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APPLIED RESEARCH

The Design and Implementation of the Lookup Table in Distortion Correction for the Optical System

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ABSTRACT Image geometric distortion is common in a large field of view optical system. It becomes a technical difficulty for high distortion rate optical systems and high resolution image geometric distortion correction. But, a crucial step in distortion correction is figuring out how to precisely obtain the index coordinates and correction parameters, otherwise known as the lookup table. In this paper, the problems in the traditional lookup table method are analyzed, and an improved lookup table method is proposed. The method is based on the traditional lookup table method with the addition of removing the wrong data of position coordinates in the correction image feature points, calculating the ideal image feature point position coordinates, handling the index coordinate out-of-bounds, and adjusting the output order of index coordinates and correction parameters. The experimental results show that the improved design method is feasible, and improves the accuracy of the correction image, compared with the traditional lookup table, the root mean square error is reduced by 93%, and the average accuracy of the fitted position over the full field of view is reduced by 51.9%, and the maximum deviation is only 0.2917%. For the correction of the large field of view optical display devices, it offers good correction effects.

INDEX TERMS Optical system, geometric distortion, distortion correction, lookup table.

I. INTRODUCTION

In the large field of view collimation imaging optical display devices, the final display images will produce different degrees of nonlinear geometric distortion due to the effect of design method and assembly process factors [1]. Its classical expression is that image distortion is caused by the displacement of pixel points in the image. The existing geometric distortions include the rotational symmetric optical system distortion and nonrotational symmetric optical system distortion [2], [3]. The optical system in collimated imaging optical equipment mainly produces nonrotational symmetric optical system distortion. The fan-shaped distortion produced by the optical system is shown in Fig. 1. The nonregular distortion caused by the optical system is shown in Fig. 2.

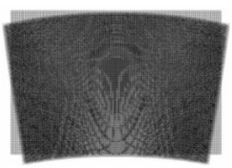

FIGURE 1. The fan-shaped distortion.

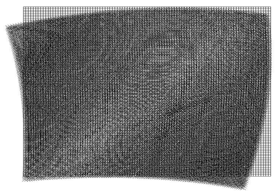

FIGURE 2. The nonregular distortion.

Distortion correction of images is commonly used as a preprocessing algorithm before image processing. It also does grayscale computation and mapping of the rectified

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image's position. It consists of two steps: the corresponding feature points between the ideal image and the corrected image are selected as the control points, the geometric correction model is used to establish the mapping relationship among the ideal image and the corrected image, and some mapping points and pixel points around the mapping point are used to complete the gray correction of the image. The process of geometric correction is the process of establishing a lookup table. At this stage, the index coordinates of the corrected image to the original image and the correction parameters are obtained using the polynomial model. The results of this stage are used for the next stage of the interpolation algorithm for grayscale calculation.

Building a geometric model is the key to traditional lookup tables. It is feasible to design geometric models using the polynomial fitting method. However, several issues arise in practice, resulting in unsatisfactory or even incorrect distortion correction results. For example, the ideal image feature points provided by the optical software are not the correct feature points, and cannot be used directly in the geometric model building; the boundary of the corrected image appears to be curled; the index coordinates are out of bounds when the original image is mapped to the corrected image; and the index coordinates output order does not take the scanning direction of the image source into account, resulting in more severe image distortion.

This paper proposed an improved lookup table method in response to the aforementioned issues. The method extends the traditional lookup table by removing incorrect position coordinate data from corrected image feature points, calculating the ideal image feature point position coordinates, handling the data with out-of-bounds index coordinates, and adjusting the output order of index coordinates.

The paper is organized as follows: In Sect. II, the principle and structure of the lookup table are outlined, in Sect. III the problems of the traditional lookup table are discussed, while the improved lookup table method is presented. In Sect. IV the specific application and results of the improved method are presented. In Sec. V the improved method is verified by the experiment, the experimental results are compared and discussed. Conclusions are drawn in Sect. VI.

