Chapter 2
Camera Calibration

2.1 Introduction

Before the entire image stitching procedures, the first problem required to be solved is the distortion caused by camera. It is known that all the images captured from a camera should pass through an optical lens to map the 3D real world view to a CCD or CMOS sensor. Because of the nature lens distortion, the shape of an original image is nonlinearly changed. There are mainly two distortions the images suffered from, which are called barrel distortion and pincushion distortion in Figure 2.1.

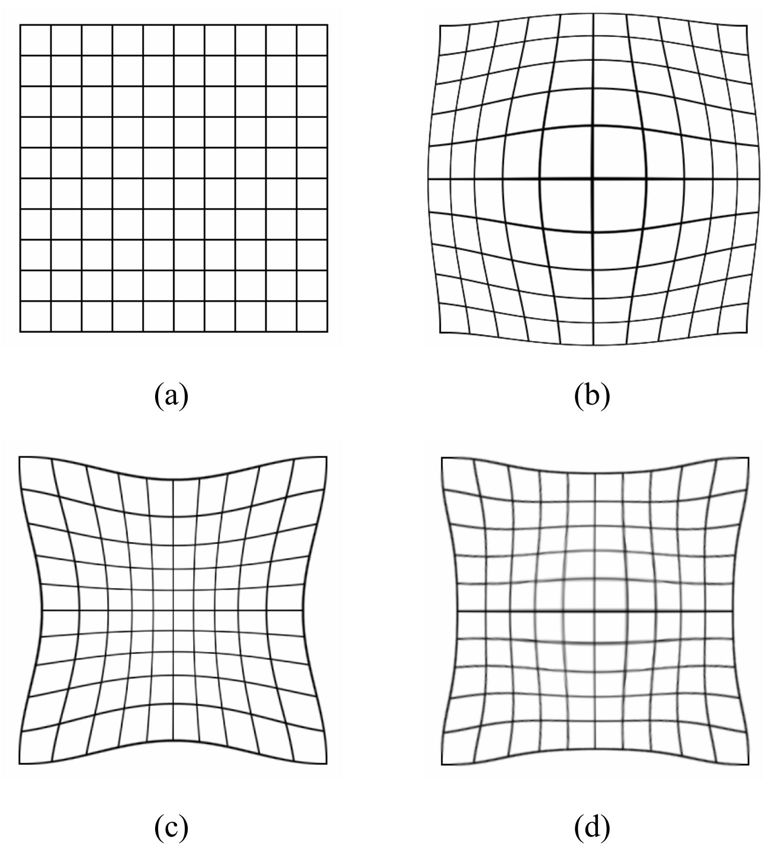


Fig 2.1 (a) Original image, (b) barrel distortion, (c) pincushion distortion, and (d) combination of barrel and pincushion distortions

Unfortunately, these distortions also nonlinearly change the original relation between two neighbor images and usually result in the failure of the image stitching process. Therefore, the camera calibration is required to correct the distorted images as accurately as possible. In this chapter, the camera calibration model is introduced first and then the undistorted images are obtained by the information of the camera from Matlab toolbox for camera calibration.

2.2 Camera Calibration Model

Physical camera parameters are commonly divided into extrinsic and intrinsic parameters. The extrinsic camera parameters are needed to transform object coordinates to a camera centered coordinate frame. The intrinsic camera parameters are the primary keys to correct the distorted images which usually include the effective focal length $\boldsymbol{f}_c = [\, f_x \quad f_y \,]$, principal point $\boldsymbol{c}_c = [\, c_x \quad c_y \,]$, skew coefficient α_c and distortion coefficients $\boldsymbol{k}_c = [\, k_1 \quad k_2 \quad k_3 \quad k_4 \quad k_5 \,]$. By the intrinsic camera parameters described above according to [6] and [12], the camera calibration model can be constructed successfully to represent the behavior of the lens distortion.

