An Efficient Correction Method of Wide-Angle Lens Distortion for Surveillance Systems

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***Abstract*—Wide-angle or fish-eye lenses are popularly used for the surveillance system due to their large field of view (FOV). However, images obtained by wide-angle cameras tend to be nonlinearly distorted owing to lens optics. In this paper, we propose a novel framework to correct the wide-angle lens distortion for surveillance systems. Our approach is based on the FOV model, which is an efficient and simple correction method. The FOV model works well for typical wide-angle lens, whose FOV is usually smaller than 150°. However, it begins to reveal problems as the FOV increases. First, we address two main problems of the FOV model and then improve the FOV model by refining the distortion curve. The proposed method is tested on images and videos with different FOV. Experimental results show the efficiency of our algorithm.**

I. Introduction

Wide-angle or fish-eye lenses are very useful to capture the large range of view with a small number of cameras. They can be classified into circular and full-frame types [1]. Since the angle of view for the circular type is 180° in all directions, it is mainly used for scientific applications, such as sky observation and solar radiation measure [2]. In contrast to that, the full-frame type is more commonly used, which has a 180° diagonal angle of view while the horizontal and vertical angle of views are smaller. Examples of images taken with both types of wide-angle lens are shown in Fig. 1.

Due to the large FOV, wide-angle lens are popularly used for various applications, such as surveillance systems and semi-automatic parking systems. Moreover, they tend to be mounted on small endoscopes to see the large range of bodily organs [3]. Here we focus on surveillance systems for monitoring large range of field. For example, in the military scenario, along with the development of sensor network, it is desirable to monitor the large range of field on each sensor node for detecting intruders. However, images captured by wide-angle cameras suffer from strong lens distortion which pulls nonlinearly image points towards the optical center as shown in Fig. 1. Since detection of intruders' position plays an important role under the military scenario, an efficient and fast correction method is needed.

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(a) (b)

Figure. 1. Examples of images taken with wide-angle lens. (a) Circular type image from [4]. (b) Full-frame type image from [5] (FOV is about 150°).

There have been many research papers to correct the wide-angle lens distortion [6-10]. The previous approaches can be divided into either polynomial-based or nonpolynomial-based methods. Polynomial-based methods have been employed to find the distortion parameters accurately. Jung *et al.* [6] refine the result of "Caltech Calibration Toolbox" for wide-angle lens distortion using inverse mapping-based extrapolation. In [7], authors propose a nonmetric calibration method, which does not rely on the calibration objects. They provide a closed-form solution to find the distortion parameters and refine them using nonlinear optimization. Although polynomial-based approaches are very accurate, they are time-consuming due to iterative process. To overcome this problem, Hartley *et al.* [8] propose a parameter-free correction method, which is noniterative and independent of radial distortion model. However, they still use the calibration objects to find the distortion center.

While the work on polynomial-based methods is extensive, little work has been done on nonpolynomial-based methods. Basu *et al.* [9] propose the Fish-Eye Transform (FET) model based on a logarithmic distortion model. It is suitable for describing the distortion of circular wide-angle lens. Devernay *et al.* [10] propose a simple and efficient distortion model based on the way that wide-angle lenses are designed. They assume that the angular resolution of the wide-angle lens is roughly proportional to the image resolution along the image radius. Since this model only relies on the FOV value, it is called the FOV model. For the large FOV surveillance

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systems, nonpolynomial-based methods are more suitable compared to polynomial-based methods due to the simplicity of implementation.

In this paper, we propose a novel framework based on the FOV model to correct the wide-angle lens distortion. First, we increase the angular resolution of the FOV model. Then, we extend the FOV model to apply for the circular wide-angle lens. The rest of this paper is organized as follows: The improved FOV model is presented to overcome two main problems of the FOV model in Section 2. The experimental results on various images and videos are presented in Section 3, and conclusion follows in Section 4.

II. PROPOSED METHOD

The FOV model is based on the simple optical model of wide-angle lens. It assumes that the angular resolution is roughly proportional to the image resolution along the image radius. Although the FOV model is very simple and efficient, there are two main problems as follows,

- The wide-angle lens optics may not follow exactly the FOV model as the FOV increases.
- The FOV model cannot be applied to the circular wide-angle lens.

To solve these problems, we improve the FOV model by refining the distortion curve. The process will be explained in the following subsection.