II. THE PRINCIPLE AND STRUCTURE OF THE LOOKUP TABLE

The lookup table is the input for the second stage grayscale calculation of the digital distortion correction system, it stores the index coordinates and the correction parameters of the corrected image to the original image. In Fig. 3, the ideal image is the distortion correction system's input, the corrected image is the distortion correction system's output, and the corrected image is presented on a digital image source [4], [5]. The rectified image is projected through an optical system with distortion, and it should be congruent with the ideal image. In particular, following geometric correction, the single pixel index is traced back to pixel point b on the ideal image and becomes pixel point a in the corrected image after geometric correction, so the gray value of pixel point a is the same as that of pixel point b. The pixel point b on the ideal image may not be a standard pixel point. To obtain the gray value of the pixel point b, we need to interpolate the operation of the gray value of the pixel point around point b and the nearest pixel point c, point d, point e, and point f. The correction parameters are the distances between pixel b and its neighboring pixel points c, d, e, and f.

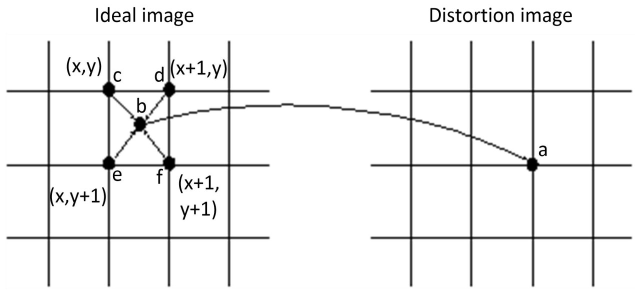

FIGURE 3. Schematic diagram of distortion principle.

Tx 16bit	*Ty* 16bit	*Q1* 16bit	*Q2* 16bit

FIGURE 4. The data structure of a lookup table.

The structure of the lookup table is shown in Fig. 4.

Tx: The number of X-direction pixels of four pixel points' base point (x, y) on the original image corresponding to the pixel point of the corrected image.

Ty: The number of Y-direction pixels of four pixel points' base point (x, y) on the original image corresponding to the pixel point of the corrected image.

Q1: The X-direction distance between the current point to the base point.

Q2: The Y-direction distance between the current point to the base point.

The base point can be one of the points c, d, e, and f, which depends on the output order of the corrected image.

III. THE DESIGN METHOD OF THE LOOKUP TABLE

A. TRADITIONAL METHODS AND PROBLEMS

Algorithm 1 depicts the design method of the traditional lookup table [6], [7]. It is divided into three steps: (1) The geometric model is built using the optical software's feature points. (2) A geometric model is used to compute index coordinates and correction parameters. (3) In the distortion correction system structure, the calculation results are output in hexadecimal form for the grayscale computing module [8].

The traditional method emphasizes the development of geometric models. Many theses show that the polynomial fitting method can properly establish the geometric model. Many issues have been discovered in practice, leading to

Algorithm 1 The Traditional Design Method of Lookup Table

1: Input the optical software's feature points
2: Create geometric models
3: Produce adjusted picture location coordinates depending on image source size and pixel count
4: Using the geometric model, calculate the position index coordinates and grayscale correction parameters of the corrected picture to the original image
5: Print the position index coordinates as well as the grayscale correction parameters

unsatisfactory or incorrect distortion correction outcomes. The next discussion will concentrate on the causes of poor or incorrect distortion correction results.

Question 1: Ideal image feature points

The effect of distortion correction is directly affected by whether or not the geometric model is valid [9]. The raw data used to generate the geometric model must be correct in order for the geometric model to be appropriately calculated. The figure of the projected image after distortion correction should be consistent with the figure of the ideal image feature point utilized in the computational geometry model in the distortion correction system structure.

