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A LASER SCANNING SYSTEM FOR 3D MODELING OF INDUSTRIAL OBJECTS BASED ON COMPUTER VISION

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Abstract. *Most of today's 3D laser scanning systems for object model digitalization relies on angular position sensors to measure rotation of a laser diode and reconstruct the object structure. However, those types of sensors restricts the object size in target and its distance from the image sensor, since reconstruction is usually based on equations for geometric triangulation, leading to high measurement errors due to the non-linear relation between angular positions and distances. In order to overcome the need of high cost angular position sensors and to increase measurement distances it is proposed here a 3D surface scanner based on computer vision that can be compact, easy to transport and self-calibrated. The system calibration include camera calibration using radial alignment constraints, image processing routines and full determination of system parameters. The complete system architecture with two laser diodes and a single camera is shown and the theoretical basis, hardware implementation and practical results obtained are presented and discussed.*

Keywords*: Computer Vision, Laser Scanning, Active Triangulation, Camera Calibration, 3D Modeling Sensors.*

1. INTRODUCTION

The traditional solution for 3D measurement is, until today, based on contact systems, such as coordinate measuring machines (Sansoni and Docchio, 2004). However, with the great advances in 3D scanning technologies, the use of laser systems are becoming common in many fields such as reverse engineering, prototyping, 3D printing, manufacturing, medical sciences, terrain mapping and cultural heritage (Tognola *et al.*, 2003, Baltsavias, 1999).

Common digitizing systems are based on three main technologies (Barhak and Fisher, 2001): coordinate measuring machines (CMMs), 3D laser scanners, and digital photogrammetry systems. The laser scanners have become the most common technique because they are fast and robust relative to other methods (Varady *et al.* 1997, Barhak and Fisher, 2001). Moreover, scanned data from a laser provides the explicit 3D coordinate points from which a surface or model can be reconstructed.

Nowadays there is a wide range of commercial 3D laser scanning systems, such as those sold by companies as Cyberware™ (www.cyberware.com), 3D Scanners™ (www.3dscanners.com), Hymark™ (www.hymark.com) and many others. Most of those 3D laser scanning systems relies on angular position sensors or the use of more than one camera to measure the rotation of a laser diode and to reconstruct the object structure (Hsuehl and Antonsson, 1997, *Tognola et al*., 2003, Cheng *et al.*, 2007). However, those types of sensors restrict the object size in target and its distance from the image sensor, since reconstruction is usually based on equations for geometric triangulation, leading to high measurement errors due to the non-linear relation between angular positions and distances. Those sensors and extra cameras are not only responsible for the inaccuracy of the systems but also for its high cost.

However, with the use of computer vision techniques to extract information directly from the image it is possible to remove the need of such sensors. By doing so, an improvement in the system accuracy could be obtained together with a high cost reduction. In this paper a system that takes advantage of computer vision techniques is proposed. Its architecture, peculiarities and results are presented and discussed and an initial evaluation of its performance and accuracy is made.

2. THE PROPOSED SYSTEM

The basic system architecture is composed by two laser diodes to project two light planes and a camera. A picture of the real system and its sketch are illustrated in Fig. 1.

