Planar-based camera-projector calibration

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***Abstract*—Structured light (SL) systems make use of a projector and a camera pair to reconstruct the 3D shape of an object. To this end a previous geometric calibration is required. Many camera and projector calibration algorithms have been proposed during decades. However, the necessity to have an easy to use system, non linked to the SL algorithm developed, still remains unsolved. This work proposes a new method for the calibration of the extrinsic and intrinsic parameters of the projector camera pair. The algorithm requires only a two-sided plane having a checkerboard at one of the sides, and does not depend on the SL algorithm used for the 3D reconstruction. Linear and non linear distortion is considered in the calibration of both devices thus obtaining good calibration results, as is shown in the experimental results.**

I. Introduction

Three dimensional measurement constitutes an important topic in computer vision, having different applications such as range sensoring, industrial inspection of manufactured parts, reverse engineering (digitization of complex, free-form surfaces), object recognition, 3D map building, biometrics, clothing design and others. Among them, structured light (SL) solutions have arised as a high-performance non contact technique. These methods are composed of a camera and a structured light projector. In this approach the active device projects a structured light pattern onto the scene, which is imaged by a camera. From this, 3D shape is extracted using the information held in the deformed recovered pattern. To this end, a previous stereo calibration of the projector-camera pair is required to accurately extract metric information from 2-D images. Different camera calibration techniques can be found in the literature [1], [10], [15], [3], as it is a necessary step in many computer vision systems. However, projector calibration is applied only in structured light approaches and represents the most difficult part in the calibration of the system. Because the projector can not see images like a camera and is just able to project the pattern, determining the correspondence between the projected image and the 3-D points becomes more difficult than for camera calibration. Moreover, distortion parameters that are introduced by the projector should be taken into account in order to achieve good accuracy results.

As Zhang and Zhu [14] stated there are three different group of projector models that have been proposed; that is, the line model, the light-stripe model and the plane structured light model. Despite the design of the two first are easier, in practice the plane structured light model is the most used. This is due to the fact that it can be regarded as the inverse of the pinhole camera model. Consequently, it is easy to adapt the formulation from the camera calibration geometry (this aspect is discussed in detail in section II). Another point to consider is the procedure pursued to calibrate the projector-camera pair. Usually, the camera is calibrated first. After that, the projector is calibrated intrinsically and extrinsically with respect to the camera, using a projected pattern. This pattern can be the same used for the 3D reconstruction (Gray code, De Bruijn or M-arrays are employed), or be designed specifically for the projector calibration. The second choice separates the calibration step from the reconstruction technique.

In this work, the projector calibration is based on a light-stripe projector model. This provides some advantages to the computation of the calibration parameters, as will be analysed in section III. Furthermore, an independent calibration pattern is employed, not depending on the 3D reconstruction method the calibration will be used for.

The paper is structured as follows: section II presents a brief overview on projector-camera pair calibration methods. Section III introduces the proposed technique for projector calibration and the corresponding design of the method, while the experimental results are presented in section IV. Finally, section V concludes with a discussion of the proposed method, analyzing the advantages and disadvantages and pointing out the future work.

II. Brief overview of projector calibration techniques

Camera projector calibration is constituted by two different steps: the camera calibration and the projector calibration. The first one has been widely studied in the literature [1], [10], [15], [3]. The second step (refering to the projector calibration) depends on the results provided by the camera calibration as is computed from the camera image point of view. Among the projector calibration techniques, some classification can be done regarding the observation for calibration object to calibrate the projector, the estimation technique used to find the geometry and the camera-projector model.

Calibration object

The calibration object refers to the setup used to project the pattern and extract the corresponding 3D points. One or more than one calibration objects can be used, having different dimensions. Regarding the dimensions of the objects, some classification is done. First, 3D reference-object-based calibration includes one or more than one fixed or mobile planes [7], [9], [2], or 3D calibration targets with known geometry [6]. The second group, 2D reference-object-based calibration, includes methods having a planar pattern where a known image is projected by the projector and imaged by the camera. This planar pattern is moved in different positions and orientations. Finally, self-calibration systems do not require any calibration object, and can be considered a 0D approach because only image point correspondences are required. An arbitrary object is successively illuminated with grating sequences from at least two different directions, and then the geometrical constraints are obtained. Through a complex mathematical computation projector calibration parameters are extracted.