Algorithm 1 in the traditional lookup table design technique would ideally be assumed that optical software can directly offer the original data feature points for constructing geometric models [10], [11]. However, in practice, it has been discovered that the ideal image feature points offered by optical software are not the proper feature points and cannot be used directly. Fig. 5 depicts a red rhombus produced using ideal image feature points in an application provided directly by optical software. The final projected image from the optical system should be consistent with the rhombus if these feature points are used to construct a geometric model and are applied to the distortion correction system. However, the distortion correction system's essential judgment of the corrected graph is that the x-axis is perpendicular to the y-axis. As a result, ideal image feature points produced by optical software cannot be used directly to create geometric models.

Question 2: The corrected image feature points

Fig. 6. shows that the red graph is the corrected image in the original data provided by the optical software for distortion correction in an optical system. The graph shows that the edges and the lower left and right corners are crimped. If the data are used directly for geometric model calculation and distortion correction [12], [13], the image cannot be corrected correctly in the lower left and right corners and the left and right edges.

So the data of the crimped phenomenon of the edge and the lower left and right corners are erroneous and need to be removed.

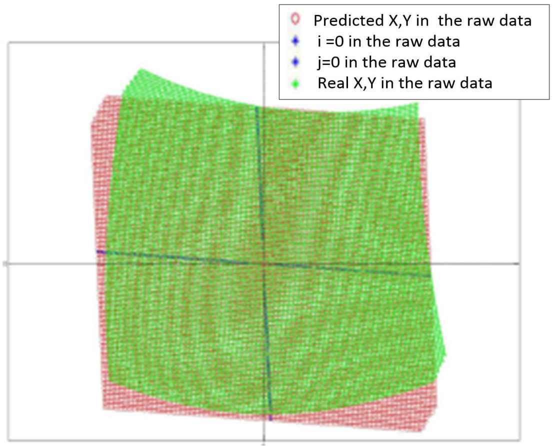

FIGURE 5. The graph drawn by the data of ideal image and corrected image which is provided by optical software.

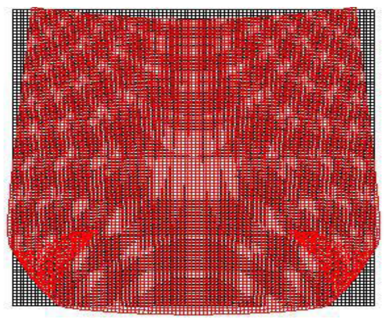

FIGURE 6. Optical software provides the ideal image and the corrected image.

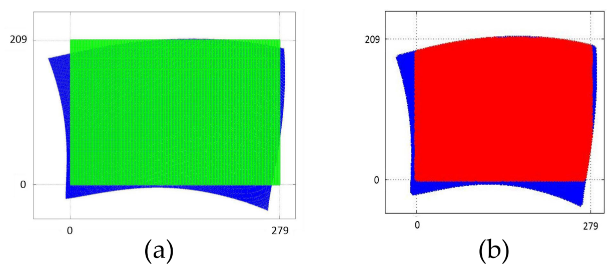

FIGURE 7. Index coordinate boundary processing results. (a) Index relationship of the corrected image to the ideal image. (b) The image after cross-boundary processing.

Question 3: Index Coordinate Boundaries

Fig. 7a. shows the corrected and ideal images after the index coordinates are generated. The green image is been corrected to the blue one. I.e. each pixel position on the green image is indexed to the corresponding pixel position on the blue image [14]. From Fig. 7a, the pixel position coordinates of the blue image are out of bounds. From Fig. 7b, the blue part is the out-of-bounds pixel index coordinates and the red is the correct pixel index coordinates.

If the out-of-bounds points are not processed, the final correction result is that the location of the edge of the image will appear in the other position image.

