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A new real-time shape acquisition with a laser scanner: first test results

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ABSTRACT

The first results of a new method for real-time shape acquisition with a laser scanner are presented. The new method is essentially based on the use of a laser beam and a web-cam. A digital filter parameters identification was studied for the laser line detection in the image. After this, a model for the reconstruction in real-time of the laser line in the space was developed. The first test rig was just conceived to validate the method; hence, no high resolution cameras were adopted. Nevertheless, the tests have showed encouraging results.

Tests were made on both plane and non-plane surfaces. First of all, it was confirmed that it is possible to calibrate the intrinsic parameters of the video system, the position of the image plane and the laser plane in a given frame, all in the same time. Moreover the surface shapes were recognized and recorded with an appreciable accuracy. The tests also showed that the proposed method can be used for robotic applications, such as robotic kinematic calibration and 3D surfaces recognition and recording. For this last purpose, the test rig is fitted on a robot arm that permits to the scanner device to 'observe' the 3D object from different and known positions.

1. Introduction

Laser scanning range sensors are widely used for high-precision, high-density three-dimensional (3D) reconstruction and inspection of the surface of physical objects [1]. The process typically consists of the following steps: planning a set of views; physically altering the relative object-sensor pose; taking scans; registering the acquired geometric data in a common coordinate frame of reference, and finally integrating range images into a non-redundant model [2]. Efficiency could be increased by automating or semi-automating this process.

The first aim of the research was to study a procedure to elaborate image of laser, in order to obtain 3-D object reconstruction; this, after an opportune system calibration. The technique was automated by developing an interactive GUI to acquire and to elaborate data.

Reverse engineering is concerned with the problem of creating computer aided design (CAD) models of real objects by interpreting point data measured from their surfaces [2,3]. For complex objects, it is important that the measuring device is free to move along arbitrary paths and that it can make its measurements from suitable directions. This paper shows how a standard industrial robot with a laser profile scanner can be suitably used for those purposes. The system is planned to be a part of a future automatic system for the Reverse Engineering of unknown objects. The system was designed around a test rig that was developed at the Di.M.E. by means of a commercial linear laser and a common web-cam; this system is moved by a revolute robotic arm.

The developed device permits to digitalize surfaces and to reproduce them, by means of machining. Such a device, hence, will permit a flexible and repeatable acquisition of forms; this is because the acquisition equipments will have an accurately controlled motion given by a robot. In fact, unlike static acquisition equipments, this equipment can move the camera system around the object to be analyzed without introducing problems of matching data. However, in this application, the vision system becomes an integrated device with the role of position transducer and recognition of shape and volume. In this way, it is possible to increase the robot performance, if the vision system is inserted into the robot control loop.

2. Experimental platform

2.1. Laser scanner module

Our rig is based on a laser profile that essentially consists in a line laser and a camera. The laser beam defines a "laser plane" and the part of the laser plane that lies in the image view of the camera is denoted as the "scanning window," Fig. 1. After an

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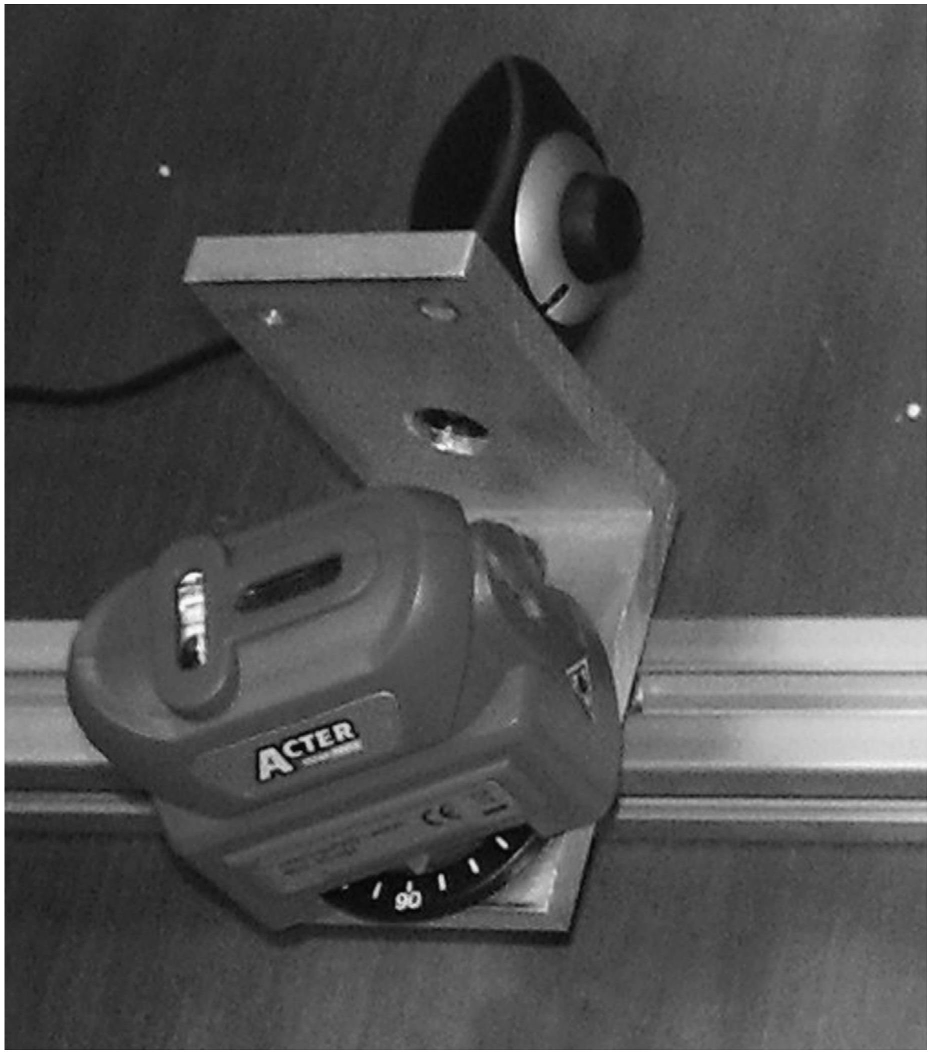

