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Review of techniques for 2D camera calibration suitable for industrial vision systems

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Abstract. In camera calibration the goal is to determine a set of camera parameters that describe the mapping between 3-D reference coordinates and 2-D image ones. Correction for image distortion in cameras is an important topic in order to obtain accurate information from the vision systems. A review of calibration techniques for the vision systems is presented among the different methods for camera calibration found in literature. The advantages and limitations of these techniques are also discussed. This work analyzes the techniques that can be useful in modern industrial context with the aim of knowing the effective distortion of the lens and the possibility to determinate the measurement uncertainty of the vision system.

1. Introduction

The industrial vision systems are widely used in many different applications: part identification of complex systems, defect inspection, Optical Character Recognition (OCR) reading, 2D code reading, pieces counting and dimensional measurement. If the system is used for measurement applications, it is necessary to calibrate preliminary the vision system. In industrial applications the most of the calibration procedure is generally devoted to the identification of pixel/mm ratio. In fact, many other optical problems can occur, like chromatic aberration, aberration of axial points, astigmatism, coma and distortion of the image. In particular, the distortion of the image is the most diffused error in image acquisition and elaboration. Usually, the top class industrial vision systems have in their software suite some tools to correct the effect of distortion of the images. The results of their application generally are satisfactory, but often it is impossible to know about the method for the characterization of the vision system, about the characteristics of the optics or about the uncertainty of the system. This problem is very important in case of critical situations (validation of very tight geometrical tolerances or research applications). In literature some methods for the camera calibration are described, which are different from the point of view of the methodology and of the parameters they take into account.

The aim of this paper is to review literature techniques for 2D camera calibration and to discuss some comments on these methods and on their suitability for industrial vision systems. All the most important methods will be described and explained, with reference to the optics features and their capability of facing optical problems. In the paper the comparison and evaluation criteria of the methods will be experimentally validated with reference to the Zhang method, applied with a commercial high performance Camera Calibration tool, acting on images of a Omron industrial vision system. Finally, the guidelines for an on-line industrial implementation of algorithms based on these methods will be also analyzed.



2. Industrial vision systems applications

During the years the number of applications in industrial contests is more and more increasing. This trend has been made easy by the combination of many factors: the reduction of the costs of the vision systems, the easier software implementation and maintenance of vision systems, the revamping and optimization of the production line, in compliance with the “zero-defect” approach. All the present time, most applications are still based on grayscale systems. Furthermore, for a large number of kind of inspection tests the algorithms are based on binary images. In these cases, it is necessary to convert the RGB image, acquired by the vision system, into a grayscale image and then to a binary one. For the transition from grayscale to binary image a threshold value of the gray level should be set, that divides the pixels that will be converted in white pixels from the pixels that will be converted in black ones. These functions are generally included in the software tool of the vision system. The dimensional measurements are usually based on the identification of the pixels describing the contour of the piece, then calculating the difference between the pixels’ position on the borders of the object under inspection. Anyway, the most common, simple and accurate technique of inspection is based on binary images.

3. Review of the calibration methods

In cases the vision systems are used for measurement applications, to calibrate preliminary the vision system is mandatory. Generally, in industrial context the calibration procedure is based on the identification of the pixel/mm ratio. This parameter is fundamental for the correct evaluation of the dimension of an object under inspection, but it is not the only parameter to check. In effect many optical problems can occur, in particular, the distortion of the image is the most diffused in image acquisition and elaboration and remarkable measurement errors can arise.

In literature some methods for the camera calibration are described. Due to the lack of information, it is likely that the tools of the industrial vision system used are among these. In the following the main literature techniques for 2D camera calibration will be reviewed, putting in evidence any comments and observations useful to discuss their suitability for industrial vision systems; aspects concerning the optics features and their capability of facing optical problems on-line are also discussed. In order to make the examination of the existing methods more complete, in the following section a procedure to obtain the calibration parameters is presented, based on a high performance commercial tool (Matlab).

