On the Influence of Fixing the Principal Point in Frame-by-Frame Multiplanar Calibration

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On the influence of fixing the principal point in frame-by-frame multiplanar calibration.

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Abstract

Calibrating sequences were a camera moves without zooming is often considered as a pure viewpoint estimation problem. Here, we demonstrate that considering varying principal point while keeping the focal length constant allows us to obtain a reprojection error similar to the one obtained with full calibration while imposing existing constraints on the camera (no zooming). Then, we propose a robust calibration process which can be used for any scene that contains planar structures. Robustness is obtained by estimating independently the principal point position and the viewpoint.

1. Introduction

Camera calibration is an important task in many vision and media applications. For example, when augmenting real video sequences with synthetic 3D elements, the camera calibration is prerequisite in order that the real and the virtual objects be properly aligned.

In this paper, we consider the common practical case where the camera moves without zooming. This is a very common situation in augmented reality when the user moves with a small camera fixed on a head mounted display. Hence the intrinsic camera parameters should be constant over the sequence. A first contribution of this paper is to prove that considering varying principal points but constant focal length over the sequence leads to more accurate and more stable calibration results.

Our second contribution is to propose an efficient and robust framework for calibrating such a sequence for scenes which contain planar structures. In order to avoid undesirable compensations between intrinsic and extrinsic parameters [1], the principal points and the viewpoints are computed independently for each frame. This can be done thanks to the center line constraint [2]. In addition, we propose a statistical propagation of the detection errors to improve the accuracy of the principal point.

Section 2 illustrates the need of varying the principal point for calibration purpose. Section 3 proposes a framework for calibrating a camera by estimating the principal point in every image. Finally, section 4 shows some experimental results in the context of augmented reality.

2. Calibration problems

Camera calibration over a sequence is often considered as either a full calibration process (when all the camera parameters are unknown) or as a viewpoint computation process when the intrinsic parameters are supposed constant and estimated beforehand. In this section we prove that even though camera moves without zooming over a sequence, accurate calibration cannot be obtained with constant intrinsic parameters. Besides, we show that constant focal length and varying camera parameters lead to a reprojection error which is similar to the errors obtained with full calibration, while imposing existing constraints (no zooming is performed).

A video sequence of our calibration target was shot without zooming nor focusing. Let $\mathbf{P} = \mathbf{K}(\mathbf{R}|\mathbf{t})$ be the projection matrix recovered from classical calibration techniques, where $\mathbf{R}$ and $\mathbf{t}$ are the orientation and position of the camera (viewpoint), and $\mathbf{K} = \begin{pmatrix} f & 0 & u_0 \\ 0 & \tau f & v_0 \\ 0 & 0 & 1 \end{pmatrix}$ is the intrinsic parameters matrix. Camera calibration is performed by computing the parameters $(f, u_0, v_0, \mathbf{R}, \mathbf{t})$ that minimize the average reprojection error:

$$min_{(f, u_0, v_0, \mathbf{R}, \mathbf{t})} \frac{1}{N} \sum_{k=1}^{N} \|\mathbf{u}_k - \mathbf{P}(\mathbf{x}_k)\|^2$$

given the 3D-2D matches $(\mathbf{x_k}, \mathbf{u_k})$. It is assumed that the aspect ratio $(\tau)$is fixed and that the image axes are orthogonal.