Fig. 1. Scanner module.

opportune system calibration, it is possible to find a relation that permits to compute in the camera frame, the points coordinates of the scanning belt on the object surfaces, starting to its image coordinates. In this way, it is possible to obtain a 3-D objects reconstruction by means of a laser beam.

The laser scanner device was realized by assembling a commercial linear laser and a common web-cam. The calibration operation will evaluate all parameters that are necessary to define the scanner module model.

2.2. Robot

In order to optimize the accuracy of the reconstruction resulting model, the scanning should be adapted to the shape of the object. One way to do that consists in using an industrial robot to move a laser profile scanner along curved paths.

The scanner laser module was mounted on a revolute robot with three d.o.f., designed and assembled at Di.M.E. (see Fig. 2). The robot acts as a measuring device to determine the scanning window position and orientation in 3D for each camera picture, with a great precision. All scan profiles captured during a scan sequence must be mapped to a common 3D coordinate system; in order to obtain this, positional information from the robot was used [4]. Fig. 3 shows the equipment.

In the developed working procedure, the robot controller and the scanner software work separately during a scan sequence, as it will be described in the following paragraphs.

3. The model of the system

3.1. Model of the laser scanner

A camera observes the intersection between laser and object: laser line points in image frame, are the intersections between image plane and optical rays that pass through intersection points between laser and object. Fig. 4 shows a sketch of the laser-camera system.

For each point in the image plane, under the assumption of the pin hole camera model, it is possible to write the following relationship:

$$\begin{cases} x_c = (u-u_0)\delta_x t \\ y_c = (v-v_0)\delta_y t \\ z_c = ft \end{cases} \tag{1}$$

with $(u_0,\ v_0)$ is the image frame coordinates of focal point projection in image plane; (δ_x, δ_y) is the fiscal dimension of sensor pixel along directions u and v; f is the focal length.

