Automated Center of Radial Distortion Estimation, Using Active Targets

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Abstract. In this paper an automated center of radial distortion estimation algorithm is explained. The method applied to the development of an autonomous camera calibration algorithm. The idea of active targets, which are controlled by calibration algorithm is the key to the autonomy in this work.

The proposed method decouples the center of radial distortion from other calibration parameters. It is shown that the proposed method approximates the center of radial distortion correctly. Also it helps to the accuracy of calibration framework.

1 Introduction

Lens distortion is part of calibration process. The research on lens distortion can be traced back to 1919, when decentering distortion was introduced [1]. Decentering distortion consists of radial and tangential components. However, different distortions can be present, tangential, radial, and thin-prism. Each distortion is described using a model.

There has been lots of research on different distortion models. In fact, there are various assumptions about the lens model in calibration process.Tsai[2] assumes only radial distortion is present. Weng et al.[3] assumes the presence of radial, decentering, and thin-prism. There are also methods that assume no distortion[4]. It has been shown that the first coefficient of radial distortion is enough for most of industrial applications[2]. As a matter of fact, the research has been focused on radial distortion model, and different models has been proposed for the case of radial distortion such as polynomial models, rational model [5] and FOV model[6]. The simple polynomial model[3] is the most popular model. However, there exist extensions to the polynomial model, such as division model[7], cubic rational polynomial model[8] and rational polynomial model[9].

A radial distortion model with known center of distortion is equal to decentering model as there is no need for worrying about tangential distortion[10]. In comparison to decentering model, there are fewer parameters to estimate. Also

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the model is more complete than the radial distortion model because of considering tangential displacements. In consequence radial distortion with known distortion center is more accurate than radial and decentering models.

In most of radial distortion models the center of image[11] is considered to be the center of radial distortion. However, it is possible to estimate the actual center. In order to estimate the center of radial distortion, it is possible to initialize center of radial distortion to the center of image and later optimize these values with other camera parameters obtained in the camera calibration process, but it can result in non-optimum results. Avoiding non-optimal result, Devernay and Faugeras[6] suggested optimization of radial distortion coefficients first and then extending the optimization to all of the parameters including center of distortion. Tardif et al.[12] provided a new constraint optimization criteria which eliminates the risk of non-optimum result. Hartley and Kang[13] introduced a method that can estimate the center of radial distortion with the use of fundamental matrix.

In this article a method of center of radial distortion estimation is introduced. The proposed method decouples the center of distortion from other parameters. The proposed method is rooted in the active target idealogy. It would be shown that the method estimates the center of distortion accurately.

In the next section active target is explained. the third section is devoted to the center of radial distortion estimation algorithm. Section four explains the experiments followed by the conclusion.

2 Active Target

Active target concept can be confused by active calibration. The key difference is the interaction style. Active camera calibration mechanisms interact with the environment by camera movements[14], and have gained attention in the field of robot vision; such algorithms' examples could be found in[15,16].

All the methods of calibration, such as Tsai[2], Weng et al.[3], Zhang[17], and Heikkila[18] where active camera is not present can be categorized as passive calibration methods. None of them has interaction with the calibration environment.

It is possible to have an active calibration algorithm while the camera is not active; and is fixed on a tripod. The idea of such an active calibration algorithm, is that the information gained from each frame could be used to signal the calibration target for the next frame. This requires the calibration target to be active and controllable by the calibration algorithm. The term active calibration could be used in term of both methods. Meanwhile, the two are totally different.

The active target approach was implemented using a pattern generator program and a LCD monitor which was responsible for screening generated patterns. These components plus the automatic image acquisition and feature extraction provided the maximum flexibility and accuracy needed for having an active target.

3 Center of Radial Distortion Estimation

In this section the basis of radial distortion center estimation is explained. At first the method of Hartley and Kang[13] is explained. Afterwards, the proposed method is introduced. The two methods are similar on the aspect of decoupling the center of radial distortion.

3.1 Hartley's Method

This method utilizes fundamental matrix for approximating radial distortion center. The idea behind fundamental matrix is that a point considered projected to the image plane using an ideal non-distorted camera becomes distorted by expansioning away from a center of distortion. The expansion can be compared with the forward movement of a camera towards a scene. In such a movement points undergo a radial distortion. In this case the center of expansion, epipole, is the same with the center of radial distortion. The center of distortion is estimated by computing the fundamental matrix[19] relating known coordinates of points in the scene and the corresponding points in the distorted image.

$$x_d F X = 0 \ . \tag{1}$$

where, X is the point coordinate in the scene; x_d is the distorted corresponding image point; F is the fundamental matrix. The center of distortion ,the left epipole, could be computed using (2).

$$F^T e = 0 \ . \tag{2}$$

where, e is the left epipole.

