DIGITAL 3D RECONSTRUCTION OF SCROVEGNI CHAPEL WITH MULTIPLE TECHNIQUES

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ABSTRACT

The use of 3D digitization and modeling in documenting heritage sites has increased significantly over the past few years. This is mainly due to advances in laser scanning techniques, 3D modeling software, image-based-modeling techniques, computer power, and virtual reality. There are many approaches currently available. The most common remains based on surveying and CAD tools and/or traditional photogrammetry with control points and a human operator. This is very time consuming and can be tedious and lingering effort. Lately, modeling methods based on laser scanners data and more automated image-based techniques are becoming available.
Initially, the goal of this work was to discuss advantages and disadvantages of those 3D modeling techniques applied to a cultural heritage building, i.e. the Scrovegni chapel in Padova, Italy, by comparing the geometry and visual quality of related models for as-built documentation, restoration and interactive visualization purposes. To this aim the chapel was imaged with a color digital camera and surveyed with both different kind of laser scanners and traditional topographic instrument. Unfortunately due to the long time wasted before all requested laser scanners were available from the dealers and difficulties encountered during the subsequent 3D modeling, due to the bad quality of some range data, at the present date only the range data model is available.
Therefore in this paper we will discuss only the results obtained by generating a unique 3D model of the Scrovegni Chapel using four different laser scanners: Cyrax 2500, Mensi GS 100, Optech ILRIS 3D and Riegl LMS-Z210. In order to assess the performance of these sensors when applied for cultural heritage survey, data quality, geometric accuracy, sensor noise, ease of use, speed of data collection, will be the topics of this work.

1. INTRODUCTION

Beside *image-based modeling* and traditional photogrammetric survey, the use of ground-based laser scanners for 3D modeling applications in the field of cultural heritage has become recently very actractive, given the capability of laser sensors to produce high-density point clouds of features in relatively short time and without the extensive use of signalized targets. From these point clouds, 3D models can be generated with sufficient accuracy for as-built documentation, restoration plans, virtual environment generations, interactive manipulation.
In order to compare the laser scanning technique with existing 3D surveying technologies such as image-based modeling and photogrammetry, a joint project between CIRGEO (Interdept. Research Center of Geomatics of the University of Padua, Italy) and the VIT (Visual Information Technology, NRC, Ottawa, Canada) was established, with the aim to create 3D models of the inside of the Scrovegni Chapel in Padua, by applying different surveying techniques. This church represents a very actractive element of the national cultural heritage for 3D modeling applications. The Scrovegni Chapel presents a simple architecture, being composed of a rectangular hall with a barrel vault, an elegant gothic triple lancet window on the façade, tall narrow windows on the southern wall, and a polygonal apse. The interior can be therefore surveyed very easily as no columns prevent a clear view of the walls and the ceiling.
Furthermore, from artistic point of view, the Scrovegni Chapel is considered a masterpiece in the history of painting in Italy and Europe in the 14th century, as the vaulted roof and walls are completely painted with frescoes, framing episodes in the lives of the Virgin Mary and Christ, executed by Giotto in his mature age. Along with 3D data, it was planned to collect digital images of these frescoes, as well, in order to perform the texturing of the final 3D model.
Regarding the laser scanner-based 3D modeling, we planned to employ different kind of sensors in order to test and assess their performance when applied for architectural surveying.
As we didn't own any laser scanner at that time, all these sensors were rented from corresponding Italian dealers. Unfortunately, given the limited time of use allowed to us, the church could not be completely surveyed using only one sensor, therefore we were constrained to generate only one model with the best range data set from all collected scans. Moreover, given the long time wasted in this first part of the work, at the present only the range-data modeling step has been accomplished. Therefore in subsequent sections a description of adopted processing methods and issues, we dealt with during the generation of the 3D model of the Chapel, will be provided.

