From the Vittoria Alata to the Mille Miglia Ferrari racing car: 3-D optical acquisition, CAD and Rapid Prototyping of unique examples of cultural value

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Abstract – This paper presents the work performed to optically acquire the three-dimensional shapes of the "Vittoria Alata" and of the "Ferrari 250MM". The former is a precious statue, the latter is a historical car. In both cases, the three dimensional raw data have been acquired by means of a range camera developed at the Laboratory, and elaborated to obtain the triangle meshes and the CAD models of the pieces. The experience highlighted the efficiency of the full optical acquisition in the frame of the conservation of artworks of cultural value as well the feasibility of the reverse engineering of full-size cars in the automotive domain.

1 INTRODUCTION

There has been in the last years an increasing demand of optical instrumentation for non-contact, three-dimensional acquisition [1]. The advantages of optical measurement with respect to contact measurement are non-invasiveness, higher speed of measurement and, often, lower cost. Nowadays small triangulators, laser stripes and range cameras are used in the manufacturing domain, to perform quality control, CAD-assisted manufacturing, reverse engineering, and fast prototyping, both as stand alone devices and in tandem operation with contact probes [2,3].

One of the areas where optical systems for three-dimensional measurement are bound to have a bright future is the preservation of cultural heritage through digitisation of monuments, buildings, statues, ancient handicrafts, and archaeological findings. In fact, the availability of high-resolution, high accuracy, optically digitised 3-D images, together with the current availability of a number of powerful software environments, specially oriented to the production of descriptive models of shapes, open the door to: (i) the remote study, by the scientist 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 in view of a possible restoration, (iii) the visualization of the pieces to fully exploit the concept of "virtual museums", (iv) the reproduction of the pieces (for example with Rapid Prototyping tools) to obtain high accuracy scaled replicas of the pieces for didactical purposes and for the production of gadgets.

Italy is still the depository of more than 80% of the archaeological - and cultural heritage of the whole world. As a consequence, it is the natural framework for an intense activity in the field of optical 3-D imaging of our patrimony [4,5]. This is achieved thanks to the increasing collaboration between the scientific community in the fields of technology and of cultural heritage. This collaboration encounters the favour of the institutions, both at the national and the local government levels.

Our Laboratory has been, for almost a decade, active in the design and development of 3-D optical digitisers [6,7]. It has recently developed OPL-3D, a whole field optical profilometer based on the projection of non-coherent structured light [8], whose efficiency has been tested on a large number of applications, ranging from quality control, to modelling and rapid prototyping, to biomedicine.

The natural commitment of the Laboratory to applied research and to cooperation with institutions led in 2001 to the establishment of an agreement between the Comune of Brescia and the University of Brescia for the study and the 3-D digitisation of one of the symbols of the City, the statue named "Vittoria Alata" ("Winged Nike of Brescia"), shown in Figure 1.a. The initial purpose of the project was to provide the archaeologist with a sufficient database that could help them to locate the statue in the correct historical period, and to attribute it to the correct artistic school. In addition, the work performed led to the complete 3-D digitisation in full colour of the statue, with a global error of 0.5mm, to its description by means of triangle and CAD models, and to the production of replicas of the original.

As a consequence of the success of the study, another exciting opportunity arose for the Laboratory to apply OPL-3D to what can be defined the second important symbol of the city: the Mille Miglia historic race. The system, in fact, has been used to measure the 1953-Ferrari 250MM shown in Figure 1.b. The work included various steps, ranging from the 3-D optical digitisation of the car body, the multi-view registration of the views, to the generation of the polygonal models, to the generation of the CAD model and to the production of a scaled replica using Rapid Prototyping tools.

The work performed was an important benchmark to test the on-site measuring capabilities of OPL-3D in the presence of very complex, large objects. In addition, it allowed us to appreciate the efficiency of the overall reverse engineering process in terms of operator time, elaboration time, and accuracy of the models, in view of fruitfully applying it in more general applications, such as the study and virtual reproduction of archaeological findings and the restyling of full-size automotive clays.