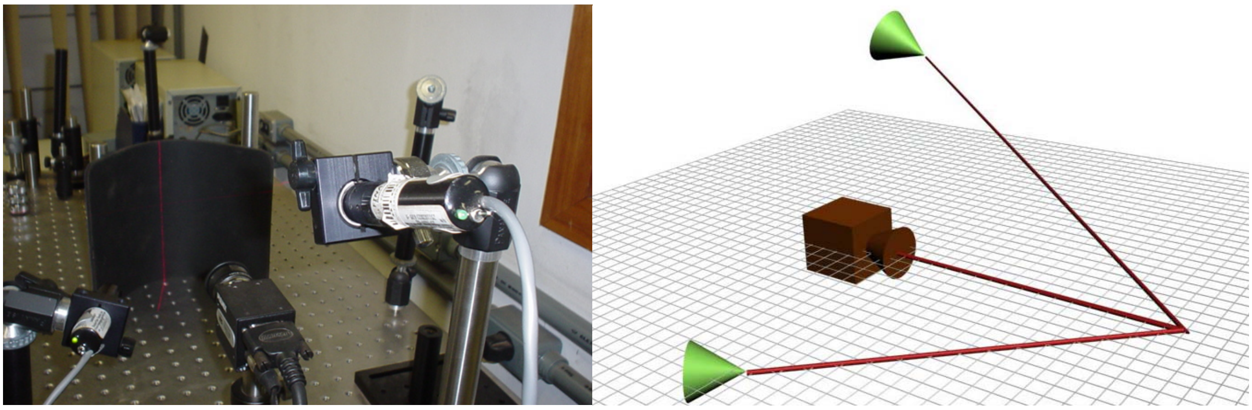

Figure 1. Implemented System and Diagram

In order to make triangulation possible, two mounting restrictions are imposed to the system. The first system restriction is the relative position of the two light planes. They must be perpendicular in order to the triangulation equations presented in Section 2.1 to be valid. The second restriction imposes that one of the laser diodes must be fixed, while the other diode have only one motion of rotation in order to keep both light planes always perpendicular.

2.1. The Optical System

Due to the motion restrictions imposed to the system it is possible to define the parameters needed for the triangulation and reconstruction of the surface depth map. In Fig. 2 it is illustrated the intersection between the two light planes and the focal axis of the camera.

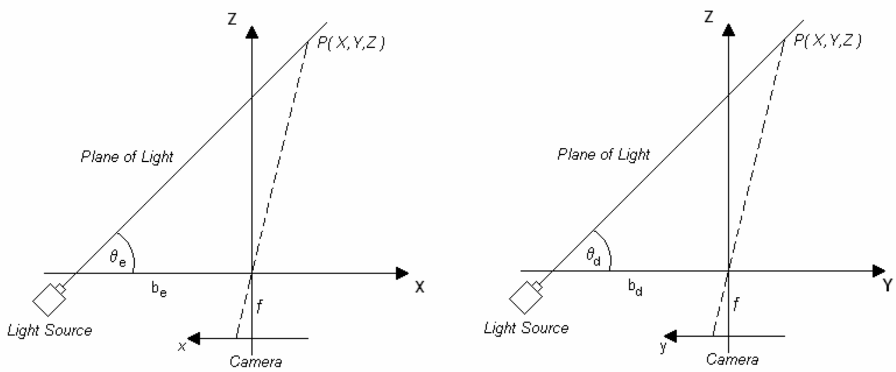

Figure 2. The two light planes and their parameters

So the system parameters can be defined as:

- b_d → Distance in the Y-axis between the camera and the mobile diode.
- b_e → Distance in the X-axis between the camera and the still diode.
- θ_d → Angle between the mobile light plane and the Y-axis.
- θ_e → Angle between the still light plane and the X-Axis.
- f → Camera focal distance.
- $\left(X_{img}, Y_{img}\right)$ → A point of the projection of the mobile light plane in the scanned surface.

Triangulation equations from the geometrical arrangement shown in Fig. 2 can be derived as:

$$\begin{cases} X = \dfrac{X_{img} b_e}{f\ \cot(\theta_e) - X_{img}} \\ Z = \dfrac{f b_e}{f\ \cot(\theta_e) - X_{img}} \end{cases} \quad (1)$$

$$\begin{cases} Y = \dfrac{Y_{img} b_d}{f\ \cot(\theta_d) - Y_{img}} \\ Z = \dfrac{f b_d}{f\ \cot(\theta_d) - Y_{img}} \end{cases} \quad (2)$$

Extracting from the image the intersection point between the two lines projected on the surface and knowing that the depth of this point must be the same no matter what equation above is used, it is possible to calculate the relation between the two laser diode angles, θ_d e θ_e:

$$\cot(\theta_d) = \frac{1}{f}\left[\frac{b_d}{b_e}\left(f\ \cot(\theta_e) - X_{\text{int}}\right) + Y_{\text{int}}\right] \quad (3)$$

One of the laser diodes is fixed, therefore the value of $\cot(\theta_e)$ is constant and known from the system calibration, the same way as b_d, b_e and f.