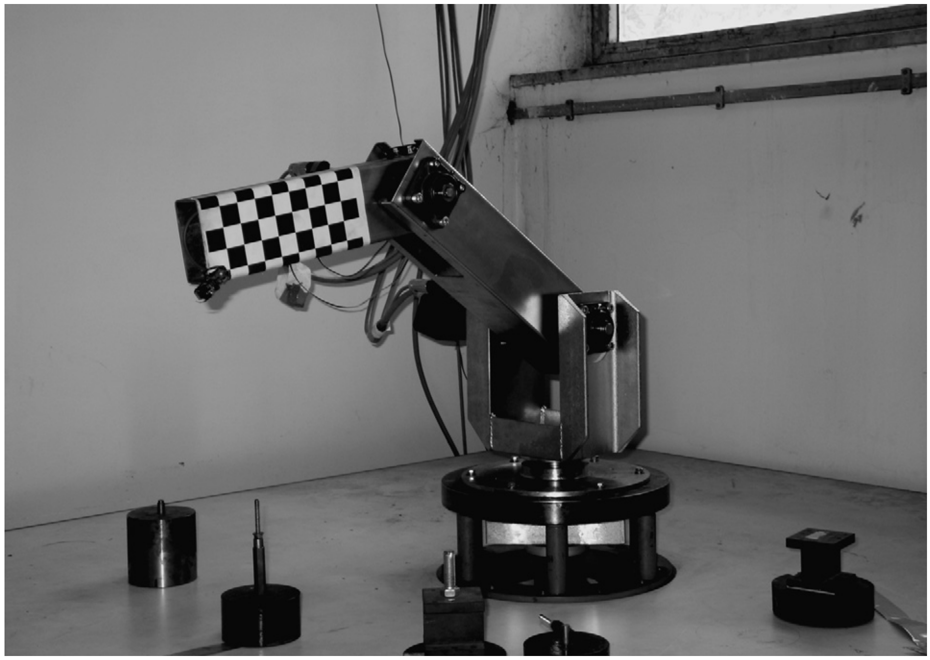

Fig. 2. Revolute robot.

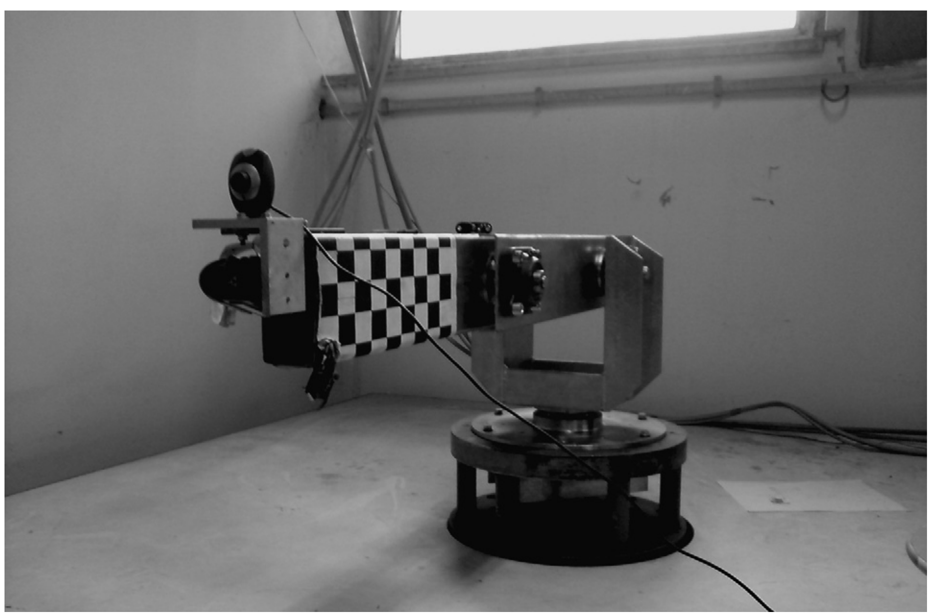

Fig. 3. The robot scanning system.

For all the points in the image plane that represent the laser path, the condition that they must belong to the laser plane is shown by following equations:

$$\begin{cases} x_c = \dfrac{(u-u_0)\delta_x z_c}{f} \\ y_c = \dfrac{(v-v_0)\delta_y z_c}{f} \\ Ax_c+By_c+Cz_c+D=0 \end{cases} \tag{2}$$

where considering a generic point, $\overline{p}_c$, in the laser plane and a vector, $\overline{v}$, orthogonal to the laser plane (for which components are *A*, *B* and *C*) the *D* is defined as follows:

$$\overline{p}_c = \left\{ \overline{x}_c \quad \overline{y}_c \quad \overline{z}_c \quad 1 \right\}^T$$

$$\begin{aligned} &\overline{v} = A\hat{i}+B\hat{j}+C\hat{k} \\ &D = -A\overline{x}_c - B\overline{y}_c - C\overline{z}_c \end{aligned} \tag{3}$$

From system (2), it is possible to write the coordinates of the points of the laser path in the camera frame:

$$\begin{cases} x_c = \dfrac{(u-u_0)\delta_x z_c}{f} \\ y_c = \dfrac{(v-v_0)\delta_y z_c}{f} \\ z_c = \dfrac{-Df}{A(u-u_0)\delta_x + B(v-v_0)\delta_y + Cf} \end{cases} \tag{4}$$

Eq. (4) permits to compute, in the camera frame, the points coordinates of the scanning belt on the object surfaces, starting to its image coordinates (u, v), in pixel. In this way, it is possible to obtain a 3-D objects reconstruction by means of a laser blade.

3.2. Model of the laser scanner on the robot

Since the laser scanner is joined to a robot, it is possible to use the knowledge of the robot position to determine the position and orientation of the scan window in the robot base frame, i.e. in the workspace. In order to achieve this goal, it is necessary to know the relationship between the reference frame of the camera and the frame of the last link of the robot; then, by means of the Denavit–Hartenberg matrix [DH], it is possible to determine in the robot base frame, the coordinates of the points that were obtained by a triangulation between the camera and the laser module.

