

Design of high resolution panoramic endoscope imaging system based on freeform surface

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Abstract. This paper introduces a novel endoscope design based on the panoramic annular staring imaging technology. This design utilizes a single optical system to realize both panoramic observation and local high resolution on a single sensor. The freeform surface is employed to improve the image quality and reduce system volume. The design results based on the commercial optical design software package ZEMAX, indicate that this optical system is able to acquire an excellent image quality with a modulation transfer function above 0.6. Compared with the traditional ones, this novel endoscope design with wide FOV is likely to decrease the diagnostic time dramatically and improve the lesion detect rate considerably.

1. Introduction

Wide field endoscopic imaging technology is pivotal in the area of both medical and industrial endoscope. However, current methods toward surrounding observation of inner surface of a tube, are mostly rely on deviating prism or complicated mechanical structure^[1-4]. Obviously, these approaches doomed to bring large aperture or long length, which are not fit for detections of small size tube or body cavity. Panoramic Annular Lens (PAL) is a kind of compact optical structure with wide field-of-view (FOV) and small distortion^[5]. The PAL design provides panoramic views and sharp imaging quality which means it is very suitable for endoscope system.

Endoscopic objectives adopting PAL structure have been reported in previous literature^[6-9]. However, there is an inevitable blind area in the centre of the existing PAL's image plane, which brings visual discomfort and pixels waste. In this study, a PAL-based endoscope design is put forward, which is able to achieve both panoramic view and local high resolution. This system takes full use of the pixels in blind area on the image surface of conventional PAL systems, and solves the contradiction between wide FOV and high resolution.

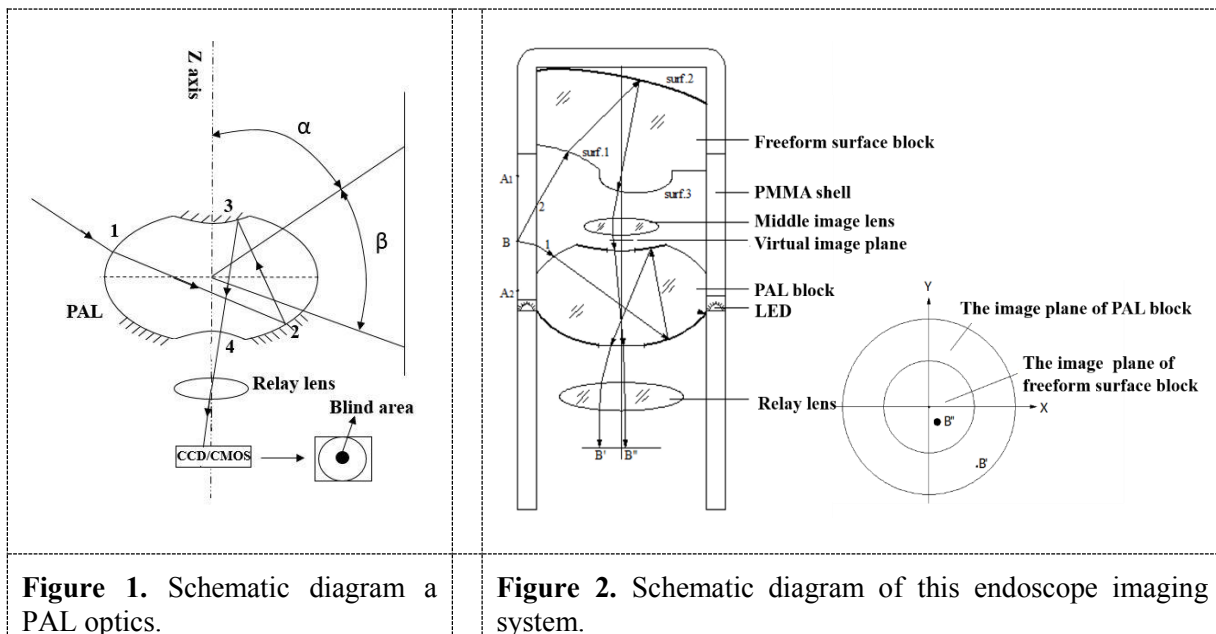
In order to solve the simultaneous imaging problem of the axisymmetric part and the non-axisymmetric part, freeform surface is employed in this optical structure, so that it has several outstanding features such as simple structure, wide FOV, small size, light weight and high resolution. Compared with the traditional large FOV endoscope, this novel endoscope imaging system is likely to decrease the diagnostic time observably and improve the rate of lesion detecting signally. Moreover, this system has a great value of application in many fields, such as the robot vision, pipeline detection, medical equipment and aerospace. Consequently, the basic research of this system is of profound significance.



