using scene graph tools. Scene Graphs are data structures used to hierarchically organize and manage the contents of spatially oriented scene data. They offer a high-level alternative to low-level graphics rendering APIs such as OpenGL.

5. LASER SCANNER-BASED 3D MODELING

Beside photogrammetric surveys, range data of the interior of the room were acquired with the Riegl LMS-Z360 laser scanning system. Given the relative small size of the room and wide field of view of the laser scanner, only 6 scans were sufficient to survey the whole volume: 4 for the walls and 2 for the ceiling. Setting a high scan resolution value and by placing the scanner in the middle of the room a spatial resolution (displacement on XY plane) of 5 mm on average was obtained. Though the acquiring software, provided in bundle with the laser scanner, offers a tool for the scan registration, both this procedure and all subsequently ones needed for the 3D modeling were performed using Polyworks Modeler of [Innovmetric, 2004]. Such a software provides a very powerful environment for the interactive modeling of real objects, whose geometry has been acquired in terms of very dense point clouds. It is composed of several modules, which allow the user to carry out all the modeling steps, keep the control over the entire process and verify the accuracy of the results through a number of dedicated tools. In this stage following modules has been employed:

– *ImAlign* for the scan alignment,
– *ImMerge* for the mesh generation
– *ImInspect* for the model georeferencing

5.1 Range Data Alignment

The interactive manual N-points alignment procedure was adopted in this case to register the wall and the ceiling scans each other. The acquisition of intensity data greatly helped the registration step, as it made easy to recognize matching points on the adjacent scans, as shown in figure 4.

As a result of this first processing step, an approximate transformation matrix for each scan pair was obtained and then used in the second stage as starting point for the refined alignment based on the well-known ICP algorithm. In both steps a scan group was locked in order to define the reference frame of the model. Then, a global ICP-based alignment algorithm was run in order to refine the results of the first stage. Such approach [see Soucy et al, 1996] yielded a very good registration, with a mean convergence value of 6.3×10^{-8}, much lower than the preset threshold (10^{-6}), and an average RMS alignment error of 0.006 m (figure 5). This result should confirm the goodness of the registration procedure implemented in Polyworks: the residual error is due to the inherent accuracy of the laser scanner. Finally, through *ImMerge*, the scans were triangulated, in order to model the room surface in terms of a unique mesh, which is the most suited representation for the model texturing (figure 6).
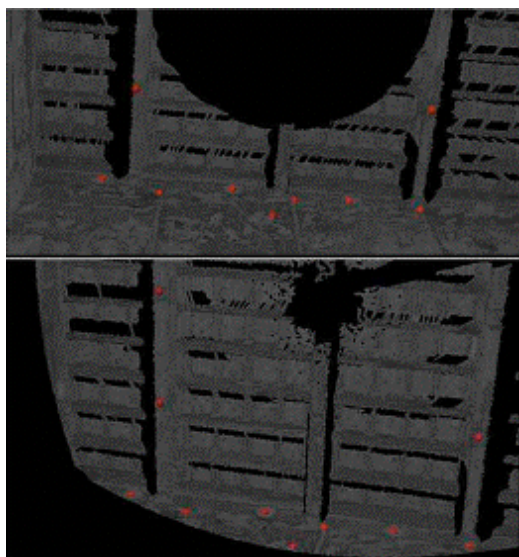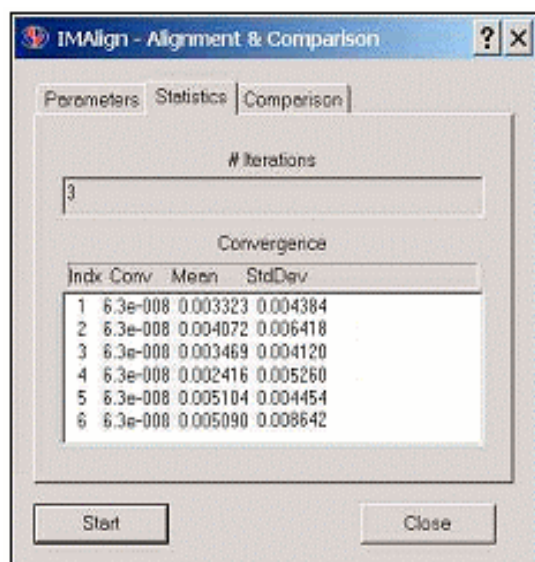
Figure 4. Interactive manual alignment.

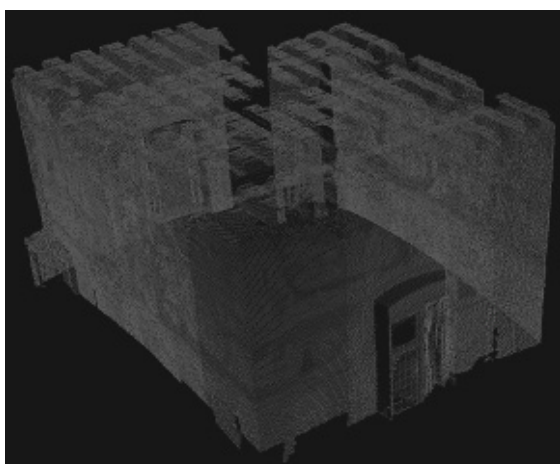Figure 5. Result of the global alignment.

