Fast Barrel Distortion Correction for Wide-Angle Cameras

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SUMMARY  Barrel distortion is a critical problem that can hinder the successful application of wide-angle cameras. This letter presents an implementation method for fast correction of the barrel distortion. In the proposed method, the required scaling factor is obtained by interpolating a mapping polynomial with a non-uniform spline instead of calculating it directly, which reduces the number of computations required for the distortion correction. This reduction in the number of computations leads to faster correction while maintaining quality: when compared to the conventional method, the reduction ratio of the correction time is about 89%, and the correction quality is 35.3 dB in terms of the average peak signal-to-noise ratio.

key words:  barrel distortion correction, optical distortion, wide-angle cameras, image enhancement

1. Introduction

Wide-angle cameras are extensively used in a diverse range of applications, from automotive sensing systems to endoscopes. The wide-angle camera is usually equipped with a special lens with a very short focal length. Such a lens is effective in providing a wide view, but it suffers from barrel distortion that can induce critical problems in many applications. For example, numerous minor car collisions are caused by distorted images that are produced in automotive sensing systems, and it is difficult to make the correct diagnoses if endoscopes provide distorted views. Correcting barrel distortion is therefore an important step in successfully applying wide-angle camera technology. For the example applications introduced above, the required correction time should be short because they operate in real time. Furthermore, the resolution of such imaging systems is growing ever higher, which in turn leads to lengthening of the correction time.

This letter presents a new method to implement a fast barrel distortion correction. The contributions of this letter are summarized as follows.

• We consider the barrel distortion a non-uniform scaling process and find that it is not meaningful to calculate the required scaling factor using the mapping polynomial exactly since the mapping polynomial itself is a model function whose coefficients are estimated. Based on this observation, the proposed method obtains the scaling factor by employing the spline interpolation of the mapping polynomial instead of calculating it directly, and thus the computations can be reduced significantly.

• The proposed method is quantitatively evaluated in terms of the correction quality and the correction time. For 3264×2448 images, the proposed method achieves a correction quality within 35.3 dB of the conventional method in average peak-to-signal-to-noise ratio (PSNR), while the correction time is reduced to 11% of that in the conventional one.

2. Barrel Distortion Correction

Fig. 1 shows how barrel distortion deforms an image: a pixel located at \((x, y)\) is moved to \((x', y')\) by the distortion, where \((O_x, O_y)\) and \((O'_x, O'_y)\) denote the optical centers of the corrected image space (CIS) and the distorted image space (DIS), respectively. This letter considers the radial distortion for which

\[
\frac{y - O_y}{x - O_x} = \frac{y' - O'_y}{x' - O'_x}. \tag{1}
\]

In this case, the two triangles shown in the figure are different in size but similar to each other, and the similarity ratio is defined as a scaling factor \(s\), i.e.,

\[
s = \frac{(x' - O'_x)(x - O_x)}{\frac{(y - O_y)}{(y - O_y)}} = \frac{(y' - O'_y)}{(y - O_y)} = \frac{r'}{r}. \tag{2}
\]

Fig. 1  Barrel distortion model: (a) CIS, (b) DIS, and (c) the relation between CIS and DIS.
where
\[ r = \sqrt{(x - O_x)^2 + (y - O_y)^2} \] (3)
and
\[ r' = \sqrt{(x' - O'_x)^2 + (y' - O'_y)^2}. \] (4)
According to this relation, \((x', y')\) can be derived as
\[ (s \cdot (x - O_x) + O'_x, s \cdot (y - O_y) + O'_y). \] (5)
The original pixel located at \((x, y)\) is moved to \((x', y')\) by the distortion, and the CIS can be reconstructed by copying the pixel intensity at \((x', y')\) in the given DIS to that at \((x, y)\) in the CIS. To obtain the pixel intensity at \((x', y')\), the DIS has to be resampled since either \(x'\) or \(y'\) may not be an integer, for which the bilinear interpolation can be employed [1]–[4]. This process is known as backward mapping, as it describes a mapping from a CIS pixel to a DIS pixel.

