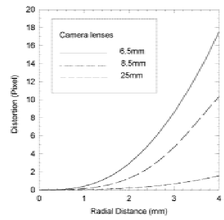
OMC Technical Brief – Camera Calibration

Camera calibration is all about getting the best geometric information from your images

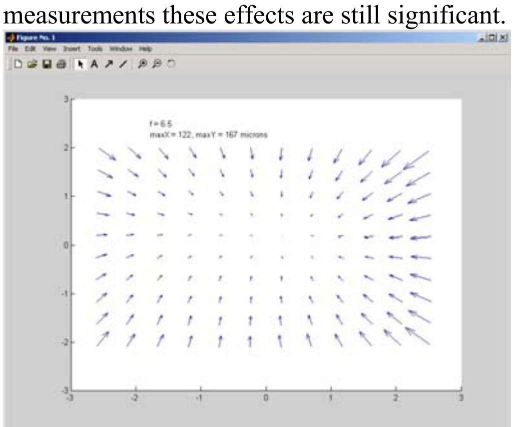


Introduction

Considering the importance of many image-processing applications it has always been surprising how few tools were available for measuring and then correcting image distortion. However, over the past few years the situation has improved. This technical brief reviews the historical development of camera calibration methods and models.

Recognising distortion in your images

The largest distortion that you are likely to encounter in a typical image is called radial distortion. The distortion in an image using fish eye lens is an extreme example. To check whether this is noticeable in your image look at any image where there is something straight in the scene (e.g. a building or a door frame) whether angled towards the camera or not. Check in the image to see whether this line is straight, if the line is bent the main culprit is radial distortion. You may notice that this effect is largest for lines near the edge of the image and negligible near the middle. In fact the distortion is just as strong for those lines but they are distorted along the length of the line and the effect is not detectable. Any other distortion in an image is unlikely to be easily recognised by eye, however, when images are used for geometric measurements these effects are still significant.



Distortion map for a 6.5 mm lens

The development of camera calibration techniques spans much of the past century and most of what can be known about the topic can be understood by reading the literature relating to photogrammetry.

Historical summary - how camera calibration models evolved

Photogrammetrists have extracted more geometric information from cameras than almost any other group. Applications are diverse, for instance, virtually all maps have been created from aerial imagery where the development of camera calibration methods derived from photogrammetric principles. Today cameras can be found measuring virtually everything and photogrammetric principles are often being used whether the end user is aware of it or not. Examples of typical objects for measurement are teeth, faces, feet, archaeology, aerospace wings, glaciers, buildings, tunnels, actors, art panel paintings, space vehicles, and surgical instruments.

It is interesting to note how photogrammetric methods have gradually evolved. In the first place, images of the ground were sufficient to produce maps. As film resolutions increased the need to correct for radial lens distortion became apparent. This was achieved by adjusting the true focal length to a new value that would evenly distribute the radial distortion throughout the image. Lens designs were created using this principle such that the distortion would oscillate about a mean value by no more than +/- 10 microns. As the integrity and accuracy of maps became more important following the World War II the effect of decentered lens elements was noticed. The biggest step change in calibration accuracy occurred when D. Brown developed both a simultaneous least squares method for solving camera model parameters and a better distortion model (which was rigorously derived to account for both radial and tangential distortion). The same model is still in use today and the method of computing the parameters for the model are essentially the same as they were in the late fifties and early sixties. In the intervening time electronic sensors have developed from being poor in radiometric and geometric terms to high resolution and radiometrically rich sensors that are geometrically excellent.

A model to correct most lenses for more than 95% of distortion effects

The mathematical model that has evolved does not have many terms considering its effectiveness. To understand the model it is necessary to define the meaning of the terms.

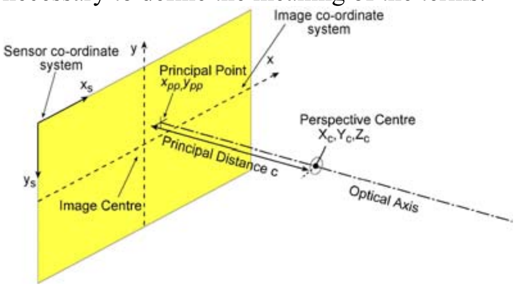
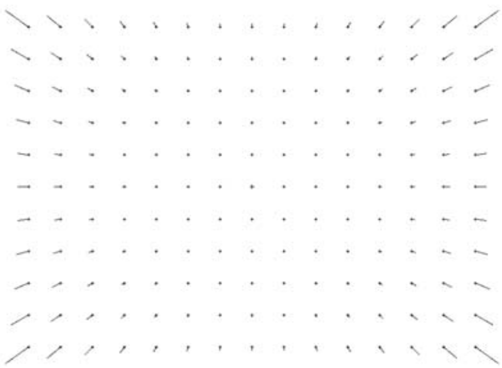


