

Designs for high performance PAL-based imaging systems

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In this study, we investigate methods to optimize the design of a panoramic annular lens (PAL) system. The design details of a PAL surveillance system, an anamorphic PAL surveillance system, a phone camera with a PAL attachment, and a PAL endoscope system are described. All these designs are optimized using a standard optical software package (Zemax). The results combine very good image quality with a modulation transfer function above 0.3, which is within the cutoff frequency of sensor chips.

OCIS codes: (220.3620) Lens system design; (120.4570) Optical design of instruments

1. Introduction

It is well known that PAL, the first 360° lens, has many advantages compared to traditional cameras. With panoramic view, simple to fabricate, small compact size, and capable of sharp imaging make PAL valuable in many applications. Although the minimal vertical field of view is not from 0°, it shows superiority in inspections and measurements such as surveillance system, phone camera, endoscopic measurement, etc.

Researchers have studied and improved many aspects of the PAL. In 1986, Pal Greguss et al. proposed design of panoramic imaging block which is known as PAL [1]. It was proved that in PAL system, good imaging performance could be achieved by employing spherical surfaces [2], and in 1995, analytical representation of PAL mapping characteristics from object to image was established [3]. PAL arrangement and image processing used in surveillance system have also been addressed [4, 5]. Recent years, some research has focused on

optical design of PAL system and products of PAL cameras are available [6-13]. However, few PAL optical designs with low system complexity for wide range of applications are proposed.

In this paper, the method of PAL-based imaging system design is given. Applied the method, a series of PAL systems optical designs are demonstrated using standard optical design software Zemax. All these optimal designs show the PAL block can be flexibly used in panoramic camera lens. Generally, PAL system is composed of 2 components, PAL block and relay lens. In our paper, we designed the PAL block which is preferred to fabrication and cost. As for the design of relay lens system, with the PAL block producing annular image mapping, the simplified relay lens system is achieved. According to design analysis, cemented doublet lens is preferable for relay lens compact in size and aberrations balancing. All the optical design details are described in the paper.

2. PAL optics and design scheme

Fig. 1 shows the characteristics of PAL system. For its cylindrical object space with the vertical field angle β is rotational symmetry around the optical axis which is the z-axis in the system. The area from α to z-axis is a blind space which is not engaged in imaging. The PAL block consists of two refractive and two reflective surfaces. Optical path can be described that rays leaving the object are refracted into the PAL block from surface 1 and reflected off the rear mirrored surface 2, then they travel forward in the lens and contact the front mirrored surface 3. Reflected back, the rays exit the PAL block from the rear surface. After leaving the PAL, the divergent rays enter into the relay lens whose mainly work is to correct and balance aberrations with the PAL block. At last, rays form annular image on the CCD/CMOS sensor.

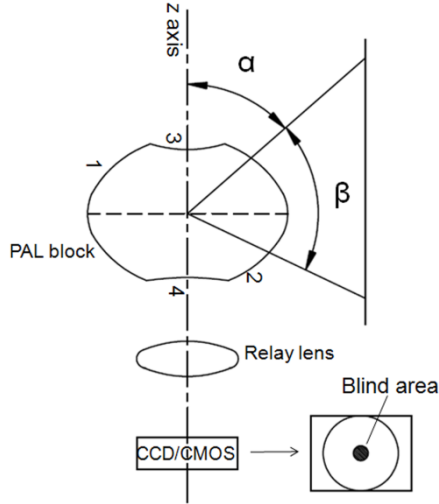


Fig. 1. PAL system

Tracing the optical path, we have some brief summary for the PAL system design. The virtual image is formed inside the PAL block. Relay lens changes virtual image into real image and condenses the image height matching with the sensor. As for annular imaging, spherical and other longitudinal aberrations are not significant to be corrected. Lateral aberrations such as coma, lateral chromatic and other lateral aberrations are major factors for the imaging quality. Understandably to regard PAL system as the $f-\theta$ lens, relative distortion can be expressed as

