Virtual and Rapid Prototyping by means of 3D optical acquisition and CAD modeling: application to cultural heritage and to the automotive domain

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ABSTRACT: In this paper, the activity aimed at the contact less acquisition, the generation of polygonal descriptive models, the generation of NURBS-based models and the reproduction by means of rapid prototyping tools of pieces of interest in both the heritage and the automotive domains are presented. The work gives an insight of how three-dimensional range cameras and suitable data modeling can be helpful in the reverse engineering and in the virtual representation of complex shapes. In addition, the research represents a valuable example of Computer Support Collaboration Work (CSCW) for the restoration and the rapid prototyping of the objects.

1 INTRODUCTION

In the last years, there has been an increasing demand of 3D optical sensors for fast acquisition of complex, free-form shapes (Blais 2004). The advantages with respect to contact probes are non-invasiveness, higher speed of measurement and, in many cases, lower cost. In addition, the availability of powerful software tools for the editing of the raw 3D data, and the modelling of the shapes opened the door to a considerable number of applications. Typical processes that can take a great benefit from the combined use of optical 3D sensors and suitable elaboration chains are the reverse engineering (RE) and the rapid prototyping (RP) of physical objects. In the manufacturing industry, RE and RP are key elements in design and production, to fulfil today’s needs of reducing time to market and overall costs, and of allowing the product restyling (Boulanger et al. 1994).

In the field of cultural heritage, the availability of 3D descriptive models of monuments, buildings, statues, and findings of cultural value, opens the door to (i) the remote study, by the scientists and/or their students, of the pieces of interest, from a common and reliable data base, (ii) the timely monitoring of the degradation of the pieces, (iii) the restoration of lost parts, and (iv) the reproduction of the pieces, both virtual, to fully exploit the concept of “virtual museums”, and physical, to obtain high accuracy scaled replicas of the original pieces (Levoy 1999).

In the automotive industry, they represent a valid aid to the stylist’s creativity. The typical process involves the fast, contact-less acquisition of the 1:1 scale model of the car body and its transformation into a three-dimensional model. This model can be further manipulated by using specialized Computer-aided Styling tools, validated by using scaled replicas, and further refined, in the framework of collaborative design (Varady et al. 1997).

All the activities expected in these domains could gather a great help by using methods and tools of the Computer Supported Collaborative Work - CSCW. The different competencies involved in the processes (Museums, Computer Graphic labs, RP centres, etc.) are often far each other, so the experts working there could exploit videoconferencing, application sharing, etc., to be more productive (Bandera et al. 2002).

In this paper, valuable examples of the application of full optical RE and RP processes to the cultural heritage and to the automotive industry are presented. The target objects, shown in Figure 1, are the “Winged Victory” (Fig. 1a) a 2 meters high bronze statue located at the Civici Musei in Brescia, one fragment of a precious majolica of the XVIII Century, found in the lagoon of Venice, and located at the Civic Museums of Udine (Fig. 1b), and the 1953 Ferrari 250MM, an historical, unique racing car (Fig. 1c).

The goal of the work in the case of the ‘Winged Victory’ was the achievement of descriptive models based on triangle meshes of the whole statue, in order to study the overall proportions and to allow the archaeologist, by means of an inductive approach, to determine the archetype from which these proportions have been generated.
In the case of the fragments of majolica, the objective was the physical reconstruction of the lost parts, in view of the real full restoration of the original object.

In the case of the ‘Ferrari’, the work was aimed at proving the applicability of non-contact gauging to perform the RE of the car body instead of using contact probes. This objective was thought to be crucial, considering that, in the automotive domain, contact probes require a considerable amount of time, especially when free-form shapes are to be modeled. In addition, they result in an overwhelming accuracy when the RE of full-size cars, and the production of polygon or CAD models are required for restyling applications.