Defining [DH] as the transformation matrix between coordinates in the robot base frame 0 (the fixed one) and those in frame 3 (the one in the last link), Fig. 5, for the coordinates of a generic point, P, exists this relationship:

$$\{P\}_0 = [DH]\{P\}_3 \tag{5}$$

The matrix [DH] depends on nine constant kinematic structure parameters that are known, and three variable joints position parameters that are given by the robot control system.

If the transformation matrix [$^cT_3$] between the camera frame and the frame of the robot last link is known, it is possible to obtain a transformation matrix between the camera frame and the frame 0, Fig. 6.

$$\{P\}_c = [^cT_3][DH]^{-1}\{P\}_0 \tag{6}$$

By means of Eqs. (4) and (6), the relationship between image coordinates (u, v) of the laser path and its coordinates in the robot base frame 0, is defined. By means of these equations, it is possible to reconstruct the 3D points in the robot base frame, of the intersection between the laser line and the object.

Errors in the robot positioning do not influence the 3D reconstruction; this is because each image is acquired and elaborated in a real robot position that is known by means of robot encoders [5].

4. Data capture and registration

The scanner video camera captures profiles from the surface of the object as 2D coordinates in the laser plane. During a scan sequence, the laser scanner module is moved in order to capture object images from different sides and with different angles-shot, according to the shape of the object.

In Matlab, an interactive GUI was developed in order to allow users to acquire and to elaborate data, Fig. 7. For each camera picture, along the scan path, the scanner derives a scan profile built up of point coordinates, in real-time.

The scanning process consists in three main phases, as shown in the flowchart reported in Fig. 8.

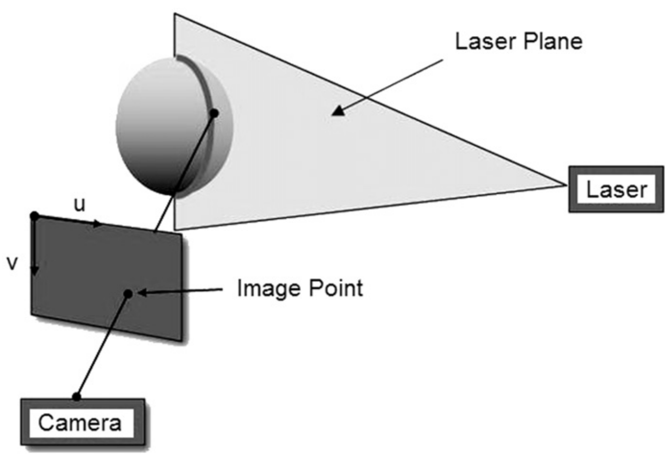

Fig. 4. Sketch of the laser-camera system.

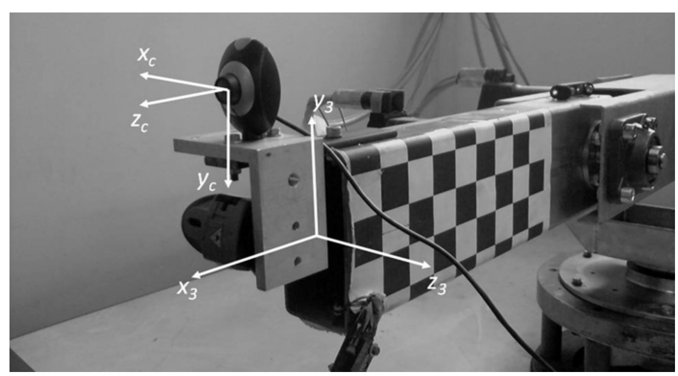

Fig. 6. Camera reference system.

