MASTER REPORT

REVIEW OF GENERAL PANORAMIC OPTICAL SYSTEMS AND DESIGNING NOVEL PANORAMIC LENS SYSTEMS WITH GLOBAL VIEW

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Abstract: Panoramic lens (PL) design is consistently a research subject due to its complexity and wide applications. Researchers have proposed many different configurations of panoramic lens systems to satisfy various applications. This paper reviews several typical configurations of panoramic lenses as well as their features: classical fisheye lenses, panoramic annular lens (PAL), and panoramic imaging reflector systems. A brief review on the design principles of these different configurations and the panoramic optical systems which use more than one type of configuration is provided in this report. We will also discuss typical design examples of each configuration and the general applications of PL systems in different fields.

1. Introduction

With the development of modern technologies, omnidirectional lens (or panoramic lens) systems are becoming increasingly important due to their great advantages compared to conventional optics. Currently, they are widely used in surveillance and security, panoramic endoscope, machine vision, panoramic projection system, and so on [1, 2]. Panoramic lens systems can achieve a super large field of view (FOV) with relatively compact structure. In general, panoramic lens systems can be classified in the following three different types based on their imaging principles and configurations: fisheye lens system, panoramic imaging reflector system, and panoramic annular lens (PAL) system. If we set the normal direction of imaging sensor as a reference, the fisheye lens system is designed to “see” the objects in the forward direction; the panoramic imaging reflector can cover the backward view;

and PAL system is aimed to collect rays from the side view. Based on these different properties, they can be designed for different applications.

This report is divided into two main parts. The first part reviews the design principles for the three typical configurations of panoramic lens systems and summarizes their specifications as well as limitations. For each type of panoramic lens system, this review also discusses typical examples for actual applications. The second part explores the designs which combine multiple configurations of panoramic lens systems to realize much larger FOV compared to the traditional single panoramic lens system. Some general application examples of panoramic lens system with multiple configurations are also provided in this report.

2. Fisheye lens system

Fisheye lens system is specifically designed for the forward view from the perspective of camera detectors as we stated above. Fig. 1 shows a typical example of the fisheye lens system. The front lenses or a lens group for collecting rays (as shown in Fig. 1(a)) must have a much greater negative refractive power than that of an ordinary inverted telephoto lens system because a fairly large back focal distance, relative to the focal length of the whole lens system, is required for avoiding an increase in the size of the lens system [3].

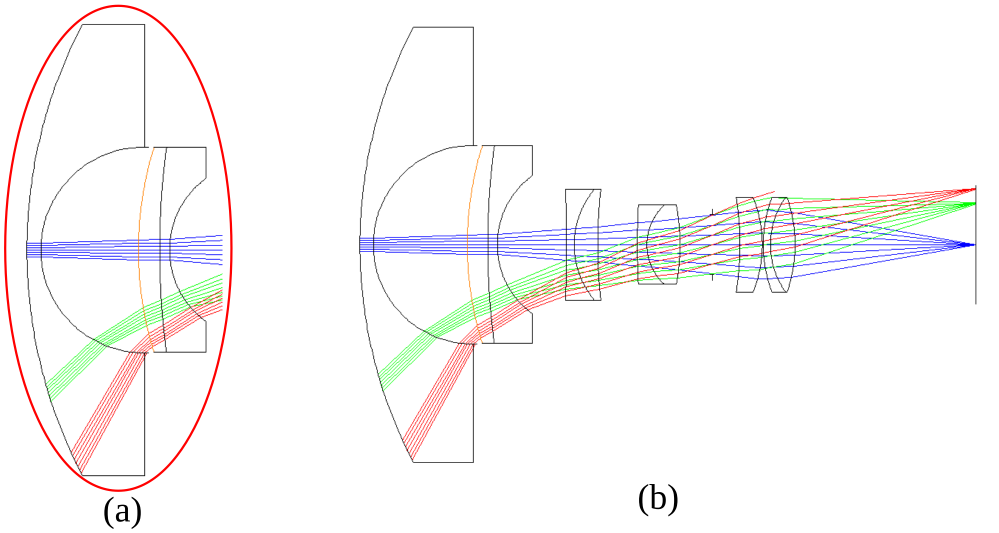


Fig. 1. Fisheye lens example: (a) fisheye lens group; (b) the whole fisheye lens system [3].

Generally, fisheye lens system consists three different parts [3-6]. The first part consists of one or several negative meniscuses, which we call fisheye lens or fisheye lens group due to the fish-eye shape. The second part is a positive group with several lenses to increase the relative aperture and correct the aberration. The third part is the lens group consisting of several negative meniscuses to correct the distortion. As a result, the 3rd part is unnecessary if there is no need to correct the distortion. The key point of fisheye lens system design is developing a fisheye lens group with a wide field of view (FOV). There exist multiple ways to achieve the target. For example, Smith and Wang using the iterative or polynomial-fit method in design of the fish-eye lens [7, 8]. Jose etc. have used the SMS2D (Simultaneous Multiple Surfaces) method to design the initial starting point for the panoramic fisheye lens system, which is very close to the final solution [9]. Lu etc. have proposed a new method of optimizing the aberrations of ultra-wide-angle and panoramic optical systems based on an aberration theory of plane-symmetric optical systems [10]. Yang etc. have derived the surface profile of panoramic objective lens by solving a differential equation which is controlled under equidistance projection scheme [11]. Based on the design algorithms, Yang's design can be applied to increase FOV of normal camera lens system directly. Besides, Harvey and Thibault discussed the performance of diffractive optics, refractive optics and reflective optics in panoramic lens system and demonstrated the advantages of refractive optics for panoramic systems due to the compact size and less stray light [12, 13].

The distortion plays a key important role in evaluating the performance of panoramic lens system. Generally, the reference height of an undistorted ray in a lens system obeys the f-θ mapping mechanism, which is given by

$$Y_{ref} = f \cdot \theta \tag{1}$$

where f is the focal length and θ is the angle of field in the object space. James etc. have analyzed the distortion performance of several patents of fisheye lens system, and provided the plot of departure from perfect linear mapping (f-θ) dependent on the angle of FOV for each fisheye lens system as shown in Fig. 2 [14].