Let $[\, X_c \quad Y_c \quad Z_c \,]$ be the space of coordinate vector, and then the normalized image projection $x_n = \dfrac{X_c}{Z_c}$, $y_n = \dfrac{Y_c}{Z_c}$, and $r_n^2 = x_n^2 + y_n^2$ can be obtained. Afterward, the new normalized point coordinate, x_d and y_d, defined after including the lens distortion can be expressed as

$$\begin{bmatrix} x_d \\ y_d \end{bmatrix} = x_r \cdot \begin{bmatrix} x_n \\ y_n \end{bmatrix} + \boldsymbol{x}_t \tag{2.2-1}$$

$$\begin{cases} x_r = 1 + k_1 \cdot r_n^2 + k_2 \cdot r_n^4 + k_5 \cdot r_n^6 \\ \boldsymbol{x}_t = \begin{bmatrix} 2 \cdot k_3 \cdot x_n \cdot y_n + k_4 r_n^2 + 2 \cdot x_n^2 \\ k_3 \cdot \left(r_n^2 + 2 \cdot y_n^2\right) + 2 \cdot k_4 \cdot x_n \cdot y_n \end{bmatrix} \end{cases} \tag{2.2-2}$$

where x_r and $\boldsymbol{x}_t$ are respectively represent the radial and tangential distortion. Once the distortion is applied, the final pixel coordinates, x_p and y_p, and the normalized point coordinate, x_d and y_d, are related to each other through the linear equation which can be described as

$$\begin{bmatrix} x_p \\ y_p \\ 1 \end{bmatrix} = \boldsymbol{CM} \cdot \begin{bmatrix} x_d \\ y_d \\ 1 \end{bmatrix}, \qquad \boldsymbol{CM} = \begin{bmatrix} f_x & \alpha_c \cdot f_x & c_x \\ 0 & f_y & c_y \\ 0 & 0 & 1 \end{bmatrix} \qquad (2.2\text{-}3)$$

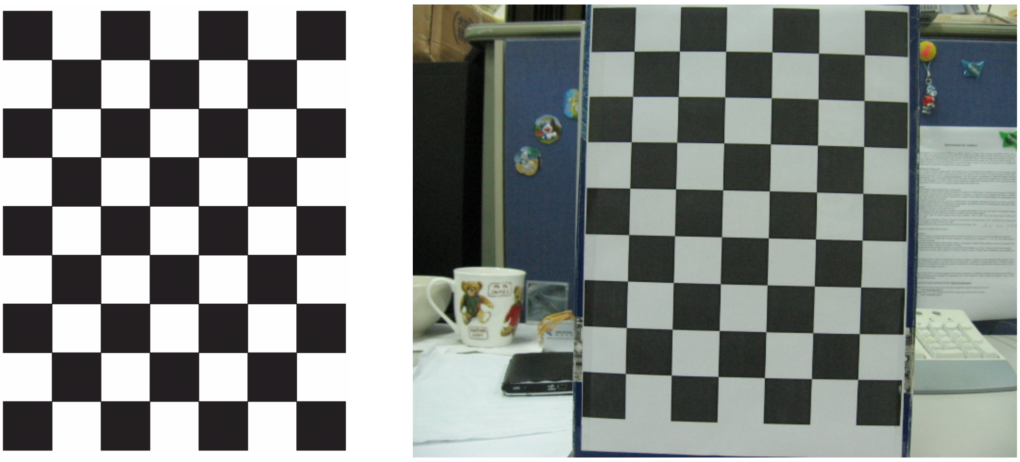
where ***CM*** is the camera matrix containing the intrinsic camera parameters.

However, if the input data are received without the hardware information of the camera, it is hard to obtain the intrinsic camera parameters directly. Therefore, several engineers from the institute of robotics and mecharonics release a Matlab toolbox for camera calibration [12] freely based on the model constructed from [6]. In next section, the basic example will be taken to let everyone learns how to use the features of the toolbox.