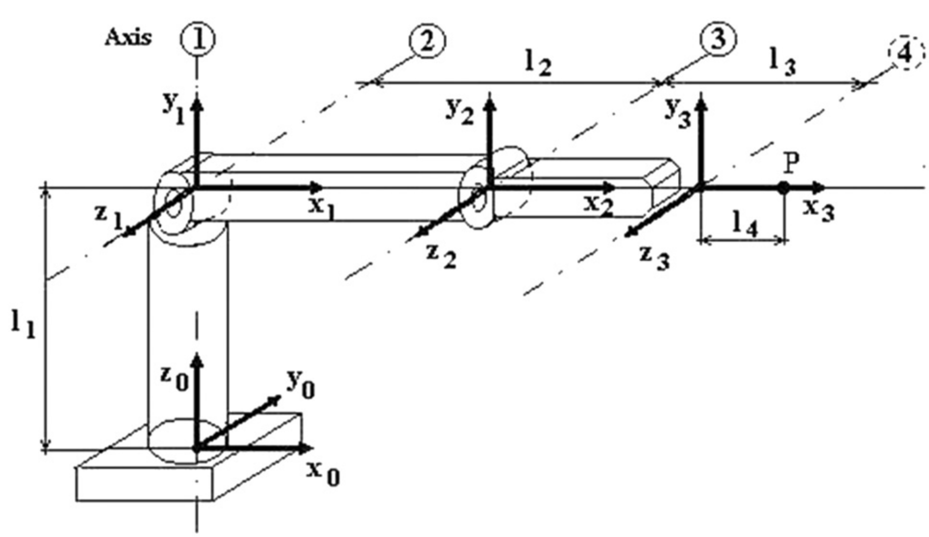

Fig. 5. Revolute robot scheme.

After a calibration procedure, the GUI allows to load all calibration parameters, i.e. the laser scanner parameters and the matrix $[^cT_3]$. To move and control the robot, a dedicated software was used. The GUI interacts with the robot control system and shows the joint position parameters of the robot in the window "position". In order to elaborate the image and to extract those pixels from the image that belong to the laser path, the developed software permits to fix some settings of the video system; then computes an identification threshold based on the intensity of selected pixels. By clicking on the button "Image," the software saves all the information that are necessary for the reconstruction, in the workspace of Matlab. The "3D generation" button permits the software to compute the positions of the laser path in the robot base frame; the result is shown on the GUI window.

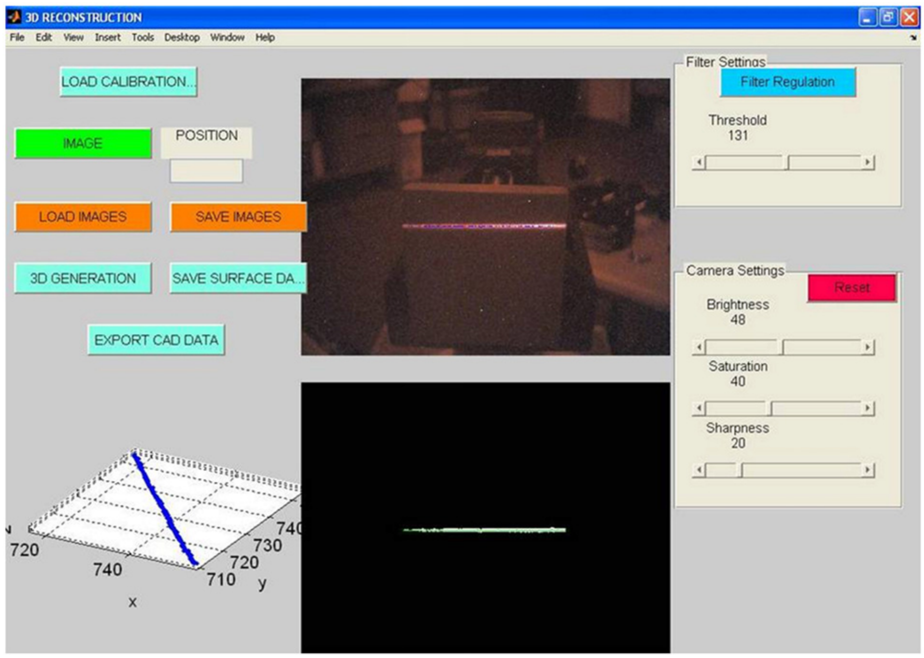

Fig. 7. A GUI of the developed software.