2. Principle of Design

2.1. PAL Optics

Figure.1 gives the characteristics of a PAL optical system. The cylindrical object space of the PAL has a vertical field angle β which is rotational symmetric around the z axis, that is the optical axis of the system. The area from α to the z axis is a blind space which is not engaged in imaging^[10]. The PAL block consists of two reflective surfaces marked by slashes in figure.1 and two refractive surfaces. The optical path can be represented in the following way. 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 4. After leaving the PAL, the divergent rays enter a relay lens that corrects and balances aberrations of the PAL block. In the end, an annular image comes into being on a Charge Coupled Device (CCD) sensor.



This work based on a miniaturized panoramic annular imaging optical system takes use of freeform surface lenses to achieve the dual function of panoramic survey and key areas magnification. The PAL block of this system images 360 degrees surrounding the optical axis of the lens to an annular image plane, and the freeform surface block in front of the PAL block amplifies the local area of the PAL's FOV, which uses the blind area of the annulus image plane for imaging. The schematic diagram of the design is shown in figure 1. As performed in the left part of figure 2, the front and back surfaces of PAL are all coated with annular reflective film (for the inside light reflection), while its interior is a transmissive region. The light from the freeform surface block passes through the transmissive area of the PAL. The relay lens forms rays from the PAL block and the freeform surface block to converge and image on the CCD sensor. The right part of figure 2 gives the distribution of image, in which the image of freeform surface block is in the center of the annular image plane of the PAL block. The material of the system shell is selected as optical plastic mainly due to surrounding view. White LEDs located at the joint of endoscopic shell and digestive wall are used to illuminate the body tissue attaching to the optical plastic surface.

In the process of design, the entire system can be divided into two subsystems, one is a PAL subsystem for side view, and the other is a high resolution subsystem for local magnification. The first step is to design the PAL subsystem to find the middle virtual image surface; secondly, designing the high resolution subsystem; finally optimizing the two subunits together.

The resolution of the CCD sensor used in this design is 648×488 . The size of pixel is $7.4 \mu\text{m}$, and its spectrum is in the visible range ($0.486 \mu\text{m} - 0.656 \mu\text{m}$). The design is optimized by a standard optical design software package (Zemax). It achieves good image quality and has a modulation transfer function (MTF) above 0.6, which is within the cutoff frequency of CCD/complementary metal-oxide semiconductor (CMOS) sensors. All the optical design details are described here.

3. PAL subsystem

For the purpose of miniaturization, in our demonstration design the surface 1 and 2 are aspheric surfaces and the material of the PAL block is Polymethyl Methacrylate (PMMA). Figure.3 shows the structure of the PAL subsystem. The largest caliber is 10mm, the PMMA shell is 1mm, and total length is 25mm. The effective focal length is -0.819 mm , and its back work distance is 3mm. FOVs of this system are shown by object height specifically, considering the gastrointestinal tract attaches to the endoscope shell during diagnosing. In a PAL system, lateral aberrations, such as lateral chromatic, coma, and others, are major factors impacting the imaging quality, when considering annular imaging^[10]. The relay lens system is just for imaging and correcting aberrations. The doublet is applied to reduce the spherical aberration.

