INTEGRATED SURVEYING TECNIQUES
IN CULTURAL HERITAGE DOCUMENTATION

F. Agnello, M. Lo Brutto

Dipartimento di Rappresentazione, University of Palermo, Via Cavour 118, Palermo, Italy
fabrizio.agnello@unipa.it, lobrutto@unipa.it

KEY WORDS: Laser scanning, Digital Photogrammetry, Cultural Heritage, CAD Modelling

ABSTRACT:

This paper is focused on integration between laser scanning data, CAD modelling and photogrammetric data collected during the survey of one façade of the monument called "Quattro Canti" in the historic centre of Palermo. The investigation has been directed to the production of a 3D photorealistic model of the monument. The "Quattro Canti" monument is formed by four cylindrical façades facing the square where the older streets of Palermo intersect; each façade has a symbolic reference to one of the seasons and is divided in four levels. The façade called "Canto dell'Autunno" has been surveyed both with laser scanning and with photogrammetric techniques.
Laser scanning data have been collected in a single scan with a resolution of about 7 mm; stereoscopical photos have been taken with a film camera Rollei 6006; all data have been referred to a topographic reference system. The investigation has been restricted to the third level of the "Canto dell'Autunno" façade. The surface model has been built from laser scanning data with an automatic triangulation process; the inconsistent parts have been substituted using CAD models and points extracted via photogrammetric image matching. Photogrammetric processes have been used also to produce a 3D orthophoto. In order to produce a 3D photorealistic model of the investigated area, photogrammetric texture mapping has been performed with a commercial software.

1. INTRODUCTION

Integration of 3D laser scanning and photogrammetric data plays at the present time a significant role in cultural heritage documentation. Connecting 3D digital surface models and raster data is a recurring demand of people and researchers interested in documentation and preservation of historical monuments.

Many researches on computer graphics and architectural surveying, developed in the recent past, deal with questions related to the extraction of 3D digital models from laser scanning and digital photogrammetric data (Beraldin et al., 2002; Remondino and El-Hakim, 2006). Further investigations are directed to the test and evaluate the procedures for texture mapping; problems related to occlusions and geometric accuracy are the main topics of these researches (Alshawabkeh and Haala, 2005).

The representation of architectural features in surfaces produced from laser scanning data is often inadequate, since sharp corners and edges are often smoothed in the triangulated surface. One of the peculiar features of historical architecture is therefore lost and the surface is particularly defective where edges are close to each other, e.g. in architectural mouldings, cornices, flat columns and so on.

Point clouds are often affected by holes, mainly due to a non-uniform and non-comprehensive distribution of points; areas not reached in the scan process result in wide areas where points are sparse or absent.

These problems could obviously be solved both increasing the number of scans and scan positions so to fully cover the surface of the object, and using high resolution scanners for complex objects. Sometimes, and not so rarely when we refer to architecture, it is not so easy to apply such solutions because of the restrictions imposed by the spatial or urban context around the monument. Referring to low range devices we should furthermore ask if it is reasonable to use high resolution scanners (e.g. short range scanners) in wide areas.

This paper is focused on procedures and methods for the production of photorealistic 3D digital models geometrically correct. 3D laser scanners, CAD modelling and digital photogrammetry have been used. The investigation has been carried out in three different steps: data collection, modelling process and photogrammetric texture mapping.

Data collection has been referred to one of the most important monuments in the historic centre of Palermo, the "Quattro Canti": four cylindrical façades placed at the corners of the square where the older streets of the ancient town intersect.

The façade called "Canto dell'Autunno", has been surveyed with topographic instruments, photogrammetric techniques and laser scanner.

The modelling process has been subdivided in: laser data processing, CAD modelling and photogrammetric process.

Laser data processing has been carried out according to a well known procedure oriented to: inconsistent data filtering, holes filling and roughness reduction. The clouds have been registered and oriented to refer point coordinates to a topographic reference system. An automatic triangulation process has been performed to generate a triangulated surface. This way a geometrically correct surface model, suitable for visualization is quickly carried out. Anyway, an accurate inspection of the triangulated surface often shows residual imperfections that can be grouped in two classes: wide holes and inadequate representation of architectural features.

CAD models of selected elements of the surface have been built; 3D models have been used to fill wide holes or substitute low definition areas of the surface model.

CAD modelling requires precise and detailed metric data; such data have been collected from laser scanning data and manual

stereoscopic measurements. All data are referred to the topographic reference system.