In all the considered cases, the acquisition of the shapes has been performed by using a three-dimensional vision system based on the projection of suitable patterns of non-coherent light. This system, called OPL-3D, represents one of the research products of the Laboratory of Optoelectronics, located in Brescia (Sansoni et al. 2003). OPL-3D has been used to perform the multi-view acquisition of all the shapes. After their alignment, the views were fused into a single one; then the triangle meshes were created and edited. These models were then sent via the Internet to the RP Laboratory located in Udine. Here, scaled replicas of the statue head and of the car were obtained, by using a RP machine. Special elaboration was applied to the majolica fragment: it was used as the initial knowledge to derive the shapes of the missing parts. In this way, all the pieces could be reconstructed, and subsequently reproduced.

The following sections detail the hardware and the software facilities used to implement the whole process, and shall give a comprehensive description of the results.

2 OPL-3D: THE OPTICAL DIGITIZER

OPL 3D is shown in Figure 2. The optical head is composed of an LCD projector (ABW LCD320) and a CCD video camera (Hitachi K3P-M3) mounted on a rigid bar, fixed on a robust tripod.

The projector projects on the surface under measurement a sequence of eleven patterns of incoherent light, formed by black and white stripes of different spatial period. The patterns belong to the well-known Gray Code-Phase Shift (GCPS) method. The video camera synchronously frames each pattern: the stripes appear to be deformed by the object shape, due to the fact that the acquisition direction is angled with respect to the projection direction. The 3D shape of the object is retrieved from this deformation, and by exploiting the optical triangulation principle.

The in-field optical measurement is carried out in three steps. In the first step, a menu-driven interface sets the triangulation geometry of OPL-3D according
to the measurement range and to the required resolution. In addition, it suggests the values of the optical parameters of the projector-camera pair, in order to adapt to the environmental light and to the surface appearance of the object.

In the second step, the operator mounts the optical devices onto the rigid bar in the suggested configuration: the mount is fully configurable, to optimize the flexibility of OPL-3D to a wide range of experimental configurations. Then, a suitably designed calibration module estimates the pose and the orientation of the projector-camera pair with respect to the reference system, in which the measurement is expressed, and compensates for radial and tangential distortion of the lenses (Weng et al. 1992).

In the last step, OPL-3D performs the measurement by projecting the GCPS sequence of fringe patterns on the surface. The projection-acquisition step is performed in 2 sec, and the elaboration is completed in 4 sec, (data storage included). A very dense point cloud is produced (typically up to 70% of the number of pixels of the video camera). Typical values of the Type A uncertainty of the measurement are about 1/1500 of the depth range.

3 ACQUISITION OF THE POINT CLOUDS

The digitization of the “Winged Victory” showed up to be critical under a number of aspects. These are (i) the high variability of color of the surface, and the low levels of brightness and contrast, (ii) the high variability of the local curvature of the shapes, and (iii) the overall extension of the surfaces to be measured. The critical aspects in the digitization of the majolica fragment were the very high reflectance and the very small surface details, especially in correspondence with the borders. The problems in the case of the Ferrari 250 MM were represented by (i) the uniform glossy red paint, (ii) the high regularity of the surfaces without edges to be used as ‘anchoring’ points to align the different views, and (iii) the large overall dimensions.

The speed of the calibration procedure and the high flexibility of the instrument, turned out to be very helpful to overcome these problems.

As an example, in the case of the statue, it was possible to perform the calibration by choosing different colors for the master (light and dark blue were used instead of white and black). In the case of the car, it was possible to vary the integration time of the video camera: it was set to 1/250 sec during the calibration, and increased to 1/50 sec during the measurement. As a result, in both cases, the system was calibrated in experimental conditions very similar to those typical of the measurement. Hence, the quality of the images acquired in correspondence with the target surfaces was optimal both in the contrast and in the brightness.

In addition, different set-ups of OPL-3D were used, depending (i) on the degree of definition required for the surface details and (ii) on the use of suitable acquisition strategies aimed at keeping the alignment errors under control.

In the former case, the objective was to find an optimal trade-off between the adherence of the models to the original shapes and the file dimension.

In the latter, the goal was to guarantee a good accuracy during the alignment of the views. It is well known, in fact, that the higher the number of the views, the higher the probability that the alignment errors accumulate in an unpredictable way, and decrease the quality of the surface representation.