2.3 Matlab Toolbox for Camera Calibration

In order to obtain the intrinsic camera parameters directly from the input images, the Matlab toolbox for camera calibration is released freely based on the algorithm proposed by Heikkilä and Silvén [6]. In this section, the camera calibration toolbox is introduced to obtain the intrinsic camera parameters by capturing the reference pattern from arbitrary distance, directions and angles.

At the beginning of all the undistorted steps, the checkerboard-like image formed by several white and black squares is used as the reference pattern to be calibrated shown in Figure 2.2(a). After capturing the reference pattern by the camera to generate the reference images such as Figure 2.2(b), it can be seen that the shape of the squares are changed resulted from the lens distortion. Figure 2.3 shows several reference images obtained from arbitrary different distance, directions and angles for camera calibration.



(a) (b)

Fig 2.2 (a) The reference pattern (b) the reference image obtained from the camera

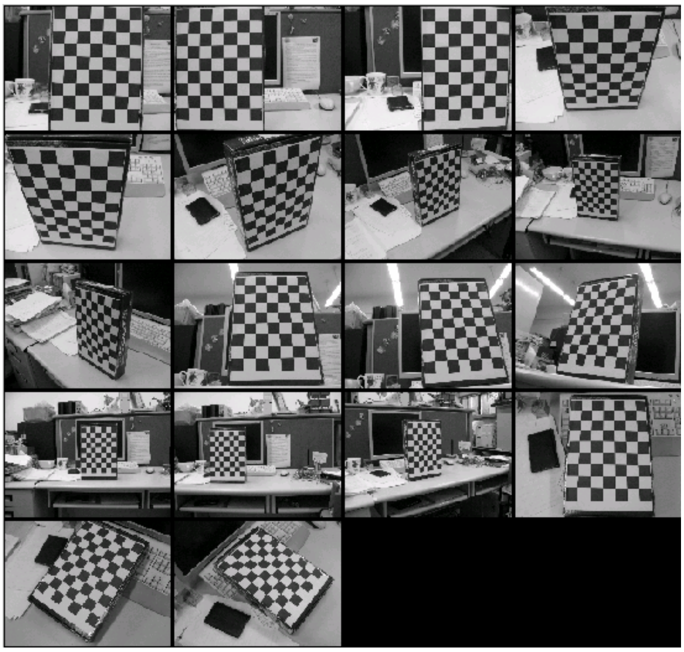
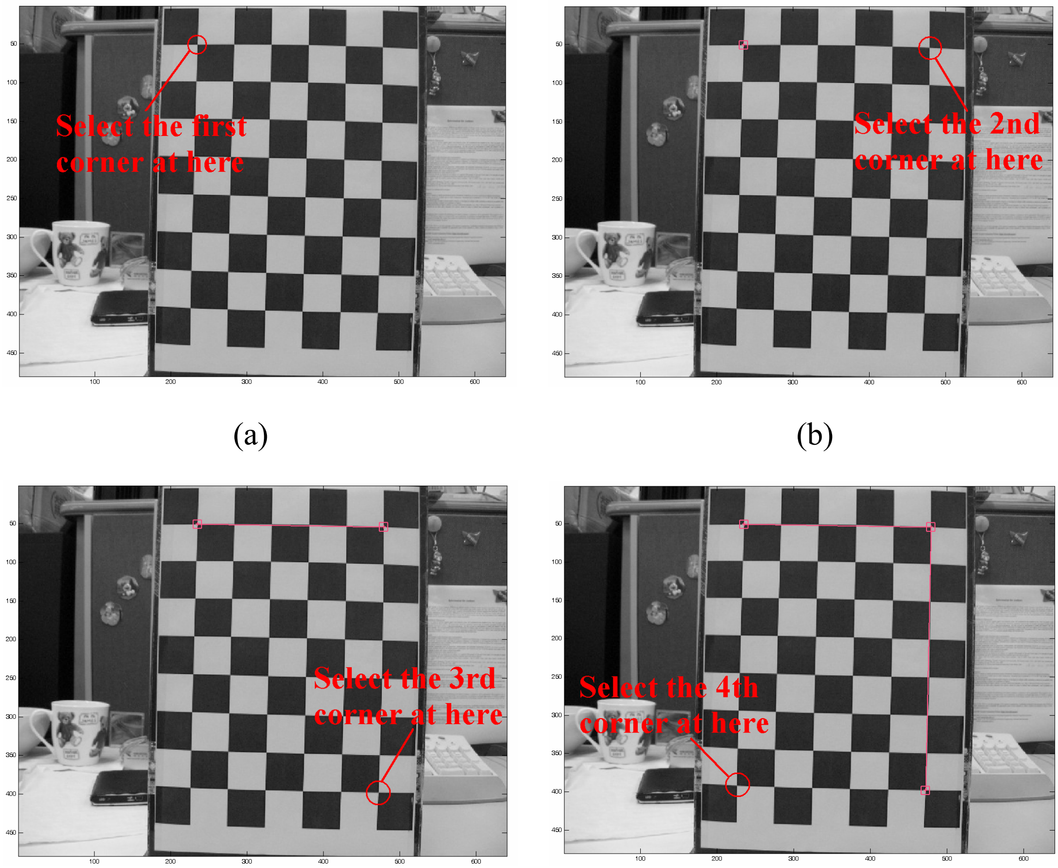