Photogrammetric process has been directed to the following goals: restitution of geometric data (points and lines) useful in CAD modelling; automatic extraction of DSM through image matching procedures.

Integration between laser scanning data, CAD modelling and photogrammetric data has produced a refined surface model that has been used in texture mapping.

Photogrammetric texture mapping has been used to produce a 3D orthophoto and a photorealistic 3D model of the monument.

1.1 THE "QUATTRO CANTI" OF PALERMO

The historic centre of Palermo was divided in two by a street east-west oriented till the beginning of the XVIIth century, when a new street, north-south oriented, was opened. Palermo took the form of a quadrilateral walled town, divided in four by the two orthogonal streets (Figure 1). The place where streets meet assumed a symbolic significance, since it was soon considered the heart of the ancient town.

Figure 1. Plan of Palermo in 1726

In the years between 1602 and 1662 some of the most important worked to the design and construction of four monumental façades named "Quattro Canti", at the corners of the crossroad. Façades are cylindrical-shaped and are divided in four levels by horizontal cornices; the first cornice bears a balcony. Columns and flat columns divide each level in three parts; in the central part of the first level is placed a statue symbolizing one of the seasons; at the second level the statue of a Spanish king; at the third level the statue of a saint protecting Palermo; at the upper end a shield with symbols of the town. The statues of the seasons are placed above fountains, while the statues of kings and saints are placed in niches sunken in the façade (Figure 2). Façades resemble each other and are distinguished only for the different features of the statues. Historians have called the

crossroad "Sun theatre" for the mutable figures that the sun draws on the façades during the day.

Façades are commonly named "Canti"; each façade is identified with the name of a season. The northern façade is the "Canto dell'Autunno", the eastern "Canto dell'Inverno", the southern "Canto della Primavera" and finally the western "Canto dell'Estate" (Figure 3).

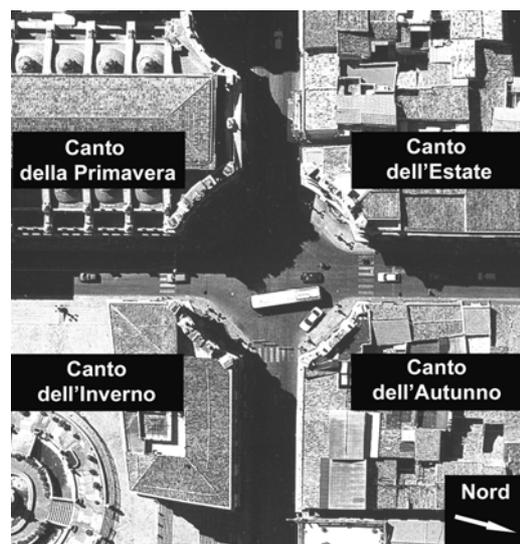Figure 2. The "Canto dell'Autunno" façade

Figure 3. Aerial orthophoto of the "Quattro Canti"

2. DATA COLLECTION

Data collection has been strongly conditioned by the extension of the crossroad, that doesn't make easy positioning topographic, photogrammetric and laser scanning devices.

The first step in data collection has been dedicated to the positioning and measurement of the vertices of a topographic network; four vertices have been placed on the sidewalks in front of each façade and four vertices on each of the balconies at the second level. Vertices on the balconies were created because the height of the façades, compared to the available space on the ground, made it difficult to collect data of the higher areas of the façades placing the instruments on the ground. Another problem in survey operations from the ground level, was the intense road traffic.

The topographic reference system has been oriented with the x axis parallel to the straight line connecting the corners of the "Canto dell'Autunno". Topographic network has been processed yielding root mean squares lower than 3 mm for xy and z coordinates.

Topographic survey has been performed with a total station Leica TCR307 and has been directed to measure the spatial coordinates of detail points and photogrammetric control points. Topographic point coordinates have then been referred to a new reference system with xy plane parallel to the plane aligning the vertical edges of the cylindrical façade; such reference system was suitable for photogrammetric process. Steel nails were fixed on the ground to permanently identify topographic network vertices; this way it has been possible to refer to the same reference system data collected at different times.

Photogrammetric survey of the "Canto dell'Autunno" has been performed with a semi-metric film camera Rollei 6006, equipped with a 80 mm lens; photographs have been taken placing the camera at an average distance of 14 meters from the object. In order to produce a stereoscopic coverage of the façade, a mobile platform has been used to take photos (Figure 4).