2. THE SCROVEGNI CHAPEL

For the Scrovegni Chapel, Giotto was asked to depict a series of stories from the Old and New Testaments, culminating in Christ's crucifixion and resurrection, and the Last Judgement. The aim was to encourage visitors to the Chapel to meditate more deeply on Christ's sacrifice and the salvation of mankind. Giotto planned an architectural structure in painted imitation marble supporting the vaulted roof, decorated as a star-spangled sky, with framed stories of episodes in the lives of the Virgin Mary and Christ on the walls (Figure 1). On the wall at the end of the church, opposite the altar, is the grandiose Universal Judgement, which concludes the story of human salvation (Figure 2). The frescoes, painted between 1303 and 1305, follow three main themes :

1)episodes in the lives of Joachim and Anna (1-6)
2)episodes in the Virgin Mary's life (7-13)
3)episodes recounting Christ's life and death
The lower parts of the walls contain a series of frescoes illustrating Vices and Virtues in allegory.

Figure 1. Inside view of the Chapel and Giotto's frescoes

Figure 2: The end wall framing the Universal Judgement

Major restoration work was undertaken in the late 19th century and again in the 1960s. More recently, damages due to atmospheric pollution, caused the painted surfaces to crumble away. Urgent restoration was carried out immediately and, on May 31 2000, a special technical installation was set up, a sort of "artificial lung". This special air-conditioned environment now both purifies the air inside the Chapel and monitors its atmosphere continuously, in order to protect these unique frescoes, some of the most important of all time.

3. LASER SENSORS

Recalling that the initial idea was to generate and compare 3D models of the church from different range data sets, four ground-based laser scanners were employed for this work: Riegl LMS-Z210, Mensi GS 100, Optech ILRIS 3D and Cyrax 2500. Each of this sensor features different performance in terms of acquisition speed, depth accuracy, maximum distance, point cloud resolution, noise, etc. A summary of their characteristics is reported in tables 1 and 2.
All the scans were acquired at night after visiting hours to be able to place the sensors in the more appropriate positions inside the church. Surveys were performed in different times, according with the availability of the laser scanner from the dealers and with the different data acquisition speeds provided by the laser scanners: altogether, all the data were collected in one week.
As previously mentioned, the whole church could not be completely surveyed using only one laser sensor, therefore we generated a unique 3D model composed of patches of the collected scans, namely: about 70% of range data are from Mensi, 15% from Cyrax, 10% from Riegl and 5% from Optech.
A more detailed description about the distribution and the quality of these range data will be the topic of the next section.

Table 1. Mensi and Riegl laser scanner specifications

MANUFACTURER	MENSI	Riegl USA
PRODUCT	MENSI GS100	LMS Z210i
PERFORMANCE		
Laser Wavelength (in nm)	532	904
Laser Power (in W, mW)	1 mW	1 mW
FDA Laser Classification (Class)	2 (US standard 21 CFR§1041.10)	1
Beam Diameter at Specified Distance (0.Y ft at X ft/Ymm at X m)	3 mm at 50 m	50 mm at 50 m
Measurement Technique	Time-of-flight	LiDAR
Average Data Acquisition Rate (pps)	5,000	8,000
Maximum Data Acquisition Rate (pps)	5,000	12,000
Distance Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)	3.2 mm at 50 m/ 5 mm at 100 m	15 mm at 400 m
Position Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)	3.2 mm at 50 m/ 5 mm at 100 m	6 mm at 100 m
Angular Accuracy	6.6 seconds	7.2 seconds
Minimum Range (feet/m)	1 m	4 m
Maximum Range (feet/m)	Up to 150 m [1]	500 m
Field of View (vertical angle)	60°	80
Field of View (horizontal angle)	360°	360
GENERAL		
Scanner Dimensions (LxWxH)	34 x 27 x 42 cm	44 x 21
Scanner Weight (pounds/kg)	13.6 kg	13

