Optics & Laser Technology 42 (2010) 628–639

Contents lists available at ScienceDirect

Optics & Laser Technology

journal homepage: www.elsevier.com/locate/optlastec

Correcting non-linear lens distortion in cameras without using a model

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ARTICLE INFO

Article history:
Received 20 February 2009
Received in revised form
4 September 2009
Accepted 5 November 2009
Available online 27 November 2009

Keywords:
Lens distortion
Image warping
Distortion models

ABSTRACT

Camera lens distortion calibration is the first step in resolving any metric application with a camera. To date, lens distortion was corrected using some existing lens distortion non-metric or self-calibration methods. Using a lens distortion model means defining a global rule to correct the entire image. This global rule does not take into account particular lens distortion effects not represented by the model. Moreover, to calibrate the model, only some features of the scene such as straight lines, circles or vanishing points are used. Since only the feature of the scene used to calibrate the model is guaranteed by the distortion rectification, it is certain that the model will not be precise. The result is an approximation of the real image distortion.

To improve the lens distortion rectification, a method without using a model is proposed. Using a set of control points distributed across the entire image, they are corrected to assure all the restrictions of the scene. With both sets of points, the points detected in the image and the undistorted ones, image local transformations are defined considering only nearby control points. Rather than calibrating a global model, local functions are characterized. The distortion correction is defined by a rectification surface composed of local surface patches each influenced by nearby control points. This method is more sensitive to local deformations and allows the image to be corrected in accordance with its distortion.

1. Introduction

A considerable volume of recent research has underlined the benefits of wide-angle and Omni directional cameras in computer vision tasks. With a wide field of view, problems such as ego motion estimation, structure and motion recovery, and self-calibration are better conditioned, yielding more accurate answers with fewer images than are required with narrow-field of view perspective cameras. On the other hand, narrow-field of view perspective cameras require careful assembly and pre-calibration before they can be used for 3D reconstruction. With the advent of variable focal-length wide-angle cameras and lenses, such pre-calibration is very difficult to achieve. In addition, many practical applications involve measurements with the image and they need the geometry of the lens. In all these cases camera lens distortion should first be modelled in order to resolve the deformation of the image.

Camera lens distortion was first introduced by Conrady in 1919 with the decentring lens distortion. Afterwards, Brown [2,3] proposed the radial, decentring and prism distortion model which has been widely used [4–7]. Some modifications to this model have been reported, focused on mathematical treatment of the initial model [8–13], or from a conceptual point of view, without any quantitative evaluation [14]. Recently, a non-parametric model for camera distortion has been proposed [15], which only considers radial distortion. Although the radial component of lens distortion is predominant, it is coupled with the tangential component and therefore this should be taken into account. In fact, the basic formula that represents the conventional model of lens distortion is a sum of three terms corresponding to the radial, decentring and thin prism components. If wide-angle or Omni directional cameras are used, high order terms of radial, decentring and thin prism components are used, which do not represent image deformation completely. In this case, [9,7] have defined specific models for fish-eye lens distortion, which try to mimic the effect of the distortion in the image rather than represent it using a high number of radial and tangential distortion terms.

To compute the camera distortion model only, several methods have been proposed that do not rely on any knowledge of the scene points, nor do they need calibration objects or any known structure. They are called non-metric calibration or self-calibration methods. These methods use geometric invariants of some image features such as straight lines [3,7,16–18], vanishing points [19] or the image of a sphere [20]. Methods such as [3,7,16–18] rely on the fact that straight lines in the scene must

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doi:10.1016/j.optlastec.2009.11.002

always be perspective projected on straight lines in the image. In addition, Becker and Bove [19] use the minimum vanishing point dispersion constraint between three mutually orthogonal sets of parallel lines to recover the distortion parameters. In this case, the inconvenience of the method is to find triplets of orthogonal lines. Other methods use correspondences between points in different images from multiple viewpoints to compute camera distortion parameters [21–23] or they are based on the fact that lens distortion introduces specific higher-order correlations in the frequency domain [24]. They are not easy to solve and are likely to produce false data in the distortion algorithm.