$$D_r = \frac{\tan \theta - \theta}{\tan \theta} \times 100\% \quad (1)$$

For wide-angle lens systems, distortion is one of the most significant characteristics, it effects on the output imaging quality. Because of the relations between distortion and pupil aberrations, appropriately choosing the pupil position benefits distortion control. It has been discussed that telecentric system (exist pupil is located at infinity) is good for correction of pupil aberrations [14] and provides other advantages for panoramic system [15-16]. According to the design principle, the telecentric PAL block indicates that the entrance pupil coincides with the focal plane of the PAL block. In actual design process, the center of entrance pupil is not precisely located at the focus of the PAL block, but near to it. Fig. 2 shows the telecentric PAL block in our demonstration designs. This structure is preferred to fabrication and could provide good imaging. It is considered to make the reflective surface 2 and refractive surface 4 into one surface as shown in Fig. 2. It indicates that the value of the radius of curvature of reflective surface 2 is equal to the value of the radius of curvature of refractive surface 4.

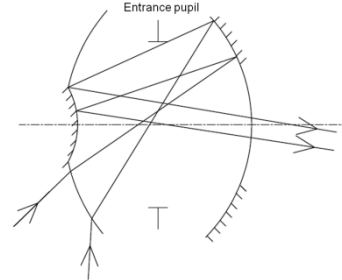


Fig. 2. Telecentric PAL block

According to the analysis above, we summarize the key points of the PAL-based system design scheme as shown in Table 1. It provides useful design method. To demonstrate, the details of four successful design examples are described below.

Table 1. Key points of the PAL-based system design scheme

PAL-based system design	
PAL block	Relay lens
Set up initial structure	Set up initial structure
1. All spherical surfaces	1. Doublet lens is preferred
2. Reasonable structure	2. Aberrations are considered
3. Virtual image inside	3. Aperture stop location
4. Telecentric system	
Combination/Optimizing Analysis imaging quality	

3. PAL surveillance system

As for a baseline of PAL optical design, Fig. 3 shows the structure of the PAL surveillance system with a focal length -0.96mm, $f/2.0$, $52^\circ \sim 108^\circ \times 360^\circ$ FOV (field of view), $0.486\mu\text{m} \sim 0.656\mu\text{m}$ spectral range, and all the spherical surfaces. The diameter of the PAL block is about 60mm. The total length is 55mm. We assume the image falls on the $1/3''$ CCD with a pixel size of $7.5\mu\text{m}$.

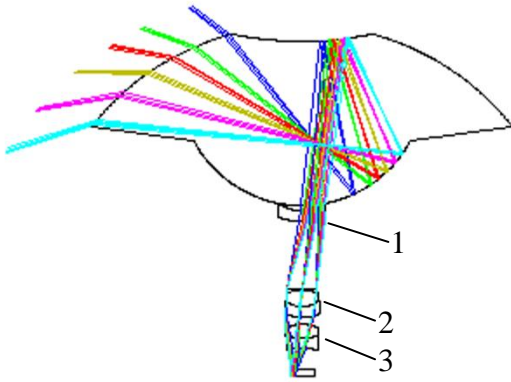


Fig. 3. Structure of the PAL surveillance system. Different colors represent different FOV which are 52° ; 70° ; 80° ; 90° ; 100° ; 108° .

To satisfy the requirement of telecentric PAL block, the entrance pupil position is 10.89mm and the focal length is 11.50mm. For the PAL used over a broad spectrum, the relay lens needs to be achromatized. Achromatization is best achieved by employing doublets in relay lens system. Two doublets are used in our design, they can also reduce the spherical aberration. However, two positive doublets suffer from the effects of astigmatism and field curvature, which may significantly degrade the off-axis image quality. With a meniscus lens, the field curvature and astigmatism can be reduced. Appropriately designed the location of the aperture stop is obviously helpful to coma correction. The PAL surveillance system design data is shown in Table 2. We can see that all the surfaces are spherical, and the materials used come from Chinese glass catalog.