Table 2. Cyrax and Optech laser scanner specifications

MANUFACTURER	Cyra Technologies	Optech Inc.
PRODUCT	HDS2500	ILRIS-3D
PERFORMANCE		
Laser Wavelength (in nm)	532	1540
Laser Power (in W, mW)	< 1 mW avg	10 mW
FDA Laser Classification (Class)	2	Class 1 under all operating conditions [1]
Beam Diameter at Specified Distance (0.Y ft at X ft/Ymm at X m)	<6 mm from 0-50 m	0.675 in at 100 ft/17 mm at 30 m
Measurement Technique	Time of flight	LiDAR (Time of Flight)
Average Data Acquisition Rate (pps)	1,000	2,000
Maximum Data Acquisition Rate (pps)	1,000	3,000
Distance Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)	4 mm at 50 m	0.275 in at 330 ft/7 mm at 100 m, [2]
Position Accuracy at Specified Distance (0.Y ft at X ft/Ymm at X m)	4 mm at 50 m	0.4 in at 330 ft/10 mm at 100 m, [2]
Angular Accuracy	60 micro-radians	0.0045 degrees (16 arc seconds), [2]
Minimum Range (feet/m)	1.5 m	10 ft/3 m
Maximum Range (feet/m)	100 m	>4,900 ft/>1,500 m typical [3]
Field of View (vertical angle)	40 degrees	[8]
Field of View (horizontal angle)	40 degrees	10 degrees, >270 w/optional pan/tilt accessories
GENERAL		
Scanner Dimensions (LxWxH)	40.1 x 33.7 x 42.9 cm	12.25 x 12.25 x 8 in/ 312 x 312 x 205 mm
Scanner Weight (pounds/kg)	20.5 kg	25 lbs/12 kg

4. THE 3D MODELING

As previously mentioned, the Scrovegni Chapel was chosen for this project because of its simple architecture: the presence of a single hall (nave) allowed us to survey the interior with ease without occlusions of the walls and the vaulted ceiling.
Conversely, the apse has revealed to be more tricky to be completely surveyed given the presence of the main altar, which made impossible to scan some parts of the walls, given the small room available between the back of the altar and the apse. This area resulted in a wide hole in the 3D model that had to be manually closed using both artificial surface patches and a few digital images as reference guide for the hole filling stage.
Since all employed laser sensors were able to acquire the intensity of the reflected beam, figures of the paints were imaged on the point clouds, as well. Such features could be often well recognized on the intensity data and therefore extensively used as reference points during the alignment procedure, as described in following subsection.

Prior to registering the scans, the range data were linearly interpolated in order to get a uniform point spacing, since they were acquired with different resolutions: 8mm for Mensi and Optech, 5mm for the Cyrax and 1 cm for Riegl. Accordingly a 8mm grid size was chosen as a trade-off between point cloud density and size of related data files being processed. However the interpolation was applied to Cyrax data only, while Riegl scans were left unchanged to avoid the addition of artificial (i.e. not real) points in the corresponding clouds. All the processing steps were carried using Polyworks [Innovmetric inc.] a powerful 3D modeling software which allows to work with multiresolution range data.
Then a 2 steps interactive manual N-points alignment procedure was adopted to register the scans with each other: matching points were easily recognized using only the intensity data, as shown in figure 3. As most part of the church was surveyed by the Mensi laser scanner, (95% of the hall and 10% of the apse), related scans were used as main data block for the registration, at this stage.

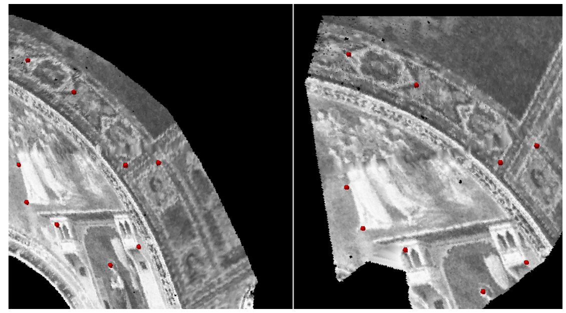

Figure 3. Interactive manual alignment.