(a) (b)

Figure 1. The statue of the "Vittoria Alata" (a); the "1953 Ferrari 250MM" (b).

2. THE OBJECTIVE OF THE WORK IN THE CASE OF THE "VITTORIA ALATA"

The statue is a 2 m high, bronze statue, collocated at the Civici Musei di Arte e Storia (S. Giulia) of Brescia. Right from the time of its discovery (July 20, 1826), there has been no doubt that the statue was fused during the First Century a.C. in Rome as an Aphrodite, and then, during the Vespasian Era transformed into a Victory by adding the wings [9]. A first doubt about the correct temporal and spatial collocation of the fusion was cast in 2001 [10]. The author suggested the hypothesis that the statue was indeed an Aphrodite of the Hellenistic Age (III Century b.C.), fused in Greece, then carried to Rome and transformed into a Victory by adding the wings later on.

This hypothesis raised a considerable interest in the Museum archaeological staff, which decided to undergo a scientific investigation to evaluate it, using all possible instruments and techniques available. Among them, the availability of a complete set of measurements of the statue was thought of primary importance to collocate it in the right temporal and spatial framework. A template-matching approach is involved: the study of the overall proportions of the statue allows the archaeologist, by means of an inductive approach, to determine the archetype from which these proportions have been generated.

It was clear to the Museum Staff that a well-performed set of measurements starting from a Computer-resident replica of the statue, would significantly simplify the study of the specialists, as well as the reliability of the results.

Firstly, the ambiguity between the measurements taken by different archaeologists would be removed if they could have access to a common database, and work on universally agreed fiduciary points; secondly the high uncertainty in the single measurement (still today often performed by means of calipers and compasses) would be removed and would depend only on the uncertainty of the optical instrument. Thirdly, the measurement could be made comfortably and the efficiency of the work would benefit from the possibility of expanding the set of points to be tested.

3. THE OBJECTIVE OF THE WORK IN THE CASE OF THE "FERRARI 250 MM"

The 1953 Ferrari 250 MM is a beautiful *Berlinetta Pinin Farina*, version presented at the International Car Exhibit of Ginevra in 1953. The model object of this study is the one having the chassis NO. 270, and took part to the 1000 Miglia race in 1953 and 1954, and to the Japanese 1000 Miglia in 1992. Ten years after, it took part to the 1000 Miglia 2002 with number 153.

In the case of the "Ferrari", the work was aimed at proving the applicability of non-contact gauging to perform the reverse engineering 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 modelled. In addition, they result in an overwhelming accuracy when the reverse engineering of full-size cars, and the production of polygon or CAD models are considered for restyling applications.