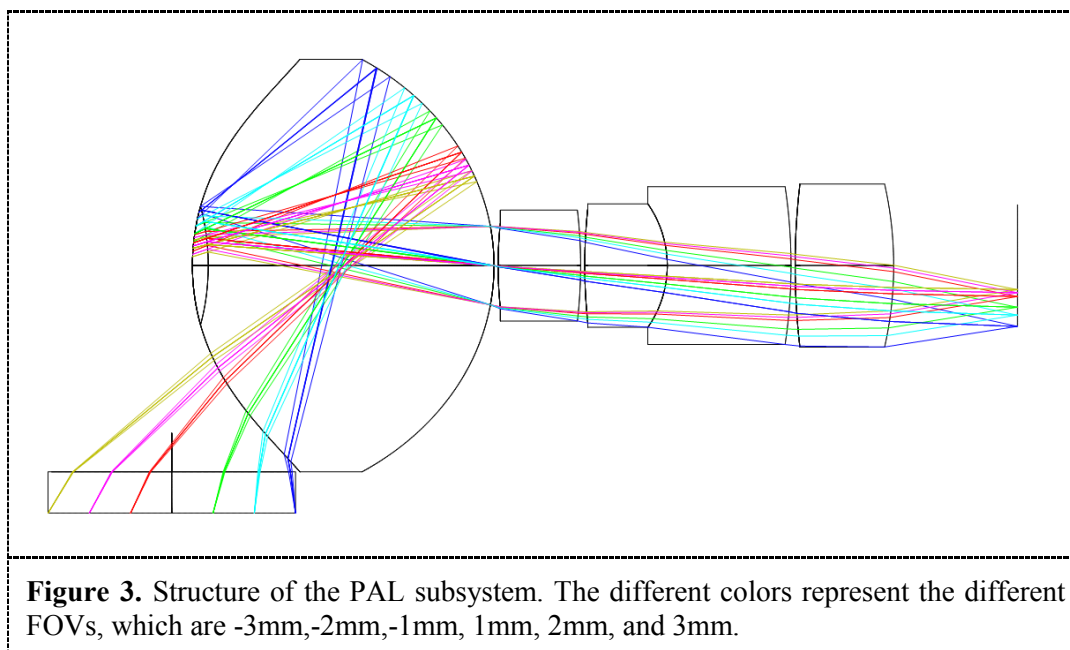
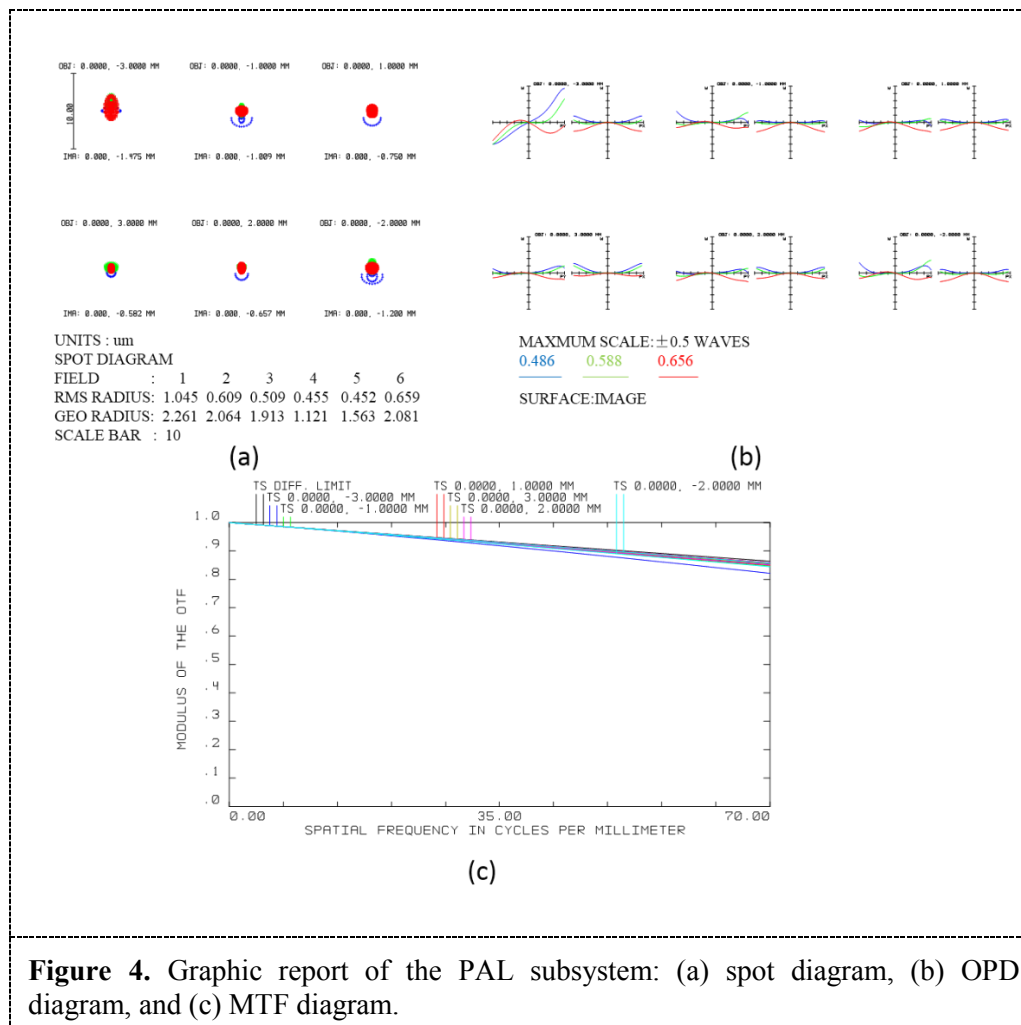


