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Design of a 360-deg panoramic capture system based on a smart phone

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Abstract. A panoramic imaging system has been developed using two afocal lenses and a smart phone that consists of cameras on both sides. An individual afocal lens has been developed with a large field of view (FOV) and a large exit pupil, which can enlarge the FOV of a smart phone camera to above 180 deg. Some issues with the smart phone-based 360-deg panoramic system, such as relative illuminance and assembly tolerance, were analyzed in detail and taken into consideration during the design procedure. A prototype has been developed with a low fabrication cost, yet producing impressive panoramic image quality. © 2020 Society of Photo-Optical Instrumentation Engineers (SPIE) [DOI: [10.1117/1.OE.59.1.015101](https://doi.org/10.1117/1.OE.59.1.015101)]

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1 Introduction

Image capturing systems with an ultrawide angle or even panoramic field of view (FOV) are becoming popular in the implementation of virtual reality (VR), surveillance systems, and driverless vehicles, to extend visual information coverage to surrounded objects.^{1–3} With the rapid growth of the above-mentioned industries, requirements for a 360-deg panoramic imaging system have become more demanding than ever before. To satisfy these industrial requirements, much research on the systems of panoramic view or similar systems is being carried out.

Pioneering work in panoramic imaging was developed with an optical structure that consists of several pieces of meniscus lenses to accommodate the large inclination changes in the incident rays of a large FOV, which is treated as a fisheye lens.^{4,5} An FOV of more than 180 deg can be achieved with the processing and design technique of aspherical lenses. An $F/\#$ 2.8 fisheye lens with an FOV and diameter ratio of 220 deg and 10.6, respectively, was developed by Nikon.⁶ A hyperfield fisheye lens with an $F/\#$ of 5.6 and an FOV of 310 deg was developed by Martin.⁷ Thibault has summarized some complex fisheye lens designs with a large FOV and a high performance.¹ With this type of fisheye camera, a panoramic view can be obtained with 360 deg on the azimuth direction and a limited angle on the elevation direction. A blind zone can be designed in the central region, and a catadioptric structure called a panoramic annular lens (PAL) is often deployed to achieve panorama.^{8,9} The basic principle of PAL was described in detail by Powell,¹⁰ while many effective designs were proposed. Based on these designs, many calibration models have been developed to provide three-dimensional panoramic view.¹¹ To enlarge the elevation view, the blind zone should be eliminated, e.g., using tiling methods, which remain valid for applications

in other imaging systems, such as multiple-projector displays,¹² head-mounted displays,¹³ light field displays,¹⁴ and holographic displays.¹⁵ Semireflective surfaces and stitched aspherical surfaces are common structures deployed to achieve this goal.^{16,17} A hyper-hemispheric lens with 260-deg FOV was achieved using semireflective surfaces;¹⁸ a lens with an FOV of 360 deg (azimuth) $\times$ 270 deg (elevation) was developed by stitching three channels of the optical path.¹⁹ However, neither fisheye lens nor PAL systems can achieve 360-deg panoramic imaging in both directions. Multiple capturing channels with FOV over 180 deg were employed to obtain the information from the whole space of 4π solid angle. Six small-sized cameras were fixed on the cubic frame to produce a 360-deg panoramic capture system, which has been one of the most popular methods.²⁰ A panoramic video with smooth transition between adjacent videos can be generated with computer vision composition.²¹ A 360-deg capturing system with depth information can be achieved with multiple groups of panoramic imaging systems, suitable for VR and AR applications, e.g., 3D 360-deg imaging by Samsung²² and light field capturing system by Lytro.²³ Commercial products consisted of two imaging channels above 180 deg are available on the market, such as Insta360,²⁴ Theta,²⁵ and Samsung Gear360.²⁶ Design strategies and tiling methods of 360-deg panoramic capturing with two channels were analyzed in detail in Ref. 27.