Fig 2.3 The reference images for camera calibration

After deriving all the reference images, it is required to extract the grid corners by clicking the four extreme corners on the rectangular checkerboard-like reference pattern in the reference image. The only thing which should be paid attention to is follow the ordering rules likes Figure 2.4 while doing the corners selection of all the reference images.



(a) (b)

(c) (d)

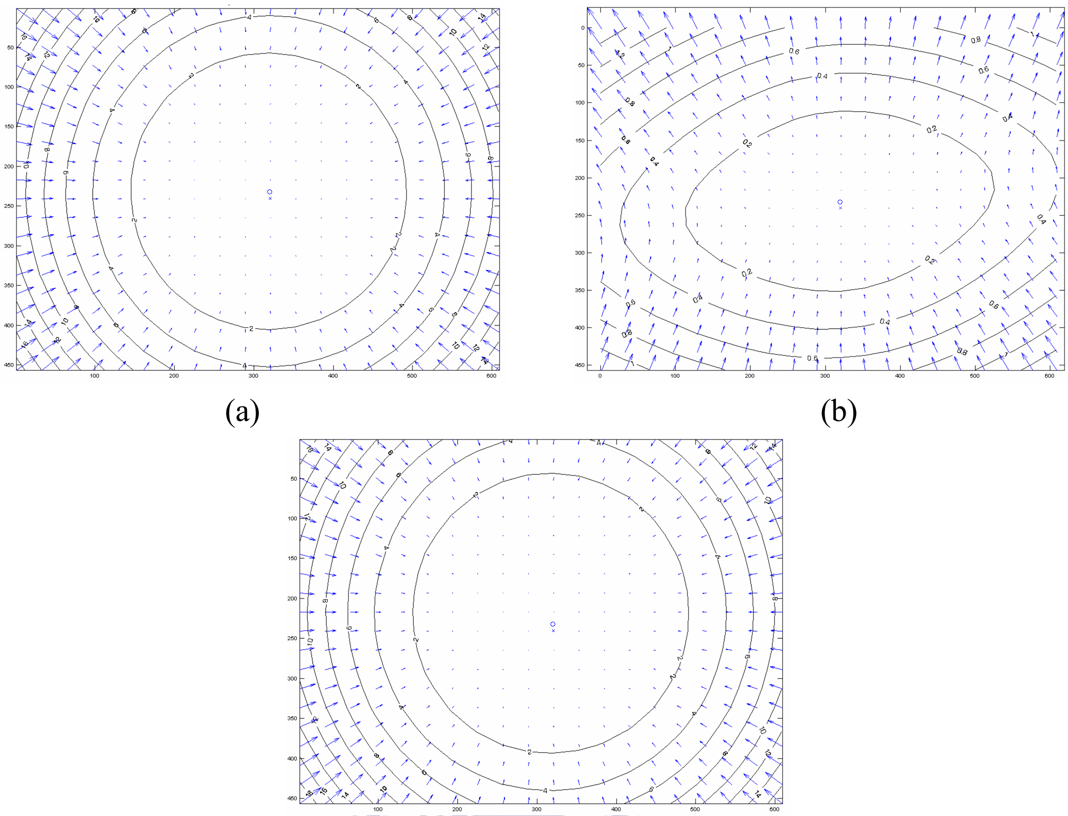
Fig 2.4 The ordering rules for corners selection

