Intrinsic Camera Calibration Equipped with Scheimpflug Optical Device

Peter Fasogbon[1,2], Luc Duvieubourg[1], Pierre-Antoine Lacaze[2], Ludovic Macaire[1]

[1]Laboratoire Lagis, University of Lille1, UMR CNRS 8219

Cité Scientifique - Bat P2 - 59655 Villeneuve d'Ascq Cedex

[2]SNCF Direction de l'Ingienerie, —, Plaine Saint Senis, FRANCE

* E-mail: faspetpeak@yahoo.com

Introduction

For many cameras to be in perfect focus, an object must be placed in a plane surface that is parallel to the image plane. However, acquiring an image at sharp focus can be very difficult when the surface of interest is located in an oblique plane to the optical axis (i.e. object plane not parallel to the image plane). It is the case when the camera observes the facade of a tall building or a decorative cobblestone pathway. The camera can be aimed upward at an angle which makes it difficult to bring the complete surface of interest in focus. Therefore, for a certain oblique plane to be in focus, the imaging set-up must obey "Scheimpflug's principle" (1).

We have used Scheimpflug technique so that the sharp camera's field of view is as wide as possible. This system is specifically designed for 3D dimensional measurement under Scheimpflug condition. So, we have to perform an intrinsic camera calibration in order to extract accurate 3D measures from 2D images. Intrinsic calibration has been extensively studied in computer vision and photogrammetry community and various techniques have been proposed over the past few years (2).

However, classical camera calibration techniques based on pinhole model cannot be used directly with Scheimpflug system set-up (3). Therefore, we describe the Scheimpflug set-up and propose an image formation model when the camera is equipped with a Scheimpflug lens. Then, we detail the intrinsic calibration method that is adapted to the Scheimpflug set-up. Finally, first experimental results are presented to assess the performance of our proposed method.

1 Scheimpflug image formation model

For classical pin-hole model, the image plane is usually parallel to the lens plane, so that it is perpendicular to the optical axis. However, for Scheimpflug set-up, the image plane is tilted at a given angle θ around the optical center (see Figure 1). This adjustment ensures that the image plane, the lens plane and the object plane intersect at a line parallel to X_c axis, denoted as "scheimpflug line" and represented as a point in Figure 1. In that case, the field of view according the oblique plane is larger than for classical lens.

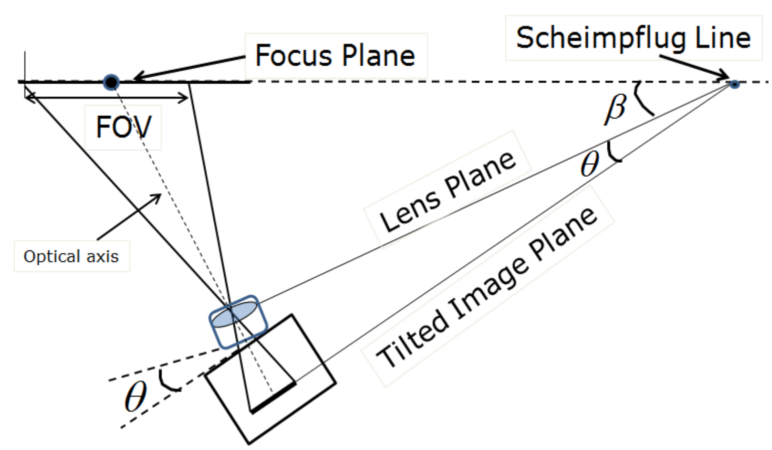

Figure 1: Scheimpflug System Set-up

A point P along the object focus plane (see Figure 2) is projected into the point p_t in the tilted image plane. Let us denote $d_i = \|\vec{O_c p_t^a}\|$ and $d_o = \|\vec{O_c P^a}\|$ the image and object distances from the center O_c of the lens along the optical axis, where p_t^a and P^a are the projections of p_t and P to the optical axis. The thin lens equations still hold for Scheimpflug set-up so that $\frac{1}{f} = \frac{1}{do} + \frac{1}{di}$, where f is the focal length. This is possible for any points along the object focus plane that are projected to the tilted image plane. When the object of interest is located at an angle β to the lens plane, the lens plane is tilted with respect to the Scheimpflug angle θ so that the focus plane is brought to the object location.