Estimation technique

The second classification refers to the estimation method used to calibrate the projector. Some techniques use least-squares (LS) method in both 2D and 3D space. This algorithm reduces the reprojection errors in the projector calibration. In 3D space the estimation of the line model or the plane model from the 3D observations is done [6], [16], [12], providing a model of the linear and also the non-linear distortion (lens distortion). Besides, 2D LS estimation works with the projector linear method, therefore it is not possible to model non-linear distortion [11], [13]. However, it is easy to implement and faster than the 3D LS estimation techniques. A last group is formed by the methods using bundle adjustment for the estimation of the projector parameters. In this technique a first linear 2D estimation is performed. After that, all the parameters are optimized using the bundle adjustment method to minimize the cost function associated to the reprojection error.

Projector model

As mentioned above, there are three different projector models used for the calibration. In the line model the projector is described as a laser spot. Therefore, six parameters are considered (three for the center and three for the direction). The light-stripe model uses a plane to describe the projector. Therefore the center coordinate and the plane direction are described. Finally, in the plane structured light technique the projector is regarded as the inverse of a camera, having the same parameters than the camera model. This is the model that is employed more often, as all the theory used for camera calibration can be adapted conveniently. A camera can be modelled by its intrinsics and its extrinsic matrices. Therefore, having a point X in 3D space, its projection in the 2D pixels frame $m = [x, y]$ is given by eq.(1),eq.(2):

$$\begin{bmatrix} sx \\ sy \\ s \end{bmatrix} = [K] \cdot \begin{bmatrix} R & \vert & T \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} = \tag{1}$$

$$= \begin{bmatrix} sx \\ sy \\ s \end{bmatrix} \begin{bmatrix} \alpha_x & \omega & u_0 \\ 0 & \alpha_y & v_0 \\ 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} r_{1,1} & r_{1,2} & r_{1,3} & t_{1,1} \\ r_{2,1} & r_{2,2} & r_{2,3} & t_{2,1} \\ r_{3,1} & r_{3,2} & r_{3,3} & t_{3,1} \end{bmatrix} \left\{ \begin{matrix} X \\ Y \\ Z \\ 1 \end{matrix} \right\} \tag{2}$$

where intrinsic matrix K contains 5 intrinsic parameters: the focal length, the image format, and the principal point. The parameters $\alpha_x = f \cdot m_x$ and $\alpha_y = f \cdot m_y$ represent focal length in terms of pixels, where m_x and m_y are the scale factors relating pixels to distance. ω represents the skew coefficient between the x and the y axis, and is often 0. u_0 and v_0 represent the principal point, which would be ideally in the centre of the image. Nonlinear intrinsic parameters such as lens distortion are also important although they cannot be included in the linear camera model described by the intrinsic parameter matrix. This radial distortion is modelled applying an iterative computation which is provided by the Bouguet's camera calibration toolbox, giving a 6th order distortion estimation.

III. A NOVEL PROPOSAL FOR PROJECTOR CALIBRATION

In these lines, a new model for projector calibration is proposed. Using the geometry provided by the camera calibration it is possible to perform a projector calibration based on the plane structured light model. To this end the extrinsic parameters of the projector are calculated placing the world coordinates at the camera center, therefore the computation of the transformation matrix is straightforward. That is, being the camera intrisic parameters defined as in eq.(3), eq.(4):

$$R_c = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

Therefore

$$P_c = K_c \cdot R_c = K_c \tag{4}$$

The transformation matrix from the camera to the projector becomes (eq.(5)):

$$P = P_p \cdot P_c = K_p \cdot R_p \cdot inv(K_c) \tag{5}$$

As mentioned above, using the plane structured light model the projector can be seen as the inverse of a camera. However, there is a problem associated with the nature of the projector that makes the calibration more complicated than that of a camera; that is, the 3D points corresponding to the 2D projected pattern are not imaged by the projector (as it occurs in the camera calibration); therefore finding the correspondences between the 2D projected pattern and the 3D points implies the use of a calibrated camera to find the 3D position of the projected pattern. A flow chart of the proposed code is shown in Fig. 1:

A. Camera calibration

Among all the techniques available in the literature to perform the camera calibration, the one using Zhang's method has been implemented by Jean-Yves Bouguet in Matlab and C++ in Intel OpenCV library [1]. This code takes into account not only the linear distortion but also the non-linear distortion, up to a six level of radial distortion and also tangential distortion. Moreover, a toolbox for Matlab is available for use.

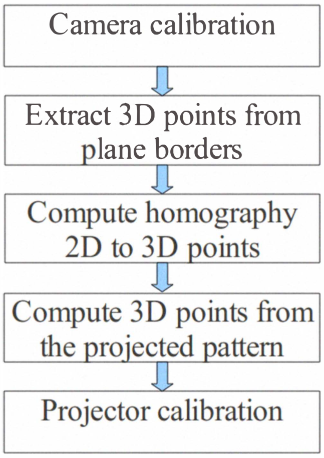


Fig. 1: flow chart of the different steps in the calibration process.