Table 1 shows the different set-ups used for the acquisition of the objects. In the case of the statue, OPL-3D was firstly configured in the so-called skeleton set-up: a shell of the whole statue (head excluded), was obtained by acquiring and merging together 110 views at low resolution (Guidi et al. 2003). Then it was configured at high resolution to acquire the head (41 views). After that, the set-up at medium resolution was used to acquire 480 views. These were overlapped to the shell, and aligned together by using it as the reference. The shell was then removed. In this way it was possible both to adjust the resolution of the measurement to the surface details and to minimize the influence of the alignment errors.

Table 1. Summary of the geometrical set ups used for the measurement of the targets. FW: width of Field of View, FH: height of Field of View, Z-Range: measurement interval; Rz: measurement resolution along the Z-Range; UA: Type A uncertainty of the measurement

<table>
<thead>
<tr>
<th>Geometrical set-ups</th>
<th>FW [mm]</th>
<th>FH [mm]</th>
<th>Z-Range [mm]</th>
<th>Rz [mm]</th>
<th>UA [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>High resolution (Statue head)</td>
<td>450</td>
<td>348</td>
<td>150</td>
<td>0,3</td>
<td>0,12</td>
</tr>
<tr>
<td>Medium resolution (Statue body and wings)</td>
<td>160</td>
<td>123</td>
<td>40</td>
<td>0,1</td>
<td>0,07</td>
</tr>
<tr>
<td>Medium resolution (Ferrari)</td>
<td>300</td>
<td>232</td>
<td>100</td>
<td>0,2</td>
<td>0,09</td>
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<tr>
<td>High resolution (Ferrari)</td>
<td>550</td>
<td>423</td>
<td>120</td>
<td>0,3</td>
<td>0,13</td>
</tr>
<tr>
<td>High resolution (majolica fragments)</td>
<td>370</td>
<td>284</td>
<td>60</td>
<td>0,2</td>
<td>0,1</td>
</tr>
<tr>
<td>High resolution (majolica fragments)</td>
<td>60</td>
<td>50</td>
<td>20</td>
<td>0,08</td>
<td>0,05</td>
</tr>
</tbody>
</table>

The acquisition of the ‘Ferrari’ was performed, in the first step, by acquiring 280 views, at medium resolution. Then, OPL-3D was configured at high resolution to acquire the car details, such as the handles and the windows borders. However, to compensate for the absence of 3D features on the car body, it was necessary to place physical, tape markers on the surface, to guarantee sufficient accuracy of the alignment.
In the case of the majolica fragment, the system was configured at very high resolution, to allow a precise acquisition of the borders, in view of obtaining an optimal fitting of the parts to be added. However, the reduced dimension of this object allowed us to limit the number of the acquired views to 10.

To acquire the shape of large, complex objects such as the ‘Winged Victory’ and the ‘Ferrari 250MM’, OPL-3D was mounted on wheels. It was moved around with its tripod and oriented with respect to the surfaces to have optimal focus condition, and minimal disturbance of reflectivity. In the case of the fragment, the object was moved with respect to the optical sensor.

The alignment of the views and their fusion into a single point cloud was performed, in each experiment, by using the IMAlign module (PolyWorks, from InnovMetric Inc., Canada), a very robust, well-engineered market available software was used. Figure 3 shows the point clouds corresponding to the statue (Fig. 3a), to the majolica fragment (Fig. 3b) and to the car (Fig. 3c).

In the case of the ‘Winged Victory’, an overall average measurement error from 90µm to 400µm was observed. The maximum error is 1.5mm in correspondence to the dress folding and the hand-made junctions of the arms and wings (Sansoni et al. 2005).

In the case of the majolica fragments, the setup allowed a fast acquisition of all the surfaces, with an accuracy of 60 microns.

