CULTURAL HERITAGE 3D RECONSTRUCTION USING HIGH RESOLUTION LASER SCANNER: NEW FRONTIERS DATA PROCESSING

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KEY WORDS: 3D, heritage, Laser Scanner, Photo-realism, Reconstruction

ABSTRACT

We present applied examples of laser scanner survey and data processing using phase measuring system. Beside the time of flight principle, the phase measurement principle represents another technique for medium ranges laser survey. High speed of acquisition, very high data density and resolution open new application frontiers in cultural heritage, but poses challenging problems with regard to data processing and 3D modelling. For example high reflectivity quality simplifies laser data investigation and photogrammetric texture mapping process. On the other side range scans dimensions requires multi resolution techniques for data processing. Survey approach and new software solution for data processing will be illustrated by means of applied examples on the field of cultural heritage

1. INTRODUCTION

In the last years, terrestrial laser scanner technology was proposed as useful and competitive approach for documentation of Cultural Heritage.
It is commonly accepted that precise documentation of the status quo is essential for the protection of a building, for scientific studies, during restoration and refurbishment, but also for the presentation to the general public.
Laser scanner technology allows to model objects in 3D with a density of measurements that cannot be acquired within a reasonable time frame with traditional technologies.
Laser scanner can be defined both as imaging and non-imaging system due to the capability to acquire 3D measurement (non-imaging characteristic) with a resolution comparable to a digital picture (imaging characteristic). Completeness, accuracy and fastness are the peculiar characteristics for which laser scanner is generally accepted by survey community as a valid support for documentation and conservation of historic buildings, monuments or archaeological sites.
Beside the most popular measurement system based on the time of flight principle, the phase measurement principle represents the other technique for medium ranges.
Phase-based scanners, existing on the market since more than10 years, were initially proposed as system for industrial applications. These systems are characterized by high speed of acquisition and very high data density and resolution. These characteristics can be considered peculiar for cultural heritage applications, but poses challenging problems with regard to efficient data processing and 3D modelling.
In this paper we present applied examples of laser scanner survey and data processing using phase measuring system in the field of cultural heritage. The paper is structured as follows. In section 2 we briefly describe phase-shift systems characteristic and acquisition methods related to the specific application. In section 3 we focus on data treatment problems and software solutions. The application of hardware and software solutions for surveying a number of rooms inside Castello del Buonconsiglio – Trento (Italy) - are presented in section 4. Application results are described in section 5. Conclusions and future perspective are reported in Section 5.

2. HIGH DESITY LASER AQUISITION

Most of laser scanner application, also in Cultural Heritage applications, presented in last years makes use of time of flight scanning systems. 3D coordinates of an object are derived measuring the time the laser signal spent from the laser head to the object and back. Generally time of flight systems allow unambiguous measurements of distances up to several hundred of metres and are generally characterized by middle speed of acquisition.
Beside the time of flight principle, the phase measurement principle is the other technique for medium ranges. High acquisition rate and high density of 3D point's acquisition are the peculiar characteristics of phase-shift systems.
Several instrument configuration of the measuring head and of the internal mirrors are available for both the measuring technologies; the geometry of the laser field of acquisition can varies from a fixed window – like a digital camera - to approximately 360° field of view.
It is not the principal aim of this paper to enter in the technical characteristics of laser system and more complete description can be found in bibliography. Table 1 briefly summaries the main differences from time of flight – based and phase-shift based systems.

