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A study of distortion correction algorithms based on aspheric fisheye lens design

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A design method of aspheric fisheye lens has been proposed in this paper, based on the requirements of automobile surround view system. The study has designed a kind of ultra-wide-angle fisheye lens, which only consists of a spherical glass lens and three aspherical plastic lenses. The maximum diameter of imaging aperture is 15. 3 mm; the working distance behind is 2.158 mm; the total length of system is 11.44 mm; the focal length is 0.97 mm; the viewing angle is 210°, and the modulation transfer function (MTF) curve is 0.35 at 60 lp/mm. Furthermore, a kind of a distortion correction algorithm for fisheye lens has been created, which calculates the position of the ideal image point with the actual image point and the obtained distortion curve and distortion model. The algorithm can correct the distorted image taken by a fisheye lens to an image without distortion, which is suitable for the human eye. The algorithm, which is simple and effective, has been applied to the automobile surround view system. It has been verified to be accurate and reasonable, after the comparison is made between the real image taken by a fisheye lens and the corrected image.

Keywords: fisheye lens, image processing, distortion correction, imaging optics.

1. Introduction

The study on fisheye lens has been drawing a growing attention, as the panoramic imaging technology has been widely applied to security surveillance, panoramic parking, driving records, rear view, video conferencing and other fields [1, 2]. Fisheye lens imaging is a new gaze panoramic imaging technology with a large field of view, which is a kind of bionic optics. It makes super wide-angle imaging with horizontal 360° and vertical 180° [3], by extracting a water-based negative lens composed of the front surface of the fisheye and the water surface and evolving it into a front negative lens. The fisheye lens collects all the image information from all sides (front, rear, left and right), without image stitching or information fusion. However, the fisheye lens cannot be widely applied yet, for its complicated manufacturing process, large size and corresponding high cost, as its design is highly complex and the fisheye lens on the market usually is composed of over eight spherical lenses [4]. In 2017, Chen and Yang announced their design of fisheye lens with six elements (1 glass and 5 plastic), which has a maximum angle of 200 degrees and a distortion of –23% [5]. One year later, Park *et al*. reported another six elements (2 glass and 4 plastic) structure of fisheye lens, which has a maximum angle of 191 degrees and a distortion of –32% [6]. In order to effectively control the aberration, both of above designs use more lens structures. However, it sacrifices the tolerance sensitivity and increases the manufacturing cost. Therefore, one of the most studied issues in optics has been how to create a fisheye lens with simple structure, small size and good image quality. Furthermore, the major problem is that the images captured by a fisheye lens is severely distorted (not horizontal or vertical), except that the center of the image remains normal, though a fisheye lens can captures a large field of view. The complex structure of the fisheye lens makes it hard to have accurate distortion correction. Therefore, the lens design utilizes a stereographic projection method. The use of aspheric fisheye lens may contribute to better three dimensional image mapping, thus simplifying distortion correction algorithms.

This paper has designed a super wide-angle fisheye lens with an angle of view of 210°, according to the requirements of the vehicle panoramic system, such as cost, tolerance sensitivity, field of view and aberration elimination. The aspherical technology makes the design only take four elements (1 glass and 3 plastic) to meet the design requirements, which simplifies the lens structure, reduces the production cost and the lens's attenuation of light, and increases the luminous efficiency of the system. Also, this paper reports on creation of a highly efficient simple distortion correction algorithm, which corrects the distortion image taken by the fisheye lens to an undistorted image suitable for human eye, based on the distortion curve obtained in the lens design. Moreover, the algorithm has been proven by experimental results to be reliable and effective.

2. Design of aspheric fisheye lens

2.1. Design parameters

This paper has initialized the lens design parameters, as shown in Table 1, with a complementary metal-oxide-semiconductor (CMOS) sensor as an imaging chip (0.635 cm in diagonal, with a matrix of 6 μm × 6 μm pixels), based on the performance of the CMOS imaging chip and the requirements of the vehicle panoramic system for the fisheye lens and the technical requirements of the lens.

2.2. Initial structure of the lens

The lens design parameters indicate the lens as an ultra-short-focus lens with a focal length of less than 1 mm. However, the rear working distance of most lenses is smaller

Table 1. Design parameters of lens.