A. Refinement by increasing the angular resolution

The simple optical model of wide-angle lens is shown in Fig. 2. Here r_d and r_u denote the radius of an image point from the image center on distorted and undistorted image, respectively. In the wide-angle lens, the rays tend to be pulled toward the optical center as mentioned. As the FOV increases, the rays may be more nonlinearly bent to capture large range of view with smaller r_d as shown in Fig. 2. Since the length of r_d is much smaller than the length of arc (*op2*) in case that the FOV is larger than 150°, the angle, which is smaller than expected, is applied to correct the distorted image (see Fig. 2). Thus, the assumption of the FOV model cannot be applied when the FOV increases too much. To increase the angular resolution, we refine the distortion curve of the FOV model by adding a simple term to r_d based on the logarithmic relationship between r_d and r_u [9] as follows.

$$r_d + \lambda \ln(1 + r_u) = \frac{1}{\omega}\tan^{-1}(2r_u \tan\frac{\omega}{2}), \quad where\ \lambda = a_1 \exp(g\frac{\omega - b_1}{180}). \tag{1}$$

Here λ and ω denote the control factor and the FOV value, respectively. Since the slope of distortion curve drastically changes with increasing FOV, λ is defined by using the exp onential function. a_1 and b_1 denote the slope weight and bias angle, respectively. g denotes the step weight.

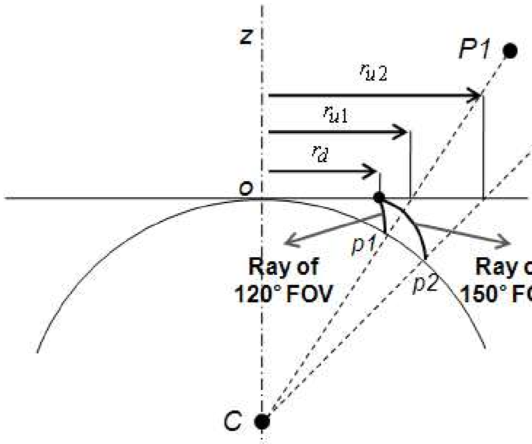


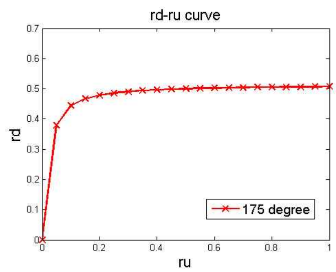
Figure. 2. The optical model of wide-angle lens. In case of 150° field of view, the angle between (*CP2*) and the optical axis (*Cz*) is not proportional to the length of r_d .

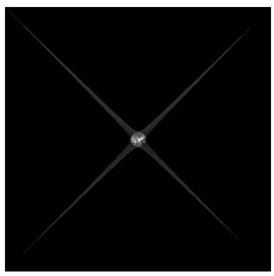
The refined distortion curve by increasing the angular resolution is shown in Fig. 3-(a). It is noted that the improved FOV model captures the larger range of view compared to the FOV model with the same r_d . Thus, the larger angle compared to the FOV model can be applied to correct more accurately the distorted image with the same r_d in the improved FOV model.

B. Extension to the circular wide-angle lens

Since the tangent function diverges around 90°, the FOV model cannot be applied to the circular wide-angle lens (see Eq. (1)). The distortion curve of the FOV model with 175° FOV is shown in Fig. 4-(a). Since the distortion curve is rapidly saturated by the divergence of tangent function, most of r_u are projected to the similar r_d . Therefore, the distorted image cannot be recovered correctly as shown in Fig. 4-(b). To solve this problem, we extend the FOV model as follows: If the FOV is 180° (i.e., circular wide-angle lens), we use the bias angle instead of the FOV to solve Eq. (1) and increase r_u to compensate for the FOV as follows,