3.1. Plumb line method

Brown [1] proposed a first experimental method to calibrate an optical system used for measurement aims. This approach, named *plumb line method*, assumes the lenses are perfectly symmetrical only at the design stage, but not in their manufacturing. The previous method like the stellar calibration, explained in the same reference, does not allow for a precise calibration because it considers in the mathematical model the lenses to be perfectly symmetric. This more realistic assumption causes the necessity to implement a mathematical model and then a practical model for camera calibration. The method needs to determine at least 10 parameters: 8 parameters of the inner cone of the lens and 2 parameters for each of the calibrated lines. In reality the lines used to calibrate the system are generally 7. Although this method is the first to be proposed for calibration of optical systems most of the aspects to be taken into account (lens geometry and characteristics, camera model) are considered; therefore, the uncertainty calibration according to this method is very satisfactory. In his paper, Brown defines a formula which could accurately model radial distortion at a range of different focal length settings. If the radial distortion parameters at two separated focal distances are known, the values for all settings between them may be accurately found. Furthermore, the method specifies the formulas for radial distortion within the photographic field of view. This is only of significance for close range camera applications. In effect, if a camera is focussed for a particular finite distance, targets at different distances will display slightly different quantities of radial distortion. The advantage of this method is the high measurement accuracy achievable (± 0.5 mm with a camera at 2 m of distance from the target), that it is comparable to the accuracy of the best technique proposed in this review. The

disadvantages of this method are the occurrence of a manual determination of the points necessary for the calibration (this could be a problem in an automated system), the needs of computer-intensive full-scale nonlinear search and the complexity to determine the real principal point as offset from the ideal axis of the lens. Some similar methods are proposed in [2-6] and the results are similar to [1]. A revolution in the close range photography was made by the introduction of cameras based on Charged-Coupled Device (CCD) sensors that allow to have directly digital images: the new devices are much smaller respect the full frame film and then the resolution of the images is less accurate. Brown's idea was developed by Clarke, Fryer [7] and Chen [8] in the 90's. In fact, these papers, apply the plumb line method in a new context. The principal innovation in these works is that only the first term of the polynomial function of the radial distortion is considered because the resolution of the images is linked to the pixel dimension and it is not necessary to study all the terms of the calibration function. This assumption is in agreement to another branch of study in camera calibration named Direct Linear Transformation (DLT) proposed by Abdel-Aziz and Karara [9].

3.2. Two stage method

Tsai [10] proposed a new algorithm for camera calibration named *two stage method*. The work starts from the same camera model considerations theorized by Brown [1], but the aim of the paper is the characterization of a real time procedure for camera calibration. The calibration procedure needs a calibration pattern composed by some black squares on white background. The procedure needs to identify the corner of the black squares. Others type of pattern can be used with the same procedure. The accuracy of the pattern is a contribution of uncertainty. After the acquisition of one image, it is possible to apply the two stage method. The first stage is useful to compute the 3D orientation and position of the pattern and to compute the scale factor. In the second stage it is possible to compute the effective focal length, the distortion coefficients and the position of the pattern on the z axis. The limit of the two stage method is based on some simplification in the camera model (called pinhole model) and the experimental results are in several cases less accurate than for others methods. The achievable uncertainty of the system can be in order of ± 1 mm with a camera at 2 m of distance from the target. An extension of this method was developed by Heikkila [11] that combines the two stage method with the DLT ones. The results of this method are discussed in the following subsection.

3.3. Direct Linear Transformation methods

Abdel-Aziz and Karara [9], Clarke and Fryer [7] and Chen [8], Sturm [11], Heikkila [12-13] proposed several methods for camera calibration based on the DLT assumption. That hypothesis presents a simplified model based only on linear equation for radial and tangential distortion and is in practical equivalent for real camera calibration to the complete model. Clarke, Fryer [7] and Chen [8] use the DLT method to simplify the algorithm of the Plumb Line Method. Sturm [11] proposed an algorithm similar to the plumb line method but based on a particular 3D calibration pattern composed of 3 different planes with calibrated white dots on black surfaces. This method reaches a very low uncertainty also without knowing the principal point of the image, the focal length, the aspect ratio and without considering the skew factor. This method is very simple to implement and very general too, but it is necessary to have a specific and very accurate 3D calibration pattern. Some similar methods are proposed in [14-16], and the results are similar to [9]. The most accurate methods based on the DLT simplification are [8,11] and the achievable uncertainty of the system is in the order of $\pm 0,6$ mm with a camera at 2 m of distance from the target. Heikkila [12-13] combines the two stage idea with the DLT and proposed a new method called "four step calibration procedure". Also in this case a specific 3D calibration object with 256 white dots on each face and a black background has to be provided. In the first step the camera parameters are calculated using a DLT method and the lens distortion is assumed to be insignificant; the focal length and the image center are known. In the second phase, the camera model is applied in compliance with the two stage method and a least square estimation technique is used to calculate the camera parameters. In the third phase, the error caused by the asymmetry of the dot projections is compensated and an estimate of the camera parameters is