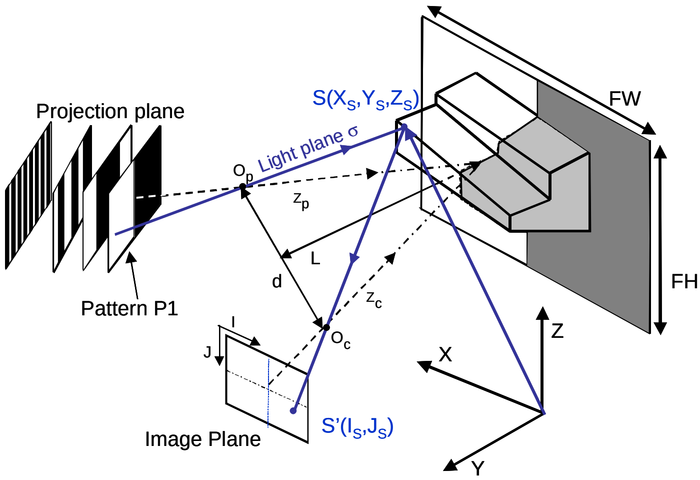
4. EXPERIMENTAL APPARATUS

4.1 The hardware for the optical acquisition

OPL-3D, the optical system used to acquire the three dimensional data is shown in Figure 2.a. The optical head is composed of an LCD projector (ABW LCD320) and a B/W CCD video camera (Hitachi K3P-M3) mounted on a rigid bar, fixed on a robust tripod. They are oriented in the absolute coordinate system (X,Y,Z) following the triangulation geometry of Figure 2.b. 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 video camera synchronously frames each pattern; as schematically shown in the figure in the case of pattern P1, the stripes appear to be deformed by the object shape, due to the fact that the acquisition direction is at angle $\alpha=\tan^{-1}(L/d)$ with respect to the projection direction. Parameters L and d are called standoff distance and system base line respectively. The images have a resolution of 782 x 528 pixels, with a depth of 8 bits.

The pattern sequence follows the well-known Gray Code-Phase Shift method (GCPS) [6]. The aim is to univocally index each direction of projection that is seen by the video camera by means of a real number, called *light plane*. The coordinates of the object points are obtained by intersecting light planes with the corresponding directions of acquisition.

(a)



(b)

Figure 2. The optical digitiser OPL-3D. a: image of the instrument; b: optical layout.

As an example, the *local* coordinates of point S in Figure 2.b, are represented by the triplet of values (σ, I_S, J_S), where σ is the light plane of direction of projection $\overline{O_pS}$ and (I_S, J_S) are the coordinates of point S', where line of sight $\overline{SO_c}$ is seen at the image plane. Local coordinates are then transformed into the *absolute* coordinates of the measurement (X_S, Y_S, Z_S) by means of suitable calibration procedures [9]. They estimate the pose and the orientation of the projector-camera pair with respect to system (X,Y,Z) and compensate for radial and tangential distortion of the lenses.

A detailed description of the calibration step is presented in [8]. Here it is worth noting that it is performed using a traceable calibration master, whose dimensional characteristics are known to an uncertainty lower than that expected from the measurement. The master is moved in the measurement volume at known positions along the measurement range; for each position the GCPS method is activated and, since triplets (X_S, Y_S, Z_S) are known for each point of the master, the unknowns are estimated. The whole calibration process is completely automated, and takes no more than 5 min. No recalibration is required unless the system configuration (i.e., values d and L) is changed.

The accuracy of OPL-3D is carefully evaluated to guarantee a confidence level of the measurement results. In the absence of accepted standards for the certification of range cameras, this evaluation is carried out by means of a suitable validation procedure, following the calibration. This procedure allows the operator to constantly monitor the quality of the captured data and, in case it goes lower than a predefined threshold, to adjust the operating parameters of the system depending on the characteristics of the surfaces to be acquired [8, 11].

The in-field optical measurement is carried out in three steps. Firstly a menu-driven interface sets the geometrical and optical parameters of OPL-3D according to the measurement range, to the required resolution, to the environmental light and to the surface appearance of the object. Then, the operator performs the calibration of the system. Finally, OPL-3D performs the measurement by projecting on the surface the sequence of fringe patterns. 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 [8].

4.2 The software for the elaboration of the point clouds

To acquire the shape of large, complex objects such as those considered here, OPL-3D is mounted on wheels. It is moved around with its tripod and oriented with respect to the surface to have optimal focus condition, and minimal disturbance of reflectivity. Following their acquisition, the cloud points have to be aligned together in a common reference system. To perform this task, OPL-3D is equipped with both self-made and commercial software, the choice depending on the number of views. In the study cases presented here, the alignment was performed by using with very robust, well-engineered market available software, (PolyWorks, from InnovMetric Inc., Canada). In particular, the IMAlign module has been used to carry out the multi-view alignment and the fusion of a huge number of views (480 for the statue and 250 for the car 2). Then, the IMMerge module has been exploited to transform the point clouds into triangle models, and the IMEdit module to edit the models. The creation of the CAD models has been obtained by using the Geomagic Studio 4.1 environment software (from Raindrop Geomagic Inc., USA).