Parameter	Specification
Image size	0.635 cm
Pixel size	6 μm × 6 μm
Field of view	210°
Focal length	< 1 mm
F/#	Fixed aperture, F/2.8
Total length	< 12 mm
Thickness of protective glass	0.4 mm
Wavelength	470 nm, 510 nm, 555 nm, 610 nm, 650 nm
Weight of wavelength	0.091, 0.503, 1, 0.503, 0.107

than the focal length. Thus, this design utilizes an inverted telephoto structure with a large working distance [7], as shown in Fig. 1, in order to incorporate the light in the large field of view into the lens and obtain a longer back working distance. Specifically,

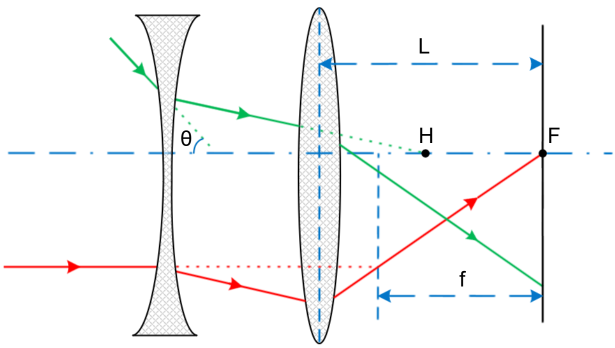

Fig. 1. Structure of the against long-range objective.

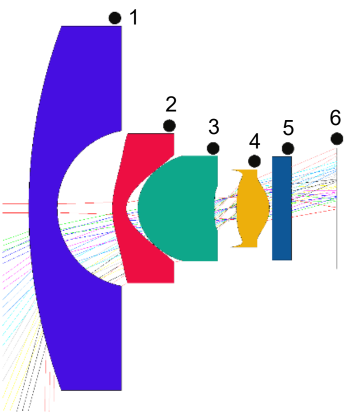

Fig. 2. Initial structure of the lens. 1, 2 – negative lens; 3, 4 – converging meniscus; 5– infrared filter; 6 – the imaging surface of the selected CMOS chip.

H stands for the image side nodal plane, *F* stands for the focal point, *f* stands for the image focal length, *L* stands for the image distance, and θ stands for the object angle of view.

The design has built the initial structure of the super wide-angle fisheye lens, with the primary chromatic aberration theory, based on the necessary constraints (F/# = 2.8; the field of view angle is greater than or equal to 180°). As the calculation of the aspheric surface is too complicated, this paper focused its calculation on the spherical