However, all the panoramic systems mentioned above must introduce the user to an extra, dedicated device to do the job, which in turn may cause inconvenience when it comes to mobility. Meanwhile, smart phones have already become very common in our daily life. The latest smart phones are equipped with at least two cameras: a front camera and a rear camera. A portable 360-deg panoramic capturing system can be developed taking advantage of the dual camera architecture of the smart phone.

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Many commercial lenses currently can extend the FOV of smart phones. In this paper, a 360-deg panoramic imaging method based on a common smart phone is presented in detail, including optical design strategies and tiling methods that have not been discussed when compared with an extension lens or traditional panoramic imaging methods in previous works. Relative illumination, assembly tolerance, and other performance related issues are analyzed in detail and taken into consideration in the optical design. As a result, a smart phone panoramic extension lens is achieved with an FOV of 210 deg and an exit pupil of 2.78 mm, whereas an afocal lens is used in the implementation. The imaging performance has also been well optimized. The panoramic extension lens can effectively enlarge the FOV of phone cameras and can be easily attached to the smart phone. Thus by deploying two groups of afocal panoramic lenses as stated, a 360-deg panoramic view can be achieved with common smart phone available on the market. A proof-of-concept prototype is fabricated as a validation of the proposed method, and a 360-deg panoramic picture can be obtained with reasonable performance at a fairly low cost.

2 System Specification

Smart phones have already revolutionized into handheld personal computers, which can play the role of a telephone, digital camera, video camera, video player, and many other multimedia functions. Currently, a smart phone consists of at least two cameras, one front camera for selfies and one primary camera on the rear. With the front and rear cameras, a smart phone can capture the scene from both sides simultaneously, as shown in Fig. 1(b). However, the horizontal FOV on both cameras is usually <70 deg, whereas the diagonal FOV cannot reach >150 deg. Though the setup is enough in most daily scenarios, it cannot acquire 360 deg surrounding information at one time.

Fig. 1 Schematic diagram of (a) the developed smart-phone-based panoramic system, (b) the image captured by the camera of a smart phone, and (c) the image captured by one developed lens with large FOV.

It has been demonstrated that a 360-deg panoramic picture can be formed by tiling two imaging channels with FOV over 180 deg. With the help of the afocal lens, the smart phone can provide two imaging channels with over 180 deg on each channel [Fig. 1(c)]. Thus a panoramic lens pair can be designed to extend the FOV to 360 deg taking advantage of both front and rear cameras, as shown in Fig. 1.

Specifications of the developed 360-deg panoramic system based on smart phone are summarized in Table 1. Each imaging channel is made up of four spherical glass lenses. The panoramic lens is employed to extend the FOV of cameras of the smart phone, thus an afocal lens. To obtain a 360-deg panoramic view, the FOV of either channel should be above 180-deg, which can capture the surrounded environment with two channels. Therefore, the panoramic lens will have to deflect 210-deg rays into an angle less than the FOV of phone cameras. The stop is set at the position away from the last surface, which leaves enough space to accommodate the extension lens with the cameras. A relatively large stop is selected to provide a loose tolerance of assembling. No vignetting within all FOV is set; that is to say, the rays are set to fulfill the stop for all field angles, which significantly improves the relative illuminance compared to other designs but makes the design process more challenging. In this design, the stop was set at the exit pupil of the afocal lens. As the developed lens will be employed along with the camera of a smart phone, the entrance pupil of phone camera should be put at the position of the exit pupil of the designed lens. If the developed lens is not “no-vignetting design,” the image will not be obtained completely when the phone camera is close to the marginal part of the panoramic system’s exit pupil. Moreover, this design strategy can significantly improve the relative illuminance of a large field view.

As the panoramic images are obtained by tiling two imaging channels, the imaging performance of each individual channels plays decisive roles. To achieve a tiled panoramic system with high performance yet compact dimensions, the optical system for one single-imaging channel needs to be well optimized. During the design process, some issues, such

Table 1 Specifications of the system.