Photogrammetric shots have been divided in four strips, corresponding to each level; strips are made of 9 images with 80% longitudinal overlapping. The whole façade has been covered with 36 photographs; the average scale of photographs is 1:175.

A film scanner Nikon 8000ED, set at 2000 dpi optical resolution, has been used to digitize photographs; in digital images pixels had a dimension of 12 μm equivalent to 2 mm on the object.

Topographic and photogrammetric data have been collected one year before laser scanning survey; they were initially directed to produce a three dimensional restitution of the whole façade.

Laser scanning data have been collected with a Mensi GS100 scanner; a single scan has been performed placing the device on the sidewalk opposite the façade, at a distance of about 28 m.

Positioning the scanner on the balcony opposite the façade would have produced a better result in point cloud, but it wasn't possible since the gate to the balcony was too narrow.

Scanning resolution has been set to an average step of about 7 mm on the object. Laser scanning output was a five millions point cloud; each point was identified by its spatial coordinates and RGB values (Figure 5). Six reflecting targets, positioned on the lower part of the façade and on near buildings, have been surveyed during the scans. Target coordinates have been also measured with a topographic total station; this way it was possible to refer the coordinates of the point cloud to the topographic and photogrammetric reference system.
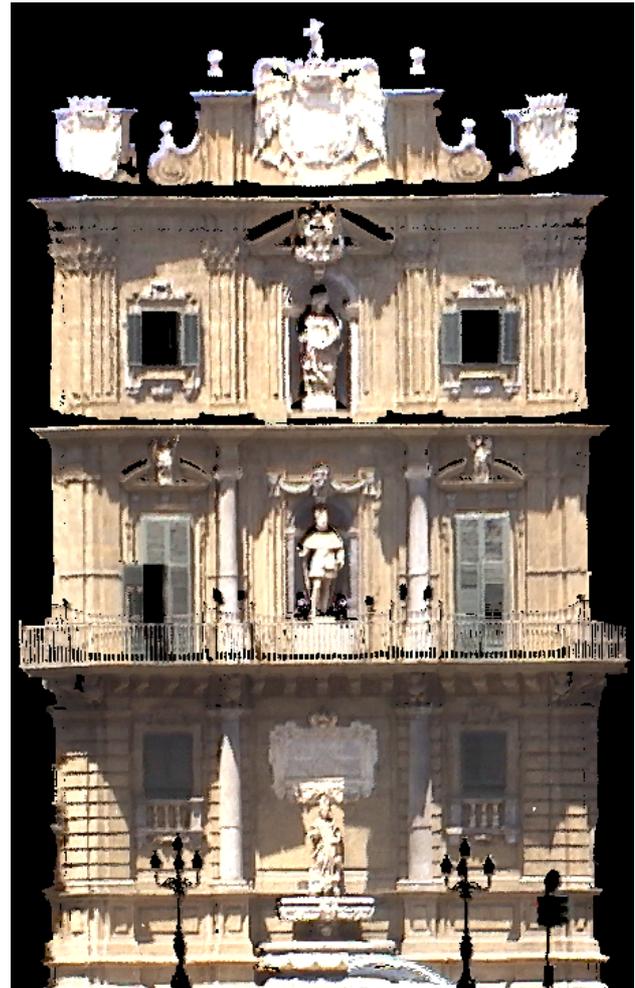

Figure 4. Photogrammetric survey

Figure 5. Coloured point cloud

3. MODELING PROCESS

Survey data processing and the following reported investigations have been restricted to the third level of the "Canto dell'Autunno" façade.

3.1 Laser Data Processing

First steps in laser data processing have been oriented to refer the point cloud to the topographic reference system, using target coordinates; residuals in point cloud registration were lower than 5 mm.

A huge amount of outliers in laser data was generated by vehicles and pedestrians; the outliers (points disconnected from the main body of the point cloud) were manually deleted.

The point cloud has then been processed to yield a non uniform triangular network; the triangulated surface was affected by a diffuse roughness and many holes. This happens quite often when using laser scanners, because of device limitations. An accurate pre-processing phase has been performed in order to filter noisy points and compute again the triangulated surface; this way a more homogeneous surface has been yield, with few spikes and only wide holes.

The surface was then edited to fill most of the holes with automatic and semi-automatic procedures.

Registration and filtering processes have been performed with the commercial packages *Inus Rapidform 2006* and *Raindrop Geomagic 8.0*.