5. EXPERIMENTAL WORK

The digitisation of the “Vittoria Alata” showed up to be critical under a number of aspects. These are (i) the high variability of colour 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 digitisation of the Ferrari 250 MM were complementary. These are (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 measurement strategy applied to overcome all the above critical aspects is described in the following.

5.1 Compensation for the surface colour and reflectivity

The colour characteristics of the targets could result into a poor quality of the 2D images acquired during the projection of the GCPS procedure on the surfaces under measurement. Due to the fact that the quality of the three-dimensional measurement strictly depends on the contrast and the brightness of the intensity information of the 2D images, it was mandatory to ensure that the whole 8-bit dynamics of the video camera could be used to codify the intensity information from the scene. This goal has been achieved in the calibration of the system.

In the case of the statue, the colours of the calibration master, originally black and white, were modified into light and dark blue (for the background and the markers respectively). They resulted in intensity images with very similar dynamics to that of the images taken in correspondence with the statue; the operating parameters of OPL-3D were estimated in those conditions.

In the case of the car the integration time of the video camera was reduced to 1/50 sec during the calibration: in this way, the system unknowns were estimated without filling up the available 8-bit dynamics, despite the high contrast of the calibration master. During the measurement, the integration time was increased to 1/250 sec, to accommodate the input grey levels over the whole 8-bit range, without altering the optical parameters of the lenses.

5.2 Use of multiple set-ups

The statue presented a high variability in shape, whilst the car was characterized by extremely regular surfaces even if, also in this case, a number of small details should be acquired. To obtain optimal models in terms of adherence to the original shapes and of reduction of the file dimension, different set-ups of OPL-3D were used, depending on the degree of definition required and on the surface details. This choice was enabled by the extremely flexibility of the instrument, and by the speed of the calibration procedure. It allowed us to acquire some parts of the statue and of the car at very high definition (e.g., the head of the statue and those parts of the body that were of interest for the study of the statue, the handles and the windows borders of the of the car). The other surfaces were acquired at medium definition, in view of achieving a good trade off between the detail of the representation and the data amount. Table I shows the set-ups used for the acquisition of the statue and of the Ferrari.

5.3 Strategy for the acquisition of the views

The acquisition of a huge number of views often implies an unpredictable accumulation of alignment errors. To keep them under control, besides the obvious consideration that the variability of the error on the single views should be kept as lower as possible, a suitable strategy for the sequence of acquisition was followed. As suggested in [12], the definition of a shell of the whole objects, built up by means of a reduced number of views at low resolution, was achieved as the first step. Then the surfaces were acquired by means of a high number of smaller views, at higher resolution. These views were aligned together by using the shell as the reference skeleton, and the alignment was optimised. The skeleton was then removed. Table I shows the set-ups used for the acquisition of the skeleton in the two cases.

Geometrical set-ups	FW [mm]	FH [mm]	Z-Range [mm]	R_z [mm]	U_A [mm]
High resolution (Vittoria)	160	123	40	0,1	0,07
Medium resolution (Vittoria)	300	232	100	0,2	0,09
High definition (Ferrrai)	370	284	60	0,2	0,1
Medium definition (Ferrari)	550	423	120	0,3	0,13
Set-up used for the skeleton of the statue	450	348	150	0,3	0,12
Set-up used for the skeleton of the car	550	423	120	0,3	0,13

Table 1. Summary of the geometrical set ups used for the measurement of the Vittoria and of the Ferrari. FW: width of Field of View, FH: height of Field of View, Z-Range: measurement interval; R_z: measurement resolution along the Z-Range; U_A: Type A uncertainty of the measurement.

5.4 The point clouds

Figure 3.a shows the point cloud corresponding to the right side of the face of the statue. To take this view, the optical head was configured in the set-up at the highest resolution, and the tripod has been elevated up to 3 meters from the floor. To acquire the head, OPL-3D was configured at the highest resolution. Figure 3.b illustrates the result of the alignment procedure in the case of the 41-point clouds obtained for the head of the "Vittoria".