Figure 6. The meshed 3D model from range data, rendered as a unique point cloud.

6. COMPARING THE MODELS

In order to compare the two models (image-based and laser scanning), the aligned point cloud was simplified (i.e. decimated), deleting most of the overlapping points. This approach has two advantages: 1) it allows to reduce the model size in terms of number of points, resulting in a small file size; 2) overlapping points lead to a redundant information that is only useful for the alignment and the subsequent triangulation step, not for the model georeferencing. It should be noted that both the georeferencing and the comparison stages has been performed only on the decimated point cloud making up the laser scanner 3D model. The triangulated model was not used here: due to the inherent "nature" of the meshing process, points are substituted by triangles and further simplifications of the cloud can occur, i.e. points can be discarded leading to a change respect with the original data.

To compare the two models, they need to be registered in the same reference system, here defined by the total station survey. Therefore the control points measured with the total station were identified, by visual inspection of the operator, both on the 3D laser and on the image-based model. As both natural and artificial targets were used, the comparison has been split in two different parts accordingly: in a first run we employed the natural features only (points selected on the frescoes) while in the second run the retroreflective targets were taken into account. This approach was adopted to check the reliability of a laser scanning model georeferencing using natural targets only, which are the unique kind of targets often available. Twenty-eight of the 50 surveyed natural targets were used as control points for the model georeferencing while the others were considered as check points to evaluate residual differences between the two models. This step was very time consuming, because those points had to be carefully selected in order to be not coincident with the ones identified as check points on the laser scanning 3D model. Moreover, two further issues ensued during this processing phase: 1) the low quality of registered intensity data made very difficult or even impossible a reliable recognition of the control points measured with the total station; 2) the retroreflective targets saturated the laser sensor, resulting in a set of undefined white spots of points, of no use for the comparison with the image-based model. For those targets, the points most probably measured by the total station were identified as the intersection of the two diagonals of the rectangular spots, and then used for the model georeferencing only. This stage was accomplished through the powerful tools available in the *ImInspect* module of Polyworks software. Basically, only 22 features on the frescoes could be well recognized and used as check points and 15 artificial targets out of 20 could be employed for the laser scanner model georeferencing.

An analysis of the comparison results using the 22 check points for both models is reported in Table 3, where RMS values denote the differences between coordinates of check points selected on a 3D model and corresponding points, measured by total station.

Table 3. Comparison between models

3D Model	# of Check pts	RMS X [m]	RMS Y [m]	RMS Z [m]
Image-based	22	0.017	0.025	0.020
Laser scanner	22	0.056	0.063	0.044

Taking into account the low values for the registered intensity data and the noise inherent to the laser, the obtained lower accuracy for the georeferenced laser scanner model was expected. On the other hand, as previously mentioned, retroreflective targets could not be successfully used for this stage, otherwise better results could be obtained. Moreover, no other kind of measurements, like distances between recognizable natural features, could be reliably used, because most of them were represented by corners or edges, which are generally not well surveyed by a laser scanner given its beam aperture. Again, artificial targets, if successfully acquired, could be more useful even for this goal.

7. CONCLUSIONS

In this paper the application of two different 3-D recording and modeling techniques, namely image-based modeling and laser scanning, for cultural heritage documentation and visualization has been presented. In image-based modeling, a consumer digital camera was used, then the acquired data was processed through a commercial modeling software to create a 3D textured model. In addition, a laser scanning model was produced with the main objective to compare the two models. The main room in the Aquila tower in Buonconsiglio castle, featuring walls frescoed by precious paintings, was chosen to carry out the comparison between those modeling techniques. To this aim control points and check points were provided by a total station survey, measuring both natural features on the walls and topographic retroreflective targets. However, due to difficulties in identifiying the latter targets in the laser scanner model, only the natural ones were used for the comparison. Nevertheless, in order to increase the accuracy on check points selection it is advisable to use artificial targets, whenever possible: if successfully acquired by the laser sensor they should provide better results than with natural features. Given our experience, we suggest to test beforhand the response of the laser to the targets being used, since some laser scanners could show an unexpected behaviour when dealing with retro-reflective targets, which leads to significant measurement errors.

Beside the discussion about accuracy obtainable by the two different 3D modeling techniques described here, a question remains still open: which technique is the best one? Based on the experience gained so far on 3D modeling and taking into account the differences between the main factors involved in such techniques (data acquisition sensors, data resolution, nature of data noise, adopted modeling procedures, etc.), it is the opinion of the authors that discussed techniques are not competitive but rather complementary. If the user needs only a semplified model of the object of interest, in short time, then image-based technique is the most appropriate one, as it can provide the 3D shape of the object through images, taken even by a consumer color digital camera. Therefore this provides a relatively fast and low cost technique for 3D modeling. Conversely, if not only the global object but also a detailed 3D shape of some of its parts are of interest, then in this case a laser scanner could be used, being capable of direct acquisiton of a huge amount of 3D data in shorter time compared to other classical survey techniques.

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