Therefore this technique has been chosen to find the intrinsic and extrinsic parameters of the camera.

Zhangs calibration method requires a planar checkerboard grid to be placed at different orientations (more than 2) in front of the camera. The developed algorithm uses the extracted corner points of the checkerboard pattern to compute a projective transformation between the image points of the n different images, up to a scale factor. Afterwards, the camera interior and exterior parameters are recovered using a closed-form solution, while the sixth-order radial distortion terms are recovered within a linear least-squares solution. A final nonlinear minimization of the reprojection error, solved using a Levenberg-Marquardt method, refines all the recovered parameters.

However, only the intrinsic parameters are used, as we are only interested in knowing the extrinsic parameters of the camera-projector pair.

B. Extract 3D points from plane corners

In this step the 3D coordinates of some specific points in the plane are computed. From the 2D positions of the plane board (seen from the camera frame) the 3D rays passing through these points and crossing the 3D points are calculated. Knowing the real distances between these points is possible to extract their 3D coordinates. This idea was first proposed by Hurtos et al. [5]. However, they used a small checkerboard printed on a corner of the plane to compute the 3D points, which lead to a non-uniform error distribution on the calibration errors, as the printed region can not be imaged by the projector and thus distortion parameters are not computed in this region. A solution to this problem was implemented in our method, and consists on having some previously marked points in the corners of the plane. These marks are designed so that the corner detection algorithm works properly on it. This algorithm provides, given some initial points, the exact 2D coordinates with sub-pixel accuracy. The idea of the method can be observed in Fig. 2:

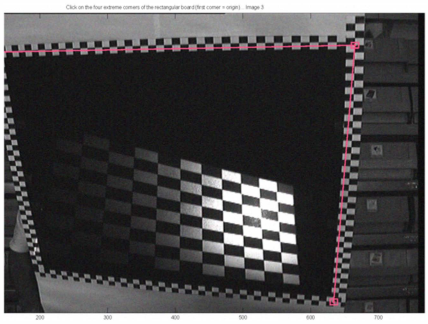


Fig. 2: Four fixed points at the corners of the plane are extracted to compute their 3D positions.

C. Compute homography

Having the 2D points of the plane corners seen from the camera and the corresponding 3D points of the plane with respect to the camera frame, the homography 2D to 3D coordinates is computed. This matrix will be posteriorly used to compute the 3D points of the projected pattern. It is important to mention that the 2D points must be normalized first; that is, must be expressed in millimeters instead of pixel coordinates. A proper algorithm considering both linear and non-linear distortion is applied, including the radial distortion and the other conversion parameters included in the intrinsics matrix (eq.(1)).

D. Compute the 3D points of the projected pattern

Next step consist on extracting the corners of the projected checkerboard pattern (which is projected over the same calibration plane where there is the attached pattern). This is done using the Bouguet functions for extracting the grid corners. With this, the 2D coordinates of the grid are extracted, with respect to the camera frame. Applying the homography the corresponding 3D coordinates are obtained. This is expressed in eq.(6 and Figs. 3, 4:

$$\begin{bmatrix} sX \\ sY \\ sZ \end{bmatrix} = H \cdot \begin{Bmatrix} x \\ y \\ 1 \end{Bmatrix} \tag{6}$$

This is done for all the corners in the image and for different images so as to obtain a big number of non-coplanar 3D points for the calibration.

E. Projector calibration

The last step involves the same functions that were previously used for the camera calibration. The projected 3D points were computed using the steps detailed in the previous section. The 2D points of the projected image are quite simple to obtain. It is only required to extract the corners of the image pattern that is being projected. It must be considered that this image has to be at the same resolution in which the projector is displayed. Having the set of 2D-3D correspondences, Zhang's method is applied using the Bouguet toolbox. Therefore, after

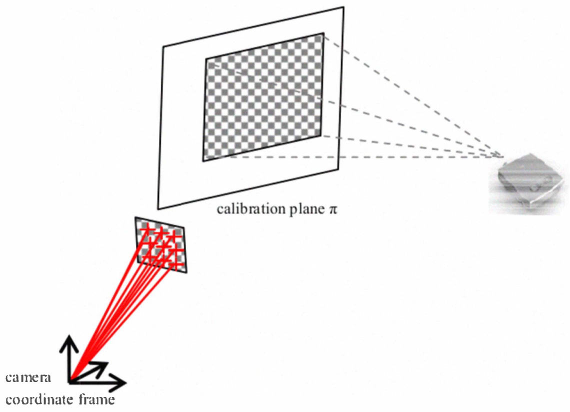


Fig. 3: Rays coming from the camera and going to the grid corners of the projected pattern.