Question 4: Index coordinate output order

The traditional index coordinate output order does not take into account the scanning direction of the image source, and all outputs should be according to the calculation order of index points [15]. For example, the order of calculation starts from the lower left, so the order of output should start from the lower left. Distortion becomes larger and larger after distortion correction in the application. The reason is that a lookup table which is the opposite distortion characteristic is adopted. That is to say, the starting point of the image source scan starts from the lower right, and the distortion characteristic of the lower right needs to be given first. Instead, the lookup table first outputs the distortion characteristic of the lower left, which leads to the situation that the distortion of the image becomes larger and larger after the distortion correction.

B. IMPROVED METHOD OF THE LOOKUP TABLE

The traditional implementation method of the lookup table is simple, only considering the polynomial fitting method to obtain the geometric model. The above questions have not been taken into account. Algorithm 2 shows the improved method. It adds four steps: eliminating the wrong data of position coordinates in the corrected image feature points; calculating the position coordinates of the ideal image feature points; processing the index coordinates out-of-bounds and adjusting the output order.

Algorithm 2 The Design Method of the Improved Lookup Table

1: Input raw data from optical software
2: Verify the corrected image's position coordinates to eliminate incorrect data
3: Calculate the ideal image's position coordinates
4: Create geometric models using polynomial fitting
5: Generate the corrected image's position coordinates
6: Calculate the index coordinates as well as the correction parameters
7: Handle out-of-bounds index coordinate
8: Adjust the output order
9: Output index coordinates and correction parameters

IV. SPECIFIC APPLICATION AND RESULTS OF THE IMPROVED METHOD

A. ELIMINATE THE WRONG DATA IN THE CORRECTED IMAGE FEATURE POINTS

The algorithm for eliminating the wrong data is shown in Algorithm 3.

Fig. 8 shows the specific application of the algorithm of eliminating wrong data in the distortion correction architecture of a diffraction optical system. The red circle is the wrong point eliminated in the horizontal direction, and the blue crosses are the wrong points eliminated in the vertical direction.

Algorithm 3 Description of the Algorithm for Eliminating Incorrect Data

1: Read a set of same data as the vertical view field
2: The points in the horizontal direction of the same vertical view field corrected image should be arranged from small to large
3: If the above rule is met then
4: The points in the vertical direction of the same vertical view field corrected image should be large in the middle and small on the two sides or small in the middle and large on the two sides
5: if the above rule is met then
6: end
7: else
8: eliminate data
9: end if
10: else
11: eliminate data
12: end if

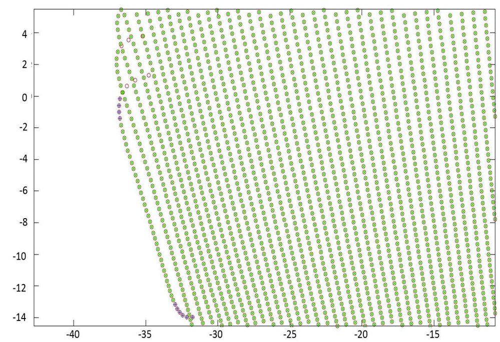

FIGURE 8. Local comparison before and after wrong data elimination.

B. CALCULATE THE POSITION COORDINATES OF IDEAL IMAGE FEATURE POINTS

The data provided by optical software includes the horizontal and vertical field-of-view of each feature point. The position coordinates of an ideal image feature point need to convert the field of view to the corresponding specific image height on the ideal image surface. The calculation method is expressed in (1) and (2).

$$\begin{cases} x = f \times \tan\alpha \\ y = f \times \tan\beta \end{cases} \tag{1}$$

$$\begin{cases} x = h \times \alpha \\ y = h \times \beta \times r \end{cases} \tag{2}$$

Equation (1) is the computational method in one collimated imaging optical system. Where f is the equivalent focal length for the optical system, α and β are the angles of the field of view. The field of view angles is obtained from the field of view conversion to radians.

Equation (2) is the computational method in another collimated imaging optical system. Where h is the near-axis ideal image height, α and β are the normalized fields of view, r is the field of view ratio in the vertical and horizontal directions after the field of view normalization.