Once the value of $\cot(\theta_d)$ is obtained through Eq. (3), Eq. (1) and Eq. (2) can be used to fully determine the 3D coordinates of each point that belongs to the line projected in the surface by the mobile laser diode.

So the complete algorithm can be summarized in Fig. 3.

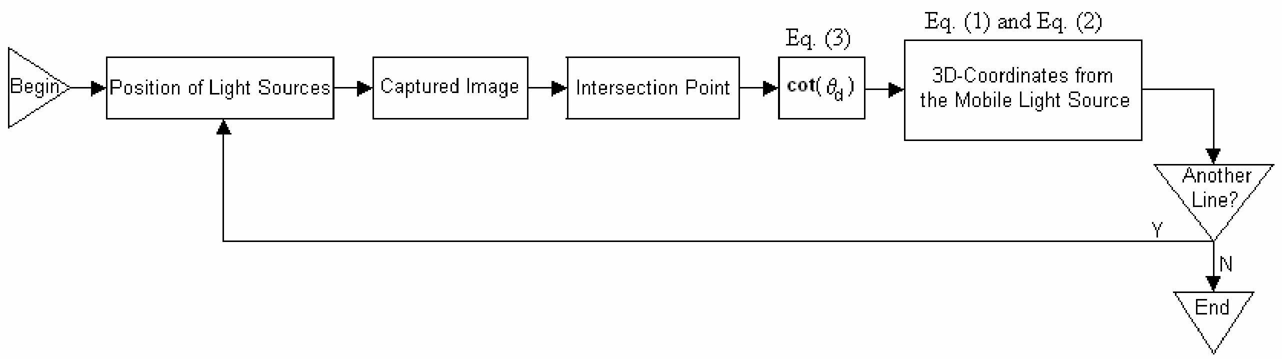

Figure 3. Surface Digitalization Algorithm

2.2. The Electro-Mechanical System

The laser scanning system requires proper fixation of the light sources, the single camera and the automatic drive motor of one of the light sources. For this purpose, it was implemented a microcontrolled interface responsible for the driving motion of the system. This interface, together with reduction gears, is able to perform a smooth movement of the laser diode, automatically scanning over the entire surface to be digitized.

For the fixation of the system components, a breadboard has been used while the project of the system container is not yet finished. In Fig. 4 some details of the laser diodes and camera mountings can be seen.

Figure 4. Optical table, camera and still laser fixation and mobile laser fixation and gearbox

2.3. System Calibration

The system calibration is intended to fully determine the optical system parameters described in Section 2.1. The calibration involves the use of a calibration board and the Radial Alignment Constraint Algorithm.

The Radial Alignment Constraint, or simply RAC was introduced by Tsai (1987) and Lenz and Tsai (1987). A radial alignment constraint is used to derive a closed-form solution for the external parameters and the effective focal length of the camera. Then an iterative scheme is used to estimate the depth component in the translation vector and a radial distortion coefficient.

The procedure is divided in two steps. The first step is the camera calibration using the RAC Algorithm and the second step is the calibration of the laser diodes.

The RAC algorithm was exhaustively described by Tsai (1987), Lenz and Tsai (1987) and Motta (1999). Therefore, it is presented here only the second calibration step.

The camera calibration routine provides a series of parameters, including the external parameters R and T that describe in space the plane where the calibration board is. The parameters obtained from the RAC algorithm are:

- R → Orthonormal rotation matrix, which aligns the camera coordinate system with the calibration board coordinate system.
- T → Distance from the origin of the camera coordinate system to the origin of the calibration board coordinate system.
- f → Camera focal length.

Figure 5. Calibration procedure

At first the calibration board, without the laser diodes is used to calibrate the camera and to calculate the plane equation that represent the calibration board.