For radial distortion, \(s\) is usually modeled as a mapping polynomial of \(R\), where \(R = r^2\). In this letter, \(f(R)\) denotes the mapping polynomial that is expressed as
\[ f(R) = \sum_{i=0}^{N} c_i \cdot R^i, \] (6)
where \(c_i\) is the distortion coefficient that can be estimated by applying a least-square method as presented in [1]. In (1), \(N\) represents the accuracy of the distortion model, which consequently affects the quality of the correction if it is based on the backward mapping.

The previous researches regarding the barrel distortion correction were mainly focused on how to elaborate the correction quality, and few of them studied for its efficient implementation to realize a fast processing in practical systems. In [2], a pipelined architecture was presented to realize a high-speed correction system. In [3], the mapping polynomial was manipulated so as to eliminate the coordinate transformation required in the correction process. In [4], a multi-cycle architecture was presented to reduce the hardware complexity by compromising the correction speed to some extent.

### 3. Proposed Barrel Distortion Correction

Barrel distortion correction entails high computational complexity. To reconstruct the CIS, we have to perform backward mapping for every DIS pixel. As described in the previous section, this process involves the calculation of \(s\) that needs to evaluate (6). Furthermore, to achieve high-quality correction for a large image, \(N\) should be increased in (6), which in turn increases the number of computations, resulting in a longer correction time.

In the proposed method, \(s\) is not directly calculated by evaluating (6), but rather is interpolated by employing a linear spline. The motivation is the fact that \(c_i\)'s in (6) are in fact estimated ones; for this case, the exact evaluation of (6) becomes less meaningful with respect to the correction time.

The proposed method obtains the scaling factor by the linear spline which is piecewise-defined for \(f(R)\). More specifically, the proposed method segments the entire range of \(R\) into \(P\) disjoint intervals for which the \(i\)-th interval ranges from \(R_{i-1}\) to \(R_i\), where \(R_{i-1} < R_i\) for \(1 \leq i \leq P\), \(R_0 = 0\), and \(R_P\) is the maximum \(R\). \(f(R)\) for the \(i\)-th interval is interpolated by a line segment that is expressed as \(m_i \cdot R + n_i\), where \(R_{i-1} < R < R_i\),

\[ m_i = (f(R_i) - f(R_{i-1}))/R_i - R_{i-1}, \] (7)
and
\[ n_i = -R_{i-1} \cdot (f(R_i) - f(R_{i-1}))/R_i - R_{i-1} + f(R_{i-1}). \] (8)
The interpolation can be performed by one multiply-accumulate operation, which is much simpler than calculating (6) directly as is done in the conventional method [2]–[4]. Figure 2 illustrates the scaling factor of the proposed method \((P = 3)\) to correct the barrel distortion for an image with a resolution of 3264 \(\times\) 2448 pixels. In the figure, the polynomial for the conventional method is obtained by estimating \(c_i\)'s based on the method presented in [1].

It is worth making additional remarks on the proposed method.

- The \(i\)-th line segment for the interpolation is characterized by \(m_i\) and \(n_i\). These values are pre-calculated and stored as constants in order to avoid recalculating them as the distortion is corrected for a particular lens configuration.
- For the linear spline in the proposed method, the discrepancy between the spline and \(f(R)\) may not be uniform for each segment, which causes that the correction performance is not spatially uniform. This problem can be alleviated by employing a spline with a larger \(P\) so as to interpolate \(f(R)\) more precisely. We should note that this does not increase the number of computations in the proposed method. As a polynomial is interpolated with a larger number of segments, it usually increases the number of computations because the process to select what segment is utilized for the interpolation becomes more complicated. However, for the barrel distortion correction usually performed in a raster-scanning order [2]–[4], \(R\) is either monotonically...
increasing or decreasing; a segment for the interpolation is selected between two adjacent segments.

