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Three-dimensional optical measurements and reverse engineering for automotive applications

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Abstract

The paper describes a very special and suggestive example of optical three-dimensional (3D) acquisition, reverse engineering and rapid prototyping of a historic automobile, a Ferrari 250 Mille Miglia, performed primarily using an optical 3D whole-field digitiser based on the projection of incoherent light (OPL-3D, developed in our laboratory). The entire process consists in the acquisition, the point cloud alignment, the triangle model definition, the NURBS creation, the production of the STL file, and finally the generation of a scaled replica of the car.

The process, apart from the importance of the application to a unique, prestigious historic racing car, demonstrates the ease of application of the optical system to the gauging and the reverse engineering of large surfaces, as automobile body press parts and full-size clays, with high accuracy and reduced processing time, for design and restyling applications.

Keywords: Optical digitisation; Reverse engineering; Automotive applications; Triangle mesh; CAD models; Rapid prototyping

1. Introduction

CAD-assisted manufacturing, reverse engineering and rapid prototypation (RP) are key elements in design and production, to fulfil today's needs of reducing time-to-market, of allowing reconfigurability and restyling of the product, of reducing the overall costs, and of achieving full quality control before and during the production process. In the last years, there has been an increasing demand from the industrial framework, of both hardware and software tools with increased simplicity and efficiency for these purposes [1]. One of the areas where this demand is greatest is three-dimensional (3D) acquisition and processing of free forms in space.

In the automotive domain, 3D acquisition systems are known to be a valid aid to the stylist's creativity: they make it possible, in fact, to transform a 1:1 scale maqette into a 3D model. This model can be further manipulated in Computer-aided Styling and Computer-aided Industrial Design software environments. In combination with modern RP techniques, the stylist's work can be validated by using scaled replicas and further refined, in the framework of collaborative design [2].

The traditional solution for 3D measurement is, till today, based on contact digitisation: the Coordinate Measuring Machine (CMM) is one of the most sophisticated and accurate measuring devices of this type. However, in addition to contact gauges there is also an increase in the demand of optical gauges. The advantages of the latter with respect to the former are a limited invasiveness, a higher speed of measurement and, often, a lower cost. A number of optical measuring devices are available in the market [3]. Some of them (small triangulators, autofocusing devices and laser stripes) have been successfully integrated in CMMs as non-contact probes [4–6].

Whenever complex, free form surfaces have to be measured in short time, and a very high measurement accuracy is not required, wide-area laser scanners and whole-field optical digitisers represent valid alternatives to CMMs. They are faster, may provide the 3D shape of the object in seconds, and are reasonably less expensive than CMMs [7–9]. These systems, when combined to CMMs in a tandem operation, represent the ideal solution even when high accuracy and fast acquisition are imperative.

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Our Laboratory has been active for years in the design and development of optical measuring devices [10,12]. The use of these devices combined with CMMs has demonstrated to dramatically decrease the measuring time with no decrease of the measurement accuracy [13]. In addition, OPL-3D, a novel, powerful optical digitiser based on incoherent, structured light projection has been recently developed [14] and put in the market under the trade name of 3DShape (Open Technologies srl, Italy).

The system has been tested in a wide number of applications, ranging from the quality control in the production of moulds, to the measurements in the realm of cultural heritage [15], and to the reproduction of objects by means of CNC machining [16].

A demonstration of the successful use of our system for 3D measurement in the automotive domain is presented in this paper, where the measurement of the car body of a historical car, a 1953-Ferrari 250MM, is described. The work included various steps, ranging from the 3D optical digitisation of the car, to the multi-view registration of the views, the generation of the polygonal models, the generation of the CAD model and the production of a scaled replica by using RP tools.

The work was a benchmark that allowed us (i) to test the possibility to substitute contact probes in the acquisition of large and generally smooth surfaces, such as the automobile bodies often are, (ii) to test the quality of the triangle mesh in order to generate accurate scaled replicas of the original car body, and (iii) to appreciate the efficiency of the overall reverse engineering process in terms of operator time, elaboration time, and accuracy of the models, especially in view of its application to full-size automotive clays.