Figure.4 is the graphic report of the PAL subsystem. The MTF effectively evaluates the imaging quality. In this system, the spatial cutoff frequency of the CCD sensor is 70 lp/mm . As figure.4(c) shows, the MTF is above 0.8 @ 70 lp/mm , which is very close to the diffraction limit. What's more, the aberration affected the image quality in FOV is balanced well, as shown in figure.4.



4. High resolution subsystem

The high resolution subsystem can be given based on the blind area on the image plane and relay lenses of the PAL subsystem, which is used to magnify the target area in the panoramic FOV. Image of the high resolution subsystem is just in the blind area of the PAL's image plane, which means the idle pixels coming in handle.

During the process of optical design, first of all, the known blind area in the image plane can be seen as the object of the high resolution subsystem to design reversely to get a preliminary basic structure easily. An axisymmetric model is used to build an all spherical initial structure, and then the freeform surfaces and mirror are added to turn optical axis and implement asymmetric design. The magnification of cylindrical lens is different in radial direction and axis direction. Therefore a cylindrical lens settled before the PMMA shell is capable of imaging the columnar gastrointestinal tract to a plane, for its character of different magnifications in two perpendicular direction. Figure.5 shows the structure of the high resolution subsystem. The distance between the mirror and the shell is 5mm. The FOV is represented by object height. As the object plane is a cylindrical surface, both the direction of x axis and y axis should be taken into consideration when setting the field data. It is telecentric in image space (which means the exit pupil is located at infinity) for uniform distribution of illumination on the image surface. The transmission part of PAL block and the relay lenses between PAL and image plane are also included in this unit, with the same optical parameters as in PAL subsystem. Lenses near the mirror are all aspheric surfaces, and are made of PMMA in terms of

correcting aberration and easy fabrication. Aspheric surface can help to increase the freeform of design. The FOV of this subsystem is just the edge of that of the PAL subsystem. And its image fills the blind area of the PAL subsystem. The magnifying factor is -0.88 which is much bigger than -0.15 of PAL subsystem. The resolution of object space is up to 0.008mm .