The main disadvantage of this technique is that if no distortion is present or the amount of distortion is small, fundamental matrix computation would not be stable and the value of epipole is meaningless.

3.2 Active Center of Distortion Estimation

Active estimation of radial distortion center is referred to the estimation of distortion center using active calibration techniques. Considering the polynomial radial distortion model, it is inferred that radial distortion is symmetric. It is also known that distortion center in optical space is the center of lens. However, because of manufacturing displacement of sensor, mechanical parts, and optical system of a camera; optical center would hardly lie on the center of sensor. As a result the imaged center of distortion would not be the center of image. This makes the search for distortion center vital.

Some properties of lens and radial distortion are self-evident. One of those properties that could be used to find the distortion center is the relationship of line's straightness and center of distortion; stated in Postulate 1.

Postulate 1. *Under presence of radial distortion a straight line is straight if and only if it passes through the distortion center.*

Postulate 1 originates from radial distortion nature. As the points of a line passing through the distortion center are in radial alignment on a line, the line straightness is not affected by radial distortion. This property is the basis of Theorem 1 which is used to find the distortion center.

Theorem 1. *Under radial distortion, two concurrent lines l_1, l_2 would stay straight if and only if the intersecting point p is positioned on the distortion center o.*

Proof. If the intersecting point p is positioned on o, then the two lines both are passing through the distortion center and are straight as stated in Postulate 1. Now consider the situation where l_1 and l_2 are both straight. From Postulate 1 could be inferred the both lines are passing through o, and the only point the two lines have in common is p; which means p lies on o. $\square$

Now it would be possible to use two concurrent line segments to find the distortion center, as shown in Fig. 1. If the straight lines $\overline{a_i c_i}$ and $\overline{b_i d_i}$ intersect point p_i lies on o, the distortion center is found. A simple search algorithm is proposed for finding distortion center; the aim of search method is minimization of p_i and o deviation by moving the calibration target in front of camera.

The main advantage of this technique is that it can even work under small amount of distortion. In case of no radial distortion, the deviation would not change that much trough movements. Such a case could be identified by testing two different positioning and presence of identical deviations.

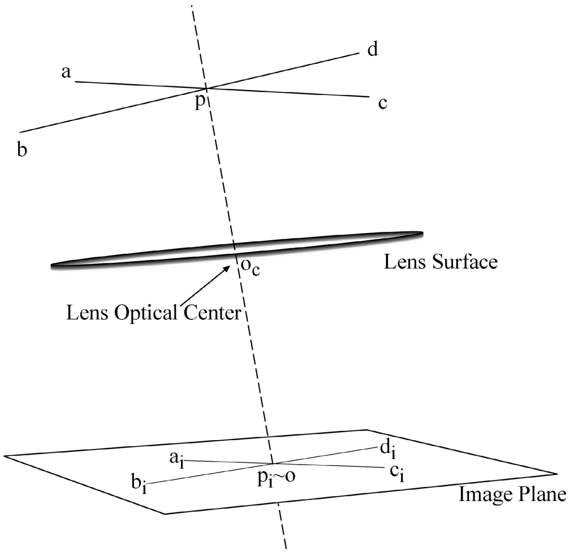

Fig. 1. Line segments and straightness property under radial distortion, the image of p, p_i, would lie on o if the imaginary line $\overline{pp_i}$ passes through optical center

3.3 Active Approach Implementation

An active target could be a *Light-emitting Diode* (LED) carried by a controlled robotic arm; or a board of LEDs, which switching them on and off shapes patterns. Approaches that rely on mechanical instruments is not versatile; flexible; precise and economical. The same is true for a board of LEDs. Another approach could be use of monitors for screening of patterns. In this case a simple *Cathode Ray Tube* (CRT) monitor would not be applicable because of its convex surface of screening area. However, a *Liquid Crystal Display* (LCD) is suitable.

A monitor depending on its setting can provide different precisions. As an example, a monitor with 1024×768 resolution; and 317mm×236mm viewable screen has pixels of approximately 0.31mm tall and 0.31mm wide; which means the pattern can have movements with precision of 0.31mm. It is obvious the precision would increase at higher resolutions.

A computer program can be used for generating different patterns and screening them on a LCD monitor. The main advantage of a monitor and a pattern generator program, is that patterns can be controlled and changed regarding the circumstances through the calibration process adaptively; having a fair accuracy. This approach also makes a fully automatic image acquisition phase possible.