Considering the camera coordinate system as the origin and a world coordinate system so that the plane equation of the board in reference to this system would be $Z = 0$, the plane equation that describes the calibration board can be determined as:

$$Ax + By + Cz + D = 0 \tag{4}$$

Where:

$$\begin{cases} R = \begin{bmatrix} R_1 & R_2 & R_3 \\ R_4 & R_5 & R_6 \\ R_7 & R_8 & R_9 \end{bmatrix} \\ T = \begin{bmatrix} T_x & T_y & T_z \end{bmatrix}^T \end{cases} \Rightarrow \begin{cases} A = R_3 \\ B = R_6 \\ C = R_9 \\ D = -\mathrm{A.T_x} - \mathrm{B.T_y} - \mathrm{C.T_z} \end{cases} \tag{5}$$

The second step in the calibration procedure is the calibration of each laser diode individually. Each laser is turned on and a number of coordinates is extracted from its projection on the calibration board plane.

Once the equation of the plane which the laser light is projected on is already determined, the camera scale factors (s_x and s_y) and the coordinates of a point of the laser projection on the plane (X_i, Y_i) are known, then Eq. (7) is obtained from Eq. (5) and Eq. (6) and fully determine the 3D coordinates of that point.

The scale factors s_x and s_y are intrinsic parameters of the camera model (Lenz and Tsai, 1987) and convert camera coordinates in millimeter to image coordinates in pixels. Those parameters are normally obtained from the camera manufacturer.

$$\begin{cases} \dfrac{X_i}{s_x} = f\,\dfrac{X_c}{Z_c} \\ \dfrac{Y_i}{s_y} = f\,\dfrac{Y_c}{Z_c} \end{cases} \tag{6}$$

$$\begin{cases} A_x = A + \dfrac{f s_x C}{X_i} \\ B_y = B + \dfrac{f s_y C}{Y_i} \end{cases} \Rightarrow \begin{cases} Y_c = \dfrac{D(A - A_x)}{A_x B_y - AB} \\ X_c = \dfrac{-D - BY_c}{A_x} \\ Z_c = \dfrac{-AX_c - BY_c - D}{C} \end{cases} \tag{7}$$

Using Eq. (7) for different points of the laser projection on the calibration board it is possible to compile an over-determined linear system using Eq. (1) and Eq. (2) and calculate the parameters b and $\cot(\theta)$ for each of the laser diodes.

$$\begin{cases} \begin{bmatrix} X_c f & -X_i \\ Z_c f & -f \end{bmatrix} \begin{bmatrix} \cot(\theta_e) \\ b_e \end{bmatrix} = \begin{bmatrix} X_c X_i \\ Z_c X_i \end{bmatrix} \\ \begin{bmatrix} Y_c f & -Y_i \\ Z_c f & -f \end{bmatrix} \begin{bmatrix} \cot(\theta_d) \\ b_d \end{bmatrix} = \begin{bmatrix} Y_c Y_i \\ Z_c Y_i \end{bmatrix} \end{cases} \tag{8}$$

2.2. The Software Developed

In order to make the surface digitalization process easy and user friendly, two computer programs were developed. The software is responsible, respectively, for calibration of the physical setup and for surface digitalization. The computer program was developed in order to turn the system to be user-friendly. The software main screens are shown in Fig. 6 and Fig. 7.