C. CALCULATE THE GEOMETRIC MODEL

We select the data as the feature points that correspond one-to-one between the corrected image (x, y) and the original image (u', v'). The transformation relations are expressed in (3).

$$\begin{cases} u' = \sum_{i=0}^{N}\sum_{j=0}^{N-i} a_{ij}x^i y^j \\ v' = \sum_{i=0}^{N}\sum_{j=0}^{N-i} b_{ij}x^i y^j \end{cases} \quad (3)$$

where a_{ij} and b_{ij} are the coefficients of the polynomials, N is the times of polynomial fittings.

According to (3), the following polynomial (4) and (5) are obtained.

$$\begin{bmatrix} x_1^0y_1^0 & x_1^0y_1^1 & \cdots & x_1^Ny_1^0 \\ x_2^0y_2^0 & x_2^0y_2^1 & \cdots & x_2^Ny_2^0 \\ \vdots & \vdots & \vdots & \vdots \\ x_L^0y_L^0 & x_L^0y_L^1 & \cdots & x_L^Ny_L^0 \end{bmatrix} \begin{bmatrix} a_{00} \\ a_{01} \\ \vdots \\ a_{N0} \end{bmatrix} = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_L \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} x_1^0y_1^0 & x_1^0y_1^1 & \cdots & x_1^Ny_1^0 \\ x_2^0y_2^0 & x_2^0y_2^1 & \cdots & x_2^Ny_2^0 \\ \vdots & \vdots & \vdots & \vdots \\ x_L^0y_L^0 & x_L^0y_L^1 & \cdots & x_L^Ny_L^0 \end{bmatrix} \begin{bmatrix} b_{00} \\ b_{01} \\ \vdots \\ b_{N0} \end{bmatrix} = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_L \end{bmatrix} \quad (5)$$

L is the number of corrected image sampling points after processing, and N is the highest times of fitting polynomials in (4) and (5). The number of coefficients a_{ij} and coefficients b_{ij} is shown in (6).

$$(N+1) + N + (N-1) + \cdots + 1 = \frac{(N+2)(N+1)}{2} \quad (6)$$

This is also the number of the matrix columns, denoted as *row*. Obviously, the size of matrix is: $\times L(\textit{the rownumber})\ row\ (\textit{the column number})$.

The two polynomial equations (7) and (8) can be solved using Matlab software.

$$\begin{bmatrix} a_{00} \\ a_{01} \\ \vdots \\ a_{N0} \end{bmatrix} = \begin{bmatrix} x_1^0y_1^0 & x_1^0y_1^1 & \cdots & x_1^Ny_1^0 \\ x_2^0y_2^0 & x_2^0y_2^1 & \cdots & x_2^Ny_2^0 \\ \vdots & \vdots & \vdots & \vdots \\ x_L^0y_L^0 & x_L^0y_L^1 & \cdots & x_L^Ny_L^0 \end{bmatrix}^{-1} \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_L \end{bmatrix} \quad (7)$$

$$\begin{bmatrix} b_{00} \\ b_{01} \\ \vdots \\ b_{N0} \end{bmatrix} = \begin{bmatrix} x_1^0y_1^0 & x_1^0y_1^1 & \cdots & x_1^Ny_1^0 \\ x_2^0y_2^0 & x_2^0y_2^1 & \cdots & x_2^Ny_2^0 \\ \vdots & \vdots & \vdots & \vdots \\ x_L^0y_L^0 & x_L^0y_L^1 & \cdots & x_L^Ny_L^0 \end{bmatrix}^{-1} \begin{bmatrix} v_1 \\ v_2 \\ \vdots \\ v_L \end{bmatrix} \quad (8)$$

Two coefficients arrays a_{ij} and b_{ij} are obtained, and then corrected equation as (3) is obtained.