Measuring System	Range [m]	Accuracy [mm]	Scan Rate [point/sec]
Time of flight	< 1500	< 20	up to 12.000
Phase shift	< 100	< 10	up to 625.000

Table 1. List of survey examples classified according to their geometric characteristic, data acquisition, and data processing

In the last years we applied 3D laser scanning technology - based on both the technologies - for surveying several large-scale objects: historical building, monuments, and archaeological sites.
The scan rate and consequently density of acquired points that mainly differentiate the two measuring technologies, determines also the acquisition methodology.
Laser acquisition requires a viewpoint planning phase in order: i) to reduce occlusion and shadows problems, ii) to avoid

viewpoints too slope respect to the object, iii) to guarantee a uniform scan resolution, iv) to guarantee survey completeness.
Preliminary inspection of the site is fundamental for an efficient survey.
After a first visual inspection of the site to be scanned, the acquisition phase can start. Generally middle-long range laser scanners are controlled by means of a portable computer (PC). Laser control software generally allows to set up: i) scan area, ii) scan resolution, iii) target recognition (for scan registration or geo-referencing), iv) RGB camera acquisition (if available).
Time of flight scanners requires and efficient control especially for scan area and resolution to avoid long acquisition times. From an operational point of view the preliminary visual inspection must be followed by controlling the laser acquisition using an external PC for each scan view acquisition. These actions are time consuming and they generally require an expert operator.
Phase shift scanners, in particular the type we tested (Imager 5003 by Zoller+Fröhlich GmbH), can acquire for example 10000 x 5000 number of pixels (points) with a horizontal field of view of 360° and vertical ones of 310° in few minutes (approximately 3 min and 22 sec). These acquisition characteristics guarantee a grid of points of 1,6 x 1,6 mm at 25 m. From an operational point of view after establishing the scan positions and the acquisition resolution, the acquisition phase can begin with scan control limited to verify if the acquisition is correct. Usually the reflectance image visualisation helps in this fast control.
In Table II we report the default values of scan resolution and relative times of acquisition in case of Low Noise and default acquisition modes for Imager 5003 by Zoller+Fröhlich GmbH.

Resolution	Points	Time (Low Noise)	Time (Default)
Super High	20,000 x 10,111	13 m 28 s	6 m 44 s
High	10,000 x 5,055	6 m 44 s	3 m 22 s
Middle	5,000 x 2,527	3 m 22 s	1 m 41 s
Low	2,500 x 1,263	1 m 41 s	50 s
Super low	1,250 x 631	50 s	19 s

Table 2. Imager 5003 by Zoller+Fröhlich GmbH: default values of scan resolution and relative times of acquisition.

Phase shift scanner acquisition can be compare to acquire high resolution photos with a panoramic camera, while time of flight scanner need an approach more similar to a normal photo-camera acquisition that need to zoom-in the details in order to guarantee resolution in reasonable time of acquisition.
In other words with phase shift acquisition, the approach is to acquire everything at high resolution and to postpone the data selection at the processing phase. The time of flight technology needs on-field selection of the areas to be surveyed at high resolution.
It is anyhow important to emphasise again that a good planning phase of the laser acquisition is a fundamental step for both the described technologies in order to avoid uncompleted or uncorrected range scan acquisitions.
In figure 1, a reflectance image relative to a single phase shift scan inside the "Sala del Camin Nero" (Castello Buonconsiglio, Trento) is a good exemplification of the "panoramic camera approach".

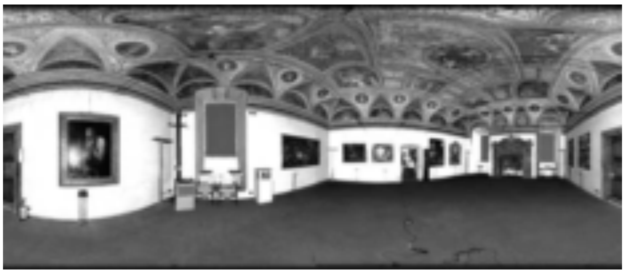


Figure 1. "Sala del Camin Nero"- Castello Buonconsiglio, Trento: reflectance image of a single scan acquisition acquired in 3 min and 22 sec.

3. SOFTWARE SOLUTIONS FOR DATA PROCESSING

The survey strategy described for phase-shift laser acquisition, postpones the data selection and integration to the data processing phase. A fast on-field acquisition allows collecting big volumes of laser data at high resolution posing challenging problems with regard to data processing and 3D modelling.
Reconstructor® Software by European Commission (EU), Joint Research Centre (JRC) is actually used by International Atomic Energy Agency (IAEA) within the context of the activities referred as Design Information Examination and Verification. IAEA has to verify that the designed and purpose of nuclear facilities is as declared by State in accordance to non-proliferation treaty obligations. The combination of Imager 5003 and Reconstructor® Software results an efficient solution for this scope.