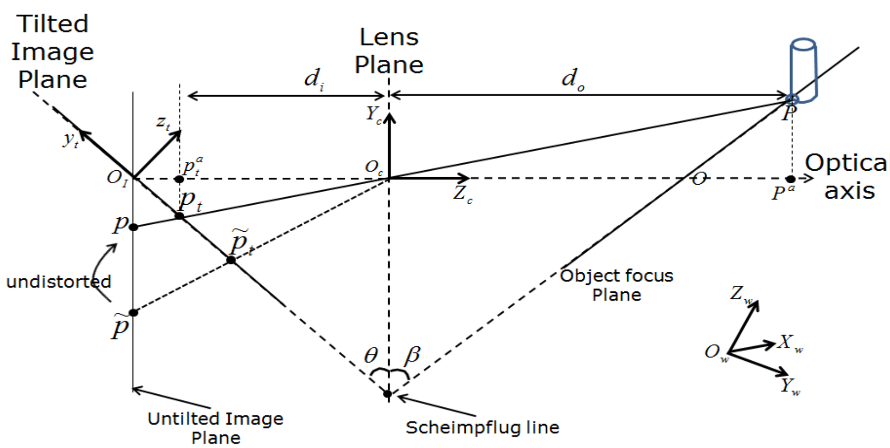

Figure 2: Scheimpflug camera model.

In order to determine the 3D coordinates of world point P from its projected point p_t in the tilted image plane, we need to calibrate the used camera. Therefore, we have proposed a Scheimpflug calibration method based on pin-hole model assumptions.

1.1 Image formation for Scheimpflug angle

The spatial pixel coordinates $p_t(u_t, v_t)$ in the tilted image plane is deduced from the coordinates $P(X, Y, Z)$ of the point in the word coordinate system under pin-hole model assumption, thanks to 3 successive equations. Equation (1) first converts the world coordinates $P(X, Y, Z)$ of a scene point into camera coordinate system $P(X_c, Y_c, Z_c)$ with extrinsic parameters, i.e. the rotation $\mathcal{R}$ and translation $\mathcal{T}$ parameters. To model the projection to the tilted image plane, we propose to consider first the virtual image plane that is perpendicular to the optical axis and is called hereafter untilted image plane. Equation (2) computes the coordinates (x, y) of the projected point into the virtual untilted image plane thanks to the focal distance f. Equation (3) transforms the spatial coordinates (x, y) in the untilted image plane to pixel coordinates (u_t, v_t) in the tilted image plane, thanks to the intrinsic parameters to be estimated, i.e. the Scheimpflug angle θ, the focal lens f, the pixel sizes s_x, s_y, and the image center pixel coordinates u_0, and v_0.

$$\begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} = [\mathcal{R} \mid \mathcal{T}] \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix} \tag{1}$$

$$\lambda \begin{bmatrix} x \\ y \\ 1 \end{bmatrix} = \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} X_c \\ Y_c \\ Z_c \end{bmatrix} \tag{2}$$

$$\lambda \begin{bmatrix} u_t \\ v_t \\ 1 \end{bmatrix} = \begin{bmatrix} 1/s_x & 0 & 0 & u_0 \\ 0 & 1/s_y & 0 & v_0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & cos\,\theta & sin\,\theta & -f\,sin\,\theta \\ 0 & -sin\,\theta & cos\,\theta & -f\,cos\,\theta \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} f & 0 & 0 \\ 0 & f & 0 \\ 0 & 0 & f \\ 0 & -tan\,\theta & 1 \end{bmatrix} \begin{bmatrix} x \\ y \\ f \end{bmatrix} \tag{3}$$

2 Intrinsic calibration steps

To estimate the intrinsic parameters and especially the Scheimpflug angle θ, we adapt the classical calibration technique proposed by Zhang et al. (4) that uses a target plane composed of n feature points and placed in the scene according to m poses. Each point of the calibration target in the world coordinate system $P^{(i,j)}(X^{(i,j)}, Y^{(i,j)} Z^{(i,j)})$ $(i = 1, .., n,\ j = 1, .., m)$ is matched to its corresponding pixel $p_t^{(i,j)}(u_t^{(i,j)}, v_t^{(i,j)})$ in the tilted image plane. The Scheimpflug camera calibration that analyses the given pixels $p_t^{(i,j)}$ in the tilted image plane, is decomposed into three successive steps as described below.

2.1 Projection to the Untilted Image Plane

As a result of distortion introduced by tilt effect, we thereby propose to perform the calibration procedure on the untilted ”virtual” image plane. The given pixels $p_t^{(i,j)}(u_t^{(i,j)}, v_t^{(i,j)})$ in the tilted image plane are transformed into points $p_c^{(i,j)}(X_c{}^{(i,j)}, Y_c{}^{(i,j)}, f)$ in the untilted image plane, and expressed in the camera coordinate system according to equations (1)-(3). For this purpose, we need to give initial values of θ, f, s_x, s_y, u_0, and v_0 (given by the manufacturer) in order to apply the above equations. These values should be very close to the true ones to ensure fast convergence of the following minimization steps.