After performing the grid corners extraction and several corner regulation steps, the camera calibration procedures are employed to obtain the intrinsic camera parameters and the reprojection error shown in Table 2.1.

Table 2.1 The intrinsic camera parameters and the reprojection error

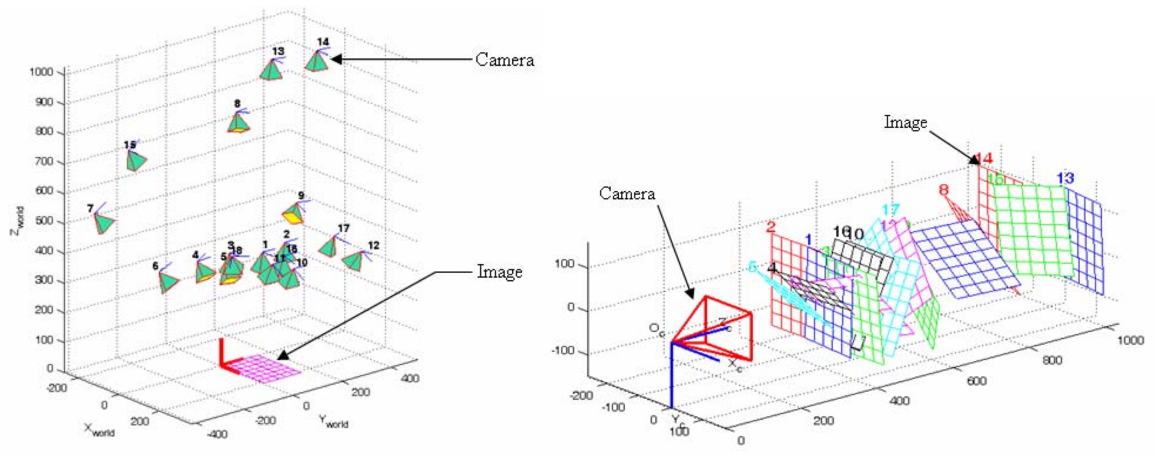
Focal length : $\boldsymbol{f}_c = [\, f_x \quad f_y \,]$	$[660.90926 \quad 660.72989] \pm [4.11542 \quad 4.43939]$
Principal point : $\boldsymbol{c}_c = [\, c_x \quad c_y \,]$	$[318.80117 \quad 231.14669] \pm [4.52952 \quad 5.24893]$
Skew coefficient : α_c	0
Distortion coefficients : $\boldsymbol{k}_c = [\, k_1 \quad k_2 \quad k_3 \quad k_4 \quad k_5 \,]$	$[-0.16915 \quad 0.08080 \quad -0.00301 \quad -0.00037 \quad 0]$ $\pm [0.01942 \quad 0.07917 \quad 0.00165 \quad 0.00156 \quad 0]$
Reprojection error :	$[0.24741 \quad 0.34478]$

While all the camera calibration procedures are finished, the distortion models and the estimation of the camera position are respectively shown in Figure 2.5 and Figure 2.6.