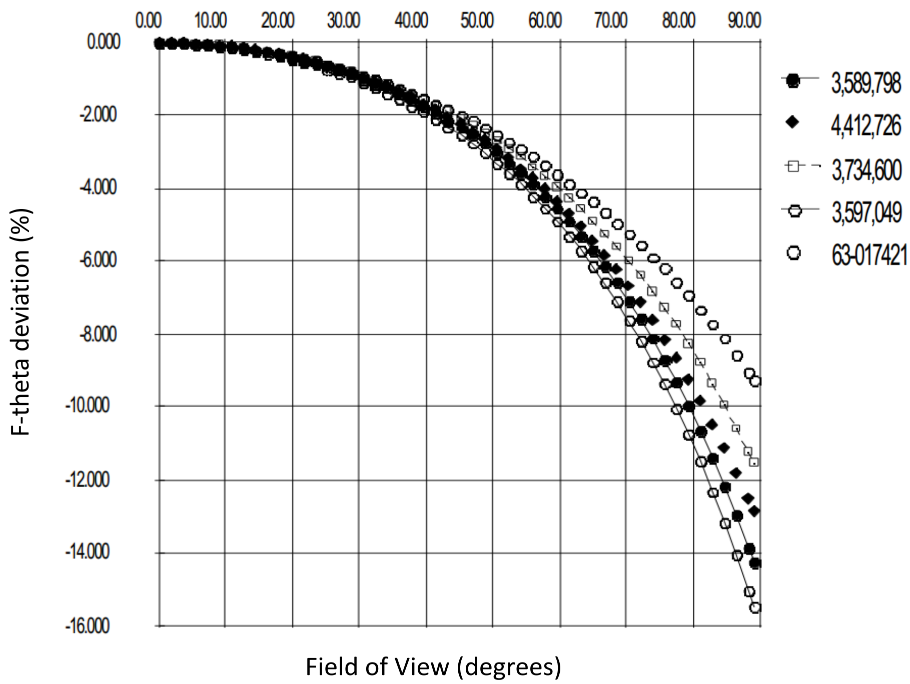


Fig. 2. F-theta distortion for different fisheye lens patents [14-18]

3. Panoramic reflector system

Using reflective mirror is another approach to generate the global view for panoramic systems [19]. Unlike the fisheye systems, panoramic reflective system can realize FOV larger than180° [20]. Due to the incomparable advantages, panoramic reflective system has found its broad applications in security and surveillance, robot navigation, map building, stereo imaging, and so on [21-26]. As shown in Fig. 3, general panoramic reflective system consists of a refractive lens system and a panoramic mirror surface. The key to develop the panoramic reflector system is to design the mirror surface. The shape of the mirror surface can be spherical, parabolic, hyperbolic surface, or any other freeform surface. If we take a equi-projection scheme to the panoramic mirror surface (which means that δ is linearly proportional to θ as shown in Fig. 3), the profile shape of the mirror can be controlled by the following equation [27, 28]:

$$\frac{d}{d\theta}\left[\tan^{-1}\left(r\frac{d\theta}{dr}\right)\right] = \kappa$$

where κ is a constant parameterizing the surface, *r* is the distance of a point on the surface to the nodal point of the camera, and θ is the radial angle of the reflected ray as shown in Fig. 3.

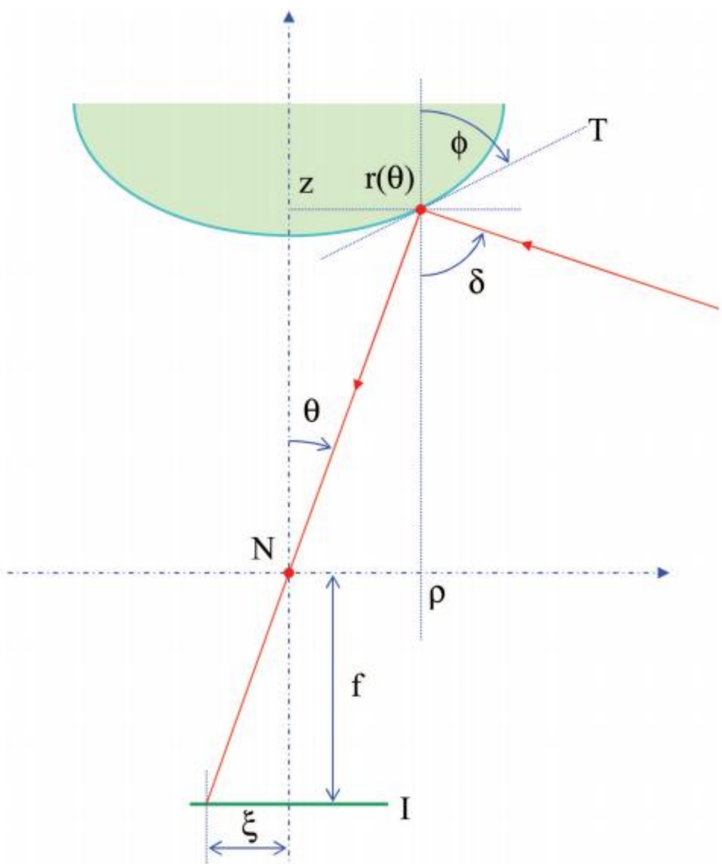
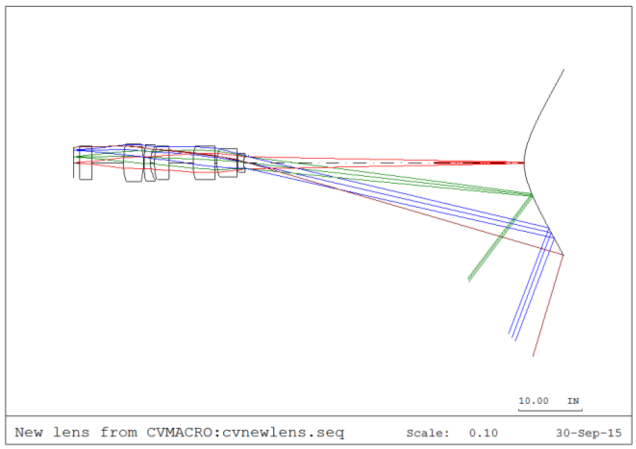