The triangulated surface is in itself a precise and detailed representation of the object. Yet we must notice that some problems, due to the position of the scanner, often affect such surfaces. Since laser scanner was positioned on the ground, laser beam could not reach several areas of the façade. Some jutting decorative elements, like cornices, occluded the areas of the façade placed just above them; tympanum as well occluded the area just behind and above it; the statue of the Saint hides a significant area of the cylindrical niche where it stands (Figure 6).

Further areas were not reached due to unexpected occlusion, e.g. the opened external shutters hid the decoration around the windows and left the beam pass beyond the surface; this way the window areas resulted in wide holes.

Figure 6. Triangulated surface extracted from laser data

3.2 CAD modelling

CAD modelling usually produces solid or surface models;. in this investigation only surface models have been produced.

CAD surfaces are defined using a limited amount of curves; therefore such surfaces can be edited modifying the generating curves. Generally CAD surfaces are generated through the uniform or non-uniform displacement of a generating curve along a rail curve.

In this investigation CAD modelling has been directed to fill wide holes and substitute the low definition parts of the triangulated surface. CAD modelling has been performed using only planar curves, automatically extracted from the triangulated surface; such curves come from sections performed with horizontal and vertical planes. Further curves have been extracted with manual stereoscopic measurements. Curves have then been edited to restore the proper geometry of corners and lacking parts.

CAD modelling process has been performed with the commercial software *Rhinoceros 4.0*.

CAD models of the following elements have been produced for wide holes filling: the lower part of the third level, with plinths of flat columns, the areas behind and above the tympanum, the cylindrical and spherical surfaces in the central niche.

CAD model of the lower part of the third level has been generated with the modelling procedure named "sweep" (Rhinoceros User's Guide, 2005) using a vertical and a horizontal section. In "sweep" process the vertical section has been displaced along the horizontal section with an invariant angle of incidence.

The area behind and above the tympanum has been modelled using two horizontal sections extracted respectively below and above the tympanum. CAD surface has been generated using the modelling procedure named "loft" (Rhinoceros User's Guide, 2005); such procedure generates the surface interpolating curves lying on parallel planes.

Two different procedures have been used to model the cylindrical and spherical surface in the central niche; the cylindrical surface has been modelled via "loft" procedure, performed with four horizontal sections. The spherical part is made of two caps intersecting each other; modelling has been performed using horizontal and vertical multiple sections to detect the the radius and the centre of each spherical cap (Figure 7).

Further CAD models have been produced to substitute the elements that have a complex and detailed geometry which is not correctly reproduced in the triangulated surface: the horizontal cornices which delimit the third level and the tympanum above the niche.

Sweep procedure has been used both in cornices and in tympanum modelling. CAD modelling of the tympanum has been performed using lines and dimension extracted with manual stereoscopic measurements; that was necessary, since CAD modelling requested sharp edges that were not detectable in triangulated surface.
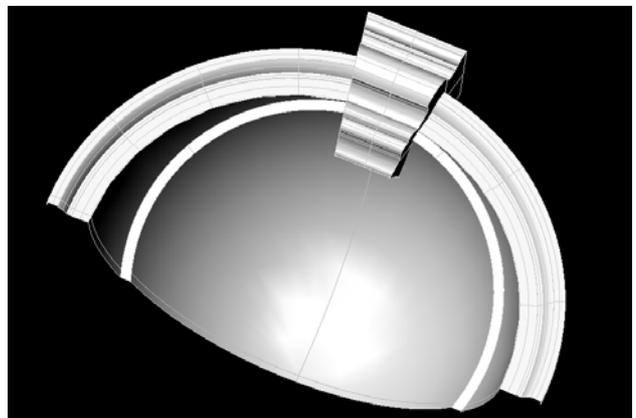

Figure 7. CAD model of the surface in the central niche

3.3 Photogrammetric process

Photogrammetric procedures have been used for lines and edges restitution and for automatic extraction of points in areas that were occluded or not visible, e.g. the decoration around the windows and the large holes in place of the windows. Such areas are correct in photographs, since at that time shutters were closed.

Photogrammetric measurements and automatic image matching have been performed with the commercial software *SOCET SET 5.3*.

External orientation parameters have been computed with bundle adjustment using the nine photographs of the third level strip (Figure 8). Planimetric and altimetrical residuals resulted lower than 1 cm.