Single display channel	
Imaging system	
Effective focal length	Afocal lens
Stop size	2.78 mm
Number of optical elements	Four spherical lenses
Wavelength	423 to 660 nm
FOV	210 deg $\times$ 2
Maximum exit field angle	47 deg
Total optical length	35.0 mm
Performances	
Vignetting	No vignetting
Resolution	Over 2000 $\times$ 1000 pixels

Fig. 2 Layout of the optics for one imaging channel.

as relative illuminance and assembly tolerance, still need to be considered.

Similar to other structures with large FOV, in this design, a meniscus lens was employed to refract the incident rays of large FOV, which can let the rays pass the stop. A combination of negative and positive lenses was chosen in our design, which is often used as a reversed telephoto structure.²⁸

As the panoramic lens is used under visible light, four representative wavelengths were selected with equal weights during the optimization process including 486.1, 546.1, 587.6, and 656.3 nm. Due to coaxial rotational symmetry, the same field angle at different directions can achieve the same performance. Thus (0 deg, 0 deg), (0 deg, 15 deg), (0 deg, 30 deg), (0, 45 deg), (0 deg, 60 deg), (0 deg, 75 deg), (0 deg, 95 deg), and (0 deg, 105 deg) were chosen as representative field angles in this design.

As the panoramic lens is an afocal lens, an ideal lens should be employed behind the last surface of the design, which can act as the camera of the smart phone (shown in Fig. 2). The maximum incident field angle of the designed lens was set to be 210 deg, whereas maximum exit field angle should not exceed the FOV of the phone camera. The imaging process of ideal lens conforms to the Gauss' formula, i.e., the half angle of the exit field θ_{exit} is determined by half of the image height h and the focal length f . Thus the exit field angle can be controlled by setting the image height:

$$\theta_{\text{exit}} = \arctan(h/f). \quad (1)$$

As the panoramic system is designed to capture the whole surrounded scene, the maximum exit field angle should be smaller than the minimum FOV of the phone camera at all the directions. The FOV of some popular smart phone cameras, including models from Apple, Samsung, Xiaomi, and Huawei, was measured showed horizontal FOV larger than 50 deg. Here, in our design, the focal length of the ideal lens was selected as 5 mm, whereas the half image height was controlled at 2.2 mm, which can make the exit field angle to be <47 deg.

The designed lens along with the smart phone shall capture the scene, and the stop was set at the entrance of the ideal lens. The stop should be large enough to provide enough tolerance when the lens is aligned with the smart phone. As the entrance pupil of common smart phone camera does

Table 2 Parameters of developed lens system.

Surface #	Surface type	Radius	Thickness	Abbe number	Refractive index
1	Spherical	41.7	2.2	77.25	1.496
2	Spherical	8.82	7.8		
3	Spherical	-18.74	2.3	77.25	1.496
4	Spherical	11.1	0.43		
5	Spherical	12.45	5.13	67.27	1.322
6	Spherical	-25.08	10.76		
7	Spherical	-59.58	2.38	48.75	1.704
8	Spherical	-14.03	3.42		
9	Stop	∞	0		
10	Ideal lens	—	5		
11	Image	∞	—		

not exceed 2 mm, a stop as large as 2.78 mm was set to increase the alignment tolerance. According to the definition of F number [D is the size of stop, while F is F number of ideal lens in Eq. (2)], an F -number of 1.8 was set in the designed system to get a large stop size:

$$D = f/F. \quad (2)$$

Based on the design strategy mentioned above, the parameters of the developed lens system are listed in Table 2, which includes radiuses, thicknesses, and the Abbe number and refractive index of the employed piece of lenses. In conventional imaging system, Nyquist frequency is half the sampling rate of a discrete image sensor. h is the half of the image height [shown in Eq. (1)], and the whole image height will be $2h$. Thus the pixel size can be expressed as $2h/R$, where R is the required resolution. According to the definition of Nyquist frequency [$1/(2 \times \text{pixel size})$], the Nyquist frequency can be shown as