3.1 Multi scale approach for data import and registration

Due to the huge memory space require by phase shift scans - more than one 1 GByte in uncompressed format - and the number of scan that can be acquired in very short time, the software was designed to works with a multi scale approach according to the following steps:

- Raw data are archived in an ordered manner and all the project hierarchy is saved in XML format. This organization is particularly useful for historical architectures where the database enables the quick browsing of the database of Buildings and Rooms. In figure 2 the data base view for the three surveyed rooms inside Buonconsiglio Castle is reported.

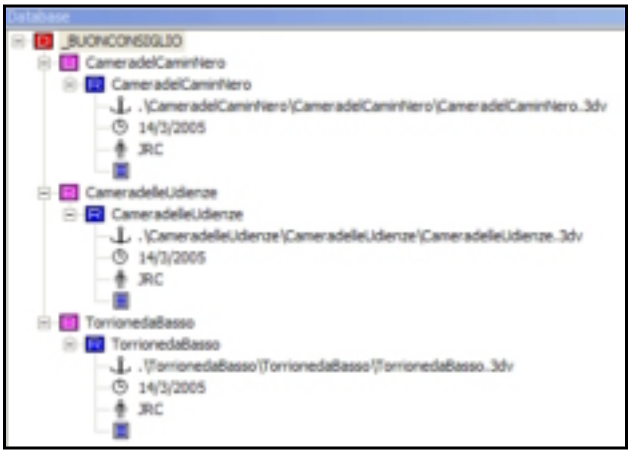


Figure 2. Data base built for three rooms inside Buonconsiglio Castle - Trento (Italy).

- Only Reflectance image is imported in the project (see figure 1) for each single scan with a sub sampling factor that guarantees both scene investigation and data processing with normal PC. A good compromise for high resolution scan (see table 2) is a sub-sampling factor of eight.
- The user can decide if i) the entire range scan (reflectance and 3D points) must imported or if ii) range scan sub-windows are sufficient.
  In the first case software allows to import complete scan at an efficient resolution in term of resolution and memory space. At this stage it is also possible to facilitate the viewing and processing of a number of scans clustering the 3D data in hierarchical structures (e.g. Octrees or Binary trees). The clustering, called level of detail (LOD), is done off-line during the pre-processing and the structure is then saved to disk for later use.
  If the important features (such as targets, important decoration or painting) are localized in particular area, the user can zoom in the range scan and select the area of interest
- The pre-processing is performed immediately after data import and it includes: i) the computation of the local surface normal for each point measured by the scanner, ii) the evaluation of the reliability for each single measurement point, iii) edge detection, and iv) laser data noise reduction.
- The registration step allows transforming range data obtained from different viewpoints into a single reference frame. In particular Reconstructor® Software provides two methods. The point-based registration method is based on the Iterative Closest Point (ICP) algorithm. The targets-based registration allows computing the transformation between the scan and external reference system. The accuracy of the resulting transformation depends on the precision with which the targets are scanned and localised in the scans. The possibility to extract targets sub-windows from high resolution scans facilitate targets detection. Registration parameters are automatically saved in the archived raw data so that roto-translation is automatically applied once a new range sub-window is extracted.

The principal steps of the multi-scale approach are summarized in the following scheme (Figure 3).