D. GENERATE THE POSITION COORDINATES OF THE CORRECTED IMAGE

According to the length i of the image source diagonal, the length-to-width ratio is: $l : w$, pixel $m \times n$ generates the position coordinates of the corrected image as x and y in (1). The coordinate system adopts the standard orthogonal coordinate system.

X direction:

$$\left(-\frac{m}{2} \times \frac{i \times 25.4 \times l}{\sqrt{l^2 + w^2}}, \left(\frac{m}{2} - 1\right) \times \frac{i \times 25.4 \times l}{\sqrt{l^2 + w^2}}\right),$$

equally divided into m parts.

Y direction:

$$\left(-\frac{n}{2} \times \frac{i \times 25.4 \times w}{\sqrt{l^2 + w^2}}, \left(\frac{n}{2} - 1\right) \times \frac{i \times 25.4 \times w}{\sqrt{l^2 + w^2}}\right),$$

equally divided into n parts.

E. CALCULATE OF INDEX COORDINATES AND CORRECTED PARAMETERS

The index position coordinates u' and v' of the corrected image to the ideal image are obtained by polynomial operation according to the geometric model. Then the ideal image position coordinates are converted into the ideal image pixel coordinates using the inverse operation in Sec. IV-D.

Index position coordinates u' and v' are generally nonintegers. We round down u' and v' as the final index coordinates u'' and v''. The calculation formula of the correction parameters is (9).

$$\begin{cases} \Delta x = |u' - u''| \times 256 \\ \Delta y = |v' - v''| \times 256 \end{cases} \quad (9)$$

F. HANDLE THE OUT-OF-BOUNDS INDEX COORDINATES

We suppose that the pixel of the image source is $m \times n$; the ideal image pixel coordinate x-direction range is *(0, m−1)*, and the y-direction range is *(0, n−1)*. The algorithm of boundary processing is shown in Algorithm 4.

Algorithm 4 Description of the Algorithm for Boundary Processing

```
1: if x<0 then
2:    use the coordinate of the leftmost data (x=0)
3: else if x> m−1 then
4:    use the coordinate of the rightmost data (x=m−1)
5: else if y<0 then
6:    use the coordinate of the bottom data (y=0)
7: else if y>n−1 then
8:       use the coordinate of the top data (y=n−1)
9: else
10:   keep the coordinate unchanged
11: end if
```

The processing results are shown in Fig.9. The blue part in Fig.9a indicates the out-of-bounds data, whose coordinate system is beyond the pixel range of the image source, and they are invalid points, while this part of invalid points on the image source is not displayed, and their color is the same as the image background color. The points in the red area are valid points, and the corresponding grayscale value should be displayed according to the grayscale calculation method. After the out-of-bounds processing, the correction graph corresponding to the lookup table parameters is shown in Fig.9b.

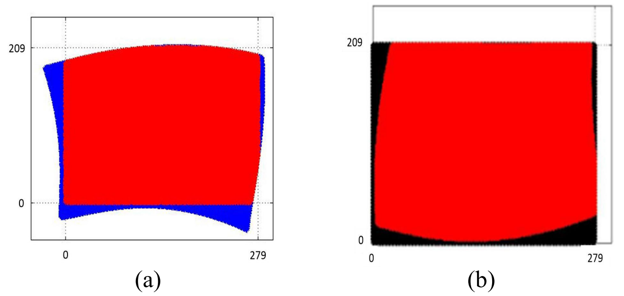

FIGURE 9. The processing results: (a) Predistorted image; (b) The image corresponding to lookup table parameters.

G. OUTPUT INDEX COORDINATES AND CORRECTION PARAMETERS

The lookup table shows the distortion characteristics of the optical system. For off-axis optical systems, the distortion characteristics are asymmetrical from top to bottom and from left to right. And the scanning direction of the digital image source can be changed arbitrarily from each corner according to the requirements of the system, i.e., start from the lower left, start from the upper left, start from the upper right, and start from the lower right. To ensure that the lookup table correctly expresses the distortion characteristics, the scanning direction of the image source needs to be considered when the lookup table store data.

