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Non-contact reverse engineering modeling for additive manufacturing of down scaled cultural artefacts

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Abstract

In recent years, reverse engineering has achieved a relevant role in the cultural heritage field. The availability of 3D digital models of artefacts opens the door to a new era of cultural heritage: virtual museum creation, artefact cataloguing, conservation, planning and simulation of restoration, monitoring of artefacts subjected to environmental degradation, virtual reconstruction of damaged or missing parts, reproduction of replicas, etc. In this paper, two different non-contact reverse engineering scanning systems were utilized for 3D data acquisition of a cultural heritage artefact. The digital data acquisition and processing procedures of the scanned geometry have been illustrated and compared to evaluate the performance of both systems in terms of data acquisition time, processing time, reconstruction precision and final model quality. Finally, additive manufacturing technologies were applied to reconstruct a down scaled copy of the artefact.

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Keywords: Reverse engineering; cultural heritage; laser scanning; photogrammetry; additive manufacturing

1. Introduction

In the industrial field, reverse engineering (RE) is the most popular method utilized for the creation of a 3D digital model of an existing physical object via diverse 3D scanning technologies (e.g. coordinate measuring machines, laser scanners, structured light digitizers, etc.) [1].

Nowadays, the different issues related to the preservation and enhancement of cultural heritage have attributed a key role to the RE technology. In 2016-17, over €100 million for research and innovation in the field of cultural heritage have been made available under the EU's research funding programme Horizon 2020 [2]. This increase in funding recognises cultural heritage as an investment opportunity where research and innovation can make a difference.

RE technologies allow to obtain high precision models of artefacts, both digital and physical, preserving the integrity and avoiding the risk of possible damages as they are based on not-in-contact acquisition techniques [3, 4].

The employment of RE methods for cultural heritage can be developed for several purposes such as the use of innovative multimedia applications in which the 3D objects are placed in their original environment such as virtual museum, or the realization of faithful 3D copies through additive manufacturing processes, and even more important for the inspection and monitoring of the environmental degradation over time of the artefacts.

In the last decades, numerous papers and projects have illustrated and successfully demonstrated the enormous potential of the RE technologies applied to the cultural heritage field [5-7].

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In 1997, the 3D digital images of the 'Madonna col Bambino' of Giovanni Pisano and of two bas-relieves of Donatello at the 'Cappella degli Scrovegni' in Padova were realized by the National Research Council of Canada and the University of Padova [8].

One of the first world wide famous application of the RE technology for cultural heritage is dated in 1999, when a laser scanner with a working volume of 3 m (width) by 7.5 m (height) was utilized to scan Michelangelo's David on its pedestal [9]. In 2003, the digital reconstruction of the great Buddha statue in Bamiyan, Afghanistan, was obtained using different types of images [10].

In last years, a new technology based on the use of unmanned aerial vehicles (UAV) was employed for outdoor applications such as the Ying County Wooden Pagoda, the Banqiao Mosque in China [11] and the Cathedral of Santiago de Compostela in Spain [12].

Generally, the methodological process applied in the field of conservation and enhancement of cultural heritage consists of three stages: acquisition of the artefact geometry with the use of RE technologies; visualization and improvement of the acquired digital model; possible use of additive manufacturing (AM) technologies to reproduce the physical model of the artefact [13].

In this paper, two different non-contact RE scanning methodologies, respectively based on a portable measuring arm (PMA) with laser scanner and a digital close range photogrammetry (DCRP) system, were utilized for the 3D data acquisition of a cultural heritage artefact consisting of a VI century sculptured column of large and complex geometry. The acquisition procedure and the following digital processing of the acquired geometry are illustrated and compared in order to evaluate the performance of both systems in terms of acquisition and post-processing time, point clouds and polygonal models quality, and precision. As final phase, the RE modelling for additive manufacturing of down scaled cultural artefact was developed and applied to the artefact under study.

2. Case study

The cultural heritage artefacts under study are located at the Basilica of San Giovanni Maggiore, Naples. The Basilica of San Giovanni Maggiore, after a long period of neglect, was subjected to a long and difficult restoration, of about thirty years duration, and reopened only in January 2012. Since then it has been managed by the Foundation of the Association of Engineers in Naples to host conventions, concerts, exhibitions and cultural events in general. The Basilica has a Latin cross plan with three naves and a transept with two chapels on the sides.