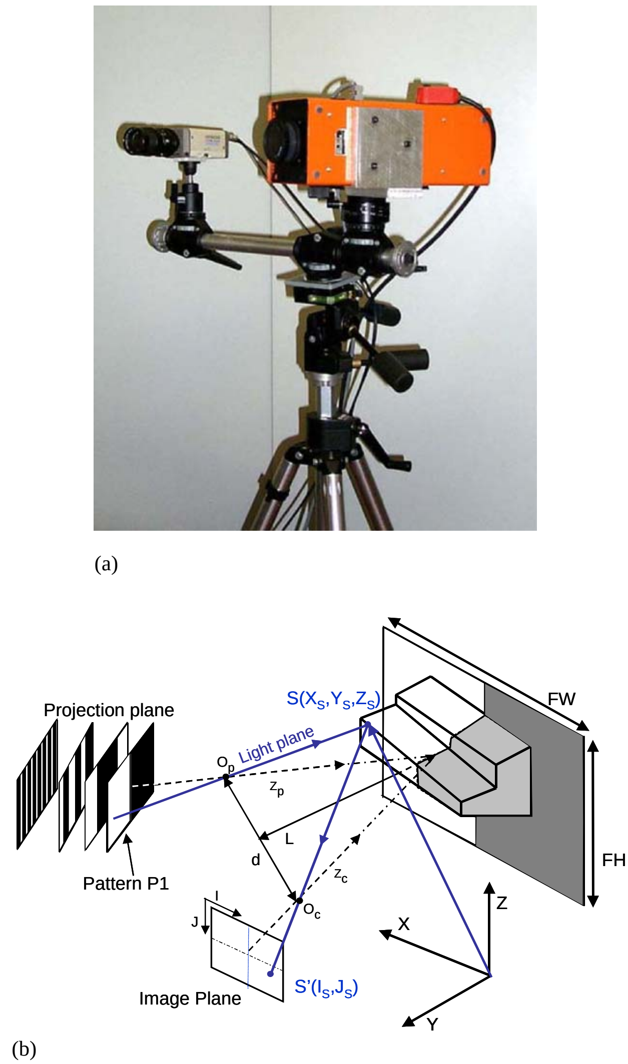


Fig. 1. The optical digitiser OPL-3D: (a) image of the instrument; and (b) optical layout.

2. Experimental apparatus

2.1. OPL-3D: the optical digitiser

OPL-3D is shown in Fig. 1a. 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 images are acquired by a Matrox Meteor II frame grabber that samples the signal at a resolution of 782×528 pixels, with a depth of 8 bits. A personal computer performs the image elaboration, the calibration of the system, and the data editing.

The camera–projector pair is oriented in the absolute coordinate system (X, Y, Z) following the triangulation geometry of Fig. 1b. In this figure, points O_c and O_p represent the entrance and exit pupils of the video camera and of the projector, respectively. Parameters FW and FH are the width and the height of the field of view. Parameter $d = \overline{O_p O_c}$ is the system base line and L is the standoff distance. The projector projects on the surface under measurement a sequence of 11 patterns of incoherent light, following the well-known Gray Code-Phase Shift method [17]. 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 an angle $\alpha = \tan^{-1}(L/d)$ with respect to the projection direction.

The aim of the projection 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. As an example, the *local* coordinates of point S in Fig. 1b, are represented by the triplet of values (σ, I_S, J_S): σ is the light plane of direction of projection $\overline{O_p S}$ and (I_S, J_S) are the coordinates of point S', which represents the intersection point between line of sight $\overline{SO_c}$ and 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 [18]. These 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.

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 (i.e., baseline d and standoff distance L) according to the measurement range and to the required resolution. In addition, it suggests the values of the optical parameters (i.e., focal length and lens aperture of the projector–camera pair), in order to adapt to the environmental light and the surface appearance of the object.

In the second step, the operator mounts the optical devices in the suggested configuration onto the rigid bar and performs the calibration of the system. The mount is fully reconfigurable, to optimise the flexibility of OPL-3D to a wide range of experimental configurations. In addition, given the fact that through the calibration procedure, the system is capable to finely estimate the operating parameters, no accurate positioning equipment is required.

In the last step, OPL-3D performs the measurement by projecting on the surface the sequence of fringe patterns. The projection-acquisition step is performed in 2 s, and the elaboration is completed in 4 s, (data storage included). A very dense point cloud is produced (typically up to 70% of the number of pixels of the video camera).