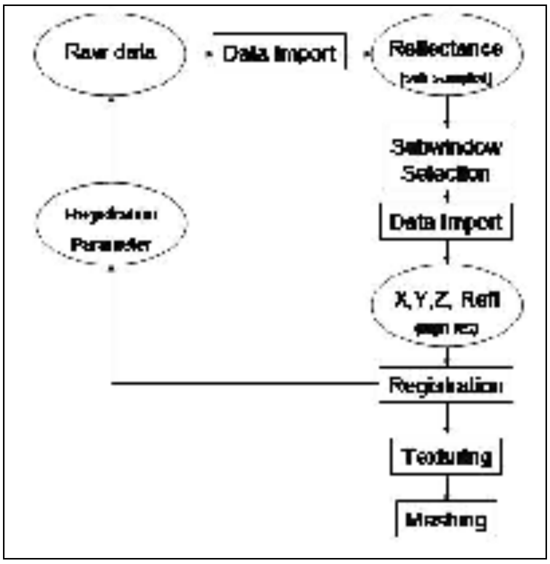


Figure 3: Principal steps of Reconstructor multi-scale approach

3.2 Texturing and modelling at high resolution

Imported range scans can be further processed before extracting final results (i.e. cross section, ortho-photo, linear or surface measurement). Two different processes are applicable: texture mapping and meshing (triangulation).

Texture mapping

The purpose of texture processing is to integrate the 3D measurements from the laser scanner with 2D information taken with an external camera. In order to project a 3D point into an image and thus assign a colour value, the software needs to know external and internal camera parameters. Through Reconstructor® Software, external and internal parameters for each image can be calculated using the 3D point cloud itself. The calibration algorithm needs a set of corresponding 2D coordinates from the image and 3D coordinates from the point cloud to compute the required parameters. High reflectivity quality simplifies point selection. Figure 3 show the selection of 3D point from reflectance image (for each reflectance pixel, 3D coordinates are known) and 2D coordinates from a high-resolution picture.

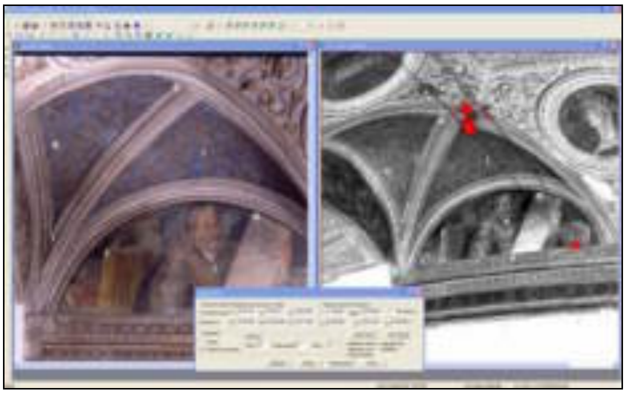


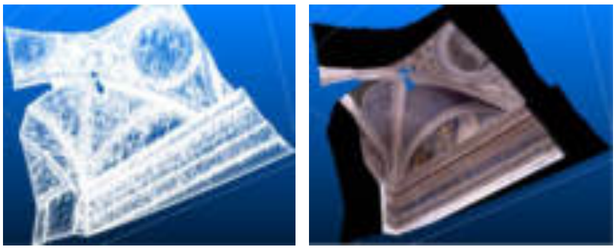
Figure 4. Reference points from the 2D image and corresponding 3D coordinates from range scan. Zoomed area in “Sala del Camin Nero” - Castello del Buonconsiglio, Trento.

If several images of the object have to be taken from different viewpoints, it is possible to mosaic them in a single texture, the images need to be balanced on a global per image basis and finally blended locally along the transition between images.

Data triangulation

Triangulation converts the set of raw 3D points into a triangulated surface. Principals aims of triangulation (meshing) process are: i) to converts the point-based data into a visually more intuitive representation (especially when mapped with reflectance or texture data), ii) to reduce the amount of data, iii) for subsequent interactive processing (e.g. when extracting surface measurements or orthophotos, for visualization purposes and animations). Reconstructor® Software provides a per scan multi-resolution triangulation based on the 2D grid provided by the scanner. Through this method triangulation is relatively easy as the neighbourhood relations are given by the 2D grid. The algorithm is able to disconnect the mesh along depth discontinuities, and to maintain high-resolution triangles model discontinuity lines (see figure 5a).