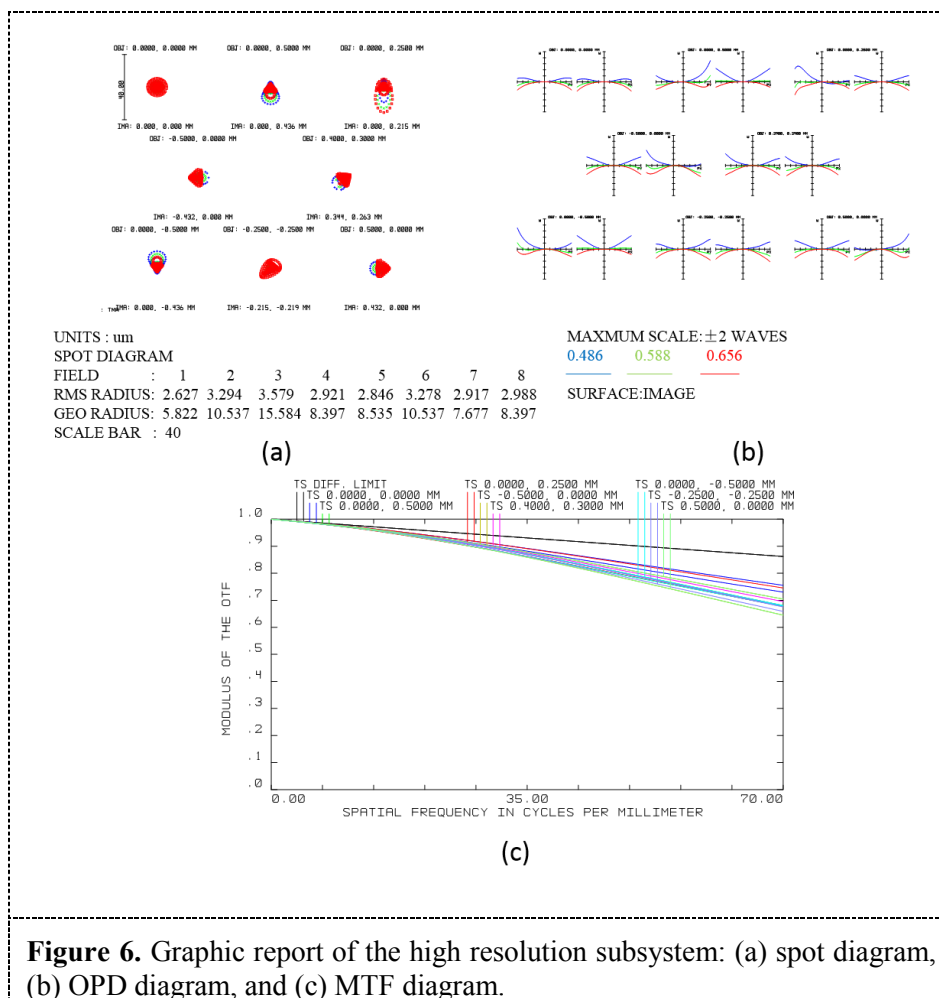
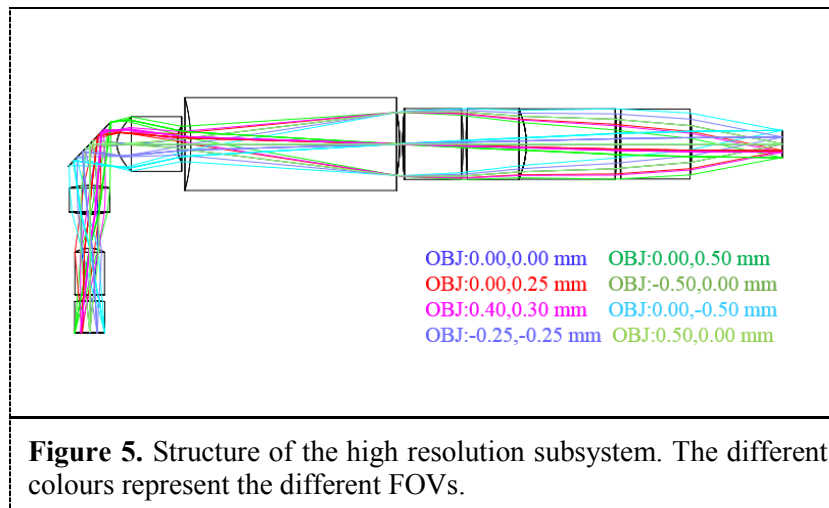


Figure 6. Graphic report of the high resolution subsystem: (a) spot diagram, (b) OPD diagram, and (c) MTF diagram.