From a practical point of view, if camera lens distortion is to be calibrated, choosing the right model and calibration method is a difficult task since several models exist and different calibration techniques compute them. The state of the art classify them according to some criteria of better results computed under some conditions but finally, none of them will represent the image deformation exactly, even with calibration data. Although data noise affects the calibration process, geometric restrictions of the scene will never be true after deformation correction regardless of the distortion model computed. The image deformation will always contain some kind of distortion that cannot be represented by the chosen model, or the calibration method will only take into account some specific feature of the scene, discarding the others. In the end, the image is warped using a global transformation mapping function represented by one of the distortion models. These distortion models will never reflect the real distortion in each part of the image since they are a global approximation according to a specific criterion, such as straight lines for example. In practice, straight lines will be straight if a method that uses this restriction is used, but if these straight lines are also parallel, distortion correction will not guarantee that this geometric restriction will be present in the scene. Distortion models and calibration methods are defined as good if they just satisfy a very specific restriction of the scene in the image. From our point of view, robust distortion correction methods are those that satisfy all geometric restrictions of the scene elements, and the state of the art have methods that considers a just very specific restriction only.

In this paper we propose a method for lens distortion correction that uses all the geometric restrictions that are included in a standard chessboard pattern. They are straight lines, parallelism and perpendicularities. Since a chessboard is going to be used in the pin-hole calibration process, we propose using this information prior to calibrating the lens distortion. In this way, the camera calibration should be understood as a two-step procedure where first the camera lens distortion is computed and corrected and, second, the pin-hole camera model is calibrated. With the distortion correction method proposed in this paper, camera lens distortion can satisfy a number of geometric restrictions of the scene without the risk of instabilities of computing a mathematical model. It has been reported [3,17] that including both the distortion centre and the decentring coefficients in the non-linear optimization may lead to instabilities of the non-metric lens distortion estimation algorithm. To avoid this, some researchers (e.g. [17]) used an exhaustive coarse-to-fine search for the distortion centre around the image centre but in the end, it has resulted in a prolonged search with no guarantees of stability [18]. To avoid instabilities and obtain a perfect correction that includes all kinds of distortions (modelled and not modelled), the image is warped with a local transformation using the original set of points extracted from the image and the undistorted points, which accomplish all restrictions contained in the calibration template. Warping the image following no distortion model allows the handling of local deformations that do not respond to any distortion model. With this method, image warping has more degrees of freedom allowing the distortion to be corrected according to the particular deformation of each image region.

The proposed method relies on the idea that an image of a structure maintains its proportions according to a perspective projection. Therefore, there are different magnitudes within the structure that are fixed independent of the position, orientation and characteristics of the camera that takes the image. If the structure has parallel or orthogonal lines, these orthogonalities and parallelisms are kept fixed according to a perspective projection. What is proposed in this paper is a method for correcting the detected points in the image to fulfil restrictions given by the features of the structure, and to warp the image using these two sets of points, the points detected in the image and the undistorted ones. From the point of view of the pin-hole model calibration, this method is very useful since fully structured templates such as chessboards are used to resolve them. This means that the same information can be used to calibrate the lens distortion before the camera is calibrated.

This paper is organized as follows. Section 2 proposes the bases of the image correction method. These are the geometric invariants of a structure, independent of perspective projection and how the location of the set of points in the image is corrected. Section 3 shows how the different camera lens distortion models do not satisfy the geometric restrictions of the scene independent of the calibration technique. Section 4 derives the image warping using both sets of points. Several experimental results from both real and simulated data are reported. The paper ends with some concluding remarks.

2. Geometric invariants

A robust image distortion correction method will satisfy the greatest number of geometric restrictions of the scene. Up to now, lens distortion calibration methods guarantee straight lines. The aim is to correct the image ensuring more restrictions than straight lines only. A full set of restrictions is defined in this section. If we follow the perspective camera model, the position of the points in the images would be given by the perspective projection of these points in the scene. Thus, if points in the scene fulfil some ratios and restrictions between them, the same ratios and restrictions will be true in the image of these points, taking into account their perspective projection. Therefore, to get the right position of these points in the distorted image, it is necessary to known these ratios and restrictions in the scene, and to try to make them true for these distorted points. The result must be a new set of points that guarantee this set of restrictions perfectly. When both sets of distorted and undistorted points are known, it will be possible to adjust the transformations to correct the image.

Therefore, the key is to define the right ratios and restrictions of these points in the scene. Since the perspective projection is unknown a priori, these ratios and restrictions must also be invariants with the perspective projection. These invariants make possible to undistort the point's positions in the image without knowing the perspective camera model. To define the restrictions easily, an image of a regular structured scene must be taken. Thus, if the structure has an equal ratio and restrictions between predefined points, both should be true when all the right positions of all the distorted points in the image will be found. If no regular structures are used, different metrics should be used to correct the distorted points in the image. To make it easier, the chosen template is the "*chessboard*" shown in Fig. 1 since ratios between different corners are equal and a set of corners form straight lines that are parallel and orthogonal between them. In addition, this