Registration of Moving Surfaces by Means of One-Shot Laser Projection*

Carles Matabosch[1], David Fofi[2], Joaquim Salvi[1], and Josep Forest[1]

[1] University of Girona, Institut d'Informatica i Aplicacions, Girona, Spain
[2] University of Burgundy, Laboratoire d'Electronique, Informatique et Image Le Creusot, France

Abstract. The acquisition of three-dimensional models of a given surface is a very interesting subject in computer vision. Most of techniques are based on the use of laser range finders coupled to a mechanical system that scans the surface. These techniques lacks of accuracy in the presence of vibrations or non-controlled surface motion because of the misalignments between the acquired images. In this paper, we propose a new one-shot pattern which benefits from the use of registration techniques to recover a whole surface in the presence of non-controlled motion.

1 Introduction

Three-dimensional reconstruction of real objects is a promising subject with many applications, such as reverse engineering, robot navigation, mould fabrication and visual inspection among others. Most range finders are based on the projection of laser beams because of its robustness against ambient light, easy image processing algorithms and high given accuracy including optical segmentation and subpixel accuracy. Please, check a quite recent survey related to laser projection [3] and other reconstruction techniques such as coded structured light [9]. In general, laser projection techniques are based on the use of a laser emitter coupled to a cylindrical lens that spread the light forming a plane that is projected to the measured surface. The projection of a laser plane only lets us to reconstruct a profile of the measuring surface. So, in most cases a mechanical system is added that permits a scanning. In some applications: a) the laser plane is projected onto a rotating mirror and reflected towards the surface; b) the laser beam is attached to a moving worm gear; c) the laser beam keeps motionless while is the object which is placed on a rotating table. All these techniques permit the reconstruction of a whole surface with high resolution. However, the accuracy strongly depends on the mechanical system used so that potential vibrations given by the environment produces misalignments and consequently the accuracy is considerably influenced. Furthermore, the sequence of images that are captured in the scanning process forces the object to be motion controlled reducing the number of applications, i.e. industrial conveyors can not be considered.

In this paper, a new one-shot 3D sensor is proposed, which is based on registering a set of 3D images from a non-controlled moving surface. Furthermore, dense cloud of

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3D points are acquired without using any mechanical system to scan the object so that misalignments in the reconstruction are neglected. Although one-shot 3D sensors have been previously used, usually a manual or mechanical process is required to align the scanned surfaces [7]. In this paper, a pair-wise-based registration method is proposed to align the cloud of 3D points with the aim of obtaining a complete surface of the scanned object.

2 One-Shot 3D Sensor

Nowadays, there are a considerably amount of lenses which can be coupled to a laser emitter which spreads the light forming a given pattern: planes, circles, dots and stripes. However, it has been demonstrated that stripe patterns are the most suitable in measuring processes because of the easy segmentation and the use of subpixel techniques in the detection of the stripe peaks. Stripe patterns also ease the search of correspondences among the slits projected and the ones acquired by the camera. The number of stripes projected is directly related to the surface resolution and to the image processing complexity. A compromising stripe pattern forming 19 slits has been chosen and the images are acquired by a on-the-shelf camera coupled with a 635 nm optical filter.

3 Calibration

Calibration is an offline process which aim is the computing of the geometry that relates the 3D points on the measuring surfaces with the projection of these points in the acquired image. This relation can be linearly approximated to the following equation:

$$P_W =^W T_L \cdot p_i \tag{1}$$

Once ${}^W T_L$ is known, 2D points in the image frame can be directly transformed to 3D points in the world reference frame. This matrix is computed by orthogonal least squares from a set of correspondences, also known as calibrating points. In order to search for correspondences, the complete quadrangle is used [2]. The original method has been adapted to calibrate the set of 19 planes obtaining the 19 transformation matrices which describes the geometry of the sensor. For every plane calibration the following steps are processed:

- Detection of the points of the laser profile in the image plane,
- Find the correspondences between points in the image plane and 3D points in the calibrating plane,
- and Compute the T matrix using the correspondences given by the previous step.

In the following sections, the three steps are described.