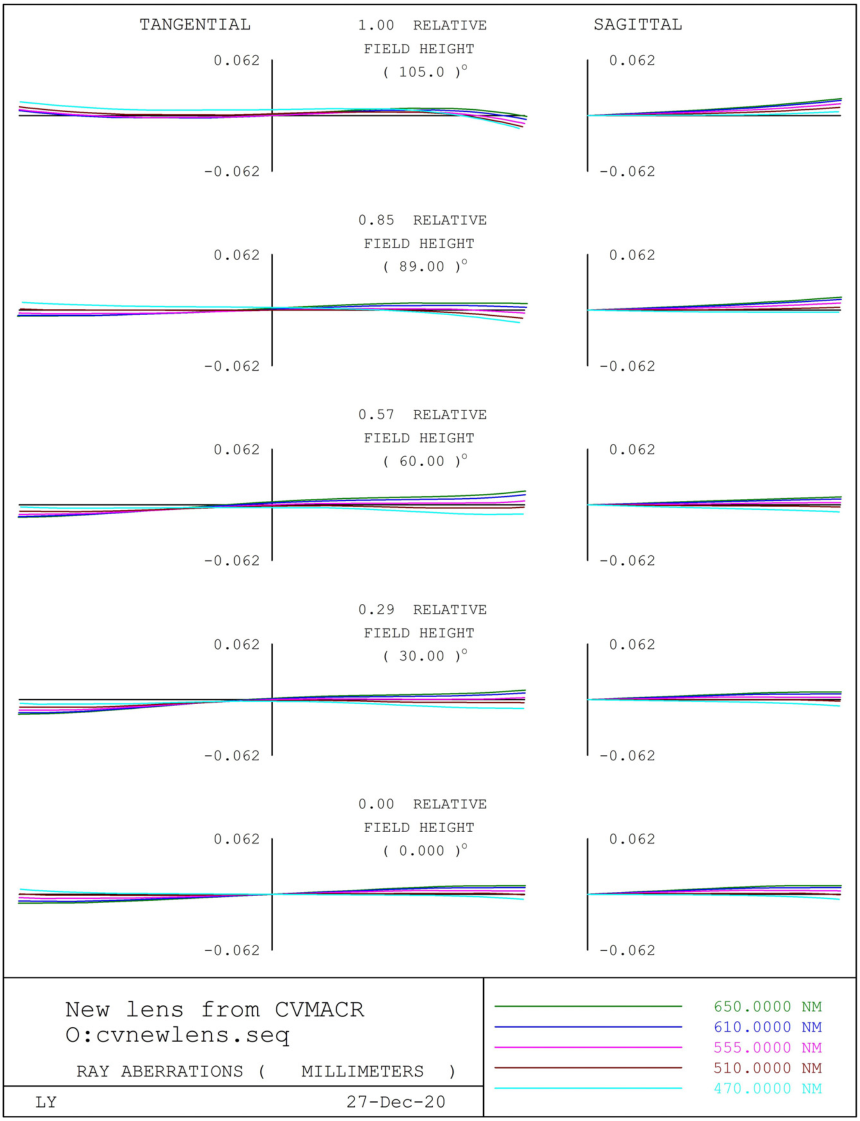

Fig. 3. The ray aberration curve for the starting point of the fisheye lens.

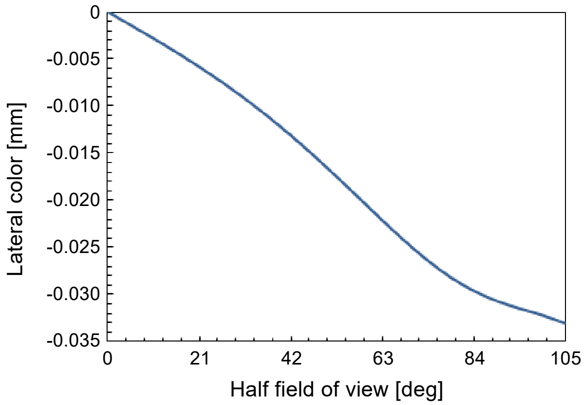

Fig. 4. The lateral color curve for the starting point of the fisheye lens.

structure. This paper has built the initial lens structure that meets the requirements, as shown in Fig. 2, with distributed optical power and optimized asphericity. The first two elements of the lens use a negative lens to incorporate input light in the large field of view, and the latter two elements use a converging meniscus to correct the input light for imaging.

Figures 3 and 4 show the ray aberration curve and the lateral color curve for the starting point of the fisheye lens, respectively. It is obvious that the initial structure of the lens must be optimized for better optical performance.

2.3. Correction and optimization of lens chromatic aberration

As the initial structure of the lens shown in Fig. 2 does not fully meet the lens design parameters listed in Table 1, further correction and optimization are required. Most of lens designs evaluate the size of lens Seidel aberration, with Seidel aberrations such as on-axis spherical aberration, coma, field curvature, astigmatism, distortion, axial chromatic aberration, and transverse chromatic aberration. However, one of the most difficult problems in fisheye lens design is to strike a balance among all Seidel aberrations, thus obtaining the best design results.

One of the solutions to having better design results is constraining and controlling the three parameters, such as the wide beam spherical aberration, coma and thin beam curvature of the lens for initial optimization of the lens, and controlling the image plane height and the modulation transfer function (MTF) of the lens. As the incident angle of the off-axis light of the fisheye lens relative to the refractive surface is large and the light is prone to total reflection, there is frequent light overflow in ray tracing [8]. As such problems are difficult to handle, they are limited and constrained in the first place.

The design ensures that the curvature of the lens can be processed and produced in reality, taking into account the lens imaging quality, the processing technology and the manufacturing cost, since errors in production process would seriously affect the assem-

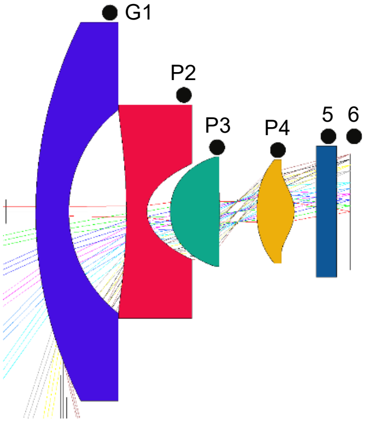

Fig. 5. Final structure of the lens. G1 – spherical glass lens; P2, P3, P4 – aspheric plastic lenses; 5– infrared filter; 6 – the imaging surface of the selected CMOS chip.