- In the proposed method, how the entire range of $R$ is segmented can affect the correction quality. There are several studies in the field of numerical analysis for obtaining a (near)-optimal linear spline to interpolate an arbitrary function. In the next section, the correction quality is evaluated for the proposed method in which a linear spline is obtained by employing the scheme presented in [5].

4. Evaluation Results

In this section, the performance of the proposed method is evaluated by correcting color images taken by a camera where the focal length of the lens mounted in the camera is 4 mm and the image has $3264 \times 2448$ pixels. Table 1 shows the correction quality that is measured by the PSNR for five sample images, where the referential quality is obtained by the conventional method with a high-order mapping polynomial. The order of the mapping polynomial is set to 6 ($N = 3$) in order to achieve the referential quality [1]. Figure 3 illustrates the correction result for one of the sample images in the table. As shown in Table 1, the correction quality of the proposed method is maintained at 35.3 dB in terms of the average PSNR even with the interpolation based on the linear spline. Table 1 also shows the correction quality of the conventional methods with lower-order mapping polynomials ($N = 1$ or 2), for which the degradation of the quality is severe. This means that a high-quality barrel distortion correction for a large image requires a high-order mapping polynomial if the correction is performed based on backward mapping. Figure 4 compares the correction time, where both methods are implemented using the C programming language and executed on a 3 GHz machine with 8 GB memory. The correction time in the proposed method is reduced by 89% of that required by the conventional method.

It would be possible to pre-calculate the backward mapping result of each CIS pixel location and to reuse it repetitively for the barrel distortion correction caused by a certain lens. In this approach, the backward mapping result of every CIS pixel location has to be stored in a memory such as the look-up table in order to be reused for the subsequent distortion correction, where the backward mapping result is stored as the DIS pixel location corresponding to each CIS pixel. If an image has $T$ pixels, each pixel location may be identified by $\lceil \log_2 T \rceil$ bits, where $\lceil a \rceil$ means the smallest integer that is not smaller than $a$. Let us consider that a DIS pixel location computed by the backward mapping process is represented by $l$ bits, where $l$ needs to be larger than $\lceil \log_2 T \rceil$ because the backward mapping result is not integer as explained in Sect. 2. Then, the memory requirement to store the backward mapping result of every pixel in the image is larger than $T \cdot l$ bits, which is substantially large in practice. For instance of $T = 4M$, the memory requirement to store the backward mapping results is larger than 88Mbits, which is not feasible in practice. Consequently, the backward mapping process is usually performed on the fly [1]–[4] in the barrel distortion correction, and the proposed method makes the backward mapping process fast significantly.

To the author’s best knowledge, this study proposes an interpolation-based method to realize a fast barrel distortion correction system for the first time. The proposed method may be employed prospectively to implement low-complexity and fast barrel distortion correction systems in further studies.

| Algorithm | Conv. ($N = 1$) | Conv. ($N = 2$) | Proposed ($P = 3$) |
|-----------|----------------|----------------|-------------------|
| Sample 1  | 20.7dB         | 26.7dB         | 34.1dB            |
| Sample 2  | 21.1dB         | 28.8dB         | 34.5dB            |
| Sample 3  | 23.5dB         | 29.5dB         | 36.8dB            |
| Sample 4  | 22.5dB         | 27.4dB         | 35.9dB            |
| Sample 5  | 20.7dB         | 26.8dB         | 35.2dB            |
| Average   | 21.7dB         | 27.9dB         | 35.3dB            |

Fig. 3 Correction example: (a) the original distorted image and (c) the corrected result by the proposed method, where the barrel distortion and the correction are highlighted by dotted lines.

Fig. 4 Comparison of the correction time.
5. Conclusion

This letter proposes a fast correction method for barrel distortion. The proposed method performs backward mapping by interpolating the scaling factor with a non-uniform linear spline. When compared to the conventional method, which calculates the scaling factor directly, the proposed method requires considerably fewer computations while maintaining comparable correcting quality. For an image of 3264 × 2448 pixels, the correction time of the proposed method is about nine times shorter than that of the conventional method, while the correction quality is 35.3 dB in terms of the average PSNR.

Acknowledgments

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