$$N = R/4h. \quad (3)$$

To achieve the tiled panoramic image with resolution above 1000 pixels $\times$ 2000 pixels, either imaging channel should achieve 1000 pixels at one direction. Thus based on Eq. (3), the Nyquist frequency should be above 115 lp/mm during the performance analysis, based on the parameters of the ideal lens. During the design of afocal lens systems, such as telescopes and beam expanders, cycles/milliradian is often used. In terms of our developed design, the output beam will finally focus on the image sensor with the help of the phone camera. Thus lp/millimeter was employed in analyzing the performance. In fact, these two unit can be transferred using the equation of "1 cy/mrad = 1000/focal length lp/mm." Thus 1 cy/mrad equals to 200 lp/mm in the analysis due to the usage of the ideal lens.

To acquire the whole view within the designed FOV, the rays should be set to fill the stop for all field angles. Another

Fig. 3 Performance of the designed system: (a) polychromatic MTF plot of the imaging system and (b) the relationship between field angle and image height.

advantage of this none-vignetting design is improved relative illuminance of the whole field. Despite of illumination correction at large FOV, it still can increase the noise-signal ratio when elevating the gray scale. The structure was changed during each cycle of optimization, and the rays may not fulfill the stop. Entrance pupil was calculated, while rays for each selected field angle were selected to make sure that the marginal area of entrance pupil was analyzed during the design process.

Based on the design methods and considerations above, the final design for one imaging channel with a 210-deg FOV is shown in Fig. 2. It consists of four pieces of lenses, all of which are spherical, with no vignetting exists for all selected field angles. As mentioned above, the Nyquist frequency should be set larger than 115 lp/mm, according to the parameter of the ideal lens and the required resolution. As shown in Fig. 3(a), the polychromatic MTF is above 0.1 at a spatial frequency of 150 lp/mm, which fully satisfies the requirement of the system design. As the entrance pupil of a phone camera is much smaller than the stop size in the design, the system final performance will be better than results shown in this section.

The panoramic system is a combination of the designed lens and the phone camera. Distortion of the phone camera was corrected prior to the experiment, so the $f - \theta$ distortion of the designed lens can reflect the final performance. The relationship between field angle and image height is shown in Fig. 3(b) as the blue line along with $f - \tan \theta$ (yellow) and

Table 3 Tolerance values of the panoramic optical system.

Tolerance item	Value
Surface radius(fringes)	3
Surface irreg. (fringes)	1
Surface decenter (mm)	± 0.01
Element decenter(mm)	± 0.01
Thickness (mm)	± 0.02
Tilt (arc min)	± 3
Glass material (nd, vd)	0.0005, 0.3%

$f - \theta$ (orange) relationships, which can be compared by the reader. The distortion will not affect the imaging performance of the system, but it may influence the image processing during the tiling method. This relationship can be treated as initial parameters during the tiling process, and the results show that the image will be slightly distorted under a large-field angle when computational correction is employed to generate the panoramic image by two imaging channels. The distortion has not been well-optimized because only four spherical lenses were employed. We feel sure that the usage of aspherical surfaces will greatly improve the performance of distortion and shorten the optical length to make it more compact.

Tolerance analysis plays an important role during the design process, because it is directly related to the optical fabrication, alignment, and cost. Suggested by optical element supplier, the tolerance requirements for a possible commercialized system are shown in Table 3, which can act as a reference in analyzing the yield rate before system processing. MTF of the imaging system was selected as the merit function when tolerance was analyzed. The frequency is set to be 90 lp/mm, which is 80% of the Nyquist frequency requirement. The tolerance results show that, under most of the scenarios, the final system will maintain an MTF above 0.1 for all FOV values (Fig. 4). The ideal lens in the designed file will be replaced by the camera of a smart phone in the actual system. As the camera cannot reach the diffraction

Fig. 4 Tolerance analysis results of the panoramic lens.

limit, the final performance will be compromised by a small fraction compared with the analyzed result. Benefited from the high performance of latest phone cameras, the system achieves relatively low tolerance sensitivity according to the analysis results. Thus implementation of the system is feasible based on a real-world fabrication and alignment.