2.2. Accuracy verification of single views

In the absence of accepted standards for the certification of range cameras, the accuracy of these systems must be carefully evaluated to guarantee a confidence level of the measurement results. In our work, this evaluation has been carefully carried out with the use of a traceable calibration master. As shown in detail in [14], it has the form of a matrix of black circles on a white background. The master has a controlled planarity (in the order of 100 μm), and is rigidly mounted onto a guide, equipped with a series of positioning holes, placed at nominal distances of 10 mm (±50 μm) spacing. The circles are at controlled positions within the master, and their centres provide the system fixed coordinates in the global reference system.

A number of them, called measurement markers, are used to estimate the unknowns during the calibration step; the others, called control markers, are used to evaluate the quality of the measurement following calibration.

During the calibration, the master is moved at known positions along the measurement range. At each position, the Gray Code-Phase Shift sequence is performed, the local coordinates of the centres of the markers are evaluated and, together with the corresponding set of global coordinates, they are used as the input of the calibration algorithm that estimates the camera and projector parameters.

The control markers are then used to check the quality of this estimate by comparing their global coordinates with those measured by the digitiser after the calibration. For each control marker, the absolute differences between the measured coordinates and the global coordinates are calculated. The software evaluates the mean values $\bar{x}, \bar{y}$ and $\bar{z}$ and the mean square errors σ_x, σ_y and σ_z of each distribution. Then, it compares all these values to a threshold, called control threshold (CT), that is set to FW/3000, for the considered set-up.

The operator checks the quality of the estimate as follows: if values $\bar{x}, \bar{y}, \sigma_x$ and σ_y are lower than CT, the influence of the errors introduced by the subpixel detection of the centres of the markers is minimum; if $\bar{z}$ and σ_z are lower than CT, the influence of the uncertainty of the positioning of the master is minimum, as well as the effect of the master planarity on the measurement. If one or more of the conditions above are not matched, the calibration must be performed again.

The consequence of this procedure is the knowledge of the overall uncertainty of the system while the measurement is performed. We note that, insofar the geometry of the measurement is not varied, all the operation pertaining to this task need not be performed again.

2.3. The software for multi-view acquisition and alignment

To acquire the shape of large, complex surfaces, multi-view acquisition and alignment of the point clouds must be performed. To this aim, the optical sensor is equipped both with a self-developed software and with a high-level market available software. This choice has been dictated by the requirement of achieving a flexible process, where both a low cost, easy to use tool for the alignment of simple surfaces, with reduced data amount, and well-engineered software modules for the management of hundreds of views can be used.

OPLAlign is the tool belonging to the class of self-developed software [19]. It is in-built in the optical system and performs pair-wise alignment by means of an iterative closest point (ICP)-based algorithm [20]. The matching algorithm in OPLAlign has been improved with respect to the original ICP procedure, especially in relation to the speed of the elaboration and to the initial estimate of the relative position between the two clouds. It is ideal for a quick alignment of the views, without requiring a specialised knowledge and background, and guarantees total compatibility with any other market available software environment.

IMAlign is the commercial module used to perform the alignment over a very large number of views. It belongs to the *PolyWorks* suite of programs (from InnovMetric Inc., Canada). It performs the registration of hundreds of views, basically following the same ICP approach as the one implemented in OPLAlign, but guaranteeing higher reliability and computational efficiency. In addition, it performs the fusion of each partial view and minimises the measurement noise in view of creating the triangle mesh.

2.4. Accuracy evaluation of the multi-view acquisition

In multi-view acquisition, alignment errors sum up. A first requirement to keep errors under control is to guarantee that the alignment of two adjacent point clouds is roughly of the same order of the intrinsic measurement error of each point cloud. This can be done using the inherent 3D features of the image, or, in the presence of very regular, planar surfaces, by providing physical markers, to be used as anchoring points between the surfaces. The alignment software should provide error histograms and maps, to quantitatively evaluate the alignment performance, and to avoid unpredictable error propagation. In addition, other measurement approaches can be used to control the overall alignment accuracy. Among these, the literature proposes several non-contact methods, such as theodolite survey and photogrammetric measurements [21,22].