The classical 9-parameters calibration has been performed on each image of the sequence. The reprojection error is plotted as reference in Fig. 1.a. We also performed calibration by fixing the intrinsic parameters. Optimization
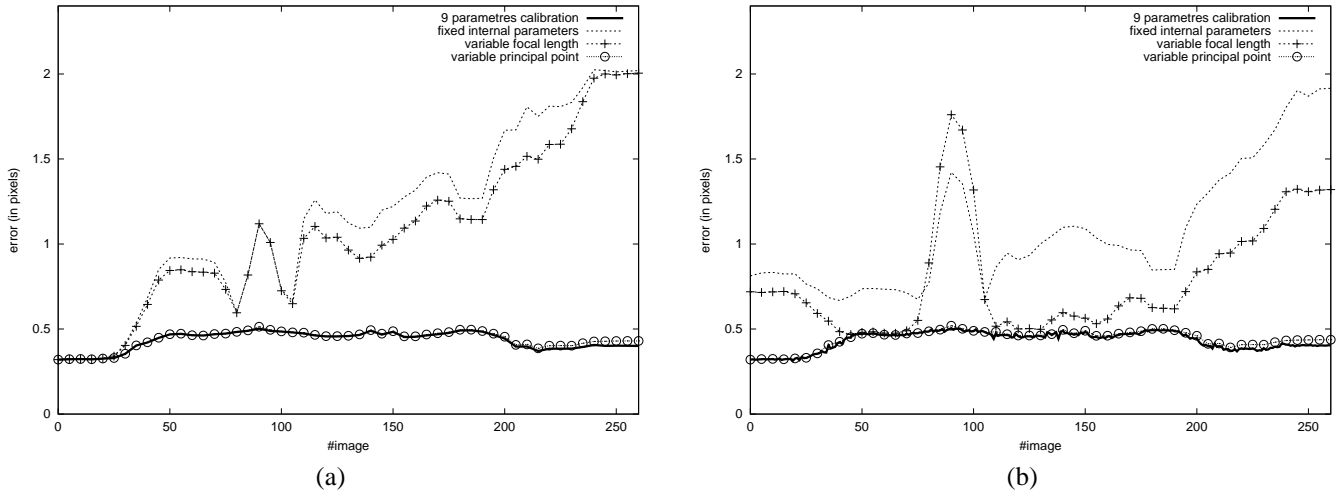
Figure 1. Comparison tests. (a) Reprojection errors: constant intrinsic parameters are the ones computed from image 0. (b) Reprojection errors: constant intrinsic parameters are the ones computed using a bundle adjustment technique.

was then achieved on the extrinsic camera parameters. Fig. 1.a exhibits the reprojection errors when the internal parameters are fixed to the values computed in frame 0. Fig. 1.b shows the errors when the internal parameters are computed with a bundle adjustment technique over the set of frames. These plots clearly prove that fixing intrinsic parameters lead to large reprojection errors. The average error is 2 pixels and for some points the error is up to 6 pixels.

These experiments suggest that non constant intrinsic parameters must be used even when no zooming or focusing is performed. In order to know which parameters are more suitable to describe the observed deviations and which ones should remain fixed, we conducted further calibration experiments using:

- a variable focal length and a fixed principal point

- a fixed focal length and a variable principal point

These experiments clearly show that (Fig. 1.a) fixing the principal point also leads to a large residual error. Fortunately, a fixed focal length and a varying principal point gives a reprojection error which is very similar to the one obtained with the 9-parameters calibration.

As the height of the camera was constant during acquisition, the z-component of translation in the world coordinates remains constant for all the sequence. The standard-deviation of this parameter for the four cases are:

case	t_z (mm.)	σ_{t_z} (mm.)
9 parameters calibration	533.76	2.97
fixed internal parameters	540.12	5.95
variable focal length	563.35	22.02
variable principal point	545.50	1.85

This table further demonstrates that the stability is better when the principal point varies and the focal length is fixed. To conclude, even if the intrinsics are theoretically constant, calibration is improved by considering constant focal length and a varying principal point. Intuitively, such varying parameters allows to cope with the fact that the pinhole model is only an approximation of a camera. In the following, we describe a robust and accurate calibration framework which implements this idea.

3. The Calibration framework

We then propose a calibration process where the set of parameters $(u_0, v_0, \mathbf{R}, \mathbf{t})$ are estimated frame-by-frame. The focal length is constant and is estimated beforehand. This process can be used in any environment which contains some planar structures. The main interest of our framework is to avoid the compensation effects that often appear between intrinsic and extrinsic parameters by estimating independently the principal point position and the extrinsic parameters. The Center Line (CL) constraint [2] is here used to estimate the intrinsic and extrinsic parameters independently. In addition, we propose a robust estimation of the principal point. Then, our framework for camera calibration follows a two-step procedure:

- The principal point is estimated at the current frame by means of the CL constraint applied over several planes.