Table 2. The parametres of the final lens.

	Surface	Material	Index	Abbe #	Type	Radius [mm]	Thickness [mm]
Object	0				Sphere	Infinity	Infinity
Lens G1	G1-1	Glass	1.773	49.6	Sphere	15.3417	1.2
	G1-2				Sphere	4.7026	2.0902
Lens P2	P2-1	Plastic	1.531	56	Asphere	–20.8072	0.75
	P2-2				Asphere	1.0529	0.842
Lens P3	P3-1	Plastic	1.634	23.9	Asphere	2.1205	1.8043
	P3-2				Asphere	–6.7506	0.6463
Stop					Sphere	Infinity	0.6892
Lens P4	P4-1	Plastic	1.531	56	Asphere	3.6173	1.3697
	P4-2				Asphere	–1.3749	0.8
IR 5	5-1	Glass	1.517	64.2	Sphere	Infinity	0.735
	5-2				Sphere	Infinity	0.4991
Image	6				Sphere	Infinity	–

bly accuracy of the lens, which would affect the yield and cost of the lens. The final structure of the lens is shown in Fig. 5, after repeated correction and optimization, and the parametres of the final lens are summarized in Table 2.

The imaging system consists of a spherical glass lens G1, and three aspheric plastic lenses, P2, P3 and P4 with the maximum imaging aperture diameter as 15.3 mm and the working distance behind as 2.158 mm, and the total length of the system is 11.44 mm. The lens fits the lens design parameters listed in Table 1, and the centering coefficient, curvature, center thickness and edge thickness of each lens meet the processing requirements. Also, the asphericity is between –2 and 2, which is compatible to the fabrication process.

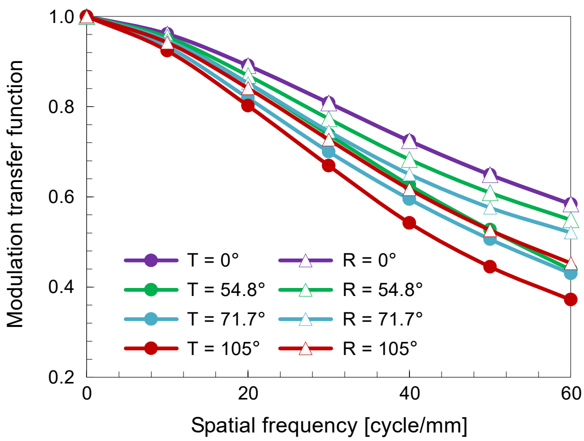

Fig. 6. The MTF curve of the final lens.

The evaluation of the MTF curve, the ray aberration curve, the lateral color curve, the lens relative illumination curve, and the lens distortion curve of the final structure of the lens shows that the system is capable of better imaging quality.

Figure 6 shows the MTF curve of the final structure of the lens at a Nyquist frequency [9] of 60 lp/mm. As shown in Fig. 6, the height of the MTF curve of all fields of view is above 0.35, and the area enclosed by the curve and the coordinate axis is large, indicating the high imaging resolution of the system; the relatively concentrated curves indicate the uniform imaging quality of each field of the system; the melon curve is close to the meridian curve, indicating the small astigmatism of the system.

The final ray aberration curve of the lens is shown in Fig. 7. Compared with the *Y*-axis before optimization as shown in Fig. 3, the ray aberration has been reduced from 0.0622 to 0.0235 mm, which demonstrates the better correction result.