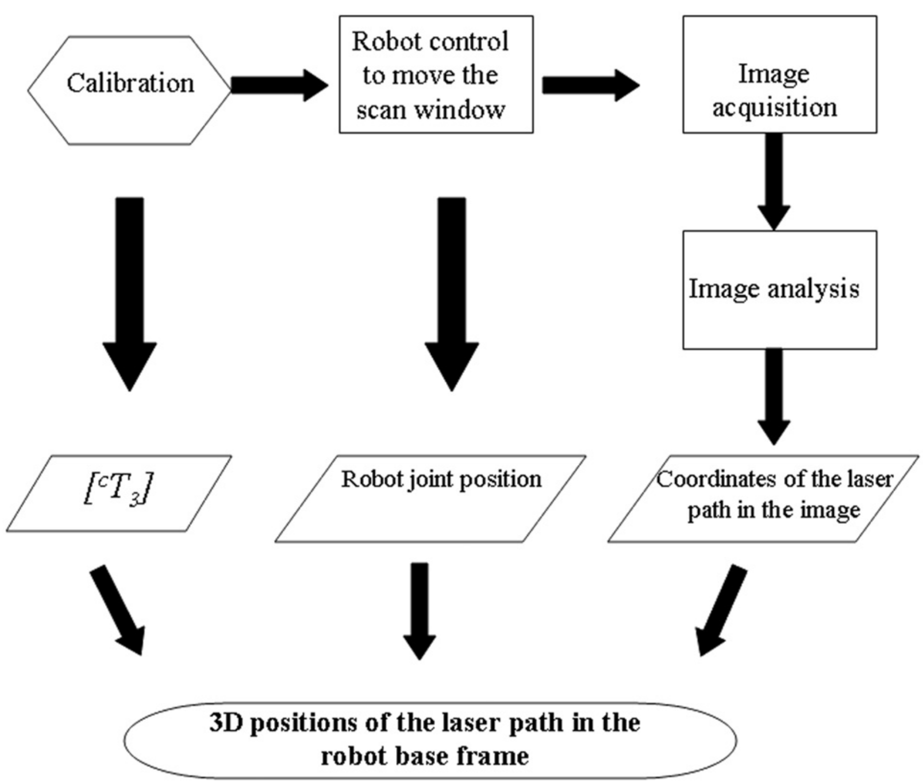

Fig. 8. Scanning process flowchart.

When the scanning procedure is completed, the user can:

- save the images and the related robot position in a file;
- save the cloud of points, represent the surface of the test object;
- export the surface information in a file format that permits to load the data from the CAD software "CATIA".

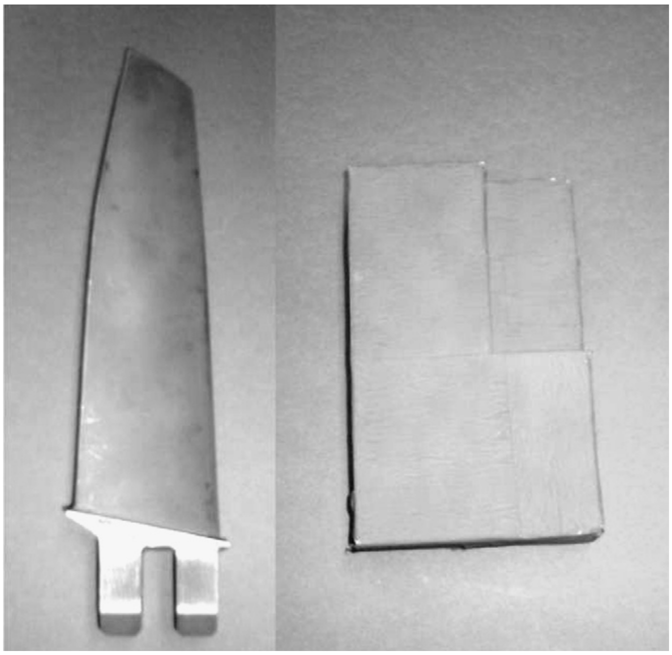

Fig. 9. Test objects.

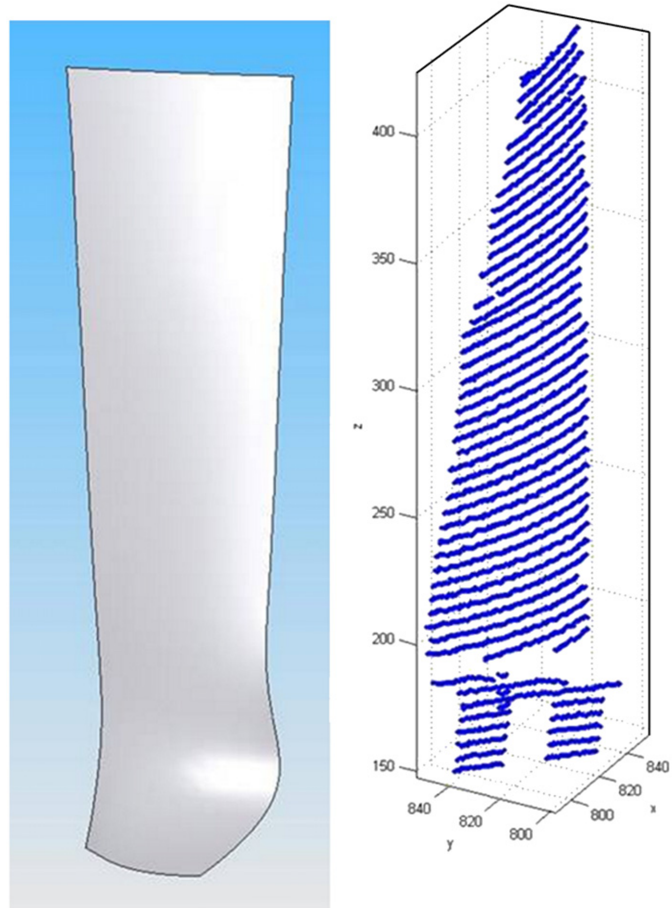

Fig. 12. First test specimen results.