Fig. 3 Schematic illustration of principle for panoramic reflector design [27]

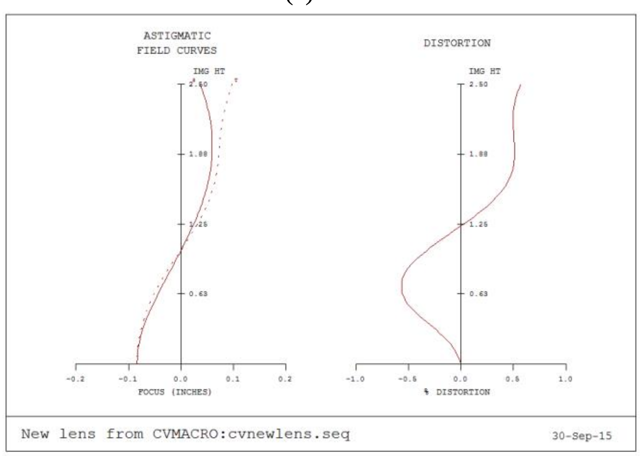
Fig. 4 shows a typical design example for the panoramic reflector system for the realization of a global view in the backward direction. From the lens performance as shown in Fig. 4(b), the distortion is below 1% and is well controlled due to the use of panoramic reflector as a collection surface. In this special design, the mirror surface is an even aspheric surface, which is given by the following formula

$$h(\rho)=\frac{\rho^2/R}{1+\sqrt{1-(1+k)(\rho/R)^2}}+\sum_{i=1}^{n}C_i\rho^{2+2i}\ , \tag{4}$$

where R is the radius of curvature at the vertex, and k is the conic constant.



(a)



(b)

Fig. 4. Panoramic reflector system design example [27]: (a) geometrical layout of the lens system; (b) astigmatic field curves and distortion curve.

Up to now, many panoramic reflector systems with different configurations have been developed. Fig. 5 shows some of these set-ups. Fig. 5(a) shows a design of

Omni-Directional Vision Sensors (ODVS) with no dead angle [29]. In the design shown in Fig. 5(b), the panoramic reflector is applied to realize a projection lens system with an ultrashort throw ratio (TR), the field curvature is also well corrected in this design [30]. Fig. 5(c) is a compact and light-weight panoramic lens (with total internal reflection) which was developed to be mounted on standard off-the-shelf video cameras [31]. The design in Fig. 5(d) uses a double lobed hyperbolic mirror to generate a pair of stereo images [32]. Both Fig. 5(e) and 5(f) show two different mapping mechanisms compared to traditional mapping mechanism for the panoramic reflector surface design [28, 33].

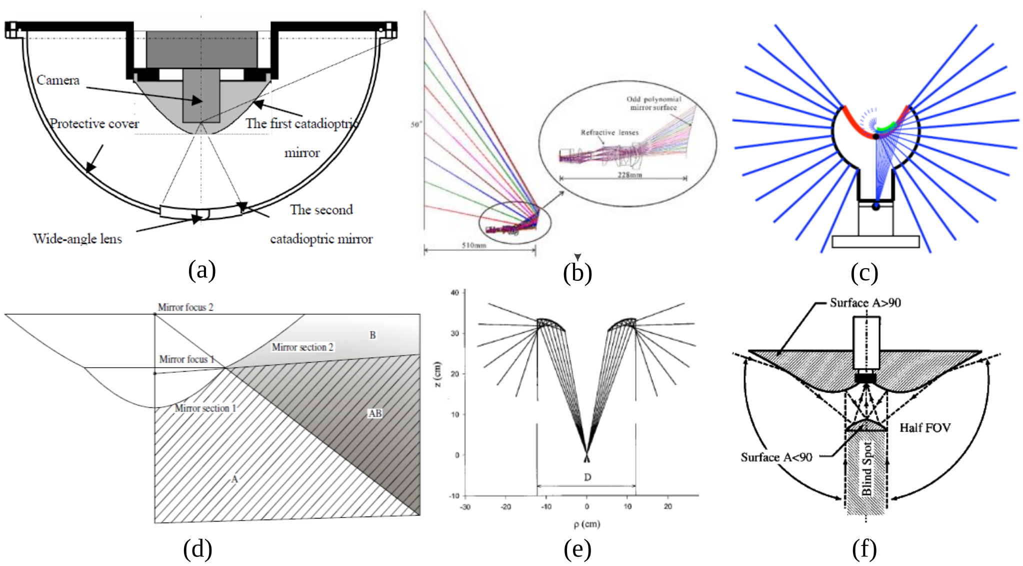


Fig. 5 Typical panoramic reflector design set-ups with different mapping mechanisms for various applications [28-33]

Fig. 6 presents some patents of the panoramic reflector systems for various applications [34-41]. In addition to one single mirror surface for ray collection, some of these designs have used multiple mirror surfaces to collect rays inside FOV.