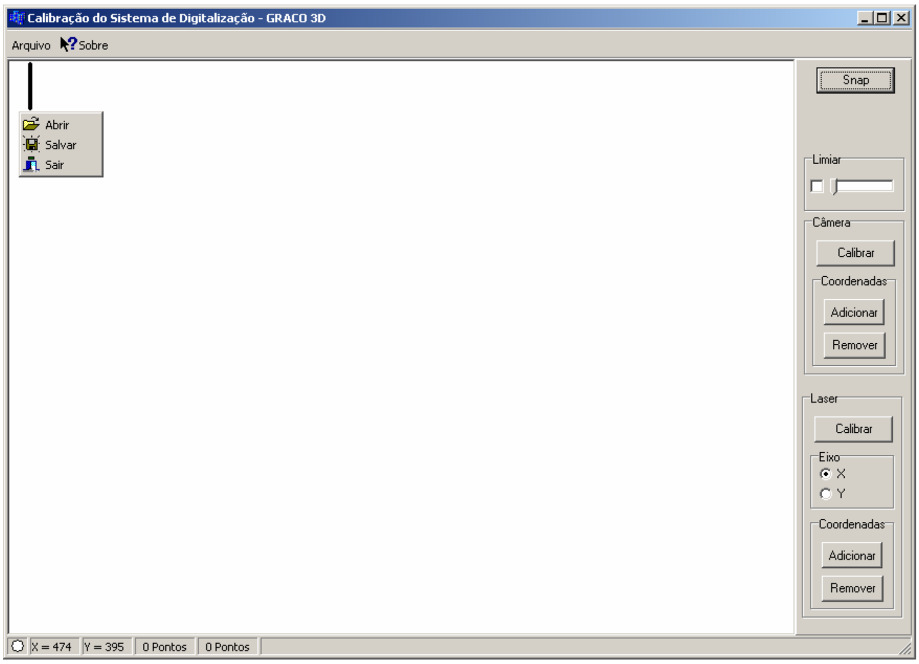

Figure 6. Calibration software main screen

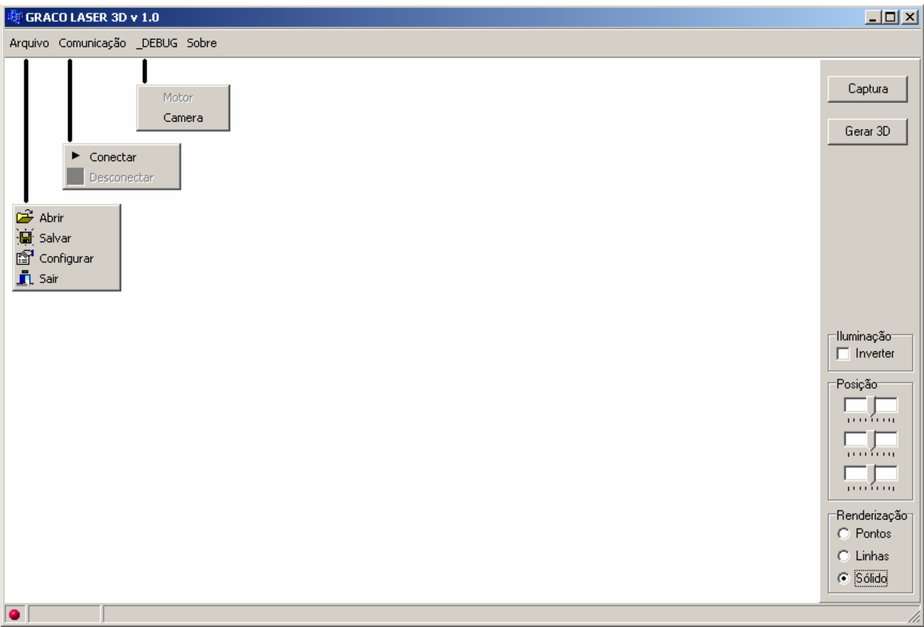

Figure 7. Digitalization software main screen

3. SYSTEM ACCURACY

In order to carry out a first study of the system accuracy, a steel gage block with a standard length in only one direction was scanned several times and the results were treated statistically according to the Eq. (9) and Eq. (10).