Fig. 2 shows a calibration framework utilizing LCD and pattern generator program. The camera calibration framework consists of two major independent programs; one is the pattern generator and the other one is a program that performs all the computation, referred to as computational program. Both programs are in connection with each other using a communication channel. A communication center is in charge of transferring information and commands between these two programs. An interpreter is in charge of coding and decoding messages from numerical string into meaningful structures and vice versa.

The pattern generator consists of a graphic unit, and a pixel-metric convertor except the communication center. The graphic unit is in charge of displaying patterns. Patterns are generated by means of feature points. The type of pattern, and feature point is requested by the computational program. A pattern is imaged using multiple frames, where only one feature point is displayed on each frame. Pattern generator is capable of performing relative and absolute positioning of a pattern (e.g. request for relative movement of a pattern to the left by one centimeter). Computational program can get metric and pixel based information of monitor by requesting it from pixel-metric convertor unit.

Computational program consists of five components except the communication center. These components are image acquisition; feature extraction; geometrical lens distortion handler; camera parameter handler; and decision unit. Image acquisition is responsible for capturing frames. Geometrical lens distortion handler is responsible for finding distortion center and radial distortion coefficients. Camera parameter handler is responsible for approximation of internal parameters using undistorted images. The decision unit is in charge of these components. Decision unit decides on the information sent from pattern generator and decides where the information should be routed. It also handles the requests from different components and decides on the destination data should

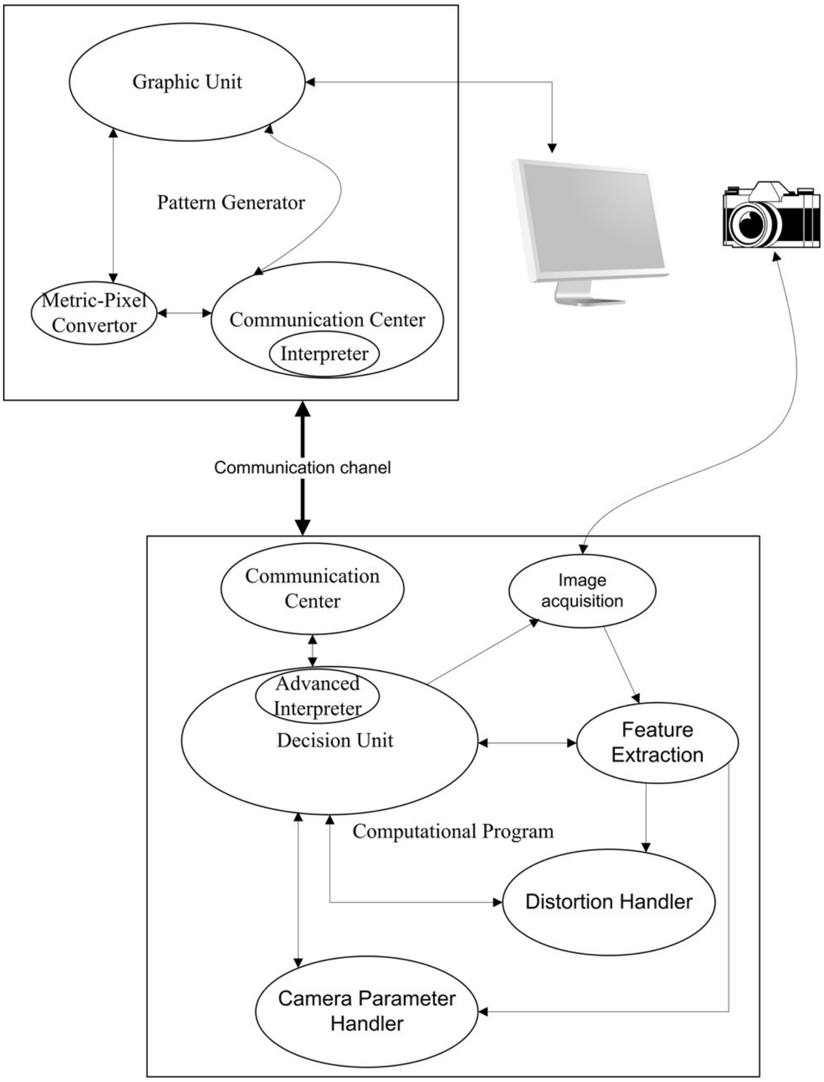

Fig. 2. Calibration framework using proposed active target implementation

be sent (e.g. it decides which component should receive the extracted features information).

4 Experiments

In this section the hardware setup and experiments performed is explained. Because of nature of active target approach the experiments are done using real data.