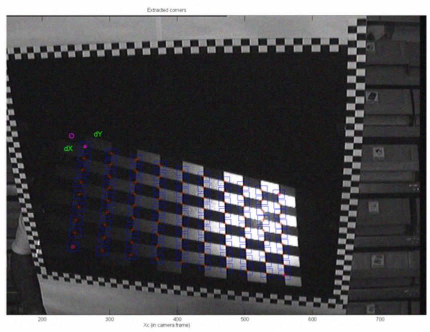


Fig. 4: Corners detection on the projected grid pattern.

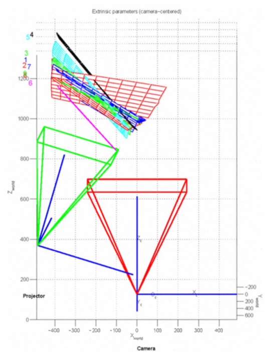


Fig. 5

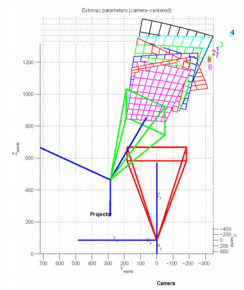


Fig. 6: Projector-camera calibration results for the given setup (extrinsic parameters).

the calibration is done we obtain the optimized intrinsic and extrinsic parameters for the camera-projector pair.

IV. Results

The proposed algorithm has been tested in real conditions. The setup used for the tests was composed of an LCD video projector (Epson EMP-400W) with a resolution of 1024×768 pixels, a camera (Sony 3CCD) and a frame grabber (Matrox Meteor-II) digitizing images at 768×576 pixels with 3×8 bits per pixel (RGB). The baseline bet ween camera and projector was about $0.5m$. The setup can be observed in Fig. 8.

The algorithm run on an Intel Core2 Duo CPU at 3.00GHz. The results of the calibration algorithm can be observed in Figs. 5, 6:

Several tests of camera-projector calibration have been performed. In order to see the performance of the method, we can make use of the reprojection error functions available in the Bouguet's calibration toolbox. Using this technique, we obtained the following error map (in pixel) (Fig. 7):

These values are in consonance with the reprojection error shown in the work of Hurtos et al. [5]. However, in the proposed approach the projector illuminates all the board considered for 3D reconstruction. Therefore, the error is computed uniformly around the imaged plane. This avoid the calibration errors produced by a non-uniform calibration parameters estimation presented in the previous work [5]. The projector calibration results mainly affected by the previous camera calibration error and the accuracy of the corner extraction function. Under normal conditions the method showed a reprojection error of around one pixel over the calibration error of the camera, being able to work optimally for structured light systems.

Finally, in order to demonstrate the aplicability and efficiency of the proposed technique a two 3D reconstructions using structured light have been performed. Two well-known structured light methods have been implemented, one one-shot (sparse reconstruction) and one time multiplexing (dense reconstruction). The algorithm proposed by Monks et al. [8] and the one proposed by Guhring et al. [4] were implemented, respectively. The results of the reconstruction of the same object can be observed in Fig. 9 and Fig. 10:

As can be observed Guhring reconstruction presents higher accuracy than Monks method (despite the roughness observed in the surface), thanks to the higher density of the cloud of points (a higher number of columns was covered). Anyway, this roughness is mainly caused by the algorithm, not by the camera-projector calibration results.

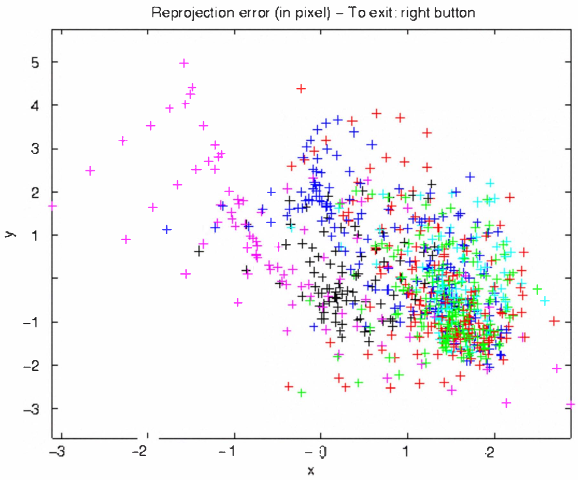


Fig. 7: Reprojection error of the projector calibration algorithm.