The quality of the 3D raw data of the ‘Ferrari’ was evaluated by means of suitable color error maps calculated by IMAlign: they highlighted that the mean value of the alignment error was equal to 0,5 mm. In the figure, the black areas of the border of the markers, and the areas that, due to undercuts and spurious local surface reflections, were not be acquired by OPL-3D, are well visible. They could be filled up and smoothed using suitable tools within both the IMAlign and the IMEdit modules. In order to optimize the time efficiency of the process, the editing was postponed to the creation of the triangle mesh, and performed by the IMEdit tool (Sansoni et al. 2004).

4 MODELING OF THE POINT CLOUDS

Following their alignment, and fusion, suitable triangle models were created and edited. The IMMerge and the IMEdit modules of the Polyworks suite of programs were used to perform this task. The editing session had the purpose of (i) filling the residual gaps between points, due to shadowed regions, undercuts, and holes in the surface, (ii) reconstructing the surfaces which were not visible, and (iii) controlling the overall topology of the triangles.

4.1 The work on the ‘Winged Victory’ and on the ‘Ferrari’

Two triangle meshes, respectively of 16 millions triangles for the ‘Victory’ and of 1,3 million triangles for the ‘Ferrari’ were obtained. Further compression resulted into the generation of suitable smaller models, representing good trade-offs between the adherence of the meshes to the original shapes and the file dimension.
The triangle representation of the statue perfectly responded to the archaeologist’s demand. In response to the selection of any triangle pair in the model, the system provided the distance between them in real time. Since the model was very accurate, the measurement of a distance between the selected triangle pair was very reliable (Morandini 2002). This model was not only ideal for the archaeologist’s work, but also for a number of other issues. A first application was the rendering of the statue for multimedia and virtual reality. As an example, Figure 4 shows the appearance of the ‘Victory’ before (Fig. 4a) and after (Fig. 4b) the virtual removal of the wings (the surface in correspondence to the body-wing connection has been reconstructed).

4.2 The work on the majolica fragments

For what concerns the majolica fragment, the triangle mesh was sent through the Internet to the Computer Graphic Laboratory of the University of Udine. Then it was imported both into a geometrical-based CAD (Rhinoceros), a solid-based CAD (SolidEdge), and into MagicsRP, a software package dedicated to the STL files manipulation. As shown in Figure 6a, it was used to reconstruct the bowl. In addition, it was used as the initial knowledge to model the handle of the majolica (Fig. 6b).

The work carried out on the ‘Ferrari’ resulted into the creation of four CAD models with 28, 24, 12 and 8 control points respectively. The Geomagic Studio 4.1 software (Raindrop Geomagic Inc, US) carried out the elaboration, starting from the original triangle mesh. Figure 5 shows the rendered view of the 8 control points CAD model.

4.3 RP activities

One of the major advantages of the RE process is to obtain, from either the triangle model or the CAD model, a topological description that can be fed to a RP machine for the creation of replicas. In order to test the feasibility of the prototyping step, the mesh of the head statue and the mesh of the Ferrari were 1:8 and 1:10 respectively scaled. Then, a 4 mm thickness was added. The models were topologically controlled and saved in the STL format. Then, they were sent to the Laboratory located in Udine.

In both cases the CIBATOOL SL 5190 has been used as the material. Figures 7-8 show the two copies. The overall dimension of the statue head is 140mm x 110mm x 133mm, whilst the replica of the Ferrari is 370mm x 150mm x 90mm. The time required to obtain the copies was 0.20 hours for the elaboration of the data, plus 15 and 12 hours respectively for the machining.
The CAD model of the majolica was used without any further variation: Figure 9a shows the 1:1 scale replica resulted from the RP process. Figure 9b shows the fully reconstructed piece, after the assembling of original fragment and of the machined parts.

5 CONCLUSIONS

In the fields of RE and RP, this paper has described the activities aimed at the contactless acquisition, the generation of polygonal descriptive models, the generation of NURBS-based models and the reproduction by means of rapid prototyping tools of pieces of interest in both the heritage and the automotive domains. The results have been already tested and validated positively by the experts of the two fields. The same experts have encouraged the prosecution of the researches. Some new experiences are going to start, both in the same fields and in others, i.e. the medical/surgical and the mechanical ones.

6 REFERENCES