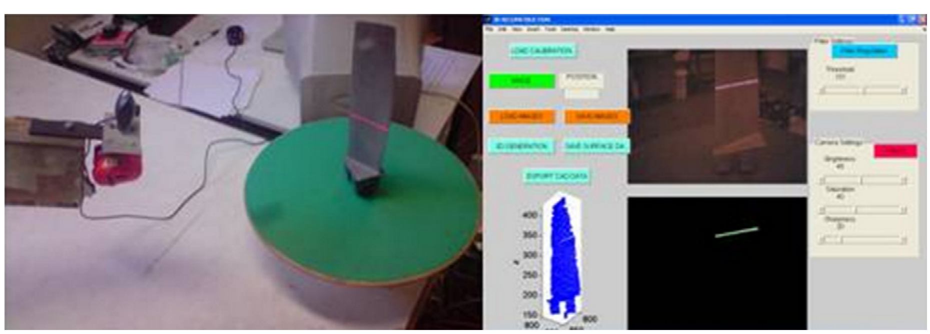

Fig. 10. Elaboration procedure of the first test specimen.

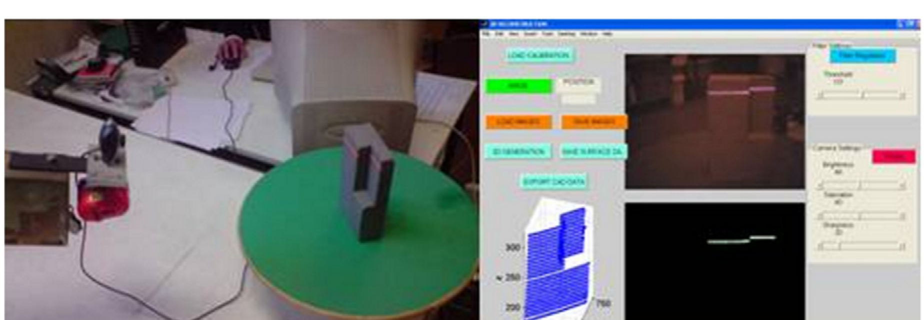

Fig. 11. Elaboration procedure of the second test specimen.

Besides, it is possible to load an image information from a preview scanning procedure, this is useful for reconstruct the same laser path information, using different calibration parameters.

5. Experimental results

The system has been first tested in a fixed robot position in order to verify both calibration and reconstruction procedures. Then the shape of some components was defined using robot to move laser scanner module.

5.1. Axial compressor blade

In Fig. 9, the axial compressor blade, used for the first tests, is shown.

In Figs. 10 and 11, it is possible to see a step of the procedure with the final results for the two test specimens.

By the software CATIA, it was possible to build the surface of the two test objects; in this way, the CAD model was obtained. This step of the 3D reconstruction method is a real reverse engineering application. The routine ‘‘Digitized shape editor’’ of the ‘‘CATIA’’ addresses digitalized data import, clean up, tessellation, cross sections, character line, shape and quality checking.