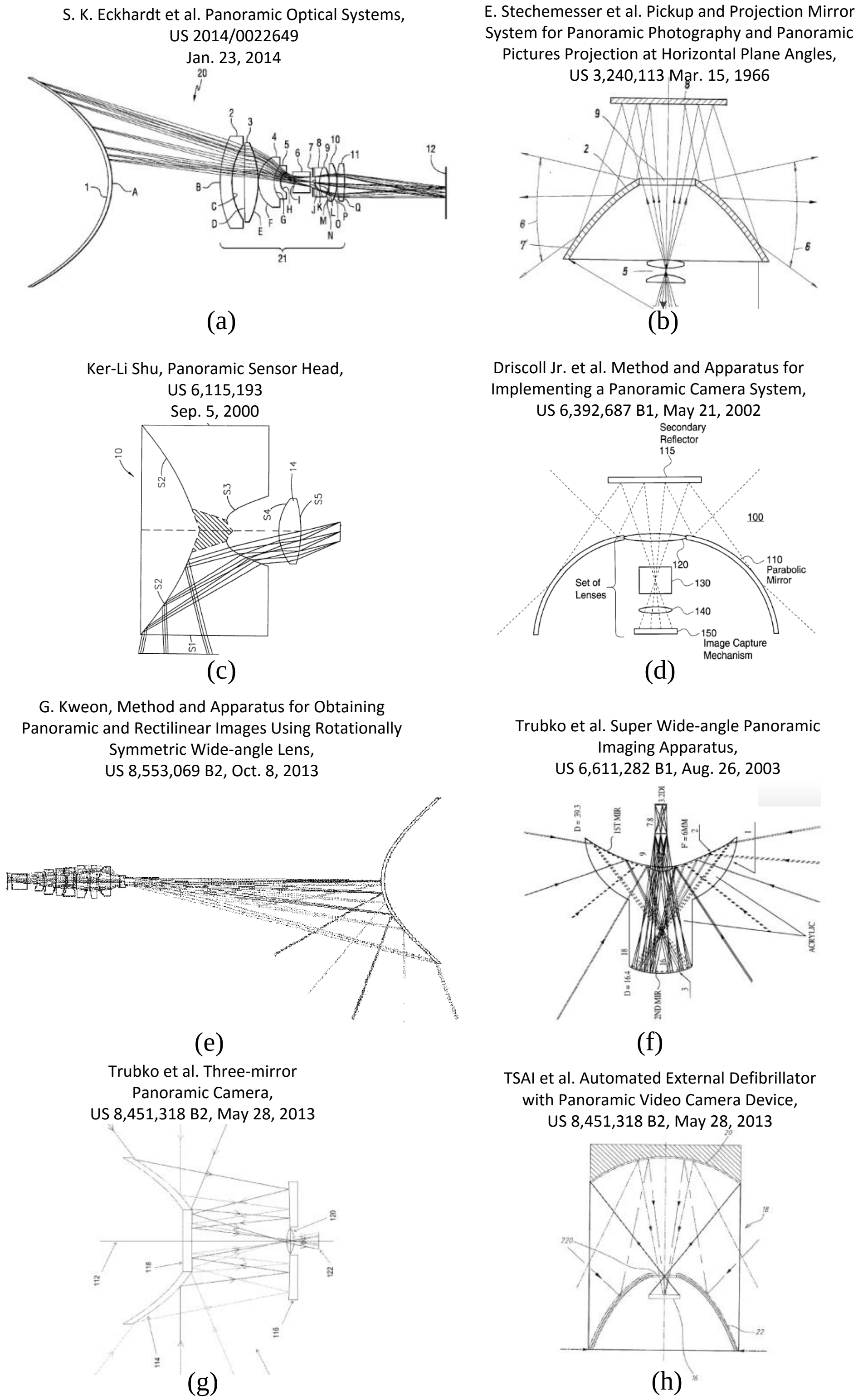


Fig. 6. Typical patents for panoramic reflector system design [34-41]

4. Panoramic annular lens (PAL) system

Panoramic annular lens, which is firstly developed by Greguss [42], has been broadly applied to generate global view for panoramic imaging systems. The PAL optical system projects the cylindrically panoramic view of 360 °around the optical axis to an annular area on the detector and thus it has a very good performance to capture the side view of the global space [43-48]. For the working principle of PAL, Ian Powell has provided detailed analysis in his paper [44]. Fig. 7 depicts the typical arrangement for the general PAL system, which comprises a panoramic block followed by a lens and a video camera. As shown in Fig. 7, each incident ray into the panoramic block experiences two reflections and two refractions. Due to different imaging quality requirements, both reflective surfaces and both refractive surfaces can be parabolic, hyperbolic, and spherical surfaces. According to Ian Powell's assertion, the spherical surface works better compared to other types of surfaces.

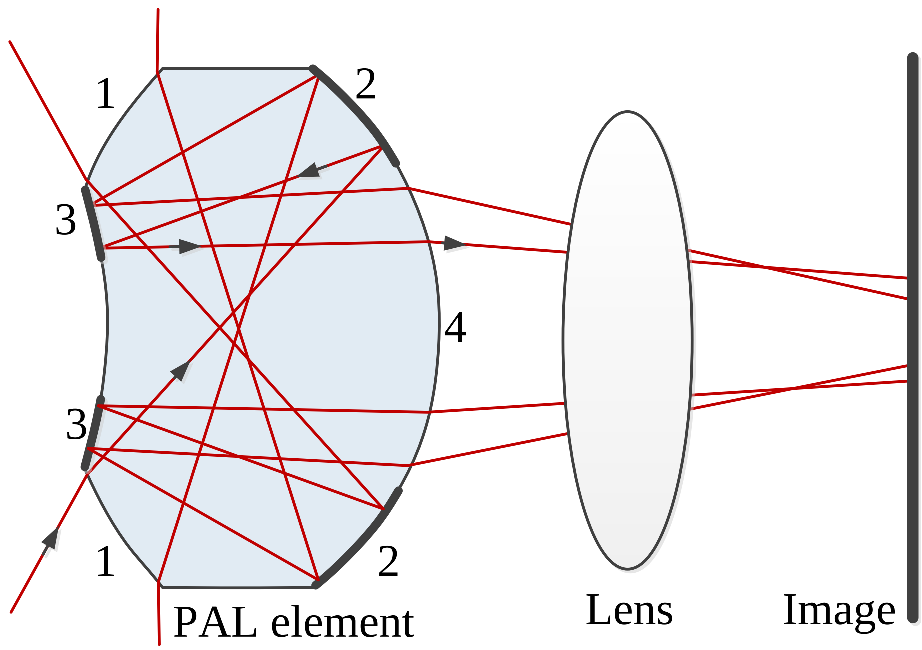
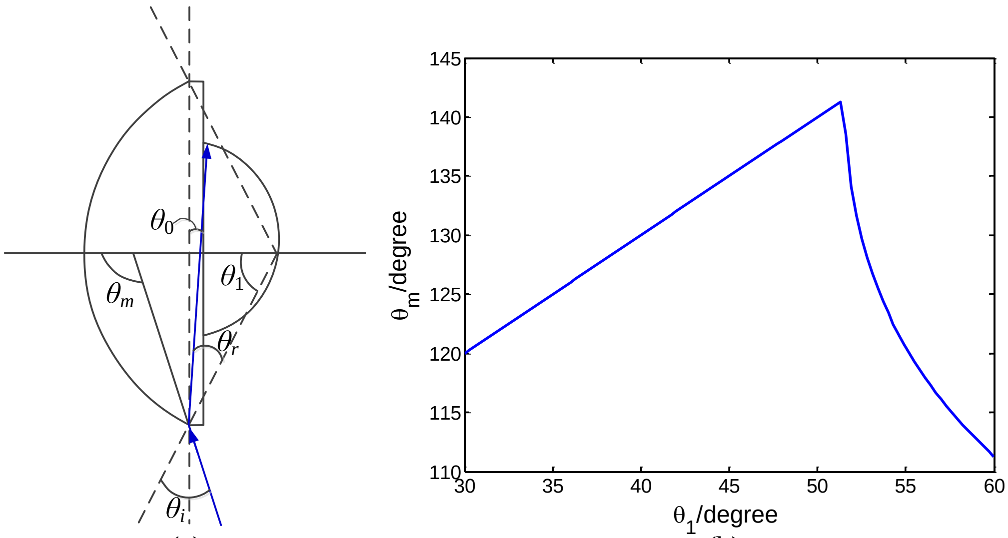