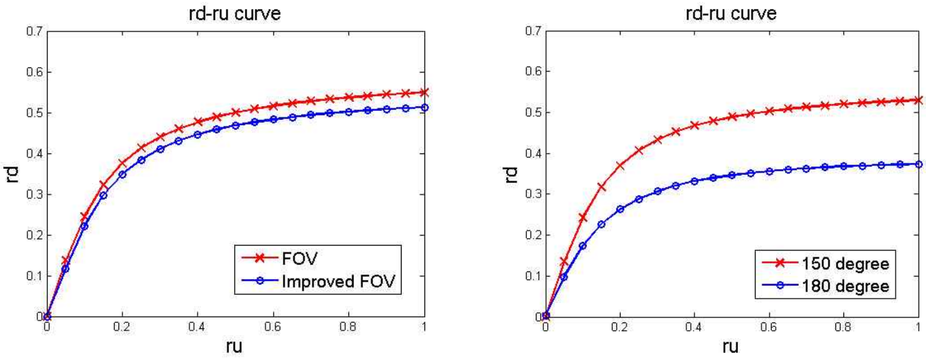
$$r_u' = r_u + d,\ where\ d = a_2 \exp(g\frac{\omega - b_2}{180}), \tag{2}$$





(a) (b)

Figure. 4. (a) Distortion curve of 175° FOV. (b) Undistorted image of Fig. 1-(a) using the FOV model with 175° FOV.



(a) (b)

Figure. 3. (a) Distortion curves of the FOV model and the improved FOV model with 150° FOV. (b) Distortion curves of different FOV on the improved FOV model.

where a_2 and b_2 denote the slope weight and bias angle, respectively. Here bias angle is smaller than the original FOV. g denotes the step weight as mentioned. Since our approach is aimed at changing the slope of distortion curve with the bias angle, d also can be defined by using the exponential function like control factor λ.

The distortion curve for circular wide-angle lens is shown in Fig. 3-(b). We can see that it is slowly saturated compared to the distortion curve shown in Fig. 4-(a).

C. Summary of the improved FOV model

To put all pieces together, the improved FOV model can be summarized as follows.

$$\boxed{r_d = \frac{1}{\omega'}\tan^{-1}(2r_u'\tan(\frac{\omega'}{2})) - \lambda\ln(1+r_u')}$$

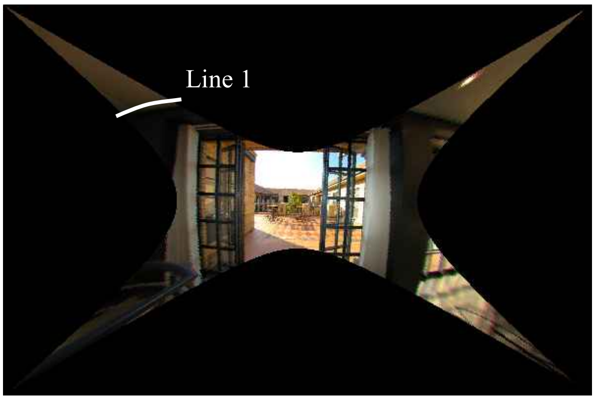
$$\begin{aligned} &if\ \ \omega = 180°,\ \ \omega' = b_2\ \ and\ \ r_u' = r_u + d \qquad (3)\\ &otherwise,\ \ \ \omega' = \omega\ \ and\ \ r_u' = r_u\\ &where\ \ \lambda = a_1\exp(g\frac{\omega - b_1}{180}),\ \ d = a_2\exp(g\frac{\omega - b_2}{180}). \end{aligned}$$

Note that the slope weight, step weight, and bias angle are set empirically through exhaustive tests. The improved FOV model can be applied adaptively with respect to the type of wide-angle lens. Due to the simplicity of implementation, the improved FOV model can be easily applied to the large FOV surveillance systems. In addition, under the military scenario, since both circular and full-frame types of wide-angle lens can be used for detecting intruders on the sky or ground, the improved FOV model is very useful.

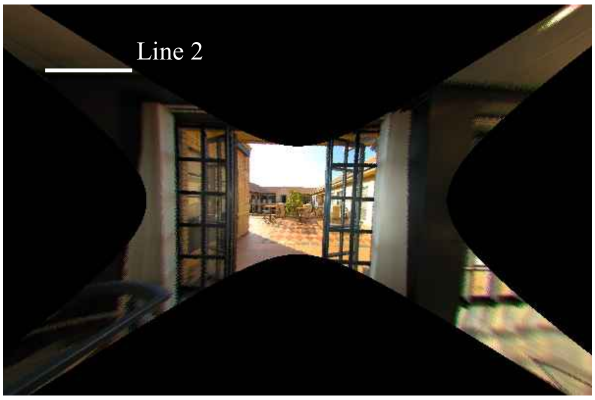
III. Experimental Results

A. Comparison of the improved FOV model with the conventional FOV model

To show the efficiency of the improved FOV model, we compare the correction performance of the improved FOV model with the conventional FOV model. First, the distorted