3 Experimental Setup and Results

The designed optical lens system was fabricated and assembled, as the prototype shown in Fig. 5, along with the 3D printed phone attachment frame and a coin for reference (one Singapore dollar). To test the performance, an experimental system was built featuring two optical lenses and a smart phone (Huawei Nova 2 Plus), shown in Fig. 6(a). The overlapping area is not very large due to the distortion and the performance of the camera on the smart phone, but it is enough when applied in panoramic stitched image. The tripod and gimbal were adjusted to a position that would not be captured by either imaging channels. Image data generated by the rear and front cameras of the smart phone were processed by a customized application installed on the smart phone. Two images with over 180 deg from both front and rear directions were captured by this application. These two images from the phone cameras are not in the same size due to different FOVs of the front and rear cameras, which are shown in Figs. 6(b) and 6(c), respectively.

The 360-deg panoramic image can be composed by projecting the spherical image on the 2-D plane, similar to the global map, when the azimuth and elevation angles are set as

Fig. 5 Modules of the imaging system.

the horizontal and vertical axis separately. Figure 7 shows a stitched photograph with a resolution of 1000 pixels $\times$ 2000 pixels taken by the prototype with two imaging channels. The value of each pixel was obtained by interpolating corresponding pixels on the captured images. The horizontal axis of the panoramic image covers an angle of 360 deg, and the tiling boundary is at the central position. On the other hand, the vertical axis of the final image covers an angle of 180 deg. Thus a 360-deg panoramic system can be achieved by attaching two compact optical components to a common smart phone, so that the scene around the device can be fully captured. When designing a system with a large FOV, the relative illumination for large angle will decrease compared with that for the central angle. “No-vignetting” design is a very useful strategy to improve the relative illumination for the system with a large FOV during the design process, which can improve the illumination issue dramatically. However, despite the no-vignetting design, the relative illumination of the marginal FOV cannot be the same as that of the central area. From the principle of relative illumination, it is determined by the aperture size and the fourth power of the cosine of incident angle. The fulfilled exit pupil cannot ensure that both of the physical quantities are the same during the variety of field angle, and the illumination will also fall with the radial position. Moreover, the coating film on each lens and the fabricated process will not be perfect, and relative illumination will also fall with the field angle in

Fig. 7 The stitched image produced by two imaging channels of the experimental prototype.

Fig. 6 (a) Experimental set-up, (b) rear channel with above 180 deg, and (c) front imaging channels with above 180 deg.

the employed phone camera. Therefore, a slight decrease can be observed from the center to the margin from the experimental results. The fall of illumination will not affect the clarity of the performance, and it can be improved by enlarging the gray scale during the image processing. Although the performance provided here is not as good as that of a professional panoramic camera, the proposed idea offers a panoramic view with reasonable image quality, compact size, and economic cost. The performance must be improved in the future with the improvement of the phone performance and the cooperation of the smart phone company, which in turn has potential value in modern VR and AR applications.

4 Conclusions

In this paper, a smart phone-based panoramic capturing system with two imaging channels was developed. An FOV of 210 deg and an F -number of 1.8 was achieved on each imaging channel, with low distortion along the entire imaging field. Rays from all field angles up to 210 deg fulfilled the stop in the system to increase tolerance. Design methods of the imaging channel based on a phone camera were discussed in detail. Prototype system was developed to show the performance of the capturing system and thus validated the proposed method. Future works of this project include further improvement of the imaging performance by introducing aspherical surface and reducing total optical length.

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