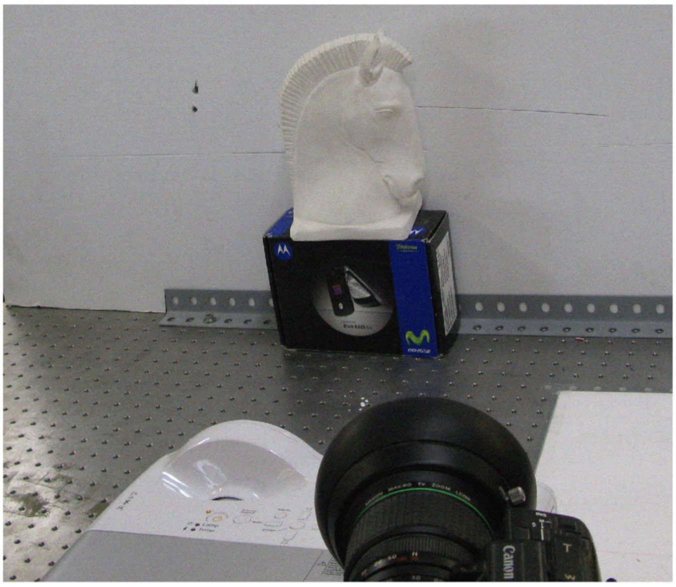
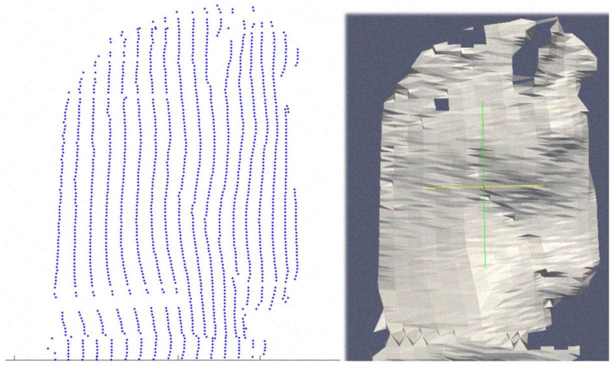


Fig. 8: Setup used for the camera-projector calibration and for the reconstruction of a 3D object.

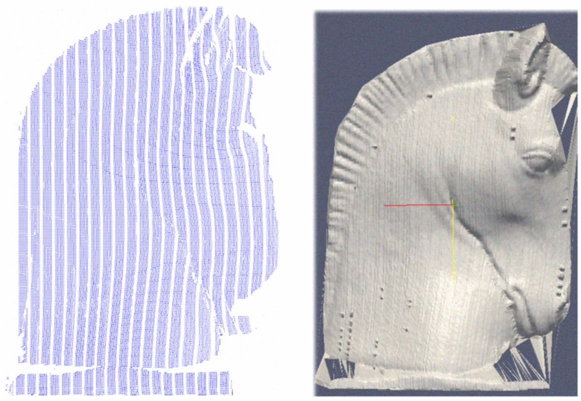
V. Discussion

In this work we described a plane-based calibration method for projector-camera systems, using a plane structured light projector model. The proposed method makes use of the Bouguet's camera calibration toolbox which implements Zhangs calibration [1]. This technique was also used to implement the projector calibration, using the fact that in the plane structured light model the projector is regarded as the inverse of a camera. Linear and non-linear distortion was considered for the calibration of both devices. Although we used the planar target and the nonlinear projector model in this paper, the idea is also suitable for 3-D reference objects and other projector models. For the 3-D reference objects, it would be just required to modify the function



(a) 3D cloud of points (b) Reconstructed 3D surface

Fig. 9: Object reconstruction using the proposed calibration technique and Monks algorithm



(a) 3D cloud of points (b) Surface reconstruction

Fig. 10: Object reconstruction using the proposed calibration technique and Guhring algorithm

that computes the homography, considering the new geometry of the projected plane or planes. The simulations and real experiments confirmed that the estimation of the projector and the camera image provides good precision. It was noticed that the error depends on the camera calibration error as it is used as a preliminary step for the rest of the calibration method. Therefore, improving the setup conditions and the corner detection step will decrease this error. Finally, a bundle adjustment on the camera calibration and the projector calibration results could be applied to improve the precision of the estimates.

Acknowledgments

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