The most interesting element of the Basilica is certainly the early Christian apse, situated behind the XVIII century baroque altar by Domenico Antonio Vaccaro. The apse, dating back to the VI century, has a semi-circular shape with four arches, supported by pillars, that looked out on an ambulatory in continuation of the aisles. During the recent restauration work, the apse was deprived of its XVII century wooden choir that covered two finely inlaid monolithic marble columns with square section. The columns configuration reveals they are of Roman making of the II century, first built for a Roman temple in that location and later utilized in the VI century for the newly constructed early Christian Basilica of San Giovanni Maggiore (Fig. 1).

Each square section monolithic marble column presents two lateral faces, in view, finely inlaid with rich decoration, whereas the other two lateral faces, largely hidden to view, have smooth surfaces with no decoration.

The two monolithic columns of 51 cm x 55 cm x 500 cm size were chosen as large cultural heritage artefacts with complex geometry to be modeled, the reasons being:

- The ancient marble columns are of exceptional historical, artistic and architectural value.
- The columns' lateral faces in view are very rich in detail and decoration.
- The recent restoration of the Basilica did not involve activities on these columns which are currently still waiting for conservative consolidation.

In this paper, the left column (red arrow in Fig. 1) located behind the apse was considered for RE modeling with reference to its two highly decorated lateral faces.

3. RE non-contact systems for 3D data acquisition

Two diverse RE non-contact scanning methodologies, respectively based on a portable measuring arm (PMA) with a laser scanner and a digital close range photogrammetry (DCRP) system, were employed for 3D digital data acquisition of the left column (Fig. 2) [7, 14].

3.1. Portable measuring arm with laser scanner

The portable measuring arm (PMA) is a high-end laser scanning platform consisting of a Romer Absolute Arm 7525 SE (Hexagon Metrology) anthropomorphic arm with seven rotational axes and a high-precision external laser scanner CMS 108 (Fig. 2a, 2b). The tubular segments of the arm, made of carbon fibre reinforced plastic, ensure maximum stability and minimum weight. The arm has an ergonomic pistol grip to enable the manual measurement of 3D points at any orientation within the arm's spherical reach (2.5 m), with a volumetric precision of ±0.058 mm and a repeatability of ±0.027 mm. The CMS 108 external laser scanner mounted on the arm allows to collect up to 30.000 points per second with a precision (2σ) of 20 µm.

Fig. 1. Monolithic marble columns (II century) in the early Christian apse (VI century) located behind the baroque altar (XVIII century).

3.1.1. 3D data acquisition with the PMA laser system

As already mentioned, the spherical measuring range of the PMA is equal to 2.5 m, corresponding to the maximum length of the arm. Accordingly, the maximum height of the object to be scanned cannot be higher than 2.5 m. As the column under study has a full height of about 5 m, the complete digital modelling with the PMA should be possible only with use of permanent scaffolding. The latter, however, would have been highly intrusive for a monument like the Basilica of San Giovanni Maggiore and thus not acceptable the Basilica's managing body. For this reason, it was decided to scan only the lower portion of the column.

Due to physical constraints of the column location (difficult to access), two diverse positioning of the PMA were necessary in order to digitalize the column lower portion allowing to cover a column volume of 51 x 55 x 77 cm^3 (width x depth x height). Each multiple scans campaign was executed by manually following the surface profile without restriction to a specific angle orientation. In Fig. 3, the various scans are visualized with different colours.

In the first scan campaign, 238 line scans were carried out to obtain a point cloud of 8,951,768. In the second scan campaign, 186 line scans were carried out to obtain a point cloud with 15,056,722 points (Table 1, Fig. 3).

The duration of the 3D digital data acquisition of the selected column volume was about 4 hours for each lateral face, for a total of 8 hours.

(a) (b) (c)

Fig. 2. The two RE non-contact scanning systems during 3D digital data acquisition: (a) and (b) portable measuring arm (PMA) with laser scanner; (c) digital close range photogrammetry (DCRP) system.

Fig. 3. The two point clouds, one for each lateral face, obtained using the PMA with laser scanner.