(a)



(b)

Figure. 5. Correction results with 150° FOV (size: 600×400). The line 2 obtained by using the improved FOV model is a more desirable result compared to the line 1. (a) Conventional FOV model result [10]. (b) Improved FOV model result [proposed].

image shown in Fig. 1-(b) is corrected using the conventional FOV model and the improved FOV model with 150° FOV. We can see that some curves remain at the boundary part of window in the result of the conventional FOV model while the distorted image is perfectly corrected in the result of the improved FOV model (see Fig. 5). Moreover, the distorted image of circular type is also corrected well as shown in Fig. 6. Although the tree is significantly bended by the circular

(a) (b)

Figure. 6. Correction result of a circular wide-angle image (size: 486 × 486). (a) Distorted image from Fig. 1-(a). (b) Undistorted image corrected by the improved FOV model.

wide-angle lens, it is straightened accurately by the improved FOV model. Therefore, we conclude that the improved FOV model is highly desirable for correction of wide-angle lens distortion.

B. *Performance evaluation on videos*

The framework for evaluating performance has been implemented by using Visual Studio 2005 (C++) under FFMpeg library, which has been utilized for MPEG and DIVX decoding. Various videos are encoded with the image size of 320 × 240. All the parameters are selected experimentally as shown in Table I. Here a_1 and b_1 are used for the correction of the full-frame type while a_2 and b_2 are used for the correction of the circular type. The screenshot of the proposed system is shown in Fig. 7. Corrected region can be magnified with bilinear interpolation in our system. The experiments were performed on the low-end PC (Core2Duo 1.8GHz). The total processing speed with different FOV is shown in Table II. We see that the proposed method is very efficient and faster which allow real-time use.

TABLE I. PARAMETER SETTING

Type	Slope weight		Bias angle		Step weight
	a_1	a_2	b_1	b_2	g
value	1	1/180	120°	150°	$\omega/20$

TABLE II. PERFORMANCE EVALUATION

Test video	Video 1	Video 2	Video 3
FOV	100°	120°	150°
Total processing speed	23.35 fps	23.39 fps	23.19 fps

IV. CONCLUSIONS

A novel method to correct the wide-angle lens distortion is proposed in this paper. The main contribution of our work is to build a more powerful correction method based on the FOV model. We first increase the angular resolution of the FOV model based on the optical model of wide-angle lens. Then the FOV model is extended to the circular wide-angle lens by refining the distortion curve with a bias angle. To validate the performance of our improved FOV model, various images and videos have been tested. The proposed method is very useful for the real-time application. According to our analysis, the improved FOV model can be applied easily to surveillance systems, which detect intruders regardless of the types of wide-angle lens.

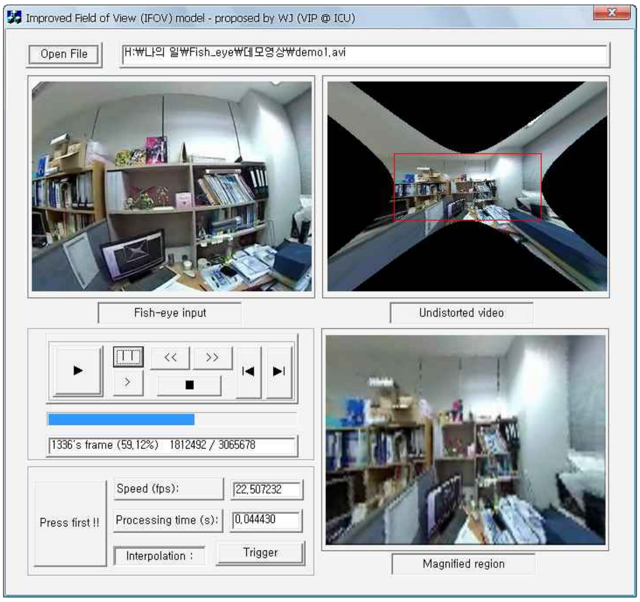


Figure. 7. The screenshot of proposed system. Region of interest (inside red box) can be magnified.

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