Fig. 4 is the MTF of the system. The MTF is effective to evaluate the imaging quality. Its spatial cutoff frequency is defined by the pixel size of CCD sensor which is $7.5\mu\text{m}$ in our system. The relation between the spatial cutoff frequency and the pixel size of CCD sensor can be expressed as

$$f = \frac{1(\text{mm})}{2 \times h(\mu\text{m})} \quad (2)$$

Put $h = 7.5\mu\text{m}$ into formula (2), we get spatial cutoff frequency $f = 67\text{ lp/mm}$. As Fig. 4 indicates, the MTF below 70 lp/mm is above 0.65 which is much higher than the resolution requirement of the CCD sensor. And the aberrations in FOV are all corrected well.

Table 2. Design data of surveillance system. Parameters of the PAL block and its relay lens

	PAL block surface				Relay lens		
	1	2	3	4	1	2 doublet	3 doublet
Radius1(mm)	38.33	-17.54	-48.64	-17.54	-6.01	7.02	4.54
Radius2(mm)	---	---	---	---	-10.04	-3.93	-6.40
Radius3(mm)	---	---	---	---	---	-7.55	7.03
Thickness(mm)	25.78	23.39	---	---	1.50	2.30/1.50	2.00/1.40
Glass	K9	Mirror	Mirror	K9	ZF1	BAK4/LAK3	K9/ZF4

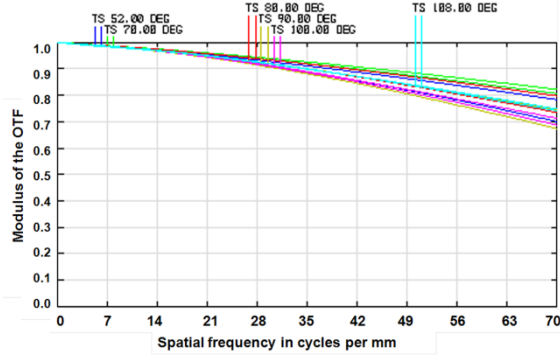


Fig. 4. MTF of the PAL surveillance system at 70p/mm. T represents longitudinal MTF, S represents sagittal MTF.

4. Anamorphic PAL surveillance system

We develop the PAL surveillance system to get optimal and efficient total 360° coverage, with an increased resolution on the periphery of the image.

To increase useful area of sensor chip [10], we add the anamorphic lens group into the PAL system. Its effect on image mapping is shown in Fig. 5.

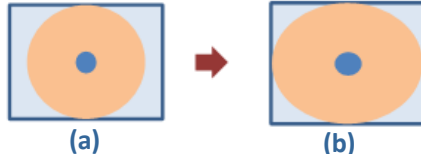


Fig. 5. PAL image mapping. (a) PAL annular image. (b) PAL anamorphic annular image.

Based on the design of PAL surveillance system in Part 3. With cylindrical lens group, we optimize the system using optical software Zemax, and get the elliptic annulus image with anamorphic ratio of 4:3 matched with CCD sensor. Fig. 6 shows the structure of the anamorphic PAL surveillance system with focal

length -0.9 mm, $f/2.0$ in short axis and focal length -1.16 mm, $f/2.7$ in long axis.

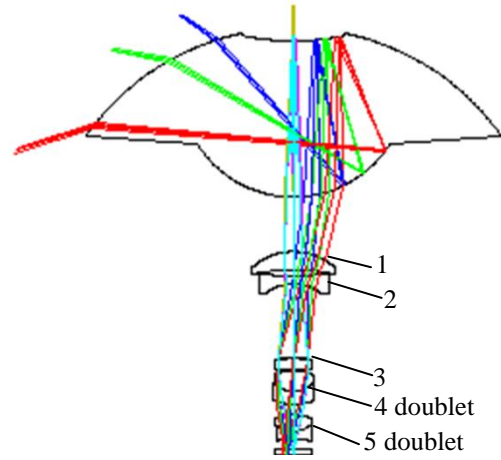


Fig. 6. Structure of the anamorphic PAL surveillance system. Different colors represent different FOV which are 55°, 80°, 108°.