According to the imaging principle of the optical system, the predistortion image shown on the image source must be unique. As shown in Fig.10, if the scanning starting point of the image source is the lower right, the lookup table should start to output corresponding data from the lower right. That is that the lookup table first outputs the predistortion characteristic corresponding to the lower right. Therefore the difference in scan starting points of the image source will affect the difference in data saved by the lookup table. Before outputting index coordinates and correction parameters, the order of the calculated results needs to be adjusted to be the same as the scanning direction of the image source.

V. COMPARISON AND DISCUSSION

The distortion data of the optical system in the large field of view optical display device is given by the optical software CODE V. The field of view size is designed 40° × 30°, and the image distortion is corrected using the improved lookup table. As shown in Fig.11, with the increase of the fitting number N, each index of fitting error accuracy gradually decreases, and when 7≤N≤8, the error is controlled within the minimum range, and the accuracy index suddenly increases when N≥10. Therefore, the polynomial fit using a fitting number of 8. The original image is shown in Fig.12a. The distorted image output from the optical system is shown in Fig.12b. The corrected image obtained by our proposed method is shown in Fig.12c. The display image obtained after the corrected image through the optical system is shown in Fig. 12d. From Fig. 12b and Fig. 12c, we see that the distorted image and the corrected image are very close to each other, indicating that our proposed method is effective.

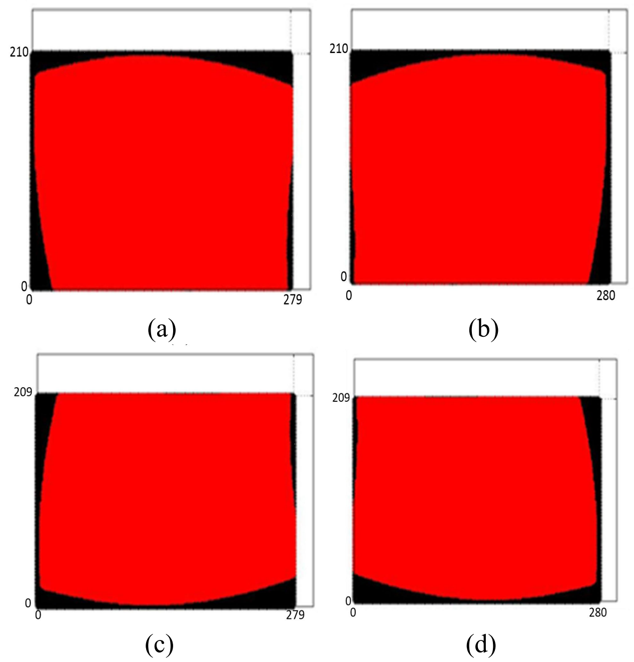

FIGURE 10. Different corrected images corresponding to different scanning models of image source. The processing results: (a) Start from the bottom left; (b) Start from the top left; (c) Start from the top right; (d) Start from the bottom right corner.

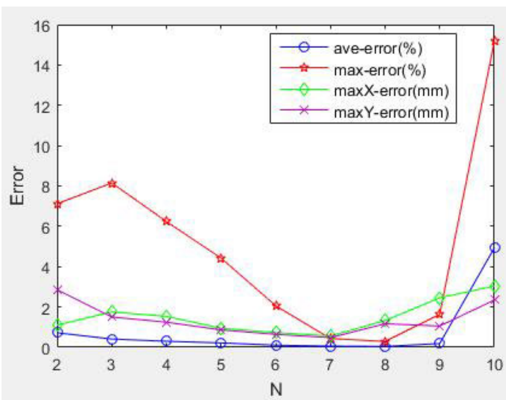

FIGURE 11. Accuracy index chart.