The chromatic aberration will affect the resolution of the lens and cause the "blue edge" phenomenon in the captured image. In order to solve this problem, the focal length and Abbe number of the plastic elements P2 and P3 should be chosen properly and satisfy the following formulas:

$$-6.33 < \frac{f_{\mathrm{P2}}}{f_{\mathrm{P3}}} < -5.54 \tag{1}$$

$$0.82 < \frac{\mathrm{Abbe}_{\mathrm{P2}}}{\mathrm{Abbe}_{\mathrm{P3}}} < 0.93 \tag{2}$$

where f_{P2} and f_{P3} stand for the effective focal length of P2 and P3, respectively, and $\mathrm{Abbe}_{\mathrm{P2}}$ and $\mathrm{Abbe}_{\mathrm{P3}}$ stand for the Abbe number of P2 and P3, respectively. With these parameters, the curvature and material of the lens elements are continuously optimized for better chromatic aberration. The lateral color curve of the final lens is shown in

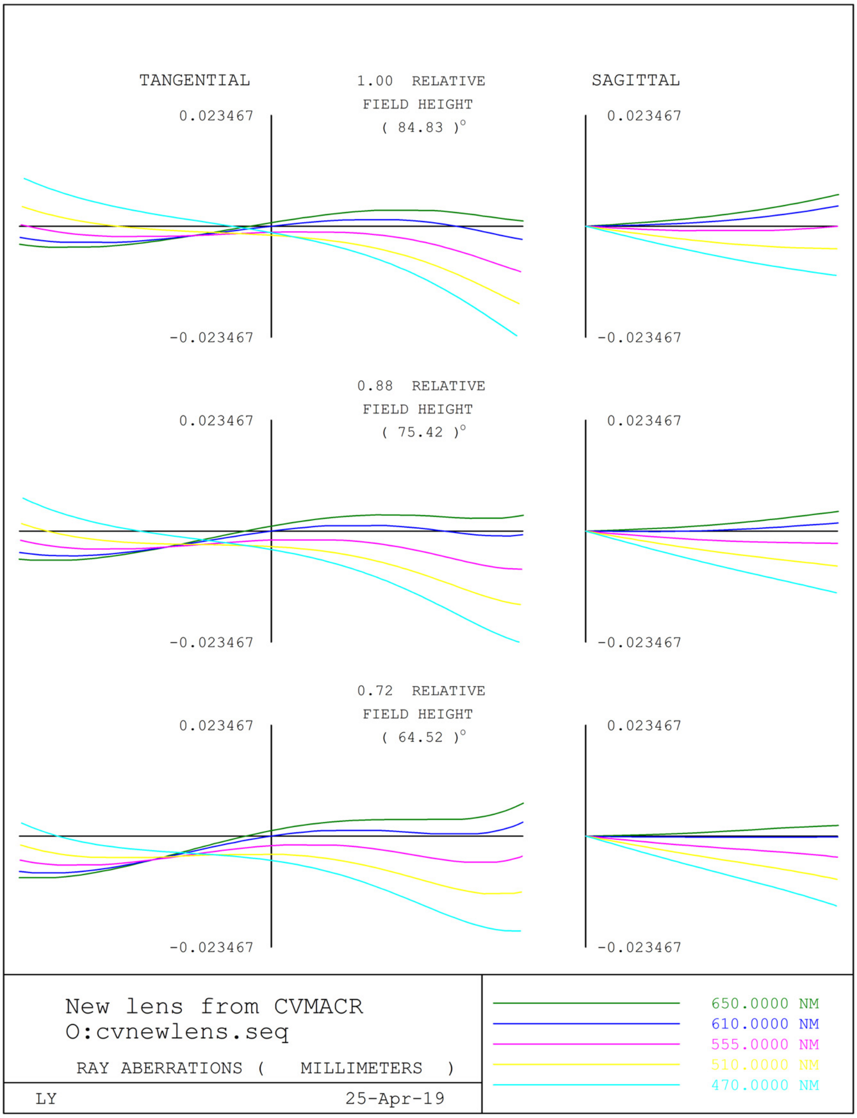

Fig. 7. The ray aberration curve of the final lens.

Fig. 8. Obviously, the final design can satisfy the lateral color control within 5 µm, which is smaller than the pixel size of the CMOS sensor.

The relative illumination is an important parameter of the fisheye lens. The four-cosine formula of ordinary lens indicates that the relative illumination of the lens is close to 0 if the field of view is greater than 180°. This design has obtained higher relative illumination by introducing distortion and aperture coma. Figure 9 shows the relative

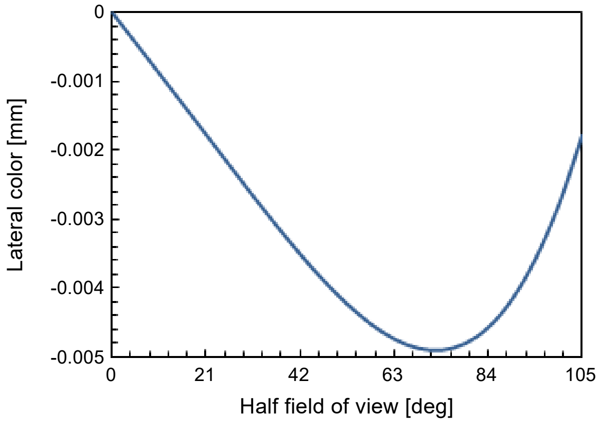

Fig. 8. The lateral color curve of the final lens.