The block used was a standard 50mm steel gage block. The accuracy of the system was calculated by using the distance d between each digitized edge of the block. The block was placed in different locations and orientations keeping both standardized edges in the vertical position, so that the distance between any two scanned points P_1 and P_2 in those edges could be determined by Eq. (11).

$$\overline{E} = \frac{\sum_{i=1}^{n} \left| d_{digitalization} - d_{standart} \right|}{n} \quad (9)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n} \left(\left| d_{digitalization} - d_{standart} \right| - \overline{E} \right)^2}{n}} \quad (10)$$

$$\begin{cases} P_1 = \begin{bmatrix} X_1 & Y_1 & Z_1 \end{bmatrix} \\ P_2 = \begin{bmatrix} X_2 & Y_2 & Z_2 \end{bmatrix} \end{cases} \Rightarrow d_{digitalization} = \sqrt{(X_1 - X_2)^2 + (Z_1 - Z_2)^2} \quad (11)$$

The scanning process was carried out 5 times, and a total of 10 measures were recorded. One of the scanning processes can be observed in Fig. 9 and the results of the system accuracy are shown in Tab. 1.

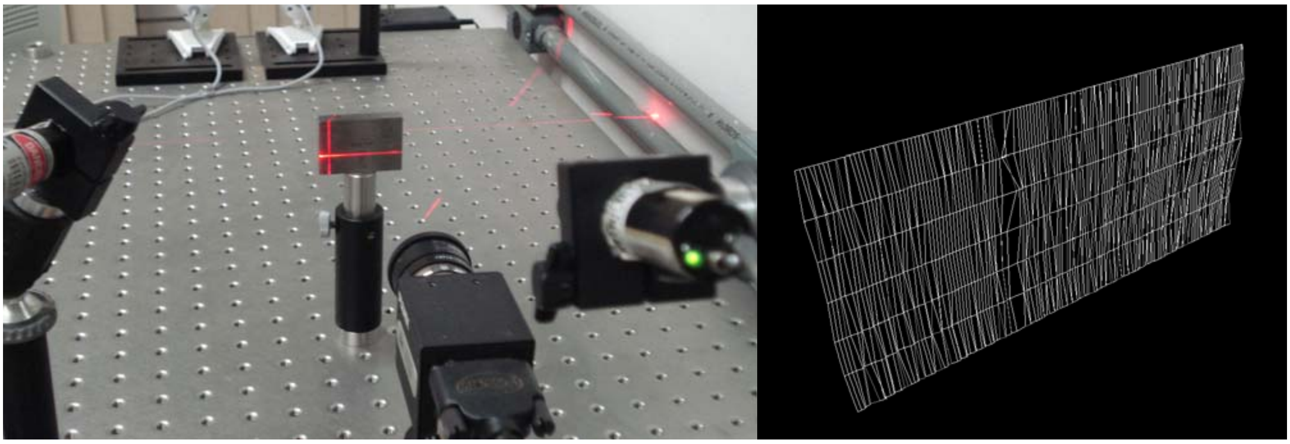

Figure 8. Standard measurement block digitalization

Table 1. Experimental results for the accuracy of the system.

Average Error [mm]	Standard Deviation [mm]	Maximum Error [mm]
0.85	0.41	1.41

4. SOME SCANNING RESULTS

Some of the results obtained with the system are presented in Figs. 9-10.