3.2. Digital close range photogrammetry system

The utilized non-contact system based on digital close range photogrammetry (DCRP) is made of simple and low-cost equipment consisting of a Samsung NX2000 24Mp mirrorless camera (5472x3648 pixels) with an APS-C sensor and a 20 mm lens mounted on a 6 m telescopic stick equipped with wireless remote control and position GPS sensor (Fig. 2c). This system can be used for indoor and outdoor RE applications and, in the case of difficult to access objects, without the employment of expensive scaffolding or mobile platforms avoiding any danger to the operator. The advantage of this technique consists of the ability to scan extremely different small or large objects by simply changing the camera lens. With digital photogrammetry, it is possible to obtain reconstructions of spatial patterns in a very wide range of sizes with very low cost equipment at an accuracy of 1/10000 to 1/198000.

3.2.1. 3D data acquisition with the DCRP system

The 3D data acquisition of an artefact using the DCRP system requires a very easy and fast setup and planning. The number images, the % of overlapping among the adjacent images and the distance between the camera and the object must be carefully calculated before the acquisition, in function of the focal length and the sensor size, to obtain the desired spatial resolution. In this case the camera needs to be placed at distance at least of 0.6 m far from column, which must be accessible for the entire height to allow the acquisition of images in diverse positions. During acquisition, the scene can be illuminated directly with the built in flash of the camera, and the lens can be set on automatic focusing.

The 3D digital data acquisition was executed by considering the entire volume of the column and the same selected column portion volume acquired during the PSA scanning procedure. The duration of the data acquisition ranged between 16 minutes for the lower portion of the column (76 photos) and 70 minutes for the entire column (277 photos). The total number of points obtained for the 3D data acquisition of the entire column was 148,133,719, whereas for the portion of the column it was 23,790,269.

In Table 1, the details of the 3D data acquisition for the two RE non-contact systems are summarised.

4. Reverse engineering digital model reconstruction

The RE digital model reconstruction of an artefact involves diverse phases: point cloud improvement (e.g. noise reduction, overlap reduction, redundant points deletion); polygon mesh where the point cloud is wrapped to draw a triangular surface connecting every 3 data points; polygon model improvement (e.g. fill holes, reconstruct mesh, optimize mesh); curves and patches generation (NURBS patch construction); CAD model construction.

In this paper, the RE digital model reconstruction of the selected volume of the column under study was performed by considering the diverse point clouds obtained with the two RE non-contact systems up to the editing of a polygonal model suitable for cultural heritage purposes.

4.1. Digital model reconstruction with the PMA laser system

Digital model reconstruction from the point clouds of the two lateral faces of the selected column portion, obtained with the PMA laser system, was done with the Polyworks V12 3D metrology software platform by Innovmetric.

For column portion digital model reconstruction, several steps are needed. First, the two point clouds were improved by noise/overlap reduction and redundant points removal. Via the “N point pairs” option, the two improved point clouds were aligned by picking several tie-point pairs on each one. Then, alignment was refined by applying the iterative best-fit image alignment algorithm to the full set of 3D images to globally minimize alignment errors (Fig. 4a).

Once the aligned and improved column portion point cloud was obtained, the generation of a high accurate polygonal model of the column portion was created with the following main parameters: max distance: 2; surface sampling step: 0.4; standard deviation: 0.064; smoothing level: medium, smoothing radius: 1.2, smoothing tolerance: 0.192; reduction tolerance: 0.0128. A polygon mesh with 3,491,802 points and 6,822,629 triangles was generated.

Since the column surface is highly complex and inlaid, the polygon model presents numerous holes/gaps that need to be filled (Fig. 4b). For automatic holes/gaps filling, the software uses a bridging distance to connect boundary perimeter points and create triangles. However, this automatic procedure could not be applied as the newly generated triangles did not blend the surrounding surfaces.

A tedious, time-consuming manual procedure to fill the holes/gaps in the reconstructed model was carried out through a typical approach which anchors a Bézier surface to cover the holes. M rows are anchored by N columns on the surface that respect the contour of the underlying mesh and not the hole shape. After surface fitting to the polygonal model, the surface is triangulated to fill the hole. Together with hole filling, a manual smoothing procedure using a brush was performed on the triangle vertices of the selected region. An optimized polygonal model of the column was built with 4,423,974 points and 8,840,255 triangles (Fig. 5).