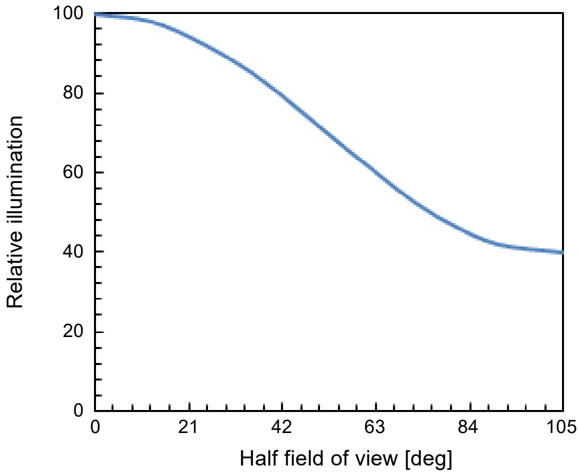

Fig. 9. The relative illumination curve of the final lens.

illumination curve of the final structure of the lens, which shows that the 0.7 field illumination is 48% of the central field of illumination, indicating that the image illumination can meet the imaging requirements.

The design of fisheye lens shall pay special attention to the distortion characteristics, for the large amount of introduced distortion into fisheye lens requires the edge field of view to be compressed at a certain degree, which directly affects the imaging visual effect. As the distortion curve of the fisheye lens is no longer a traditional one, the traditional distortion calculation method makes the distortion approach infinity in the 180° field of view. There are four types of fisheye lens models recognized in the industry: stereographic, equidistant, other solid angles, and orthogonal. This design

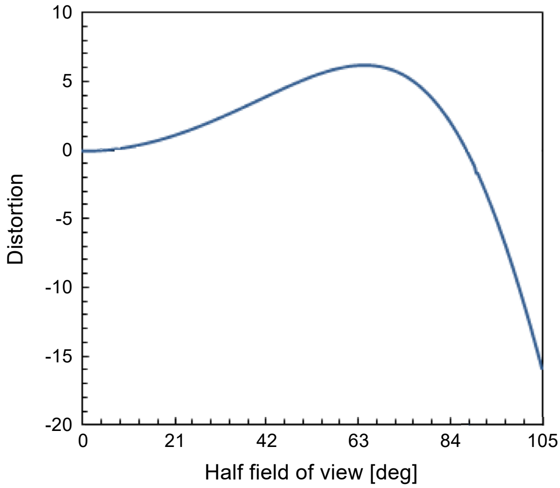

Fig. 10. The distortion curve of final lens.

adopts a stereographic model with the smallest distortion, which follows the object-image correspondence of

$$y = 2f\tan(\omega/2) \tag{3}$$

where y stands for the ideal image height, f stands for the focal length of the lens, and ω stands for the object angle of view. The edge imaging of this model is relatively less compressed, which makes future distortion correction easier. Figure 10 shows the distortion curve of the final structure of the lens relative to the stereoscopic model. The vertical axis represents the distortion, which is the deviation between the designed lens and the used model, and the horizontal axis represents the half angle of view. Calculations indicate that the TV distortion of the lens imaging is within 20%, which meets imaging requirements of the lens.

3. Distortion correction algorithm and its application

The object and image of general lens imaging conform to the principle of similarity [10], for general lens imaging is a one-to-one correspondence between points and points of different planes. However, the fisheye lens imaging is a planar and non-planar correspondence [11], which makes a special imaging effect, commonly known as distortion. Although such effect is very popular in some cases, it is unacceptable in many cases where a fisheye lens must be used, which requires the distortion of the fisheye lens to be corrected.