An additional requirement for optimal alignment accuracy is to keep the number of views at a minimum, without sacrificing measurement resolution. The achievement of this compromise can be obtained by a measurement strategy that is based on the build-up of a low/medium resolution shell of the overall surface, which guarantees the obtainment of closed surfaces. This is then followed by the acquisition of a higher number of high-resolution views that are aligned using the shell as the 'skeleton' [23]. This strategy requires the use of the optical system in different measurement set-ups, each of which has to be independently calibrated. The ease of recalibration of our system and the flexibility in the change of set-up is, in this context, strategic.

It is worth noting that the accuracy achieved by the alignment is not degraded by the following editing process of the acquired 3D surface.

2.5. The software for the creation of the triangle mesh

To create the triangle mesh from the point cloud, the PolyWorks *IMMerge* module is used. It allows the operator to finely adjust the value of a number of parameters that make this step as flexible as possible, and optimises the mesh both in terms of the accuracy with respect to the original point cloud and in terms of the number of the model triangles.

Once created, the mesh is optimised and topologically controlled, especially in view of producing an STL closed file, to be used by a stereo-lithography machine. The PolyWorks *IMEdit* module carries out this task. It is a very powerful tool for mesh editing, by means of quasi-automatic transformations (e.g., 'fill hole' operations, surface smoothing, triangle optimisation), and uses specific functions specialised to reliably reconstruct even seriously corrupted portions of the surface. Following optimisation, the mesh is generally compressed. The PolyWorks *IMCompress* module is used to achieve a number of meshes derived from the original model, and characterised by lower file dimension. It is thus possible to choose the optimal trade-off between accuracy of the representation and memory occupancy among the sets of the meshes.

2.6. The software for the creation of the CAD models

To obtain the mathematical representation of the surfaces, OPL-3D is equipped with *Geomagic Studio* 4.1 (from Raindrop Geomagic, USA). It is a market-available, sophisticated software environment, which creates in an automatic way the patch layout and the NURBS-based representation of the shapes starting from the triangle mesh. Geomagic Studio privileges the automation of the whole process with respect to the fine, local editing of the surfaces: this dramatically reduces the operator time and results in a CAD model that, to our experience, can be optimised with very little additional editing.

3. Experimental

3.1. The acquisition of the views and the multi-view alignment

The 1953 Ferrari 250MM is shown in Fig. 2. To perform the measurements, the car was placed on an overhead-travelling crane in the workshop. Since OPL-3D is portable, and does not need recalibration when it is moved around the object, the tripod was mounted on wheels to facilitate the movements around the car. Fig. 3 shows an example of projection of a pattern, out of the set of 11 patterns that belong to the Gray Code-Phase Shift sequence, performed as a preliminary test of the colour calibration of the system. Due to the high number of views to be taken, the IMAlign module has been used.

The digitisation of the Ferrari 250MM showed up to be critical under a number of aspects. These are (i) the

Fig. 2. The Ferrari 250MM.

Fig. 3. Projection of one out of 11 patterns of the Grey Code-Phase Shift sequence on the car body.

high regularity of the surfaces without edges to be used as 'anchoring' points to align the different views, (ii) the glossy red paint, and (iii) the large overall dimensions. The measurement strategy applied to overcome all the above critical aspects is described in the following.

3.1.1. Use of physical markers

IMAlign is based on a semi-automatic procedure, which allows the alignment of each 'floating' view with respect to those already 'locked' together in a common reference system. The basic mechanism requires the selection of at least three fiduciary points in each of the views. In the experimental case considered here, it was observed that, when the selection of the points was performed in correspondence with the edges of the surface, the matching was very fast and accurate (i.e., the error introduced by the alignment was lower than the uncertainty of the measurement). However, when regular portions of surfaces had to be aligned, the computation time dramatically increased, the alignment was inaccurate, and it very often failed.