To acquire the other segments of the statue, the "skeleton" of the statue was captured, by aligning 110 point clouds suitably selected to keep the alignment error as low as possible. Then the accurate point cloud of the statue was acquired (the set up at medium resolution was used). First the body was measured, by turning around the statue with the instrument at different heights, then the arms and finally the wings. The point cloud obtained from the combination of 480 views shows an average measurement error from 90μm to 400μm for the 90% of the surface. The maximum error is 1.5mm in correspondence to the dress folding and the hand-made junctions of the arms and wings [14].

An example of the acquisition of the Ferrari is shown in Figure 4, where the alignment between two views is also presented.

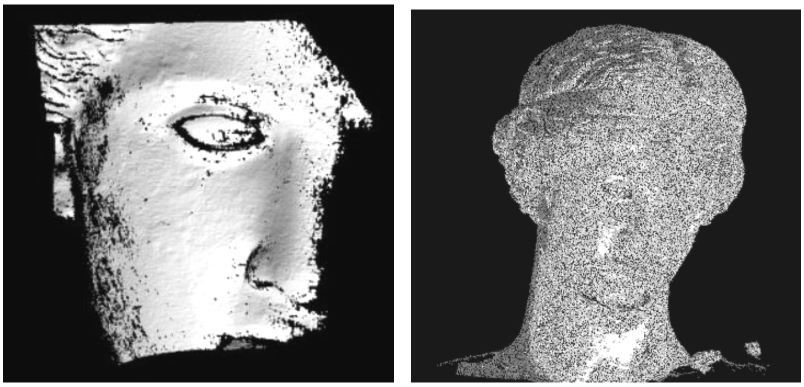

(a) (b)

Figure 3. Point cloud acquisition of the “Vittoria Alata”. 3.a: single point cloud corresponding to the right side of the face of the statue; 3.b: result of the alignment of 41 view of the head.

It is well observable in the figure the presence of white tape markers, placed on the surface to act as robust fiduciary points. In fact, the preliminary tests revealed that the extreme regularity of the surface could result in even gross errors during the alignment, unless physical markers were used as fiduciary points. It is worth noting that, in the case of the statue, the extremely high variability of the surfaces intrinsically produced a number of three-dimensional features that were used as anchoring points during the alignment.

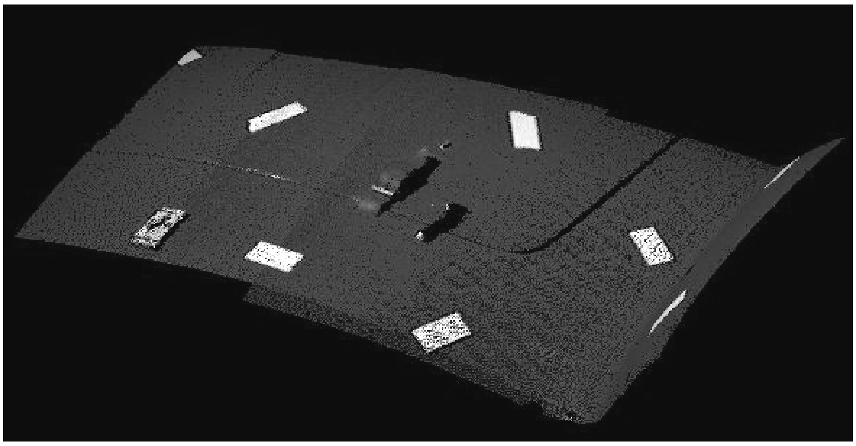


Figure 4. Alignment of two views of the “Ferrari 250MM”

Similarly to the previous case, the skeleton of the car was obtained, and then the details were added. The quality of the alignment was evaluated by means of suitable colour error maps calculated by IMAlign: they highlighted that the mean value of the alignment error was equal to 0,5 mm.