3.1. Distortion correction algorithms of fisheye lens

Figure 11 shows the fisheye lens imaging projection model, which is a projection from the curved object to the image plane. However, the projection of the ideal object to the

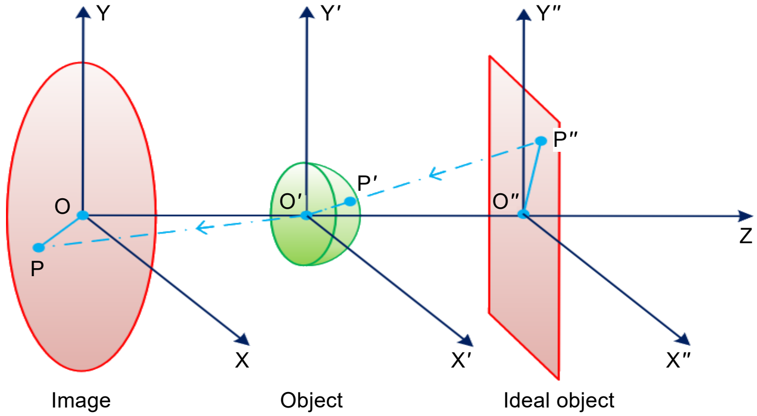

Fig. 11. Projection model of fisheye imaging.

image plane conforms to the principle of general imaging system. OXY stands for the image plane; $O'Y'Z'$ stands for the object plane; $O''Y''Z''$ stands for the ideal object plane; Z axis stands for the optical axis of the fisheye lens; P stands for the image point; P' and P'' stand for the corresponding object points of P in the object and the ideal object plane, respectively.

The general imaging system is based on the

$$y = f\tan(\omega) \tag{4}$$

model, but the fisheye lens obtained in this design is based on the stereographic model, which is based on the model of Eq. (3) [7]. Lens distortion correction is to correct the actual image captured by the designed fisheye lens to an ideal image that conforms to the general imaging principle.

As shown in Fig. 10, the horizontal axis stands for the distortion between the designed lens and the model used. The distortion coefficient D is obtained by the polynomial fitting of the lens distortion curve. The fitted polynomial curve is as shown in the following equation:

$$D = a\omega^5 + b\omega^4 + c\omega^3 + d\omega^2 + e\omega + f \tag{5}$$

In the equation, a, b, c, d, e, and f stand for known constants; ω stands for the field of view of the lens. The study needs to select the appropriate power order to balance the calculation accuracy and calculation speed. The curve fitting accuracy reached 99% when the highest power is 5 in the experiment. The relationship between the actual distortion and the field of view and relative distortion is derived, as shown in the equation:

$$\mathrm{Dis} = \frac{\omega(1+D) - \tan\omega}{\tan\omega} \times 100\% \tag{6}$$

Therefore, the algebraic relationship between the actual image point and the corrected ideal image point is obtained. However, the geometric relationship between

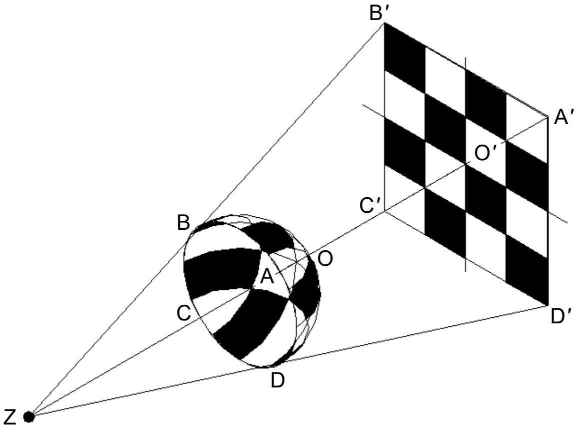

Fig. 12. Geometry diagram of imaging plane.

points in actual calibration still needs to be found [12]. The geometric relationship of the image and the plane is shown in Fig. 12. The point on the surface of $ABCD$ is mapped to the plane of $A'B'C'D'$ based on the principle of linear propagation of light. The $ABCD$ center point slice and $A'B'C'D'$ are both perpendicular to the optical axis ZO, and the projection of ZA on the surface of $ABCD$ is collinear with the projection of ZA' on the plane of $A'B'C'D'$. Thus, the geometric relationship between the actual image point and the ideal image point can be derived. The corrected image surface can be obtained based on the actual image plane of the fisheye lens and the algebraic relationship, and the geometric relationship between the image and points.