Calibrated and re-projected pictures (textures) can be applied on mesh model obtaining a geometrically corrected 3D model at high resolution as shown in figure 5b)


(a) (b)
Figure 5. a) Mesh model b) Textured model. The model corresponds to the area visible in figure 4.

4. STUDY EXAMPLES

The combination between a phase shift scanners (Imager 5003 by Zoller+Fröhlich GmbH) and Reconstructor® Software was tested in two different campaigns inside Buonconsiglio Castle in Trento city (Italy). The castle was the residence of the prince-bishops of Trento from the second half of the XIII century until the secularisation of the principality in 1803 and it consisting of different buildings constructed against the thirteenth century city walls.
We surveyed four painted rooms located inside the Palazzo Mango building, which was built under commissioned of prince-bishop Bernardo Cles (1514 - 1539), next to the oldest Castelvecchio building to be a magnificent residence inspired by Renaissance canons.
Stua della Famea (or Locus refectionis) room was surveyed in the first campaign during restoration jobs. Laser scanner survey concentrates on ceiling characterized by frescos decoration and paintings. Main objective of the survey is to acquire the complex geometry of the ceiling to be combined with the simple geometry of the rest of the room surveyed with traditional topographic techniques. Despite the relative small planar dimension of the room (around 10m x 8m), nine scans were necessary to avoid shadows problems due to obstacles for the restoration purposes. Laser survey was completed in around two hours at high resolution.
Camin Nero, Udienze, and **Torrione da Basso** rooms were full scanned with main objective of collecting the entire geometry of all the rooms and to produce textured models and orthographic views. Thanks to the 360° x 310° view of the scanner and to the lack of obstacles during the survey, few scans per room where necessary to have the complete geometry. In 1.30 hours laser survey was completed.
In table 3 number of scan and time of acquisition (including scanning time only and survey logistic) for each room are summarized.

Room	N° scans	Acquisition time
Stua della Famea	9	2 h
Camin Nero	4	30 min
Udienza	4	30 min
Torrione da Basso	3	30 min

Table 3. Number of scan and survey time per room

In figure 6 the comparison between a phase shift scanner and high resolution panoramic photo is particularly notable. The irregular shape of Torrion da Basso rooms is difficult to be surveyed; the adopted scan technology is capable to acquire all geometric information in few minutes.

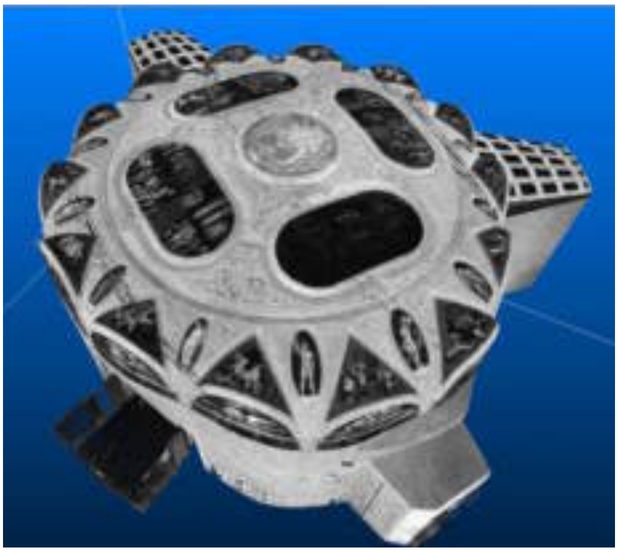


Figure 6. Torrion da Basso range scan at high resolution

5. RESULTS

The main objective of the Stua della Famea survey is to provide complete but simplified geometry of the ceiling. The geometric information has to be combined with traditional topographic survey of the remaining part of the room. The need to simplify the geometry, maintaining the important features, comes from the necessity of producing simplified 3D models with software incapable to manage high density cloud of points. Reconstructor® multi-resolution meshing tool was used to simplified dense cloud of point. As shown in figure 7 dense point are preserved along the discontinuity line; the combined usage of point and edges allows to built simplified 3D model with modelling software like Rhinoceros or 3D StudioMax which are capable to handle reduced amount of points.