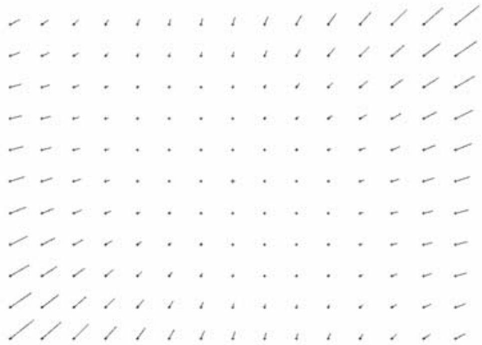
Diagram describing the terms used

Radial lens distortion is modeled by an odd series polynomial and is mapped about what is termed the principal point. The location of this point will rarely be in the centre of the image as the exact alignment of the lens and the position of the sensor are not usually considered important in the design of a typical camera. The number of terms used will depend upon the lens being used. One term will model that majority of the distortion but further terms usually refine the correction still further.



Radial lens distortion vectors for pin-cushion distortion – the grid represents the corrected image and the ends of the vectors the observed positions. In a map for barrel distortion the vectors would be pointing from the grid towards the principal point

The next most important element of the model concerns a correction to the non-symmetric elements of lens distortion caused by the lens elements not being perfectly aligned in the lens itself. The term commonly used is *tangential distortion* or sometimes *decentering distortion*. The magnitude of tangential distortion is typically about 15% of the size of radial distortion.



Tangential distortion vectors

The final part of the model takes into account any difference in the size of the pixels in **x** and **y** and also any non-orthogonality in the image.

	Params	Equations
Radial distortion	R_{xy}	$K_1r^3 + K_2r^5 + K_3r^7 + ...$
Tangential distortion	T_x T_y	$P_1(r^2 + 2(x - x_{pp})^2) + 2P_2(x - x_{pp})(y - y_{pp})$ $P_2(r^2 + 2(y - y_{pp})^2) + 2P_1(x - x_{pp})(y - y_{pp})$
Scale difference in x	a_x	$A(x - x_{pp})$
Non-orthogonality	b_x	$B(y - y_{pp})$
Radius	r	$\mathrm{Sqrt}\ ((x – x_{pp})^2 + (y - y_{pp})^2)$
Corrected x position	$x_{corrected}$	$x_{old} - x_{pp} + R_{xy} + T_x + a_x + b_x$
Corrected y position	$y_{corrected}$	$y_{old} + y_{pp} + R_{xy} + T_y$

All the components of the mathematical model

Level of accuracy required across whole image (pixels)	Model parameters required	Comment
0.5 - 2	Modify c to average distortion	Gross lens distortion removed
0.2 - 0.5	c, K_1	Next level of distortion removed
0.15 - 0.3	c, x_{pp}, y_{pp}, K_1	Improvement due to principal point location
0.08 - 0.15	c, x_{pp}, y_{pp}, K_1, P_1, P_2	Decentering distortion added
0.04 - 0.08	c, x_{pp}, y_{pp}, K_1, K_2, K_3, P_1, P_2	Higher order lens distortion terms
0.01 - 0.04	c, x_{pp}, y_{pp}, K_1, K_2, K_3, P_1, P_2, A,B	Sensor orientation parameters required

Approximate indication of which lens parameters to use to obtain a given accuracy - note each lens is different and so no absolute advice can be given

Methods for estimating the distortion parameters

The model discussed so far is able to correct for the vast majority of lens distortion. The problem that the user is faced with is how to estimate the value of these parameters. Most methods work by varying the parameters to minimise difference between an object shape and its projection onto the image. When the minimum difference is obtained the resulting set of parameters will describe the distortion of the lens at the focal setting being used. Suitable 3-D objects can vary from straight lines or a planar grid of points.

In one simple method, which uses straight lines, there is no need to know the size or separation of the lines as long as they are straight. There is also no need to compute the camera's position with respect to the lines. It is not possible to estimate with any degree of accuracy the centre of the image (the principal point) or the focal distance (the principal distance). For most purposes though the calibration will be good enough.

Other schemes use planar objects such as one or two boards with a pattern of squares. Images of the boards are taken from varying directions. The intersection of the corners of the squares identify points that can be uniquely recognized in each image. The scheme works by estimating the 3-D location of all of these points as well as the camera location with respect to each image. The 3-D points are projected into each image and the final calibration results in the principal distance and the principal point being determined at the same time. See OMC's camera calibration software for further details of how we calibrated cameras.