3.2. Correction algorithm examples

The fisheye lens with a super large field of view obtained in this design has been fabricated and applied to automobile surround view system. Figure 13**a** shows the captured

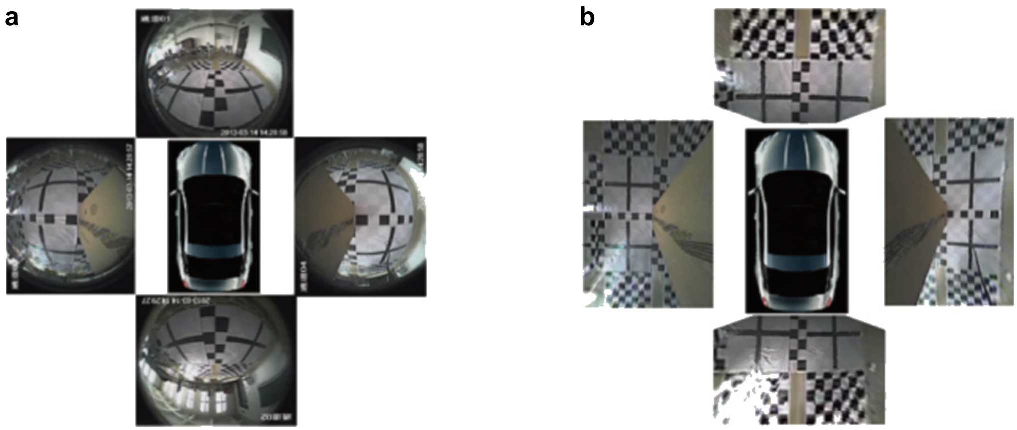

Fig. 13. Image captured by fisheye lens (**a**), and corrected image in automobile surround view system (**b**).

Fig. 14. Panoramic image by seamless stitching.

image by fisheye lenses in the front, rear, left and right directions of the vehicle body in the system. The CMOS of the fisheye lens is a PAL/NTSC chip from ON Semiconductor. The image taken in its PAL format possesses a visible area of 0.635 cm in diagonal, a pixel array of 768 pixels × 576 pixels, the size of which is 6 μm × 6 μm. The focal length of the lens is 0. 97 mm and the field of view is 210°. Figure 13**b** shows the corrected image by the above distortion correction algorithms. The comparison between the Bayer pattern and the two crosses before and after correction shows that the algorithm is accurate and feasible. In addition, the method of lookup table (LUT) is used to optimize the processing efficiency in the hardware implementation of the algorithm. Thus, the real-time performance is proved to be in line with the demand of end users.

The corrected four pictures, as shown in Fig. 13**b**, need to be stitched to be applied to the automobile surround view system. Figure 14 illustrates the panoramic image by seamless stitching, which is an extended study of this paper. Thus, the driver can monitor the surrounding environment of the vehicle in real time through the control monitor on a pilot place, without dead angles, which makes the driving and parking easier.

4. Conclusions

This paper has conducted an in-depth study on the design of aspheric fisheye lens. The study has obtained the design parameters and constructed the initial structure, based on the requirements of the lens of the panoramic imaging system. Also, the study has obtained the optimized lens structure after Seidel aberration correction. The use of aspherical technology makes the design only take four elements (1 glass and 3 plastic) to meet the design requirements, which simplifies the lens structure, reduces the production cost and the lens's attenuation of light, on the other hand, increases the luminous efficiency. The lens possesses the maximum imaging aperture diameter of 15.3 mm, the working distance behind of 2.158 mm, total system length of 11.44 mm, focal length of 0.97 mm, and field of view of 210°, with the MTF curve reaching 0.35 at 60 lp/mm. The whole system delivers good image quality, with simple structure and small size. This paper has conducted further study on distortion correction algorithms, for the fisheye lens, which will produce severe distortion while obtaining a large field of view. In the study the ideal image point position has been calculated, basing on the distortion curve obtained in the lens design and the distortion model with an actual image point, thus creating a highly efficient and simple fisheye lens distortion correction algorithm to correct the image distorted by fisheye lens to an undistorted image suitable for the human eye. The designed fisheye lens and distortion correction algorithm have been applied to the vehicle panoramic display system. This algorithm has been proved to be accurate and feasible, after comparing the actual captured images and the corrected images.

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