In our case, the use of tape markers was chosen as the solution of election due to the fact that the majority of the surfaces exhibit an extremely high regularity and planarity, and that the use of tape did not hinder the state of the car surface. At first, dark colour markers were used: it was expected that these black areas could not be measured and would result as holes, and, as such, be used as reliable fiduciary points. This turned out not to be the case: as a consequence of the calibration optimised for the red shiny paint, and of the high overall instrument performance, even the black markers were easily measured. Hence, white matt tape markers were considered to be a better choice. They could be easily measured as in the previous case, but presented a dark perimeter of non-measured points due to the high contrast between the colour of the marker and that of the paint. Within each perimeter, one or more fiduciary points could be easily defined, and a good quality of the alignment was obtained. Fig. 4a shows an example. Four 'floating' views (numbered from 1 to 4) have been aligned to view '0', taken as the reference. The good quality of the alignment can be appreciated observing the histograms in Fig. 4b that show the error distribution between each aligned view and the reference view. The maximum standard deviation over all the views is equal to 0.25 mm.

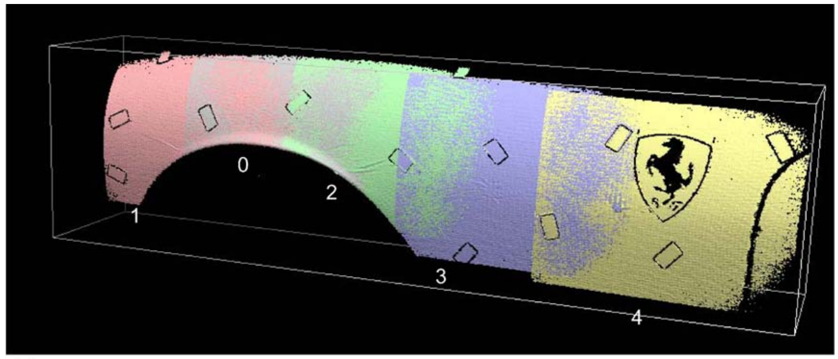
3.1.2. Compensation for the surface colour and reflectivity

The second critical aspect in the measurement was the colour of the car. The 'Ferrari red' resulted in low dynamics in the acquired fringe patterns and, hence, into measurements of low quality. To overcome this problem, the integration time of the video camera was reduced to 1/50 s during the calibration step: 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 s, to accommodate the input grey levels over the whole 8-bit range, without altering the optical parameters of the lenses.

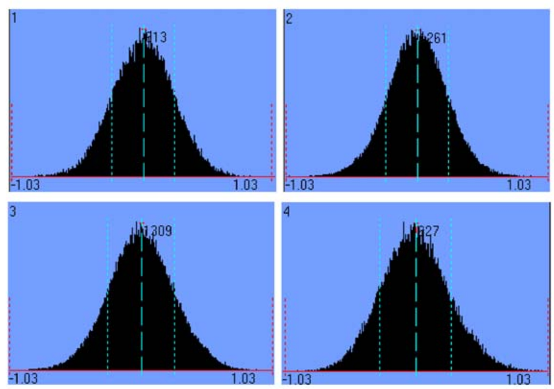
A residual problem was the high reflectivity of the surface, which resulted in holes (i.e., invalid data) on the surface, whenever the images saturated. This effect was compensated for by acquiring a redundant number of views, each taken at a different angle with respect to the surface normal.

3.1.3. Multi-resolution approach

To overcome the last critical aspect of the measurement, i.e., the car large overall dimensions, the combination of a complete low-resolution 'skeleton' with high-resolution point clouds superimposed to it



(a)



(b)

Fig. 4. Alignment of five adjacent point clouds: (a) visualisation of the aligned views; and (b) histograms of the error distributions.

Table 1
Summary of the geometrical set-ups used for the measurement of the Ferrari

Geometrical set-up	Setup1	Setup2
FW (mm)	550	370
FH (mm)	423	284
Z-range (mm)	120	60
R_z (mm)	0.3	0.2
U_A (mm)	0.13	0.1

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.

Fig. 5. Whole point cloud of the Ferrari 250MM.

was performed, following the guidelines already explained in Section 2.4. The system has been set and calibrated in two set-ups, whose performance and uncertainties are listed in Table 1. The former (called Setup1 in the Table) has been used to acquire the shell: in this way, a good trade-off between the measurement accuracy and the overall number of the views was achieved. The second set-up (Setup2 in Table 1) has been used to acquire, with a higher resolution, all the shapes in correspondence with the details of the car body (door handles, beams, small details).

The overall point cloud, resulting from the alignment and fusion of 280 views, is shown in Fig. 5 (3D raw data). 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. In the figure, the black areas of the border of the markers, and the areas that, due to under-cuts and spurious local surface reflections, were not 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 optimise the time efficiency of the process, the editing was postponed to the creation of the triangle mesh, and performed by the IMEdit tool.