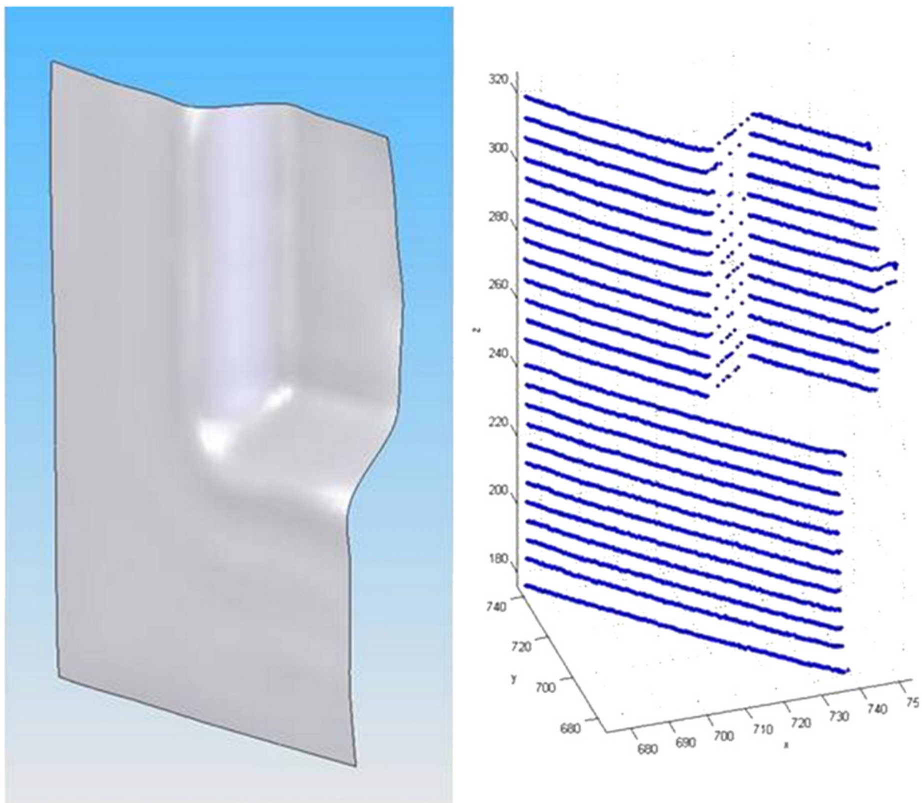

Fig. 13. Second test specimen results.

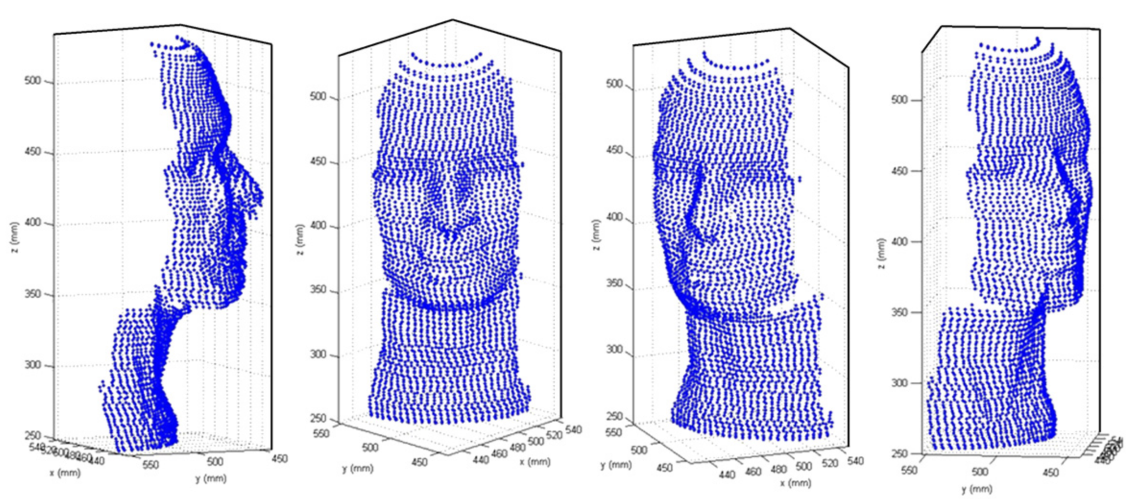

Fig. 14. First test results on a mockup face analysis.

Figs. 12 and 13 show the comparisons between the clouds of points and the respective surfaces for each object.

5.2. Mockup face

Another set of tests was made on a more complex surface by using a mockup face. In Fig. 14, the acquired cloud of points for a mockup face are shown.

The first tests on this more complex surfaces, demonstrated a good effectiveness of the 3D reconstruction method also when many variations of shape are present. The reconstruction was obtained with a single scansion; the latter was made by assigning a particular path to the robot. In Fig. 14, it is easy to observe that all the main characteristics of the face are reproduced.

This first tests have demonstrated that this application that moves the camera system around the object to be analyzed, without introducing problems of matching of data, allows a better capture of forms; this unlike the static acquisition equipments.

6. Conclusion

The first results of a new method for real-time shape acquisition with a laser scanner are presented. Although the test rig has been conceived just to validate the method (hence no high resolution cameras were adopted), the tests have showed encouraging results.

The test results also confirmed that it is possible to calibrate the intrinsic parameters of the video system, the position of the image and the laser planes in a given frame, all at the same time. Moreover the surface shapes were recognized and recorded with an appreciable accuracy.

The tests also showed that the proposed method can be used for robotic applications, such as robotic kinematic calibration and 3D surfaces recognition and recording. For this last purpose, the test rig was fitted on a robot arm that permitted to the scanner device to 'observe' the 3D object from a different and a known position

Further tests will concern a detailed analysis of the sources of errors and the verification of the accuracy achieved. As far as the latter aspect is concerned, the authors believe that a better system for tracking the position of the robot arm could enhance accuracy.

Finally, the authors would like to point out that the solution proposed is relatively low cost, scalable and flexible. It is also suitable for applications other than RE, like robot control or inspection.

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