Fig. 7 Typical panoramic annular lens system

The key point of PAL optical system design is to specify the parameters of panoramic block such as size and thickness. The dimension of the panoramic block limits the theoretical maximum FOV of the whole optical system as shown in Fig. 8(a). Obviously, the angle θ_1 defines the final thickness of the PAL element with given aperture. Due to the condition that the refracted ray after the first refractive surface has to hit the rear mirror surface, θ_0 should be positive. For a given θ_1, the maximum acceptance angle can be theoretically derived as:

$$\theta_m = \theta_1 + \arcsin\left(n \cdot \left(\frac{\pi}{2} - \theta_1\right)\right) \tag{5}$$

where n is the refractive index material of the PAL lens. The relationship expressed in this equation is displayed in Fig. 8(b). From the plot we can see that the FOV reaches its maximum when θ_1 is around 50°. Actual PAL optical system usually has a FOV smaller than140° because the size of incident beam cannot be only a single ray. Nevertheless, we still need to approach θ_1 to be around 50° so that we can realize a much more stable design for the PAL element.



(a) (b)

Fig. 8 (a) PAL element with front refractive surface and rear reflective surface; (b) Maximum acceptance angle of PAL element dependent on θ_1.

Figure 9 shows some example of PAL optical systems [48-54]. Fig. 9(a) shows the structure of a doublet PAL for the correction of chromatic aberrations [48]. As shown in Fig. 9(b), researchers use two mirrors combined with two lenses to construct the PAL element of much more light-weight design [49]. The design shown in Fig. 9(c) has a finite to finite conjugate mechanism with a crossed mapping between the object space and image space [50, 51]. Figs. 9(d) to (f) are PAL based designs for applications of phone camera systems, surveillance systems, and endoscopic systems separately [52]. The distortions for these three optical systems are all below 6%, well controlled for this large FOVs. Fig. 9(g) shows a design of panoramic stereo imaging with single optical system which combines two PAL optical systems together [53]. The object position can be calculated through triangulation algorithm in the stereo imaging system. Fig. 9(h) shows the design structure for an in vivo capsule endoscope [54]. In this design, a PAL optical system is applied to capture the side view of environment.