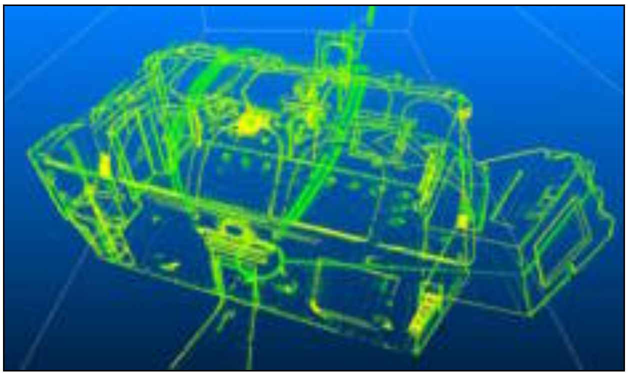


Figure 7. Dense point are preserved along the discontinuity line and simplified in flat areas using Reconstructor® multi-resolution meshing tool.

For Camin Nero Room, Udienze Room, and Torrione da Basso the main object is to produce a complete textured model from which extracting orthophotos and measurements.
The point-based registration method, based on the Iterative Closest Point (ICP) algorithm, is used to join together range scan relative to each rooms.

Through the zooming approach, full resolution laser data are extracted from raw data in correspondence of the interesting pictorial areas where digital pictures are available.
High resolution images are calibrated, re-projected and finally applied on mesh model obtaining a geometrically corrected 3D model at high resolution.
Virtual survey tools of Reconstructor® software are used to define the proper planes for orthographic re-projection. The textured model is orthographically projected according to defined plane (Figure 8a) and an orthographic picture (orthophoto) at high resolution can be produced (Figure 8b)


(a)


(b)

Figure 8. a) Orthographic projection plane definition, b) Orthophoto at high resolution

Reconstructor® tools software are finally used to extract cross section and export point overlapped with relative raster orthophoto in AutoCAD®
PointCloud (AutoCAD® plug-in by Kubit GmbH) is adopted for producing final architectonic draw. Through this tool is possible to import in AutoCAD dense cloud of points which are overlapped with orthographic picture. Architects or restorers can easily draw on 2D orthographic view or on 3D cloud of point.

6. CONCLUSION AND FUTURE DEVELOPMENT

Both laser scanner instruments and 3D data software are in continuous development.
Laser scanner development is mainly oriented:

- To reduce laser dimension and weigh.
- To increase accuracy and resolution.
- To increase range of acquisition.
- To reduce time of acquisition
- To increase accuracy in positioning laser head along the local verticality: the possibility to set instrument verticality with high accuracy should simplify geo-referencing phase.
- To acquire colours information using internal or external digital camera.
- To reduce laser control by external PC by simplifying acquisition set up and including memory unit inside laser machine.

We could verified that Imager 5003 by Zoller+Fröhlich GmbH results well developed in term of accuracy and resolution (with in the range of acquisition < 25 m). High speed of acquisition automatically reduces the control time through external PCs. The scanner is not jet supply with external RGB camera but high resolution reflectance help texture mapping process.
Software Reconstructor® results efficient for high resolution data processing due to its multi-resolution approach. Texture mapping and meshing implies of course manual operation by expert user which is however reduced with a good acquisition planning and when dense cloud of points and high-resolution images are used.
Next development will be along the line of producing a more efficient viewer capable of: i) managing both structured (range scans) and not structure (generic point clouds) laser data, ii) organizing un-structured data for texture mapping and meshing, iii) automatically producing animation video along virtual path defined by the user inside the 3D model.

ACKNOWLEDGEMENTS

The data used for the modelling has collected thanks to the collaboration with Arch. Piconese (Rovereto- Italy) and the gentle approval of Soprintendenza per i Beni Storico – Artistici Provincia Autonoma di Trento (Trento, Italy). High resolution digital pictures are provided by Arch. Piconese.

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