Figure.6 gives the graphic report of high resolution subsystem. As figure.6(c) shows, the MTF is above 0.6 @70lp/mm, which is higher than the resolution requirement of the CCD sensor. Further, the aberration affecting the image quality in FOV is balanced well, as shown in figure.6.

5. Results

The final important step is combining the two subsystems together into an integrated endoscope. The Multi-Configuration function in ZEMAX software is able to optimize two different units simultaneously. The two subsystems have different FOV, image height and entrance pupil, but they share the same locations of stop and image surface. A little adjustments to the high resolution subsystem can help to solve the inevitable light blocking problem caused by the small displacement between the cylindrical lens and the shell, but the image quality may be impacted slightly.

After repeated optimization, we get the optical structure of the whole endoscope, as illustrated in figure.6, and the optical parameters is shown in Table.1. The results show that the imaging quality of this system is very well balanced and the volume size meets the requirement of endoscopy. Freeform surface lenses help to solve the simultaneous imaging problem of the axisymmetric part and the non-axisymmetric part. In addition, the results of FOV and object space resolution shows that this endoscope can realize panoramic survey and local high resolution. The tolerance result analysed by ZEMAX indicates that the stability of this system meets the requirements of engineering processing.

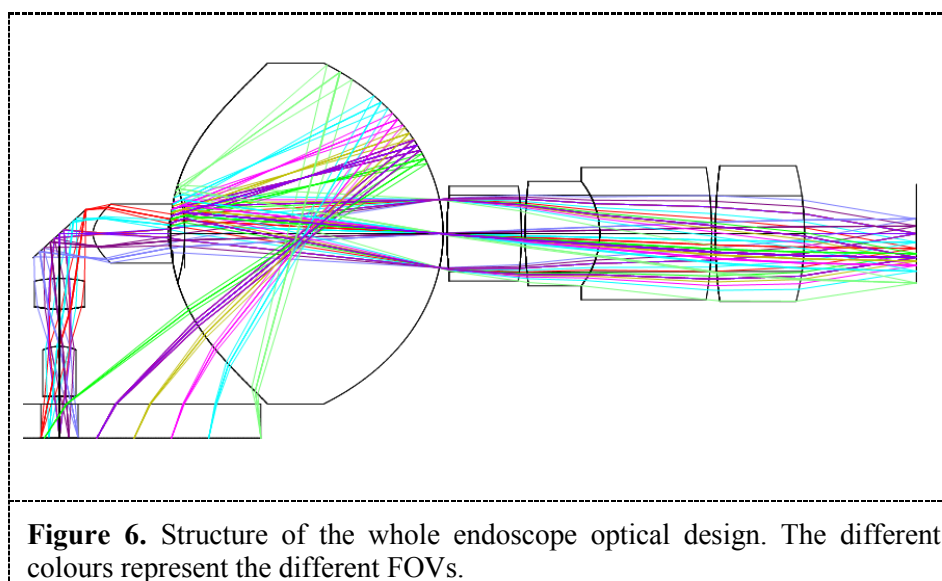


Table 1. Optical parameters of PAL subsystem and high resolution subsystem

Optical parameters	PAL subsystem	High resolution subsystem
Spectral range	486.1nm~656.3nm	486.1nm~656.3nm
FOV	(60° ~ 97.5°)×360°	(-10.2° ~ 10.2°)×20.4°
Finite object distance	6mm	6mm
EFL	-0.82mm	2.12mm
Working F/#	2.8	2.65
Object space resolution	0.047mm	0.008mm
MTF (full field)	MTF>0.8 @70lp/mm	MTF>0.6 @70lp/mm
Spot size	RMS radius<1um	RMS radius<4um
OPD	±0.5 waves	±2 waves
Image plane	Radius =1.5mm	
Volume	Total length =23.5mm, Diameter =10mm	

Conclusion

The high resolution panoramic endoscope imaging system based on freeform surface is proposed in this work, which achieves both panoramic viewing and partial magnification. In comparison to the traditional endoscopes with wide FOV, this design gives possibility to reduce the diagnostic time and improve the lesion detect rate without regular rotation. More importantly, this system has potential use in robot vision, pipeline detection, medical equipment and aerospace. This basic research is of great importance for the further fabrication.

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