Automatic image matching relative to the windows area has been performed with the *SOCET SET* module *ATE* (Automatic Terrain Extraction); a regular grid with a step of 5 mm has been extracted. The process has produced good results in the surface around the window; worse data have been resulted in the central area of the windows, due to the irregularity of the shutters that has produced several mismatches and irrelevant points.

Photogrammetric procedures have therefore been used to compute the external orientation parameters of the images used in orthorectification and texture mapping processes.

Orthorectification has been performed successively using the 3D surface model resulting from data integration and surface editing process.
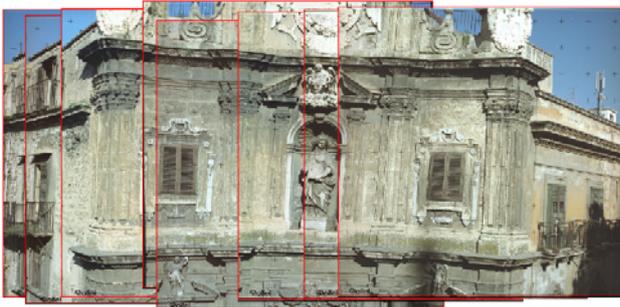

Figure 8. Photogrammetric strip of the third level

3.4 Data integration and surface editing

The surface model of the third level of the "Canto dell'Autunno" façade has been built integrating data resulting from laser scanning survey, CAD modelling and photogrammetric image-matching.

Laser scanning survey has been performed to produce a triangulated surface; CAD models and photogrammetric process have been performed in order to refine and correct the triangulated surface.

Integration process can be performed only if heterogeneous data are compatible; therefore CAD models and photogrammetric data are to be converted in point clouds or triangulated surfaces.

CAD modelling has produced NURBS models that have been converted to triangulated surfaces. Triangulation process has produced a non uniform triangulated surface; curved or complex elements are detected with a proper amount of triangles, whereas few triangles are used in flat or simple elements. This is a meaningful difference if we compare it to the laser surface, whose triangles have quite similar dimensions and a more homogeneous distribution.

Photogrammetric image matching has produced the point clouds of the windows area; such points have substituted the laser scanning points (Figure 9).

CAD and photogrammetric surfaces result correctly positioned in the laser triangulated surface, since they are referred to the same reference system. Small mismatches have been corrected using an automatic procedure that exactly matches all triangulated surfaces at the same time, using the overlapped regions. Triangulated surface from laser data is the reference for all other models; that's why registration process has been performed locking laser surface and letting other models move.

The last step in data integration was directed to remove polygons of laser surface overlapped to polygons from CAD and photogrammetric data; such process has been performed both automatically and manually.

Data integration has produced a refined surface model, clean and watertight, with a proper resolution in complex shaped areas (Figure 10).
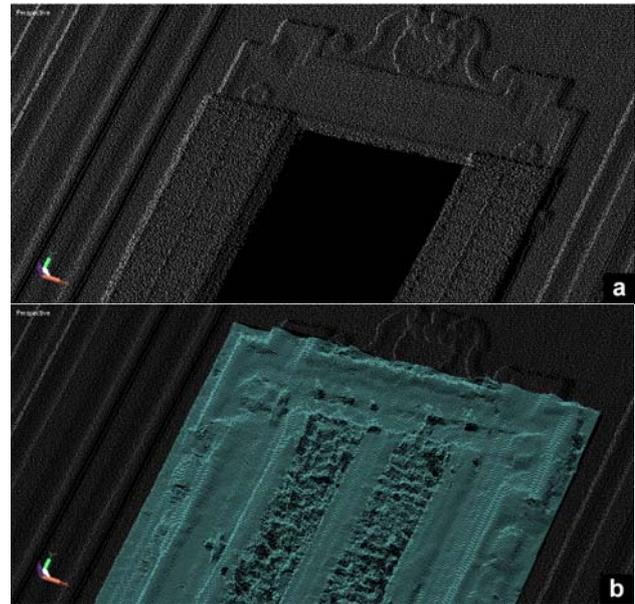

Figure 9. Area of the right window: a) laser scanner point cloud, b) integration with photogrammetric points

4. PHOTOGRAMMETRIC TEXTURE MAPPING

Textures can be added to three-dimensional surface models with different processes, that can be classified as follows:

- CAD models texture mapping: this process is performed manually through visual inspection, to fit textures to the geometry and dimensions of CAD models. Such procedure is generally performed in packages for rendering and video output such as *3DS Max*, *Cinema 4D* , etc. In this procedure only visual inspection is used to check the correspondence between texture and model;
- triangulated surface texture mapping: non-calibrated and non-oriented images are mapped onto a triangulated surface usually extracted from laser data. Such procedure is available in packages for laser data processing (*Rapidform, Realworks*, etc.). It is performed through visual detection of corresponding points in raster image and in triangulated surface;

Figure 10. Area of the tympanum: a) triangulated surface from laser scanning data, b) integration with CAD models

- photogrammetric texture mapping: textures are mapped onto surfaces using the projective correspondence between image and surface, with a procedure that performs a sort of inverse perspective.