6. THE TRIANGLE AND THE CAD MODELS

The triangle models were created starting from the point clouds. Then, the editing session was performed. It had the purpose of (i) filling the residual gaps between points due to shadowed regions, undercuts, and small holes in the surfaces, (ii) reconstructing the surfaces which were not visible, and (iii) controlling the overall topology of the triangles. In the case of the statue this task took a considerable amount of time, but was greatly facilitated by the intrinsic accuracy of the original point clouds. In the case of the car, the regularity of the surfaces simplified the work. The high-resolution model used by the specialists to study the statue is shown in Figure 5.a [14]. Further elaboration of this model resulted into the optimal decimation of the triangles, the definition of the STL file and the production of the scaled replica of the statue, shown in Figure 5.b.

(a) (b)

Figure 5. 16 million triangles model of the “Vittoria Alata”. 5.a: front side plus colour; 5.b: scaled replica (30 cm high) of the statue obtained after proper decimation of the model.

The model of the car is shown in Figure 6. As in the previous case, it was used to create the 1:10 scaled replica of the car body by means of rapid prototyping tools [11]. In addition, the CAD model of the whole car was created. An example of the quality of this model is presented in Figure 7.

7. CONCLUSIONS

In this paper, the work performed to fully digitise very complex shapes of interest in the archaeological and in the automotive domains have been presented. The use of an optical three-dimensional range system developed at the Laboratory allowed to demonstrate the efficiency of non-contact instrumentation to acquire free form shapes, to model them and to reproducing them, in the frame of a typical reverse engineering process.

Figure 6. 1,3 million triangles model of the “Ferrari 250MM”.

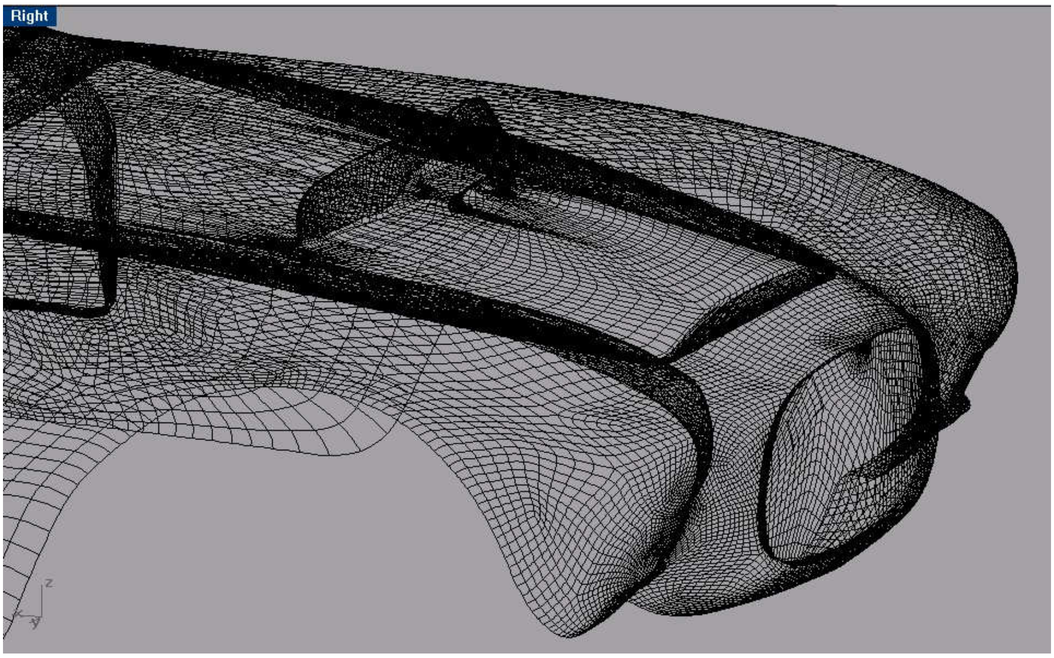


Figure 7. CAD model of the “Ferrari250MM”

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