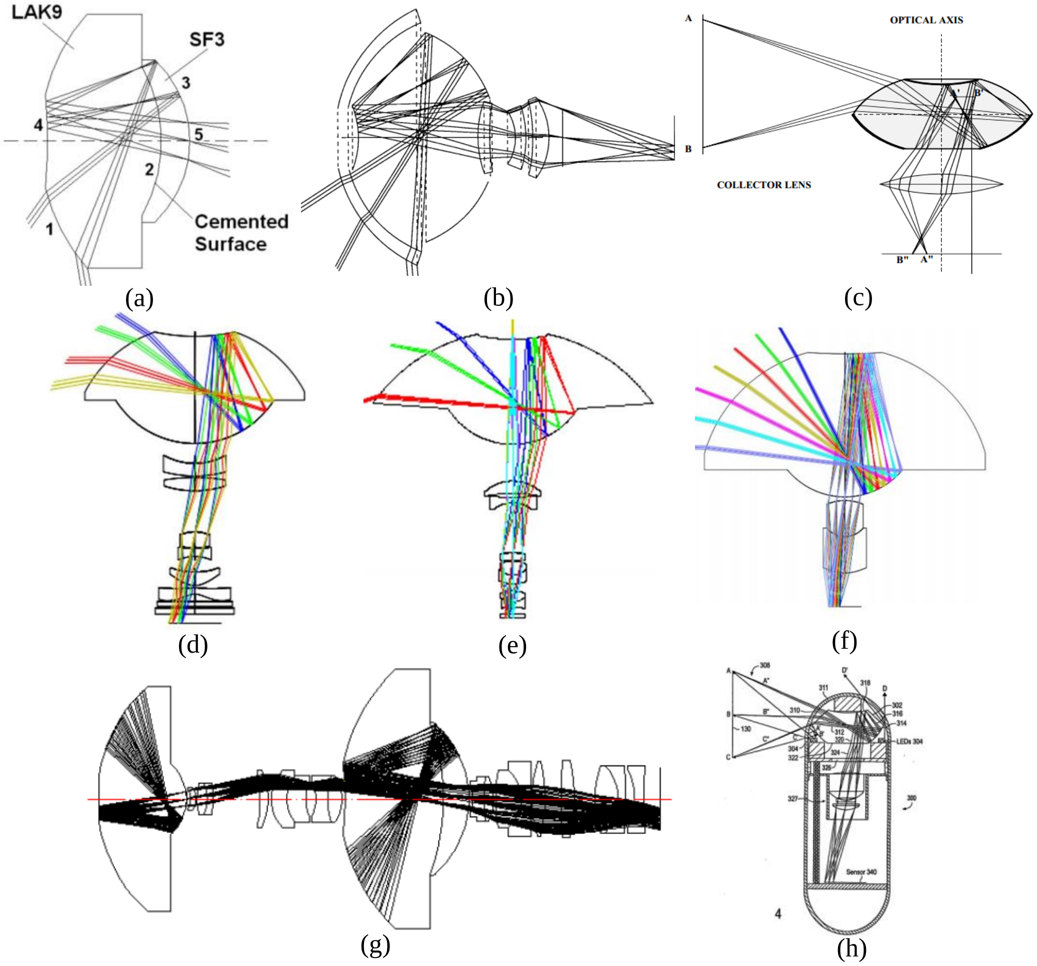


Fig. 9. Typical applications of PAL optical systems [48-54]

Fig. 10 shows some patents of related PAL optical systems for various applications [55-64]. Among these patents, the PAL elements are designed with either spherical surface or aspherical surface (Fig. 10(a)). In additional to being combined with general camera lens system (Fig. 10(e), Fig. 10(f), Fig. 10(g), and

Fig. 10(i)), the PAL element can also be coupled with zoom lens system (Fig. 10(b)), relay lens system (Fig. 10(j)) for some specific applications. Fig. 10(d) shows a new structure of PAL element to capture the panoramic side view of object space, where there is no crossed ray tracing inside the PAL block. The patent shown in Fig. 10(c) is a PAL block consisting of three different pieces, which are designed to correct the chromatic aberration.

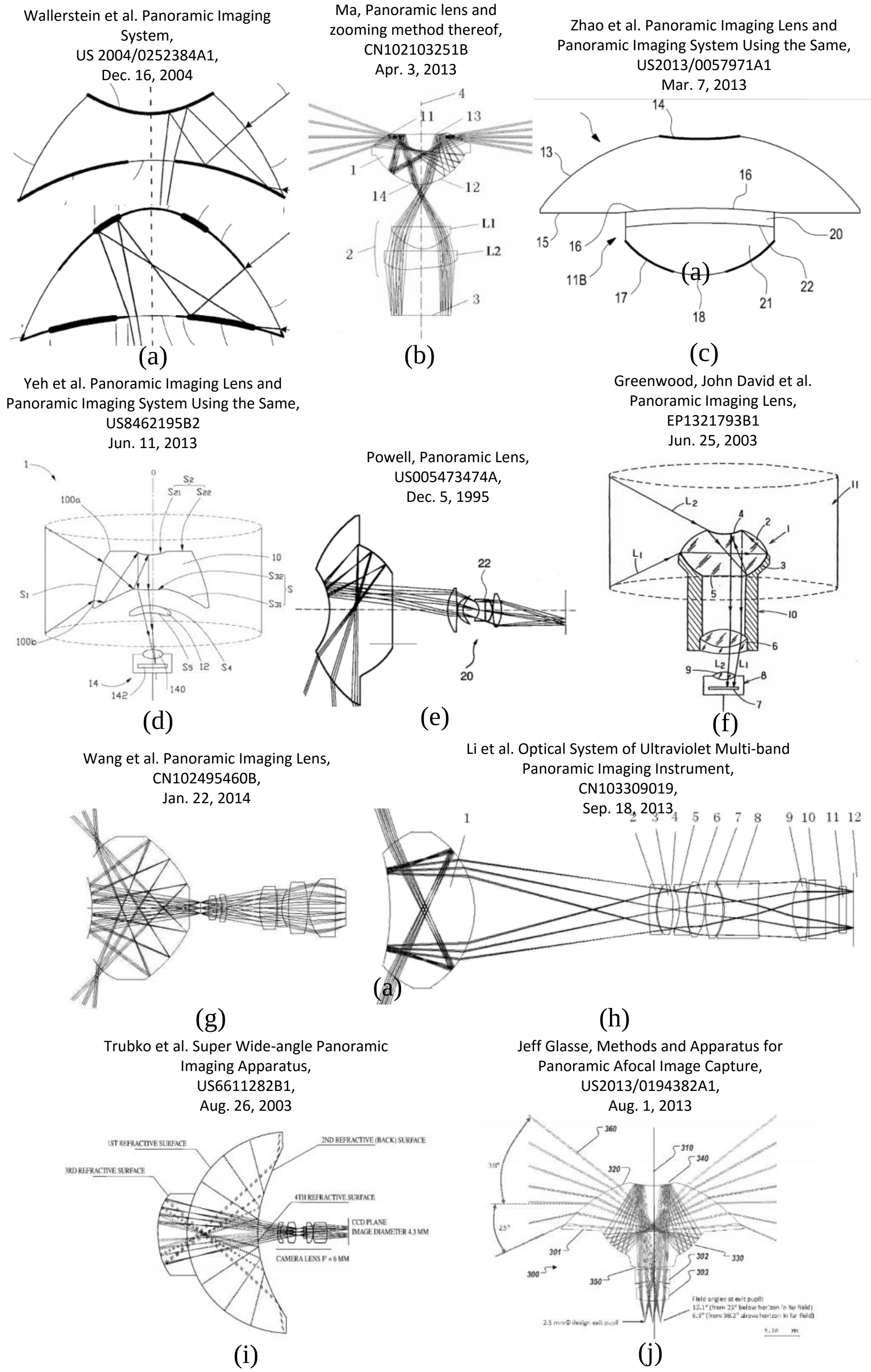


Fig. 10. Typical patents for PAL optical systems [55-64]

5. Panoramic lens system with multiple views

In previous sections, we have discussed three types of panoramic optical systems, which are specifically designed for various views in the object space. To increase the field of view, two or more types of panoramic optical systems are often integrated into a single system. In this section, we discuss several configurations of the panoramic lens systems with multiple views.