After all the scans were manually aligned, a global ICP-based registration algorithm was applied in order to refine the results of previous step. Such approach [Soucy et al, 1996] yielded a very good registration for the Mensi scans, with an average RMS alignment error of 0.006 m, confirming the goodness of the registration procedure implemented in Polyworks: the residual error is due to the inherent accuracy of the laser scanner. However, if remaining scans of the Cyrax, Optech and Riegl laser scanners are taken into account, then the RMS grows to about 1cm, as showed in figure 4. This increase could be explained considering that, among employed laser sensors, the Riegl was the noisiest and related scans were used to join the range data from the nave (surveyed mainly with the Mensi) with the ones from the apse (completely surveyed by the Cyrax only).
An example of the comparison of noise content between range data of Riegl, Optech and Mensi laser scanners is presented in figures 6 b-d, which relate to the survey of the surface of the wall displayed in figure 6a.

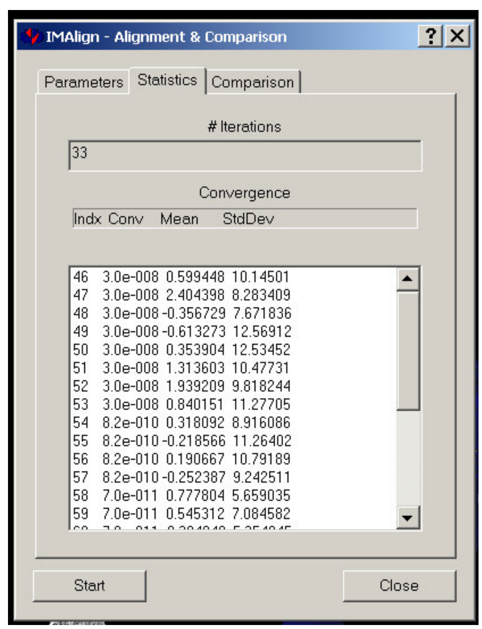

Figure 4. Results of global alignment

Figure 6a. Surface showed as point clouds in figures b-d

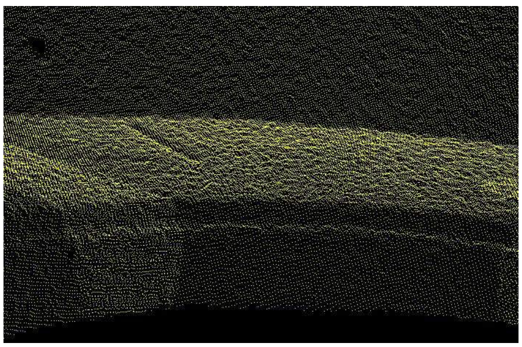

Figure 6b. Noise content of Riegl scan.

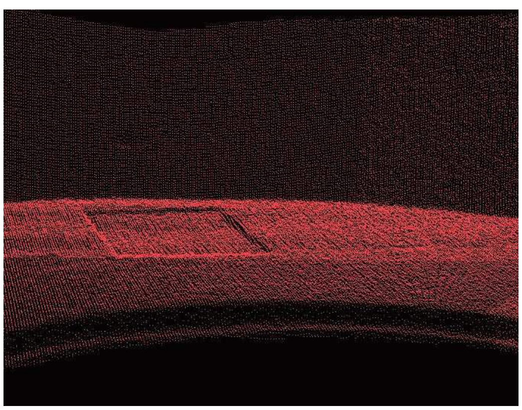

Figure 6c. Noise content of Mensi scan.

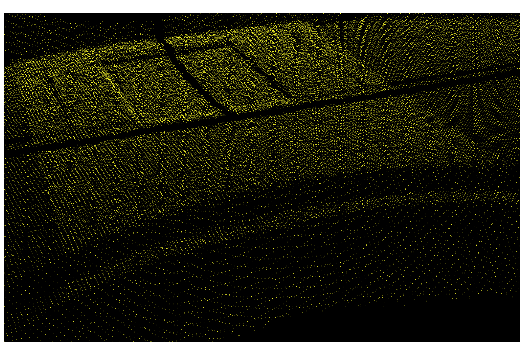

Figure 6d. Noise content of Optech scan.