Photogrammetric texture mapping can be performed in two different ways. The first method is based on multiple images approach for surface reconstruction and automatic texture mapping (Remondino and El-Hakim, 2006). This procedure uses photogrammetric bundle adjustment, with or without camera self-calibration, to compute the external orientation parameters of images. This process can be performed with several commercial packages (*Photomodeler, Shapecapture, iWitness*, etc.); such packages do not allow integration of hetereogeneous data in surface reconstruction process. The second method uses photogrammetric stereoscopic images, to compute the external orientation parameters, and triangulated surfaces, extracted with different techniques. In this procedure image orientation can be performed with photogrammetric packages (*SOCET SET, LPS* etc.); surface reconstruction can be performed with laser scanning packages (*Rapidform, Geomagic*, etc.). This way it is possible to yield a 3D orthophoto and then use it in texture mapping process.

In this investigation the last of the above reported texture mapping processes has been tested; this process has the advantage of using a refined triangulated surface with a high level of detail. Such procedure requires anyway a longer and more articulated processing.

Texture mapping of the third level of the "Canto dell'Autunno" has been performed with the commercial photogrammetric software *Z-MAP* produced by Menci Software.

The triangulated surface resulting from data integration and surface editing has been used to compute a 1cm regular DSM (Figure 11).

Images from the photogrammetric strip have been used to produce a 3D orthophoto.

3D Orthophoto and DSM have been used to build a photorealistic surface model that can be visualized with *3DPIX*, a Menci Software free package (Figure 12 - 13).
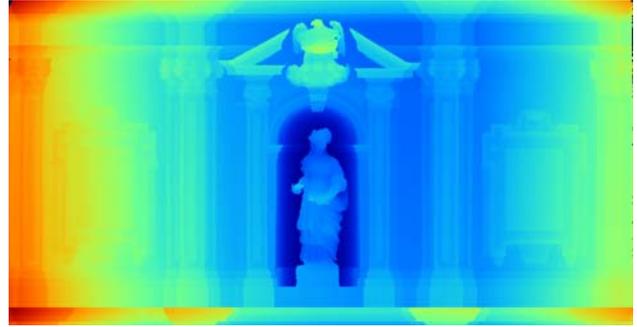

Figure 11. DSM used in orthorectification process

Figure 12. 3D photorealistic model

5. CONCLUSIONS

The work reported in this paper is a part of a wider investigation on a procedure for the integration of laser data with CAD models and photogrammetric data. Procedures for the production of 3D orthophotos and photorealistic 3D models have been performed using commercial photogrammetric packages.

Such procedure has been tested on a part of the façade of a meaningful monument in the ancient town of Palermo. A photorealistic 3D model of the selected area has been produced.

A triangulated surface of the selected area has been created from laser scanning data; such surface has been refined and completed using CAD models and photogrammetric data, extracted both with manual stereoscopic measurements and with automatic image matching process.

CAD models and photogrammetric data have been integrated to laser data in a triangulated surface model; low resolution areas have been substituted with the corresponding CAD models and wide holes have been filled with photogrammetric data. Such model has a better geometric accuracy and is more complete than the initial triangulated surface extracted from laser data.

The procedure tested in this work can be applied in different contexts; a meaningful role is played by operators able to

Figure 13. Perspective view of the 3D photorealistic model

decode the geometries extracted from the triangulated laser surface and build correct 3D CAD models.

The photorealistic 3D model has been produced using the refined triangulated surface and images with known external orientation parameters. Since images and triangulated surface are referred to the same reference system, mapping process results geometrically correct. Residual problems in the photorealistic 3D model are mainly due to a non complete coverage of the surface in the images.

Further investigations should be directed to refine the texture mapping process and find a diffuse standard for visualization and geometric inspection of photorealistic 3D models.

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