4.2. Digital close range photogrammetry

The acquired images obtained from the DCRP system were processed through an image-based 3D modelling software: Agisoft PhotoScan. This software is based on the structure-from-motion (SFM) and dense multi-view 3D reconstruction (DMVR) algorithms, and allows to build 3D models by unordered image collections that depict a scene, or an object, from different viewpoints. First, the software performs the alignment of the images, on the basis of common points in the source photos (Fig. 6), and matches them to obtain a single point cloud using a scale-invariant feature transform (SIFT) approach (Fig. 7).

After image alignment, the generation of a dense point could and then of the polygonal model was carried out automatically by the software in few minutes; it allows also to generate a photorealistic texture on the 3D polygonal model (Fig. 8).

In particular, 35 minutes were necessary for the dense point cloud generation, 27 minutes were utilized for filling the holes and the creation of the polygon mesh, and the texture was generated in 3 minutes.

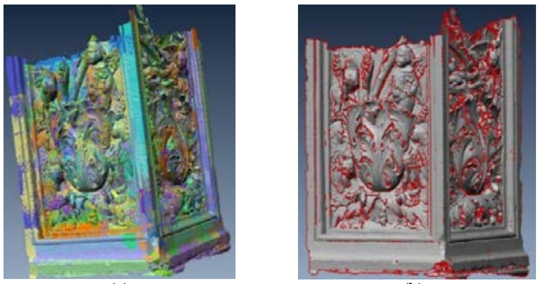

Fig. 4. (a) Alignment of the point clouds of the two lateral faces; (b) generated polygonal model containing holes.

Table 1. Data acquisition details for the two RE non-contact systems.

RE non-contact systems		
Scan data	**Laser**	**DCRP**
Scanning procedure	Each scan was executed by manually following the surface profile without restriction to a specific angle orientation	Before acquisition, the number images, the % of overlapping, the distance between the camera and the object must be calculated
Line scans / photos	1st scan campaign: 238 lines 2nd scan campaign: 186 lines	Photos: 76 (portion) 277 (entire)
Number of points	1st scan campaign: 8,951,768 2nd scan campaign:15,056,722	23,790,269 (portion) 148,133,719 (entire)
Duration of acquisition	4 hours for each scan campaign, for 8 hours in total	16 min (portion) 70 min (entire)

Fig. 5. Improved polygon mesh of the column portion.

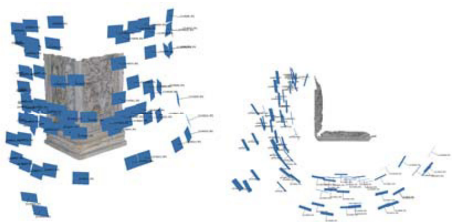

Fig. 6. Alignment of the acquired images.

Fig. 7. Column point cloud generated by the DCRP system

Fig. 8. Polygonal model and polygonal model with texture

5. Results comparison and discussion

Two different comparisons were performed between the results obtained with the two diverse RE systems: the first was carried out by comparing the two obtained point clouds whereas the second was performed considering the two polygonal models generated from the acquired point clouds.

Both the evaluation procedures were carried out considering the results obtained with the PMA laser system as standard reference and calculating the shortest distance between the two results represented as a coloured map.

As regards the first type of comparison, a CloudCompare v2.7 open source software was used. In Fig. 9, the two point clouds comparison is shown. In the coloured map, the chosen maximum distance, highlighted in red, is 5 mm, whereas the minimum distance, depicted in light green, is 0 mm. It can be seen that the distance of almost all the points of the two clouds is < 2 mm, while for the rest of the points the distance is < 0.3 mm.

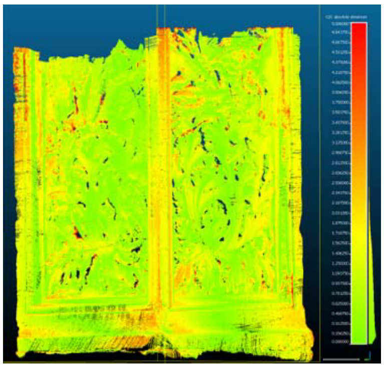

Fig. 9. Point clouds comparison.

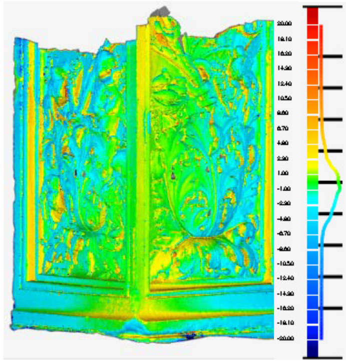

Fig. 10. Polygonal models comparison

For the polygonal models comparison, the utilized software was Geomagic Control 2015.