Beside numerical results of the alignment, Polyworks is also able to display an error map, where the residual 3D distances between points of overlapping scans are displayed in different colors. Using this tool we noticed that the residual error was distributing in different way accordingly to the performed alignment: evenly along the overlapping area if scans of different sensors were involved, with varying density in the case of the same laser scanner (Figures 7-9). Such unexpected behavior cannot be well explained: no further comparisons could be done using scans from the same sensor, as these parts of the Chapel represented the missing areas in the Mensi data sets and were surveyed by no more than one laser scanner.

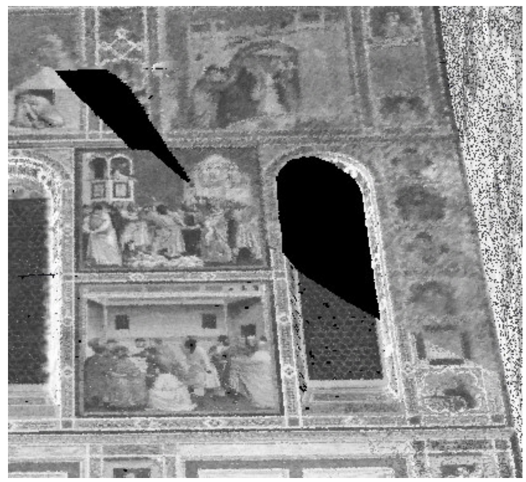

Figure 7. Holes in the Mensi data.

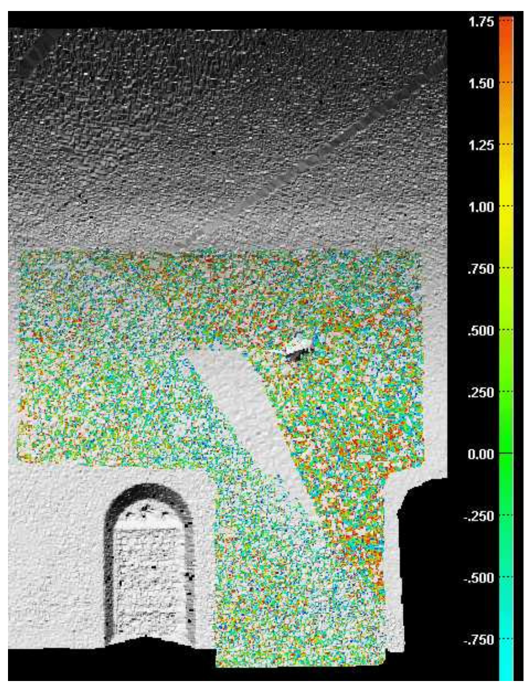

Figure 8. Errormap of Optech-Mensi scan alignment.

Figure 9. Errormap btw.adjacent Optech scans

As previously mentioned, in order to generate a 3D model of the Chaple with adequate accuracy, we planned to choose the best scans among the whole data set of range data acquired with the four laser scanners. Unfortunately that could not be always done as in some cases both the Cyrax and the Optech sensors provided a bad intensity response, what made more difficult or even impossible to use the scans for the alignment. Moreover intensity issues of those sensors showed up in different ways. In the case of the Optech scanner some scans presented so low intensity values, where the laser beam hit the walls with tilted angle (i.e. no vertical scan), that no features could be recognizable at all (Figure 10), resulting in unuseful scans.

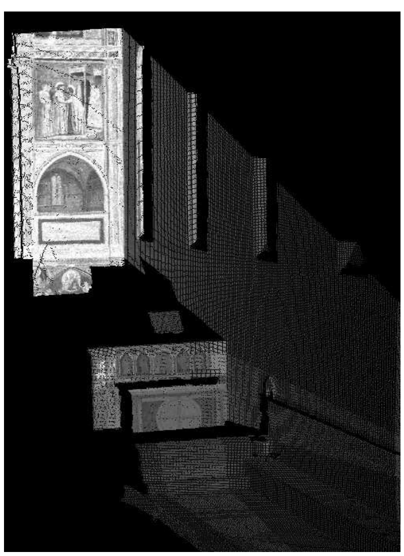

Figure 10. Effect of laser beam tilting in Optech scans

On the other hand, the registered intensity values of Cyrax scans looked like to be biased, i.e. shifted towards the darker area of the light spectrum. In this case, for each scan the corresponding histogram of intensity data was computed and after visual analysis a constant shift has been applied, in order to increase the brightness of the scan at a sufficient level for feature matching (Figure 11 and 12).