3.2. The triangle model

The IMMerge module generated the triangle model from the point cloud, the requirement being of obtaining a reliable adherence to the fine details of the car while maintaining a smooth representation of the surface. Needless to say, the regularity of the car shapes guaranteed that this operation would not alter the accuracy of the measurement.

The triangle mesh was then edited by the IMEdit tool, which proved to perform ideally and in short time with this type of geometry (again, the regularity of the surfaces greatly favours the use of automatic editing procedures). The editing session had the purpose of (i) filling the residual gaps between points, due to markers, shadowed regions, undercuts, and small holes in the surface, (ii) reconstructing the surfaces which were not visible, and (iii) controlling the topology of the triangles in order to provide a closed STL model, for the reproduction by means of fast prototyping machines. Fig. 6 shows the result of this task: the model is a 1.3 million triangles, 75 MB STL file.

3.3. The creation of the CAD model

The Geomagic Studio 4.1 software carried out the creation of the CAD model from the 75 MB triangle mesh. The patch layout was generated in two steps. The former step was automatically performed by the software, and the operator was requested to set only a few input parameters (i.e., the number of the patches, the granularity parameter, etc.). The procedure was straightforward, and produced the initial patch layout. The latter step was operator assisted. A powerful set of tools allowed us to locally adjust the patches, in order to improve the initial patch layout, thus facilitating the subsequent generation of the NURBS and optimising the quality of the CAD model. Fig. 7 shows the patch layout obtained at the end of this step.

Once the patches were optimised, the NURBS were generated. Again, the software automatically performed this operation, once the number of the required control points was set. In our case, four CAD models were obtained, with 28, 24 12 and 8 control points. The dimensions of the IGS files were 164, 127, 34, and 15 MB, respectively. The CAD models with 28 and 24 control points were not further used, due to their huge dimension. The two other models were manually edited. The time required for this step, as well as the one needed to perform all the elaboration previously described, are detailed in Table 2. In the 12-control points model, 75% of the NURBS deviations are within $\pm 20\,\mu m$, 20% within $\pm 89\,\mu m$, and 5% within $\pm 300\,\mu m$. In the 8-control points model, the quality of the NURBS slightly decreases, as shown by the colour error map in Fig. 8. Here, 60% of the deviations are within $\pm 20\,\mu m$, 30% are within $\pm 89\,\mu m$, and 10% within $\pm 400\,\mu m$. It is worth noting that the quality of the model is still high. As an example, Fig. 9 shows the surfaces corresponding to the left-door handle of the Ferrari: here, 50% of the NURBS are within $\pm 20\,\mu m$, and the residual deviations are within $\pm 89\,\mu m$.

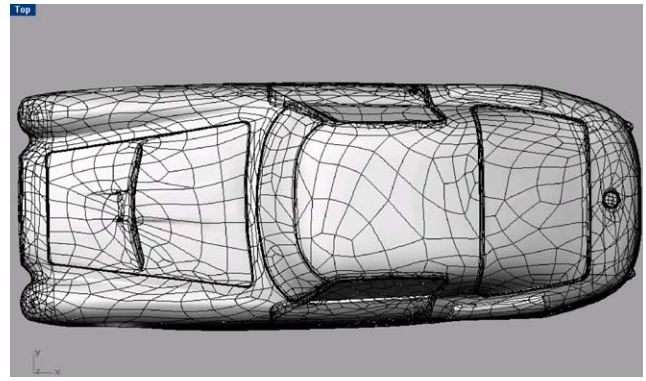


Fig. 7. Generation of the CAD models: patch layout.

Table 2
Average duration of each task in the reverse engineering of the Ferrari 250MM

Number of views	280
% of acquired surface	80%
Acquisition and alignment	5 days
Creation/editing of the mesh	2 h/4 days
Creation of the patch layout automatic/manual	3 h/1.5 days
Automatic generation/manual editing of the NURBS	1 h/1 day

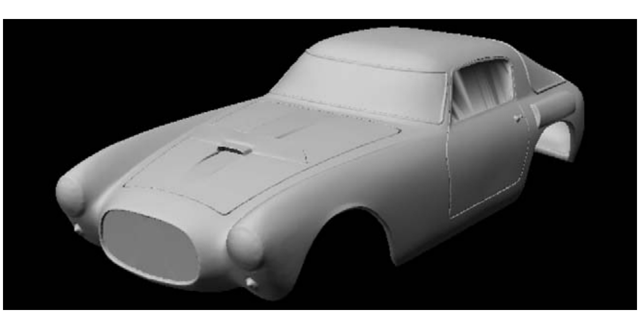


Fig. 6. Triangle mesh of the Ferrari after the editing session (rendered view).