- The viewpoint is computed using the updated principal point position and the constant focal length from any viewpoint algorithm.
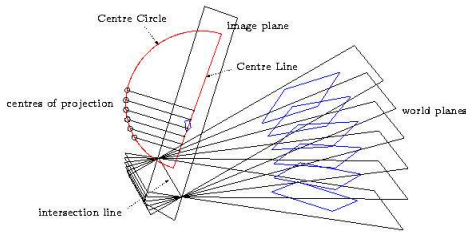
Figure 2. Poncelet's theorem (from [2]).

In the following, we first recall the fundamental center line constraint. Then the calibration algorithm is described.

3.1. Center Line Constraint

The Center Line constraint is based on Poncelet's theorem [5] that states:

When a planar figure is the central projection of another planar figure, these figures remain in perspective correspondence when one rotates the plane of the first around its intersection with the plane of the second; the center of projection then lies on a circle, in a plane perpendicular to this intersection. As a result, if one projects this circle orthogonally onto the image plane, one obtains a line segment that is the locus of the principal point (see fig.2).

The equation of the straight line containing the principal point, namely the Center Line, is given by [2]:

$$Au_0 + Bv_0 + C = 0 \qquad (1)$$

where

$$\begin{aligned}
A &= -\tau^2(H_{31}^2 + H_{32}^2)(H_{31}H_{12} - H_{11}H_{32}) \\
B &= -(H_{31}^2 + H_{32}^2)(H_{31}H_{22} - H_{21}H_{32}) \\
C &= \tau^2(H_{31}H_{12} - H_{11}H_{32})(H_{11}H_{31} + H_{12}H_{32}) \\
  &\quad +(H_{31}H_{22} - H_{21}H_{32})(H_{21}H_{31} + H_{22}H_{32})
\end{aligned}$$

and H is the homography transformation between a plane in the 3D space to the corresponding 2D image.

3.2. Principal Point Estimation

In the seminal work about CL, the authors assumed that the principal point position is constant over a sequence and proposed to determine it as the intersection of the center-lines that correspond to a given plane which is visible in several images. Here, we use this constraint in a different way: the CL constraint is used with several visible planes in every image. As a result the principal point is updated in each image by intersecting the corresponding center lines.

In the original work about CL [2], statistical variations on homography estimation or lines intersection are not considered. However, the estimations are sensitive to some factors as the plane orientation, the number of key-points or their distribution in the image. Then, we suggest to take into account the statistical fluctuations on key-points used to compute homographies, and propagate these deviations up to the principal point computation.

Computing the homographies between two planes is a well known problem that is addressed in [3]. The deviations on the homography coefficients can be estimated as a function of the statistical variations on the key-points that are extracted and matched through the sequence. Given the covariance one the homographies for the N_p observed planes, the center lines are obtained by using the Eq. 1, and the propagated covariance is approximated by:

$$V[A_i, B_i, C_i] = J_i V[H] J_i^T$$

where J_i is the Jacobian matrix of the line parameters (A_i, B_i, C_i) respect to the coefficients of H_i.

A robust estimation of the principal point can now be computed as the intersection of the center lines weighting each distance as a function of the covariance [4]:

$$(u_0, v_0) = argmin G(u_0, v_0) = \sum_{i=1}^{N_p} \frac{\|(A_i, B_i, C_i) \cdot P_c\|^2}{P_c^t(V[A_i, B_i, C_i]P_c)}$$

where $P_c = (u_0, v_0, 1)^T$. The main advantage of optimizing this function, instead of the sum of geometric distances to the lines, is that G takes into account that noise does not affect homogeneously the different CL, and it allows us to reduce the sensibility of the principal point to poorly estimated lines (see Fig. 4)

4. Application to real-time camera tracking

This framework has been applied to real-time camera tracking for augmented reality. The system described in [6] is used to compute the extrinsic parameters of the camera. This system is based on correspondences of key-points that are located on planar structures.