In Fig. 10, the coloured map is reported together with the distribution of the points. It can be noted that the overall distance of the polygonal models ranges between ±0.5 mm (green) and ±2 mm (yellow, light blue).

From the two types of comparison, it can be noticed that the two RE models obtained with the two diverse RE system are substantially similar. The divergence between the two RE models is very low but the real difference is given by the definition of the details. In Fig.11, the same portion of the two polygonal models is shown to visualize the high details definition obtained with the PSA laser system compared to the one achieve with the DCRP system.

In Table 2, a further comparison between the two RE systems is reported in terms of number of acquired points, number of triangles, data acquisition time, post-processing time, precision, RE system costs. The DCRP system is very low cost and faster than the PSA laser system, but the latter is more accurate and precise.

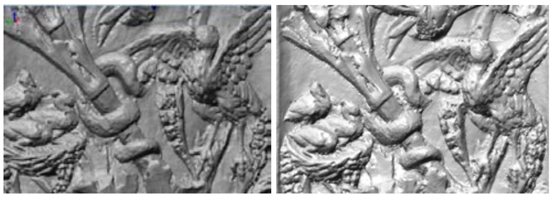

Fig. 11. Same detail of the polygonal model obtained with the PSA laser system (left) and with the DCRP system (right).

Table 2. Comparison between the two RE non-contact systems.

	PMA	DCRP
# of points	24,008,490 (for both scans campaign)	23,790,269
# of triangles	8,840,255	8,103,117
Acquisition time	8 h (4 h for each side)	16 min
Post-processing time	30 min for each point cloud (1 h); 40 min for polygon mesh creation; 5 days for 3D model reconstruction.	35 min for dense point cloud; 27 min for polygon mesh creation; 3 min for the texture.
Precision	±0.027 mm	±0.058 lateral ±0.139 vertical
RE system costs	High	Low

6. Additive manufacturing of a down scaled column copy

From the reconstructed digital models of cultural heritage artefacts, additive manufacturing technologies allow to directly build physical copies of the artefacts or their details, such as scale models of statues, bas-reliefs, architectural structures, etc. [13].

In the framework of this work, RE modelling for additive manufacturing was developed and applied to obtain a down scaled copy of the column under study using a fused deposition modeling (FDM) technique on a Delta Wasp 40x70 machine (Fig. 12). The 3D model mesh from the DCRP system was decimated to 1,109,256 triangles to obtain a 20% down scale copy of the original column. The XY resolution of the machine was 100 μm and the material adopted was polylactic acid (PLA) extruded at 215°C with a nozzle of 0.4 mm diameter on a heated bed at 50 °C, setting a layer height of 0.2 mm, using a feed rate of 40 - 85 mm/s and an infill of 5%. The fabrication time was 32 h and 43 min and the final workpiece size was 73 x 75 x 514 mm.

Fig. 12. Down scaled column copy fabricated by additive manufacturing.

7. Conclusions

Two diverse RE non-contact scanning systems, a portable measuring arm (PMA) with laser scanner and a system based on digital close range photogrammetry (DCRP), were employed for the reverse engineering (RE) of a cultural heritage artefact consisting in a II century monolithic marble column of Roman making.

The 3D digital models of the marble column, obtained with the two RE systems, were comparatively evaluated in terms of point clouds and polygonal meshes via coloured maps defining the minimum and maximum distance between the two results. By this comparison, the 3D digital models derived from the two scanning campaigns appear to be similar. The two point clouds have an overall distance ranging between 0.3 - 2.0 mm, whereas the overall distance of the polygonal models ranges between 0.5 - 2.0 mm.

By examining the two utilized digital reconstruction procedures, it is shown that the PSA laser system is more accurate and precise, whereas the DCPR system is less costly and time consuming.

In order to construct a down scaled copy of the column under study, an additive manufacturing technology based on a fused deposition modeling technique was applied by using the 3D digital model obtained from the DCRP system.

Authors’ contributions and acknowledgements

The sections on RE through PMA were mainly contributed by the group of the University of Naples Federico II. The sections on RE through DCRP and additive manufacturing were mainly contributed by the group of the Politecnico di Bari and Polishape 3D srl. All other sections where equally contributed by both groups who jointly read and approved the final manuscript.

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