2.2 Target-image plane homography estimation

The projective transformation between each pose of the calibration target plane and the untilted image plane is an homography. To estimate it, we need feature points $P^{(i,j)}(X^{(i,j)}, Y^{(i,j)}, Z^{(i,j)})$ of the calibration target, and their corresponding pixels $p^{(i,j)}(u^{(i,j)}, v^{(i,j)})$ on the untilted image plane. We can then apply the normalized Direct Linear Transformation algorithm (DLT) method to extract the homography matrix $\mathcal{H}_{(j)}$ at each pose j of the calibration target (5).

2.3 Camera parameter estimation

We can estimate the camera's constrained intrinsic parameters $\mathcal{K} = [f_x, f_y, u_0, v_0]$, and extrinsic parameters $[\mathcal{R}_{(j)}|\ \mathcal{T}_{(j)}]$ from the earlier refined homography $\mathcal{H}_{(j)}$ using the method of by Zhang et al. (4). According to the proposed Scheimpflug image formation, the tilt effect can be seen as a form of large radial distortion.

Given an initial value of the tilted angle θ, coupled with the preceding estimated camera parameters, we can apply use bundle adjustment technique to refine the full parameters based on Levenberg Marquardt iterative as:

$$\min \sum_{j=1}^{m} \sum_{i=1}^{n} \|p^{(i,j)} - \hat{p}^{(i,j)}(\mathcal{K}, \mathcal{R}_{(j)}, \mathcal{T}_{(j)}, \theta)\|^2 \tag{4}$$

,

where $\hat{p}^{(i,j)}$ are the estimated coordinates of the projected pixel that depend on $(\mathcal{K}, \mathcal{R}_{(j)}, \mathcal{T}_{(j)})$.

3 Results

For the experimental results, a firewire camera with a resolution of 1280x1024 pixels whose size is $0.0067mm \times 0.0067mm$, and a canon TS-E focal 24mm Scheimpflug lens tilted to approximately $\theta = 1.5°$ have been used. The feature points are extracted from 25 images captured at different orientations from the camera (see Figure 3). Moving the calibration target with several orientations to cover the camera's field of view for calibration procedure is not always easy to perform in case of limited depth of field.

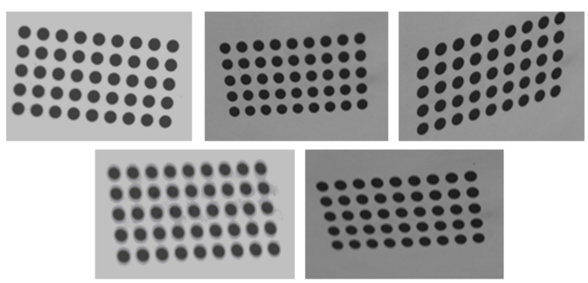

Figure 3: Five examples of images captured by the camera under Scheimpflug set-up.

The target is composed of circle grids rather than checkerboard so that the feature points can be well detected even when the images are blurred. The diameter of the circle pattern is 5 mm, the extracted feature points are the circle gravity centers and the distance between two feature points is 7.5mm.

Parameter	f_x	f_y	u_0	v_0	f(mm)	$\theta(^\circ)$	Mean error	Standard Deviation
Unit	(mm)	(mm)	(px)	(px)	(mm)	$(^\circ)$	(px)	(px)
Value	3717.3	3716.0	517.5	587.8	24.9	1.49	0.15	0.037

Table 1: Calibration result from combined target.

The feature extraction and calibration procedure explained earlier provide the calibration results detailed in Table 1. We have assessed the calibration performance by computing the mean and standard deviation of re-projection error over the 25 captured images. Scheimpflug angle has been well estimated and the mean error allows accurate 3D measures.

4 Conclusion

A new method for the calibration of cameras under Scheimpflug conditions has been presented. This method extends the pin-hole camera model where the image plane is perpendicular to the optical axis, by adding the Scheimpflug tilt angle θ. To simplify distortion as a result of the tilted effect, we proposed to project the pixels on the tilted plane to the untilted ones using the proposed formation model. We assume that the tilt effect can be considered as large radial distortions, so we do not need to simplify the radial distortion parameters afterwards. Then, we can extract camera parameters from the projected pixels on the untilted image plane using the same approach as Zhang et al. method (4). Finally, a bundle adjustment approach based on Levenberg-Marquardt is used to refine the intrinsic camera parameters.

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