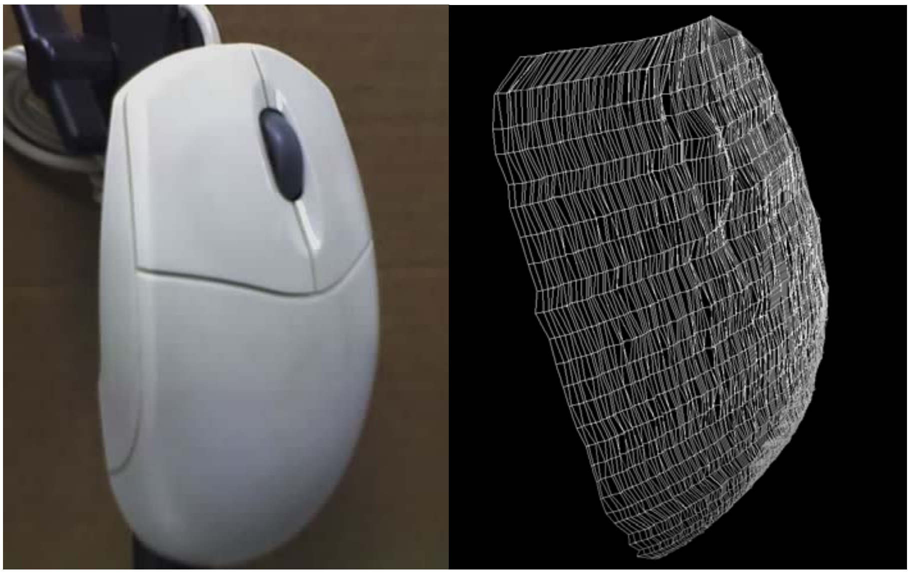

Figure 9. Digitalization of a mouse surface

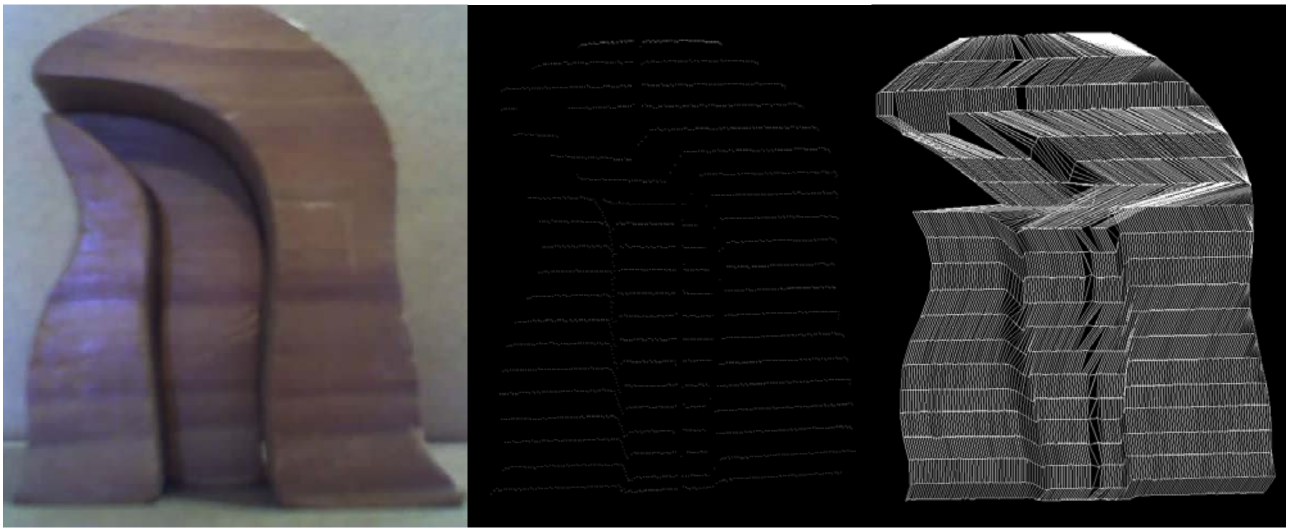

Figure 10. Digitalization of a toy surface

5. CONCLUSIONS AND FUTURE WORK

In this paper the development of a laser scanning system that relies on computer vision techniques eliminates the need of using angular position sensors, and experimental results are discussed. It was also presented an assessment of the system accuracy, showing optimistic results.

The benefits of the proposed laser digitizer system span from the ease of use, potential high accuracy to the possibility of digitizing objects in a much farther distance then common laser scanning systems do, due to the accurate and fast self-calibration routine. Since the system eliminates the need of a skilled operator and the system dependence to an angular position sensor, the approach described here offers a low cost and high accuracy option for digitalization of large volumes and at greater stand-off distances.

The automatic calibration routine has also proven its efficacy, getting rid of different measurement systems to calibrate the system.

Future works in the project involve the development of the complete and automated 3D scanning system in a compact hardware, including software for image renderization to yield the best fit of surfaces to the cloud of points acquired from the laser scanning process, together with a deeper analysis of the system accuracy.

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