Table 3 is the design data of the system. The 1st and the 2nd relay lens are cylindrical lens whose back surface is toroidal. Cylindrical lens focus or expand light in one axis only, which can produce and reduce astigmatism. In Zemax programming, the cylindrical lens surface type is Toroidal [11]. We use REAY and REAX operands in Merit Function Editor to control the image length-width ratio. To achieve better aberration correction with a simple configuration, the aspherical profile is applied on the back surface of the 2nd relay lens, which is away from the aperture stop. Consequently, the field-dependent aberrations, such as astigmatism and distortion, can be controlled more effectively.

Table 3. Design data of anamorphic surveillance system. Parameters of the PAL block and its relay lens.

	PAL block surface				Relay lens				
	1	2	3	4	1*	2*	3*	4 doublet	5 doublet
Radius1(mm)	39.00	-17.50	-37.00	-17.50	9.45	-35.70	13.99	8.14	7.20
Radius2*(mm)	---	---	---	---	28.65	7.02	54.13	-4.39	-4.39
Radius3(mm)	---	---	---	---	---	---	---	-9.80	11.64
Thickness(mm)	25.78	23.39	---	---	2.80	1.20	1.81	3.10/2.00	2.50/1.20
Glass	K9	Mirror	Mirror	K9	K9	LAK52	ZF1	BAK5/ZBAF21	QK3/ZF11

The back surface of the 1st and the 3rd relay lens are toroidal. The back surface of the 2nd relay lens is even asphere with coefficient E4=9.068e-005, E6=1.307e-006.

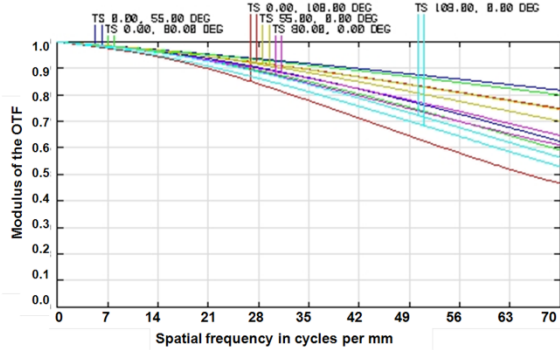


Fig. 7. MTF of the anamorphic PAL surveillance system at 70p/mm. T represents longitudinal MTF, S represents sagittal MTF.

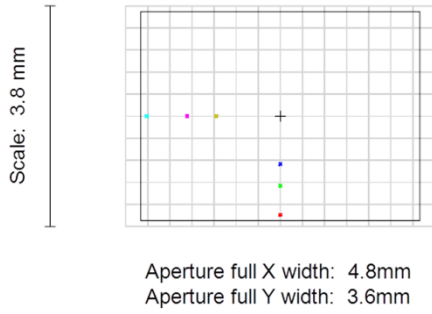


Fig. 8. Footprint of anamorphic PAL surveillance system on image plane. Different colors represent different FOV of $x=\pm 55^\circ$, $\pm 80^\circ$, $\pm 108^\circ$, and $y=\pm 55^\circ$, $\pm 80^\circ$, $\pm 108^\circ$.

The MTF below 70 lp/mm is above 0.45 as shown in Fig. 7, it can be seen that all the aberrations are corrected effectively. Tracing rays on the image plane, we get the footprint as shown in Fig. 8 with image area $3.4\text{mm} \times 4.6\text{mm}$, which is well matched with the $1/3''$ CCD sensor.

5. Phone camera with PAL attachment

As another application, PAL can be used as a dismountable attachment for phone camera. There are two shooting mode that one is normal mode whose FOV is $0^\circ \sim 30^\circ$ without PAL attachment; while the other is panoramic mode whose FOV is $57^\circ \sim 100^\circ \times 360^\circ$ with PAL attachment. To design a 5 mega-pixel panoramic camera, the resolution is required higher. In our design, a pixel size of the CMOS sensor is $1.75 \mu\text{m}$. The aperture is set to $f/2.8$. Fig. 9 (a) shows the structure of the phone camera in normal mode with a focal length 4.6mm, and 5.0mm diameter. While Fig. 9 (b) shows the structure of the phone camera in

panoramic mode with a focal length -0.82 mm, and 13.3mm diameter.