Results were obtained on a 1000-frames sequence of a room corner. Artificial markers were added into the scene in order to compute the CL constraints (figure 5). One important point is that it is not necessary to know the relative positions of the markers, as each marker provides one CL constraint independently from the others.

Figure 3 shows the evolution of the principal point over the sequence. An example of the estimated principal point is shown in Fig. 4: as marker 1 lies in a nearly fronto-parallel plane, the covariance of the corresponding CL is higher than for the other planes. Consequently, the principal point is closer to the lines issued form markers 2 and 3. The Figure 5 shows the reprojection of the scene in frame 600, when the principal point is kept constant in the middle of the image (fig 5.b) or is updated using the method
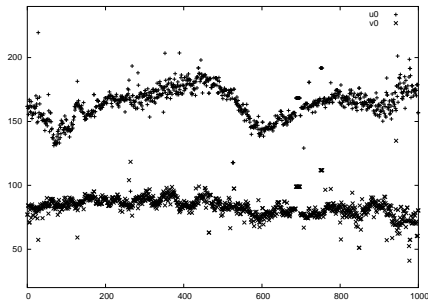
Figure 3. Evolution of the computed principal point over the sequence.
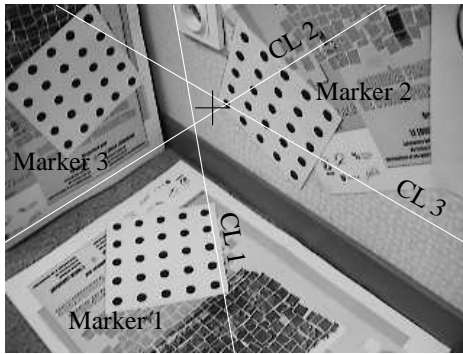

Figure 4. Estimated principal point and center lines for one frame of the sequence.

described in section 3 (fig 5.c). In both cases a drift is observed, due to approximation errors that accumulate over time (this inevitable drift is mentioned in [6]). However, the reader may notice that the drift is much less important when the principal point is updated (see for example the basis of the vertical planes).

5. Conclusion

The paper has demonstrated that using a variable principal point and a fixed focal length is a convenient way to describe a moving camera without zooming nor focusing. For scenes containing planar structure, we show that the intrinsic and the extrinsic parameters can be estimated independently, giving rise to a robust calibration scheme.

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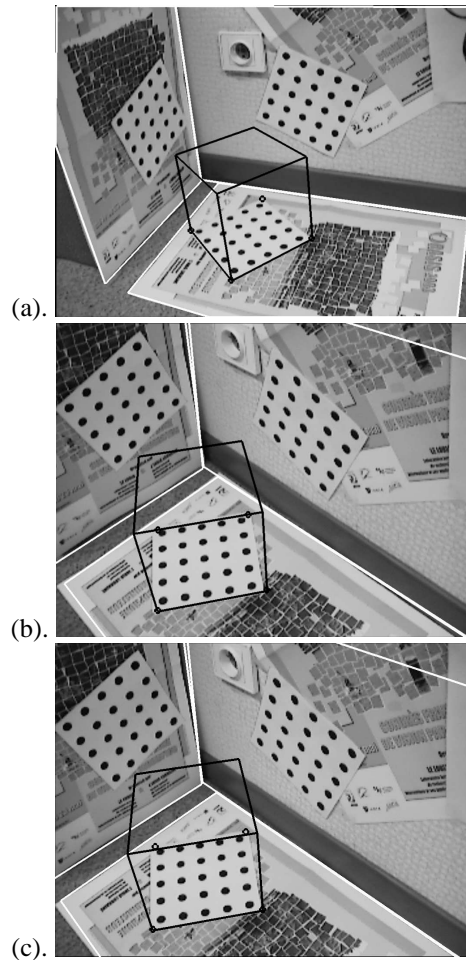

(a).

(b).

(c).

Figure 5. Results obtained on a 1000-frames sequence of a room corner. (a) A multi-planar structure is defined and a cube is added in the first image of the sequence. (b),(c) Re-projection of the scene in frame 600 when the principal point is fixed (b) or is changed frame-by-frame (c).

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