3.1 Points in the Laser Profile

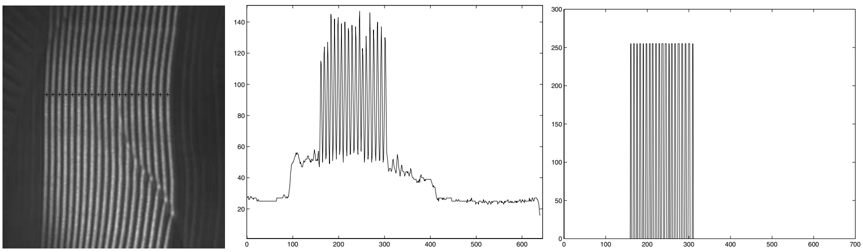
When a unique plane is projected to the scene, the peak detection with subpixel accuracy can be determined with high accuracy using a FIR filter approach [4]. However, when more planes are projected, the derived curve of the profile (shown in fig.1b) is high influenced by the neighborhood. In some situations, the derived curve does not cross to zero at the maximum value of the intensity profile. To solve this problem, an adapted methodology that is based on a previous work related to coded structured light is used [8]. First of all, the first derivative is computed using the convolution of each row with the vector [-1 -1 -1 0 1 1 1]. Then, the second derivative is computed obtaining the enhancement of the peaks compared to the intensity image. A threshold is finally used to segment the stripes as follows:

$$\begin{cases} 0 \;\; \textit{if } f_i" < mean(f) + var(f) \\ 255 \;\; \textit{otherwise} \end{cases} \tag{2}$$

$$f_L' = conv([1 \;\; -1 \;\; -1\; 0\; 1\; 1\; 1], [f(p_i - 3) : f(p_i + 3)]) \tag{3}$$

where f is the intensity profile curve and f_i" is the second derivative in each pixel of the row. As can be seen in the fig. 1c, the interval of each peak can be found easily analyzing all the pixels in a consecutive order. For each interval, the central value is computed as an approximation of the position of each maximum. Then, a local derivative is computed in each estimated peak as follows:

where $conv$ is the convolution, and $f(p_i)$ is the value of the intensity profile in the i*th* estimated peak. The pass to zero of the f_L' function give us the sub-pixel position of the peak of each laser stripe. Furthermore, if the intensity value of this points is less than a threshold, this peak is not considered.



(a) Image obtained by a camera with optical filter after peak detection

(b) Intensity profile of a row of the image

(c) Binarized second derivative of on row of the image

Fig. 1. Process of obtaining the laser peaks

3.2 Correspondences Between Points in the Image and 3D Points

The methodology is based on the *complete quadrangle* [1]. The principle of this method is the cross-ratio between the complete quadrangle and the acquired image of this quadrangle (see fig. 2).

$$\frac{\overline{A'P_A'}}{\overline{A'G'}} = \frac{\overline{AP_A}}{\overline{AG}} \tag{4}$$

As A,B are known 3D points, and A', B' and P'_A can be found analyzing the acquired image, P_A can be determined. The same principle is applied with point P_B. If quadrangle is moved along the Z-axis, a set of 2D-3D correspondences can be found for each Z position. Using this set of correspondences, eq. 1 can be solved determining the transformation matrix. In general, only two points are used for every plane position. Note that calibration accuracy is related directly to the number of correspondences used. In order to improve the accuracy, a set of points along the laser stripe are selected. More details are presented in [2].

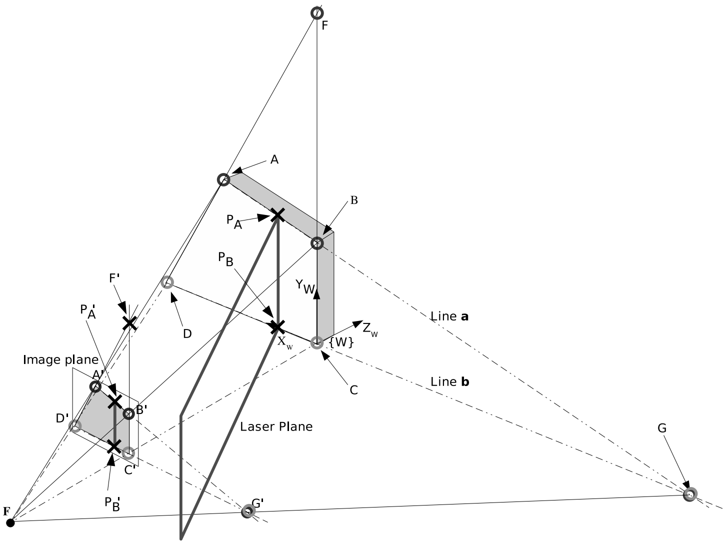


Fig. 2. Cross-ratio and the complete quadrangle used to determine 2D-3D correspondences

3.3 Compute T Matrix Using Known Correspondences

Now the transformation matrix can be obtained by minimizing eq. 5 which has been easily obtained arranging eq. 1.