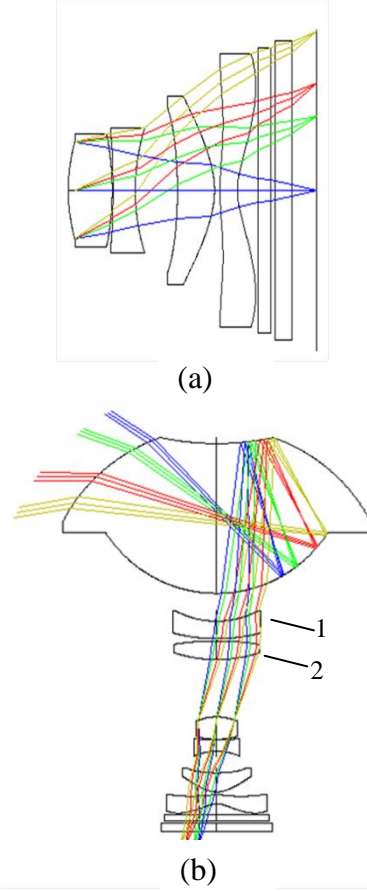


Fig. 9. Structure of the phone camera. (a) Without the PAL attachment. (b) With the PAL attachment. Different colors represent different FOV which are 57° , 70° , 90° , 100° .

The optical system illustrated in Fig. 9 (a) is a 5 mega-pixel mobile phone lens which is optimized well [12]. Table 4 is the design data of PAL attachment, which is composed of PAL block and its relay lens. For telecentric PAL block, the entrance pupil position is 2.62mm and the focal length is 3.03mm. In Table 4, all the surfaces are spherical. It is not difficult to design a PAL attachment for a phone camera whose aperture stop is located at the first surface. The key to design the PAL attachment is to design a telecentric optical path in its image space, which makes it easier to join the phone lens.

As the pixel size of CCD sensor is $1.75 \mu\text{m}$, according to formula (2), we get the spatial

Table 4. Design data of PAL attachment. Parameters of the PAL block and its relay lens

	PAL block surface				Relay lens	
	1	2	3	4	1	2
Radius1(mm)	7.90	-6.00	-11.98	-6.00	-4.00	11.86
Radius2(mm)	---	---	---	---	-7.65	-6.3
Thickness(mm)	7.52	6.82	---	---	1.50	2.30
Glass	K9	Mirror	Mirror	K9	ZF6	K9

cutoff frequency of 285 lp/mm. In Fig. 10, it can be seen that the MTF below 285 lp/mm is above 0.3 within the $0.7\times$ full field of view, and all the aberrations are corrected effectively. This imaging performance meets the design requirements.

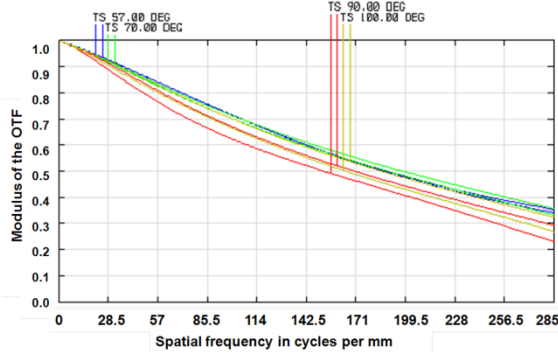


Fig. 10. MTF of the Phone camera with PAL attachment at 285p/mm. T represents longitudinal MTF, S represents sagittal MTF.

6. PAL endoscope system

Because of panoramic view, small, compact size, and high resolution, the PAL has advantages used in endoscope system [20-22]. The following is a design example of a medical endoscope which may easily be adapted or scaled up in size for other hollow-cavity inspection applications. Our design is very simple and extremely compact as shown in Fig. 11. The optical system measures 7.62 mm diameter, 8.12mm total length, and -0.27mm focal length. Aperture is set to 2.0, FOV is $30^\circ\sim 90^\circ\times 360^\circ$, and CMOS sensor with a pixel size of $2.2\mu\text{m}$ is used.