recalculated. The last step is the “image correction”; in other words, all the others unknown parameters, not calculated due to simplification in the camera model or in the DLT method, are now synthesized in a couple of values used to correct the center point of the camera. These values are calculated with a specific formula based on the inverted camera model. The achievable uncertainty of the system is in order of ± 0.07 pixels that correspond at ± 0.02 mm with a camera at a distance of 0.5 m from the target. The empirical correction allows to find the camera parameters for the calibration with a very good approximation but the method appears very difficult to be applied in industrial context being based on a 3D calibration pattern.

3.4. *Unknown orientations plane*

In the end of the 90s, Zhengyou Zhang studies a different technique of camera calibration [17]. He proposed a procedure that requires only a simple planar pattern (cheaper respect to a 3D pattern) based on black squares on white surface, which can be also printed with a laser printer. The quality of the pattern is of concern in the uncertainty budget, but in a lot of cases a good calibration can be achieved also with a printed pattern. The only request of this technique is the necessity to observe the pattern at different orientations (at least two, but in our experience it is better to use almost 15 orientations because this is also a contribution of uncertainty). The most interesting aspect of this method is that is not necessary to know the original distance or orientation of the pattern from the camera neither the motion during the calibration. The found calibration parameters are very similar to the ones calculated by Brown [1] or Tsai [10] methods, but the calculation procedure is based on the maximum likelihood estimation. This statistical approach is possible because there are some different views of the same pattern. This way the approach introduces another contribution of uncertainty. Therefore, this method isn't the most accurate, in fact the achievable uncertainty of the system is in order of some tenths of pixel but it results to be very quick and flexible; the pattern is cheap and then can be easily applied in industrial context. For these reasons in the authors' opinion these methods can be evaluated the best in compliance with the aim of this paper.

3.5. *Others*

The problem of camera calibration was analysed by others researchers that find several solutions also with a large amount of experimental results. These solutions are related to a specific problem of camera inspection in certain situation like high-speed tensile testing machine [18], guide unmanned vehicles [19], surface profiling applications [20] or older joint analysis [21].

4. **Camera calibration in Matlab**

In the paper the comparison and evaluation criteria of the methods will be experimentally validated with reference to the Zhang method, applied with a Camera Calibration toolbox for Matlab [22] acting on images of an Omron industrial vision system.

This toolbox is available on the web and recently has been included in Matlab Computer Vision System Toolbox [23]. The last version has been developed with a specific app to guide the user in a camera calibration. The application can use online camera or some images acquired previously. The steps in compliance with Zhang method are acquisition of several images with the calibration pattern in different positions, extraction of the corner of the black squares of the pattern, calculation of the calibration parameters. In output the system gives back all the information with their uncertainties like focal length, principal point, skew, radial and tangential distortions. By this way, it is possible to use the results of camera calibration to automatically correct future images acquired with a self-generated Matlab script. Our experimental equipment (Fig.1) are composed by Omron FZ-SC2M camera and VS-1214V optics, 2D calibration pattern and the elaboration are made with Camera Calibration toolbox for Matlab [22]. The acquired images (Fig. 2) are imported to Matlab and elaborated with Camera Calibration toolbox. The corner extraction is made manually in compliance with the toolbox procedure. The automatic elaboration gives back us the results synthesized in the bottom of Fig. 3. In

the upper part of Fig. 3 the effect of radial distortion on the CCD pixels is shown. For simplicity only the radial distortion has been taken into account.