Typically, composite optical systems combining panoramic reflector and fisheye lens system can capture both front field of view and backward field of view at the same time with a single camera sensor (as shown in Fig. 11(a), (c), (e) and (g)) [65-68]. In most of these designs, a lens is covered on the panoramic reflector to extend FOV from backward view to the side view, which can also be taken as a modified structure for traditional PAL element. Fig. 11(b) and (d) show two examples of combining the panoramic reflector and fisheye lens system together to generate the stereo image with a single camera sensor [69, 70]. Fig. 11(f) shows a typical example of combining PAL optical system and fisheye lens together to capture both front view and side view at the same time [71]. In conclusion, through combination of two different panoramic optical systems, super large FOV or stereo image will be easily realized with only single camera sensor.

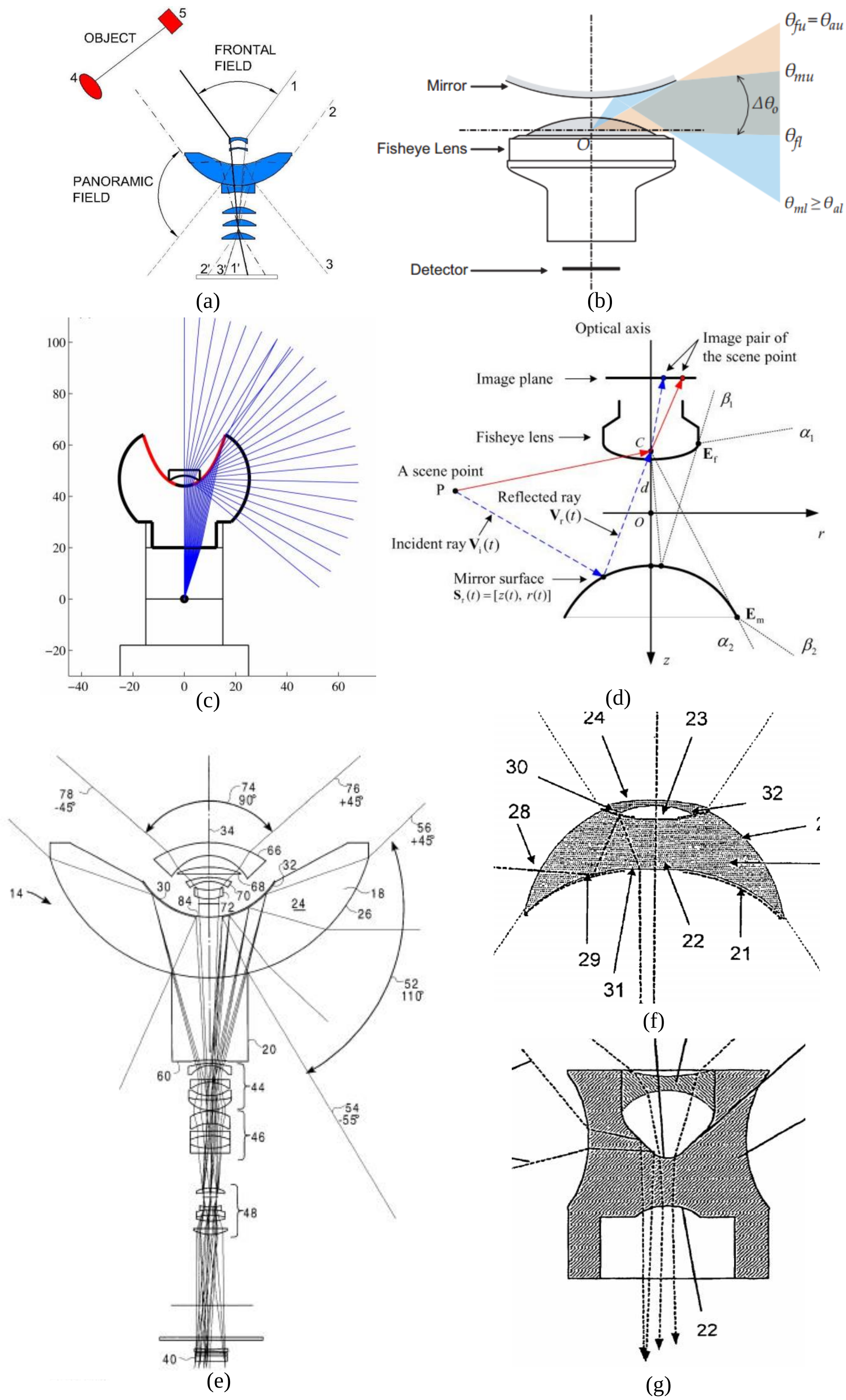


Fig. 11 “Dual view” panoramic optical system design examples [65-71]

6. Obstruction-free, panoramic lens system design with triple views

In previous section, we have reviewed several design configuration with dual views in the object space. In this section, we combine all these three different panoramic optical systems together to capture all triple views with a single CCD sensor: front view, side view and rear view. Specifically, we apply the traditional fish lens system to capture the front view of the global space, use the classic panoramic annular lens block to collect rays from the side view of global space, and implement the panoramic reflector system to see the rear view of the global space. With these special combination of optical systems, we can finally realize a full field of view of $360° \times 270°$ with no obstruction in the front space.

Fig. 12(a) shows the design of a fisheye lens system to capture the forward view of the object space at f/# of 7.2 and half field of view (HFOV) of 0° to 60°. Fig. 12(b) shows the design of a PAL block combined with the same camera lens system to collect rays from the side view of the object space at f/# of 5.8 and FOV of 60° to 85°. Fig. 12(c) shows the panoramic reflector system combined with the same camera lens system to capture the rear view of the object space. The reflector system is designed at f/# of 7.4 and HFOV of 75° to 135°. As seen from the three designs, they can be implemented into the same composite lens system since they share the same camera lens system. Fig. 12(d) shows the way to assemble these three different optical systems. Due to the high requirement of super large FOV, the numerical aperture for each field is relatively small.