Figure 11. Iintensity response of Cyrax 2500

Figure 12. Modified intensity response of Cyrax 2500

After scan alignment, using *ImMerge* module of Polyworks, the registered point clouds have been triangulated getting a unique mesh composed by several millions of triangles. At the present the 3D model of Scrovegni Chapel is still under editing, in order to fill the holes due to occlusions and to generate a simplified version of the model for texturing purposes. Figure 13 shows a global view of the meshed model.

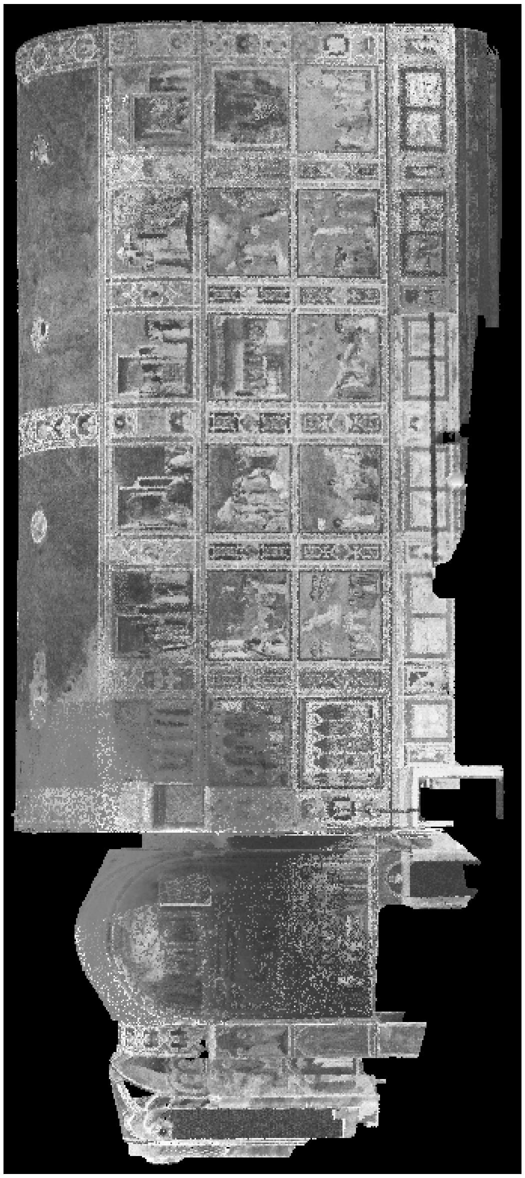

Figure 13. The meshed 3D model of Scrovegni Chapel

5. CONCLUSIONS

In this paper a short review of issues related to a 3D survey with multiple ground-based laser scanners has been presented.
A very precious and famous artistic piece of the Italian cultural heritage; the Scrovegni Chapel in Padua, Italy, was surveyed using four different laser sensors. This church was choosen because of its simple architecture, which allows a clear view of most of the structure, and the presence of frescoes, painted by Giotto in 14th century, whose figures could be used to easily identify matching points during the scan alignment stage. As the church could not be completely surveyed with only one laser scanner, the corresponding 3D model has been obtained mixing together the best data sets collected with the four sensors. During surveys, two of them showed an unpredictable behaviour, resulting in a low quality of the intensity response, what in some cases prevented us to use collected scans for the alignment.
Basically this work showed that range data collected with different scanners and resolutions can be succesfully merged together to generate a unique 3D model, even if the final model accuracy can be mainly dominated by the more noisy sensor.

However this experience highlighted a further issue related to the range data-based 3D modeling applied to cultural heritage objects: though laser scanners allow to collect a huge amount of data in short time, the data processing and editing stages can become very time consuming when a detailed 3D model of architectural shapes is required, given their high complexity.

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