The paper provides an integrated and comprehensive test of the accuracy that can be achieved by distortion correction with a traditional lookup table and improved lookup table

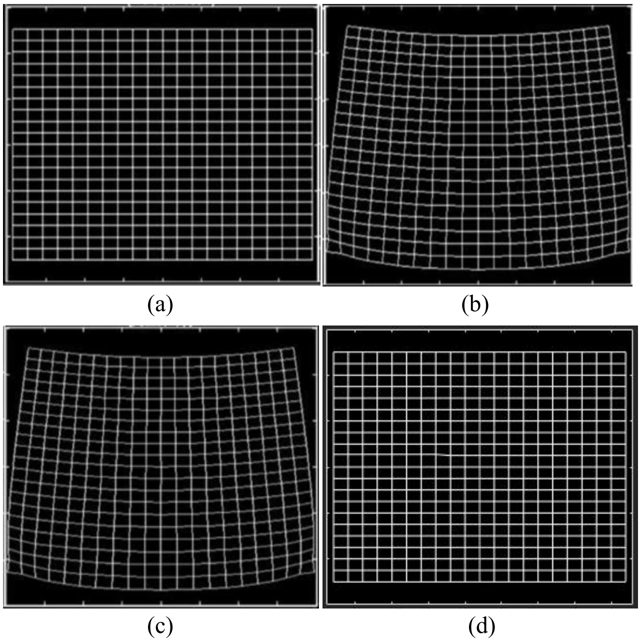

FIGURE 12. Verification results. (a)Original image. (b) Ideal Distorted image. (c) Corrected image.(d)Displayed image.

TABLE 1. The accuracy table of the traditional lookup table and the improved lookup table.

Method	The offset distance /mm		RMSE			Fitting position accuracy	
	$MaxE_x$	$MaxE_y$	$RMSE_x$	$RMSE_y$	RMSE	Aveσ/ %	Maxσ/ %
The traditional method	0.7078	0.6131	0.0925	0.0856	0.1261	0.0910	2.2590
The improved method	0.5640	0.4790	0.0057	0.0088	0.0088	0.0438	0.2917

using three measures of accuracy, the specific values of which are shown in Table 1. Data were obtained by the traditional method from the paper [4] published by the project team. The offset distance visually gives the correction error of the spatial transformation, and the maximum values of the offset distance, $MaxE_x$, and $MaxE_y$ are given here. The root mean square error(RMSE) reflects the extent to which the corrected image deviates from the ideal distorted image. The accuracy of the fitted position over the full field of view is consistent with the distortion characteristics of the large field of view optical displays, and the closer to the edge, the greater the distortion value. From each accuracy shown in Table 1, it can be seen that the improved lookup table method is better than the traditional lookup table method. Among them, the RMSE is improved by 93%, the average accuracy of the full field of view fitted position is improved by 51.9%, and the maximum deviation is only 0.2917%.

VI. CONCLUSION

The accuracy of the lookup table is related to the accuracy of the geometric distortion correction. This paper improved the design process of the traditional lookup table in response to problems discovered in the practical application of distortion correction; it adds the elimination of the incorrect data of position coordinates in the image feature points after correction, the calculation of the position coordinates of ideal image feature points, the index coordinate out-of-bounds processing and the output order adjustment. And remedies to these four issues are suggested. The actual application demonstrates that the revised design process considerably increased the accuracy of aberration correction and that the specific solution is effective and viable; when compared to the standard lookup table, the root mean square error is reduced by 93%, the average accuracy of the fitted positions throughout the full field of view is reduced by 51.9%, and the maximum deviation is only 0.2917%. It is a good correction for the distortion of optical display devices with a large field of view. The original data processing method in polynomial fitting, which includes the calculation of ideal image feature points and the elimination of corrected image error data, can also be used to simulate the architecture of distortion correction in this paper, which will be verified in the following step.

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