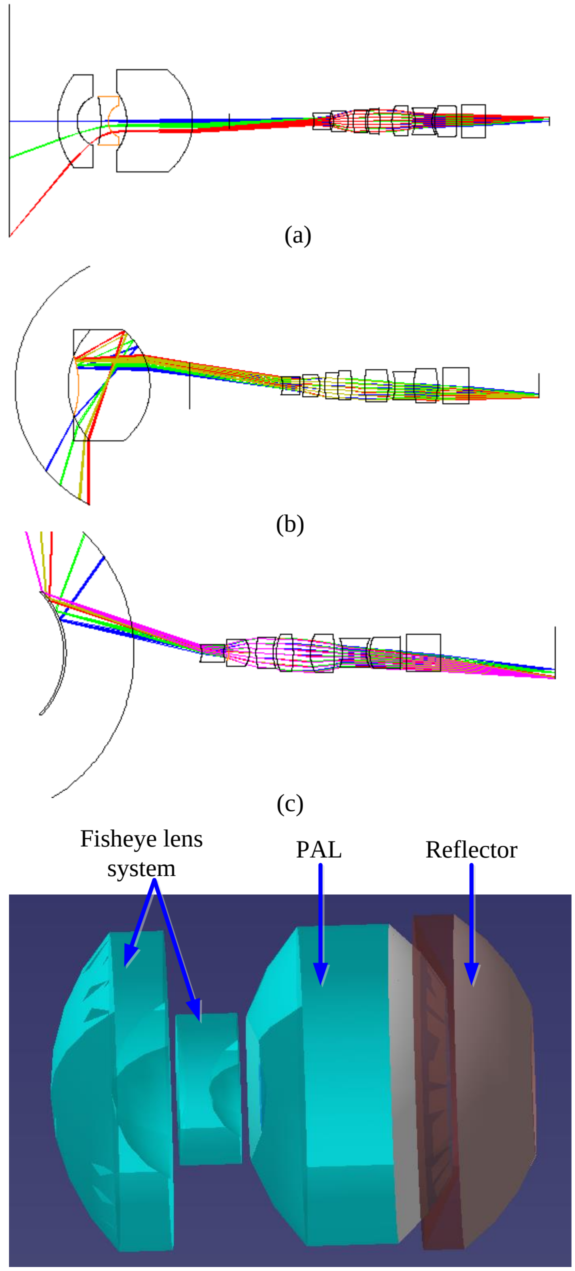
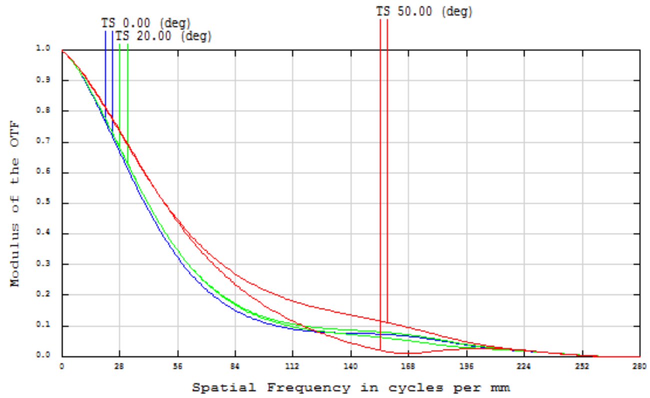
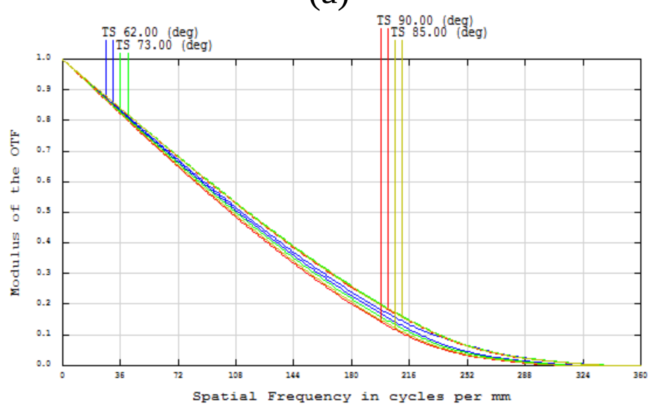


Fig. 12. Triple view lens system: (a) fish-eye lens system for forward view; (b) PAL lens system for side view; (c) panoramic reflector system for rear view; (d) mechanic assembly of the three panoramic optical systems.



(a)



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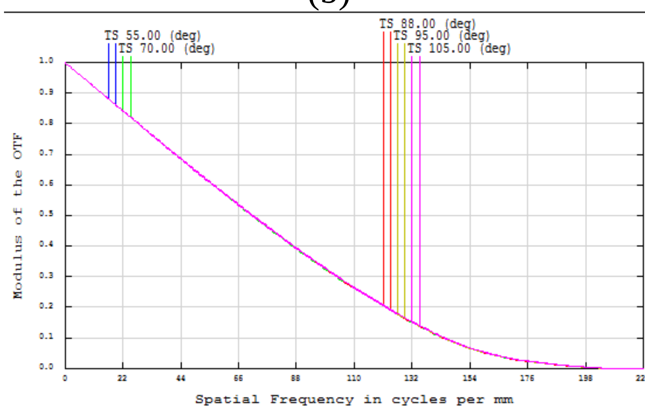

(c)

Fig. 13. MTF of the triple view optical system for different parts: (a) fish-eye lens group for forward view; (b) PAL lens system for side view; (c) panoramic reflector system for rear view.

7. Conclusion

In conclusion, we present a review of state-of-the-art panoramic optical system design, ranging from classification, design consideration to imaging mechanism of various types of panoramic lenses. In addition, we analyze the magnitude of distortion for some examples of panoramic optical systems quantitatively.

Panoramic optical systems have been demonstrated to have broad applications in surveillance, robotic vision, endoscopic optical systems, and so on. We believe that they will be playing more and more important roles in the development of future optics technologies. Further research to improve the performance of panoramic optical systems and correct distortion of large FOV is required to meet the increasing daily applications.

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