(a) (b) (c)

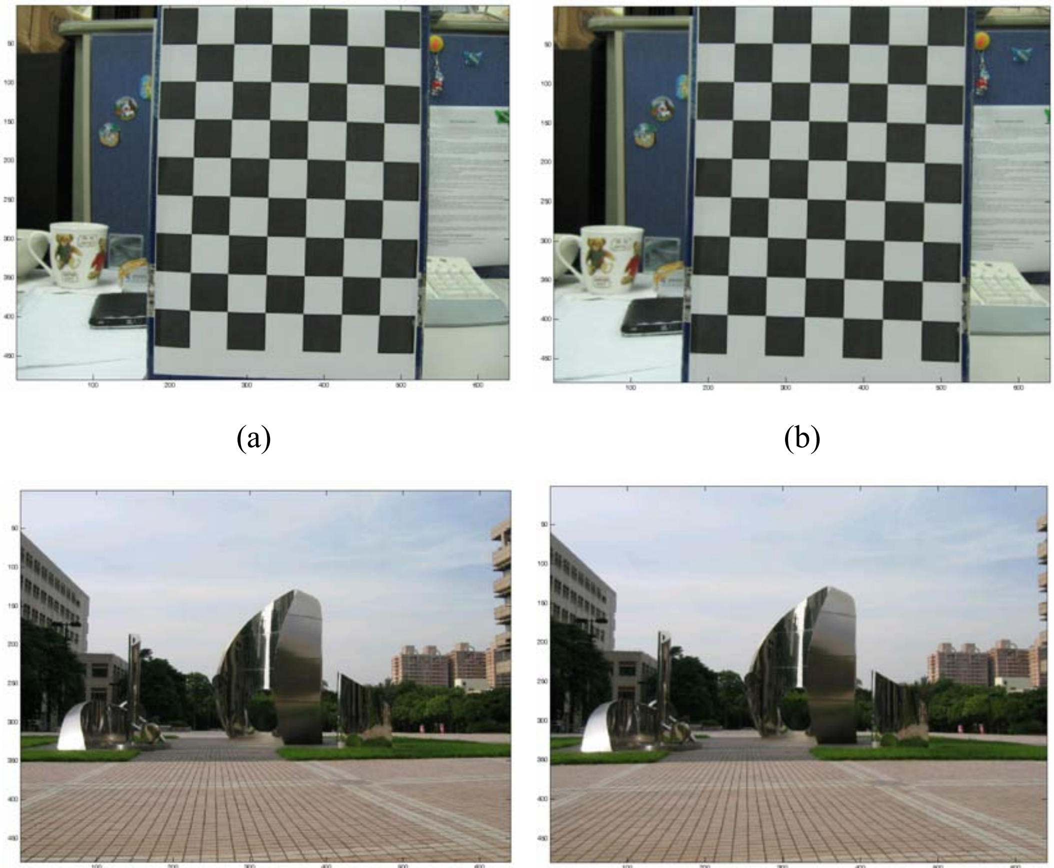
Fig 2.5 (a) Radial component of distortion model, (b) tangential component of distortion model, and (c) complete distortion model



(a) (b)

Fig 2.6 The estimation of the camera position (a) the world-centered view, (b) the camera-centered view

Finally, the reference images and other images taken from the same camera can be successfully calibrated according to the intrinsic camera parameters based on the camera calibration model and toolbox described above. In Figure 2.7(b), it can be seen clearly that the shape of the squares which within the region of the reference pattern are recovered after camera calibration. Furthermore, another images captured from the same camera also can be successfully calibrated such as Figure 2.7(d) by the same intrinsic camera parameters and camera calibration procedures.



(a) (b)

(c) (d)

Fig 2.7 The original images (left), and the undistorted images (right)

In this chapter, the camera calibration model and the useful Matlab toolbox are introduced to correct the lens distortion caused from the camera. After the camera calibration procedures stated above, all the undistorted images can be obtained as the input images for the image stitching process and make it successful with high performance.