3.4. The scaled replica

One of the major advantages of the reverse engineering 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 75 MB triangle mesh was 1:10 scaled, and a 4 mm thickness was added. The model was topologically controlled and saved in the STL format. Then, it was sent through the

Internet to the Laboratory of Fast Prototyping of the University of Udine (Italy). Fig. 10 shows the 370 mm × 150 mm × 90 mm prototype. The CIBATOOL SL 5190 has been used as the material, the time required to obtain the copy was 0.20 h for the elaboration of the data, plus 12 h for the machining.

4. Discussions and conclusions

In this paper, we have presented a case study of 3D optical acquisition and reverse engineering of large free form surfaces applied to the automotive domain. The various steps leading to the CAD models and to the scaled replica of a prestigious car have been described and commented. The results obtained highlighted the capabilities of our range system to on-site accurate measurements of 1:1 car bodies, even in the presence of non-cooperative surfaces.

In this work, extreme benefit was obtained by the portability and ease of use of the sensor, equipped with fast and accurate on-site calibration tools, also in conjunction with software modules for the process of accurate, dense point clouds. The process described is obviously applicable to the reverse engineering of any full-size car or maquette, with a tangible benefit to car makers. Thus, the approach described here, and the availability of reliable commercial versions of optical digitisers such as ours, can be seen as innovative and, at the same time complementary, to other 3D acquisition equipment (CMMs, with or without optical heads) whose main limit is in the measurement volume to cost ratio when acquisitions over large surfaces are of election.

As far as our experience is concerned, optical 3D gauging with OPL-3D over measurement volumes comparable to that of case study considered here, did not present any substantial problem, in the presence of adequate operator skills. This obviously may not hold in the case of much larger volumes (e.g., trucks, ships), where theodolite-based, or photogrammetry-based approaches are strongly encouraged to be used in conjunction with close-range cameras to guarantee the required accuracy of the alignment.

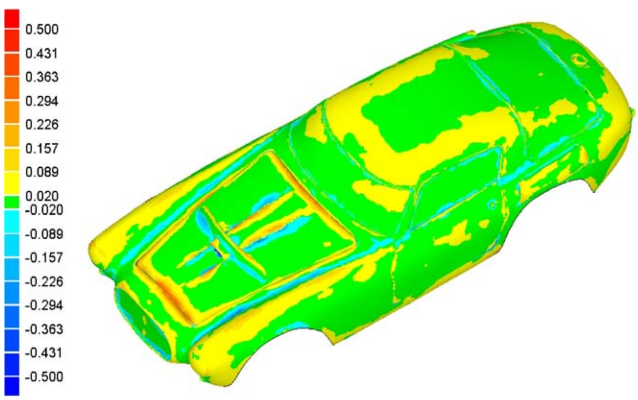


Fig. 8. Colour coded error map of the 8-control points model.

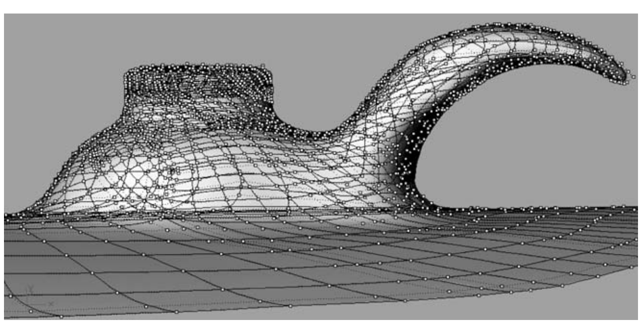


Fig. 9. CAD representation of the left-door handle.

Fig. 10. 1:10 scaled replica of the Ferrari 250MM obtained from the 75 MB triangle mesh.

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