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Robotics and Computer-Integrated Manufacturing 20 (2004) 359–367
Robotics and Computer-Integrated Manufacturing
www.elsevier.com/locate/rcim

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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0736-5845/$ - see front matter
doi:10.1016/j.rcim.2004.03.001

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.

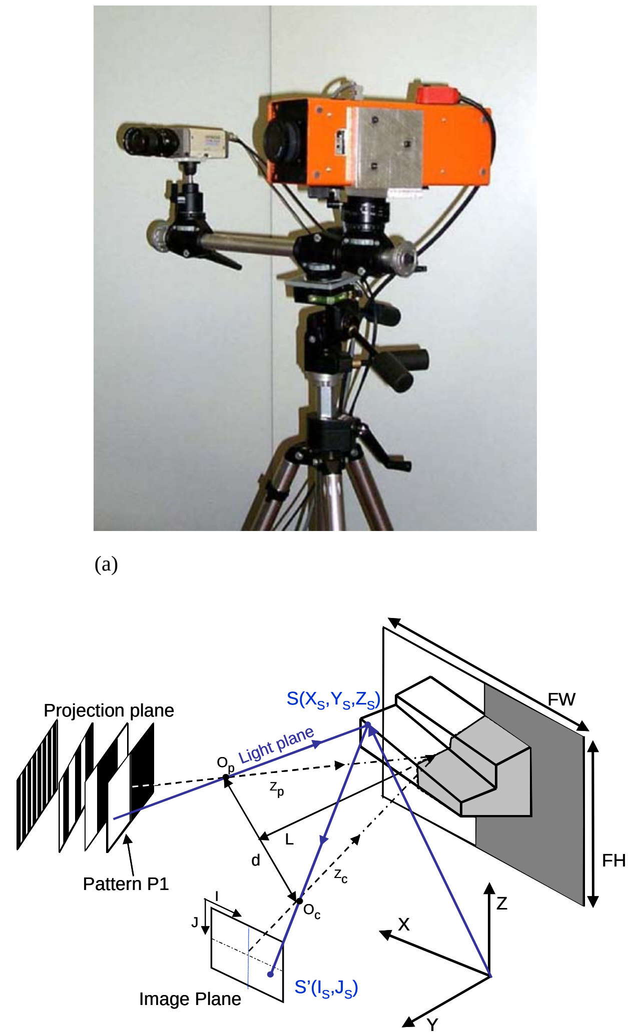

Fig. 1. The optical digitiser OPL-3D: (a) image of the instrument; and (b) optical layout.

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