The Omron FZ-SC2M camera has a CCD resolution of 1600 x 1200 pixels being a high-end quality camera for industrial applications. The optics used has also a very good quality and the calibration results

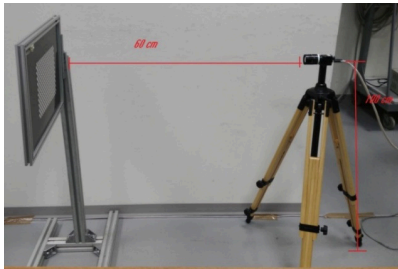


Figure 1. Experimental equipment.

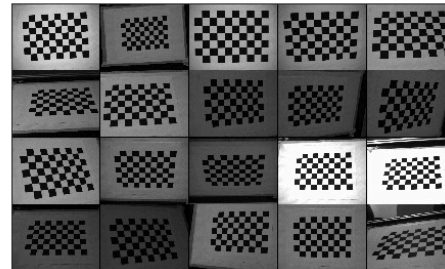


Figure 2. The acquired images.

confirm the expectation. Nevertheless, each optics is a single piece, because the lens is very difficult to manufacture. The optics under calibration has a theoretical centre (also named principal point) in the pixel 800 x 600 (at the centre of the CCD), in fact the real principal point is in pixel 818 x 599. This error, if not correctly evaluated, can generate a measurement error in order of 1.1% on the horizontal axis. Another very interesting result for our purpose is the radial coefficient; this figure represents the mean pixel error due to the curvature of the lens. The mean value is quite contained (in order of -0.1 pixels) thanks to the high manufacturing quality of the lens, but at the edge of the lens it can be three orders of magnitude higher (in order of 10 pixels), in particular on the left edge. This error probably is a combination of two different situations: the distortion of the lens and the error on the principal point. The sum of these two error, if not correctly evaluated, can generate a measurement uncertainty in order of $\pm 1.5\%$. Otherwise with calibration of the lens the uncertainty contribution of these factors is limited to the uncertainty measurement of the radial coefficient, that is one order of magnitude lower (0.01 pixels). Another important contribution in the uncertainty budget is the pixel error or in other words the maximum error of discrimination on one surface, due to the pixel dimension. In this case the pixel error is 0.35 pixels on the horizontal axis and 0.39 pixels on the vertical one. Generally, in a high quality calibrated vision system this is the main contribution to the uncertainty budget of the system.

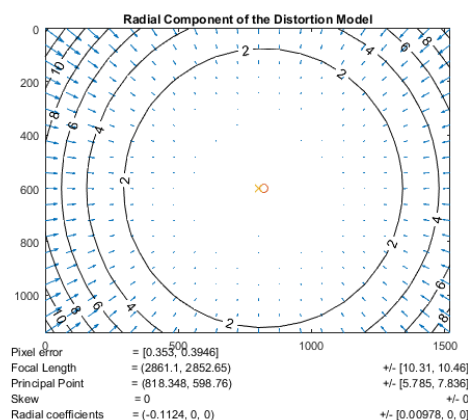


Figure 3. Radial distortion and calibration results.

5. Discussion

The existing activities of camera calibration have been discussed. For each method advantages and limitations have been identified and analysed. Some comments have been provided, concerning the

suitability of using the methods in industrial context. The Zhang method has been extensively investigated and appears to be a good choice for camera calibration in the industrial context. A possible practical solution based on the Matlab toolbox is presented with an experimental test. The main advantage of applying this method is the possibility, after the calibration, to assign an uncertainty to the measure obtained by the vision system. This is very appealing in customer-supplier relationships for companies operating with certified quality management system. The guidelines for an on-line industrial implementation of algorithms based on these methods have been also analysed. The results are encouraging and foster further research.

6. Future work

As a natural follow up of this work, an implementation in an industrial context will be carried out. Generally, the limitation of Matlab algorithms is the difficulty of using them in real applications. However, in this case a “black box” tool, receiving in input the raw image and providing in output the image corrected with the calibration parameters, can be devised. A Matlab Compiler SDK, capable to convert the Matlab code in C/C++, has been recently released, and this will allow implementing this method in the common industrial software based on C/C++ languages.

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