$$\begin{bmatrix} \vdots & & \vdots & & & \vdots & & & \vdots & & \vdots \\ u_i & v_i & 1 & 0 & 0 & 0 & 0 & 0 & -u_i \cdot X_i & -v_i \cdot X_i & -X_i \\ 0 & 0 & 0 & u_i & v_i & 1 & 0 & 0 & -u_i \cdot Y_i & -v_i \cdot Y_i & -Y_i \\ 0 & 0 & 0 & 0 & 0 & 0 & u_i & v_i & 1 \; -u_i \cdot Z_i & -v_i \cdot Z_i & -Z_i \\ \vdots & & \vdots & & & \vdots & & & \vdots & & \vdots \end{bmatrix} \cdot \begin{bmatrix} t_{11} \\ t_{12} \\ t_{13} \\ t_{21} \\ \vdots \\ t_{43} \end{bmatrix} = \begin{bmatrix} \vdots \\ 0 \\ 0 \\ 0 \\ \vdots \end{bmatrix} \qquad (5)$$

where t_{ij}'s are the parameters of the ${}^{W}T_L$ matrix. The solution is obtained from the computation of the vector θ that minimizes equation $A \cdot \theta = 0$. A good estimation using Orthogonal Least Square technique is computed from the eigenvector corresponding to the smaller eigenvalue of matrix $A^T \cdot A$.

4 Reconstruction

Once the system is calibrated and the transformation matrices for every stripe computed, the 3D points can be reconstructed by using their corresponding transformation matrix. So, next step in reconstruction is stripe segmentation and the correspondence problem. A robust stripe identification has been implemented which label every stripe when all them are present for a given image row [3]. This information is used as a seed to complete the stripe identification by region growing that allows us to identify the stripes in the presence of occlusions and cuts. Then, once every image pixel is labelled to the corresponding stripe, the surface reconstruction is accomplished.

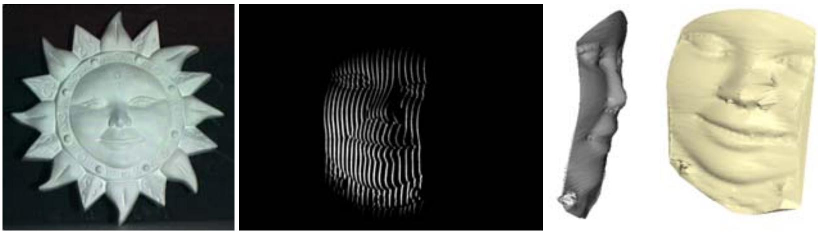
A further step deals with the interpolation of the 3D profiles obtained with the aim of obtaining a continuous surface. The function used to approximate the surface is the following:

$$z = ax^2 + by^2 + cxy + dx + ey + f \tag{6}$$

The parameters are obtained by Least Squares as follows:

$$\begin{pmatrix} a \\ b \\ c \\ d \\ e \\ f \end{pmatrix} = (H^T H)^{-1} H^T \begin{pmatrix} z_1 \\ \vdots \\ z_i \\ \vdots \\ z_n \end{pmatrix} \; where \;\; H = \begin{pmatrix} x_1x_1 & y_1y_1 & x_1y_1 & x_1 & x_1 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ x_nx_n & y_ny_n & x_ny_n & x_n & x_n & 1 \end{pmatrix} \tag{7}$$

The results of the reconstruction are shown in fig 3. In spite of only 19 planes are used to acquire the surface, the resolution of the final reconstruction is enough in free-form shape objects. Furthermore, details not acquired by the sensor can be obtained in the registration process, where some partial views are fused.

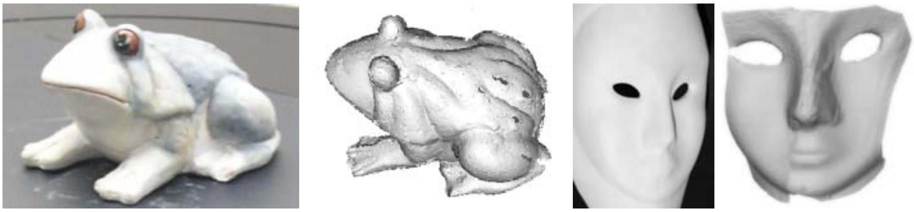


(a) Free form shape Object (b) Image of the laser stripe projection (c) Reconstructed surface