The video camera used in this experiment is a Sony camcorder (DCR-TRV460E) equipped with a CCD sensor, and a 2.5–50mm Sony lens. The lens focal length was kept to 2.5mm, which is the widest possible focal length in all the experiments. The camera is capable of USB streaming, so no digital to analog converter is needed. The frames are directly grabbed at the resolution of 640×480 in RGB color space and later converted to grayscale. A 15" TFT monitor with native resolution of 1024×768 (Sony SDM-HS53/H) was used to screen the patterns generated by pattern generator. A user defined color space with maximum backlight used meanwhile the experiment. All the frames where grabbed at daylight setting, where no other external light source is present. It was tried to have the camera optical axis orthogonal to image plane as shown in Fig. 3.

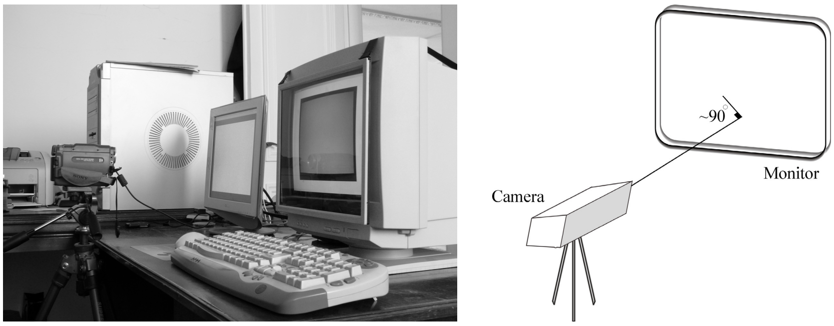

Fig. 3. Hardware setup used during the calibration process

Two crossing line segments are used as the calibration target. Their length grow to the size of image plane. The lines are generated and screened on the monitor. The hardware setup makes movement of lines by 0.3mm precision possible. However, as only the start, end and crossing point of these line segments are needed[20], the pattern generator only screens these interest points. Each interest point is screened and imaged independently.

The proposed active algorithm and the method of Harley and Kang[13] were compared. The video camera used has a fairly small distortion. In consequence the Harley's method fails to approximate the center and converges to the center of image as the distortion center. However, the proposed method approximates the distortion center accurately. The result is summarized in Table 1.

In order to test the accuracy of proposed method. The camera was fully calibrated under two different assumptions. First using the estimated center of distortion and again under the assumption of center of image. The result is summarized in Table 2. The calibration result was used to approximated the angle between two plane of a holder. Fig. 4 shows the holder. The ground truth is 90°. As shown in Table 2 the accuracy of the calibration using estimated center of distortion outperforms the center of image assumption.

Table 1. Center of distortion estimation

Algorithm	**Distortion Center**
Proposed Method	(321.6408, 247.4743)
Harley and Kang [13]	failed→(320, 240)

Table 2. Camera calibration and angle estimation results, f_i is the focal length in i_{th} direction, s is skew, u_0 and v_0 are principal point's coordinates, c is the center of radial distortion, k_1 and k_2 are the first two coefficients of radial distortion

	Calibration result	
	with known center of distortion	*without known center of distortion*
f_x	713.4747	719.5320
f_y	732.942	741.2015
s	−0.2157	−0.1802
u_0	242.4362	241.3101
v_0	322.1570	323.4587
$c(c_x, c_y)$	(321.6408, 247.4743)	(320, 240)
k_1	−0.01450	−0.01550
k_2	−0.00126	−0.00086
Estimated Angle	91.5585 °	93.8413 °

Fig. 4. A holder with ground truth 90 °, used for angle estimation

5 Conclusion

In this article a new approach to center of radial distortion estimation was introduced. The center of distortion estimation method originates in active calibration idea. However, the approach used has been based on active targets, which gives a new synthesis to active calibration.

The center of radial distortion can help to the increase of calibration precision. The center of radial distortion could be approximated using parametrization of distortion center and other camera parameters. Afterwards applying an iterative optimization technique. However, this require full camera calibration and is also vulnerable to trivial solutions.

There are also other techniques which require no iterative scheme. These methods focus on some especial properties of vision systems such as fundamental matrix. However, they sometimes suffer from some limitations such as amount of distortion.

The proposed algorithm is capable of approximating center of radial distortion without any prior information. It decouples the distortion parameter. This increases distortion coefficient approximation precision and calibration accuracy. As it was shown the proposed method approximates radial distortion center even in presence of small distortion value.

Camera calibration using the estimated center of radial distortion results in a more precise angle estimation. The meticulous result of angle estimation is an exemplar of center of radial distortion importance and accuracy of proposed algorithm.

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