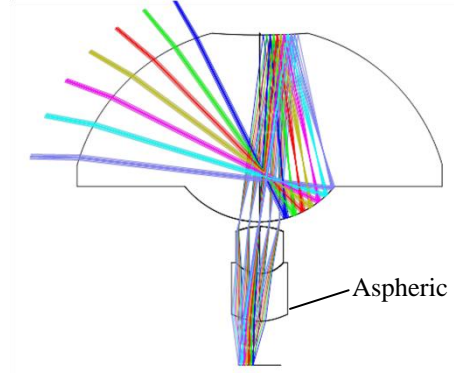


Fig. 11. Structure of the PAL endoscope system. Different colors represent different FOV which are 30° ; 40° ; 50° ; 60° ; 70° ; 80° ; 90° .

Table 5 is the design data of the system. Because the structure is very simple and the FOV is not very large, we don't employ the telecentric PAL block in this system. Relay lens system comprises just one cemented doublet with an aspherical surface located close to the image plane. All the aberrations are corrected satisfactorily with the help of the aspherical surface on the doublet lens.

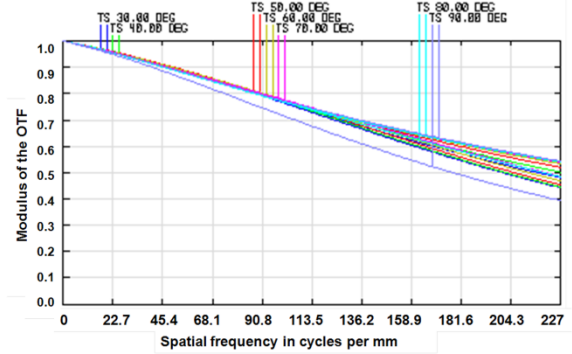


Fig. 12. MTF of the PAL surveillance system at 227p/mm. T represents longitudinal MTF, S represents sagittal MTF.

Put CMOS sensor pixel size of $2.2\mu\text{m}$ into formula (2), we get spatial cutoff frequency $f=227\text{ lp/mm}$. As Fig. 12 indicates, the MTF

Table 5. Design data of PAL endoscope system. Parameters of the PAL block and its relay lens

	PAL block surface				Relay lens
	1	2	3	4	Doublet*
Radius1(mm)	4.00	-2.05	-14.02	-2.05	1.23
Radius2(mm)	---	---	---	---	-0.65
Radius3*(mm)	---	---	---	---	-1.07
Thickness(mm)	4.10	3.93	---	---	0.99/1.00
Glass	PMMA	Mirror	Mirror	PMMA	PMMA/PC

below 227p/mm is above 0.38 which matches with the resolution requirement of the CCD sensor. And the aberrations in FOV are all corrected well.

7. Conclusions

We proposed the method of PAL-based imaging system design. Applied the method, we successfully designed a series of PAL-based optical systems for wide range of applications. We make all the surfaces of PAL block spherical and the reflective surface 2 and refractive surface 4 into one surface. It is preferred to fabrication, either by diamond-turning or by molding from plastic. As a baseline, a surveillance system optical design which features high image quality is given. Its MTF below 70lp/mm (the cutoff frequency of CCD with a pixel size of 7.5 μ m) is above 0.65. Furthermore, we presented the design of anamorphic PAL surveillance system. By employing a group of cylindrical lens in the system, elliptic annulus image with anamorphic ratio of 4:3 is achieved, and the MTF is above 0.55 below 70lp/mm. As a dismountable attachment for phone camera, PAL provides panoramic view with simple structure and high image quality that the MTF below 285 lp/mm (the cutoff frequency of CMOS with a pixel size of 1.75 μ m) is above 0.3 within the 0.7 \times full field of view. PAL is advantageous when used in endoscope. We design a small, compact size, and high resolution PAL endoscope with 7.62mm diameter, 8.12mm total length, and MTF above 0.38 within 227 lp/mm (the cutoff frequency of CMOS with a pixel size of 2.2 μ m). The PAL applications are more than we illustrated in our designs. We expect that the PAL-based system would be widely used in our

everyday life, the anamorphic PAL and the PAL attachment could be flexible applied in optical systems.

8. Acknowledgement

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