Fig. 3. Experimental results with a real object

5 Registration

When a set of free views from a given object are already available, registration can be applied to align all these views among them with respect to a reference system and



a)Real Object b)Final Registration c)Real Object d)Final Registration

Fig. 4. Final Results

Table 1. Registration results of the frog using real data

	Rotation angle error			
	Pair-wise (ICP)		Our proposal	
Real angle	Computed angle	Error	Computed angle	Error
45°	44.11°	0.89°	44.11°	0.89°
90°	88.41°	1.59°	88.41°	1.59°
135°	132.92°	11.08°	124.20°	10.80°
180°	168.60°	11.40°	183.86°	3.86°
225°	213.00°	12.00°	228.27°	3.27°
270°	256.39°	13.61°	271.67°	1.67°
315°	300.75°	14.25°	316.03°	1.03°

obtain a complete reconstruction of the object. A state-of-art of Registration methods has been recently published [6]. The results of this work pointed out that the best technique to register range images is a robust variant of ICP [10] which was classified as a pair-wise registration technique. Once all the images have been registered in pairs using Zimβer method, a global minimization is applied with the aim of reducing the global error. A graph of connectivity is constructed analyzing if two views are connected by a common surface region. The goal is to compute the transformation of each view to the reference frame throughout the path in the graph with minimal residual error, where the error is computed as the mean of the distances between point correspondences for every pair of views [5]. Dijkstra algorithm is applied to determine the optimal path in graphs to solve this problem, obtaining a reduced graph. At last, the paths with minimal error are the ones used to register the set of views and the object reconstruction is completed. Figure 4b shows an example of the registration of 8 different views of an object where the images has been captured by using a Minolta Vivid 700 Scanner and the object where placed on a non-controlled rotating table. This figure evaluates the accuracy of the proposing registration method. In table 1, the rotation error obtained is compared with the results of traditional pair-wise without refinement. Furthermore, figure 4d shows the results of the registration of ten views captured by the one-shot scanner proposed. Obviously, reconstructions are not as accurate as the Minolta equipment, but note that the proposed scanner captures 3D information in a single image and moreover the registration can be refined by the capturing of more and more views of the same object.

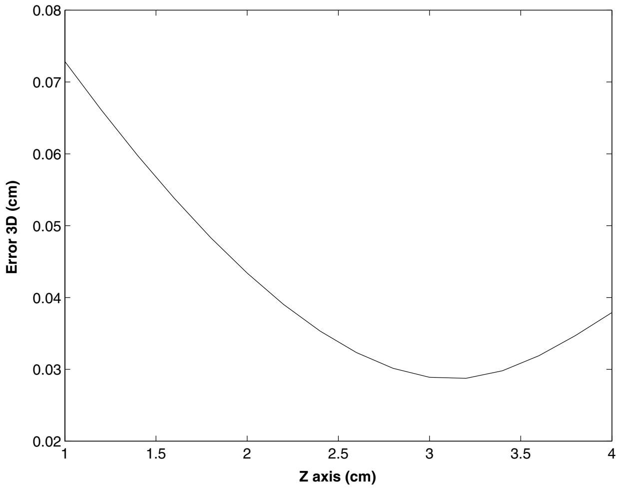


Fig. 5. The accuracy obtained related to depth, i.e. the Z-axis

6 Experimental Results

A set-up consisting of one on-the-shelf CCD camera, a 635 nm LASIRIS laser emitter and an optical lens which spreads the laser beam into 19 planes has been arranged conforming the imaging system. Both camera and laser are located on a portable platform where their optical axis form a angle of 60^o and the distance between them is approximately 20cm. A calibrating quadrangle has been located at several distances from the system in increments of 2 mm. The closest plane is located at 20 cm. from the imaging system. For every quadrangle position, two images are acquired: a) the first is an image of the quadrangle; b) the second is the projection of the laser on the quadrangle. The first image is used to determine the parameters of the quadrangle while the second the geometry of the laser. Then, every laser stripe is determined by a sequence of 16 correspondences which are used to compute the transformation matrix for each stripe. The accuracy of the system is computed from the discrepancy between the reconstructed 3D points and the 3D points used in the calibration process. The results are shown in fig. 5. The error is represented with respect to Z-axis which is the axis more sensitive and directly related to depth. The results gives a good accuracy in a narrow area covered the center of the calibration area while the accuracy decreases in the vicinity.

7 Conclusions

This paper presents a new one-shot imaging system, which is based on a single on-the-shelf camera and a stripe laser pattern. The system benefits from one-shot techniques to recover the 3D shape of surfaces in non-controlled motion environments or even in the presence of vibrations. Registration is used to align every 3D acquisition with respect to a world coordinate system obtaining a complete reconstruction of the measuring object. The calibration benefits from the use of the complete quadrangle and image processing from the use of a nice stripe peak detector with subpixel accuracy. Experimental results show that the accuracy obtained in the reconstruction step is quite acceptable (less than 0.5 mm. in the centered area) and the visual quality of registered surface satisfactory.

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