Wide field-of-view foveated imaging system

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We have designed and demonstrated a simple, wide field-of-view (FOV = 60°) foveated imaging system utilizing a deformable mirror. The deformable mirror is used to dynamically correct the off-axis aberrations that limit the useful FOV of the system. The system mimics the operation of human eye through creating an image with variable spatial resolution and can be made significantly smaller and more compact than a conventional wide FOV system. Experiments show that this system can be used in many areas where size, weight, and data transmission bandwidth are critical.

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Adaptive optics is playing an ever-increasing role in imaging and laser projection applications. The success of adaptive optics has sparked interest in other applications such as improving the flexibility and capability of imaging systems. There exists a growing need for small, light-weight imaging sensors with wide field-of-view (FOV) and high data transmission rates[1−4]. Many military and civilian applications could benefit from such systems. Foveated imaging is used to selectively enhance resolution in a wide FOV imaging system. This selective enhancement reduces the bulk and complexity of the optical system and the data transmission and processing requirements on the sensor system.

It is well known that human visual acuity is highly resolved only within a few degrees around a small section of the retina called fovea, and decreases towards the peripheral FOV. However, human can still detect objects or movements near the peripheral FOV. But in order to highly resolve such objects, they would have to center their eyes so that the image of the object forms on the fovea. In foveated imaging, the optical system or image software creates images with spatially varying resolution. This allows significant compression of the image even standard video compression is applied before. In order to mimic the operation of human eyes, we designed an imaging system with the f-number of 6.1 and a field angle of ±30° using the optical design code ZEMAX. The system is constituted of two ordinary lenses. We add a Zernike phase surface — an infinitely thin phase plate, where the phase is described by a Zernike polynomial — placed at the entrance pupil plane. Theoretically, by placing the Zernike phase surface at a pupil plane, the phase of the wavefront at any field angle can be corrected beyond diffraction-limited performance. Without adding Zernike phase surface, the imaging system could not achieve diffraction-limited performance at any field angle.

Wick *et al.* used a liquid crystal spatial light modulator (LCSLM) to correct the distorted wavefront and realize the foveated imaging[1−5]. The LCSLM consists of a thin cell of birefringent liquid crystal material sandwiched between two pixilated transparent electrodes. The variation of optical path length is called the optical path difference (OPD). Applying different voltage at each pixel across the liquid crystal, we get different refractive index of the liquid crystal according to the compensation for the OPD in the distorted wavefront. The transmissive LCSLM's performance of modulation depth is very important. The phase-only dynamic range of the patent productor of Boulder Nonlinear Systems Incorporation (BNSI), 256 × 256 pixels LCSLM, is only $0 - 2\pi$[6,7]. In order to get required change of the refractive index, Harriman *et al.* developed a high figure-of-merit liquid crystal using the transmissive LCSLM supplied by BNSI. The full modulation depth of the device at 633 nm is about 3π, which is the largest known modulation depth up to now. Liu *et al.* fabricated a novel liquid crystal phase modulator (LCPM) and the imaging quality of the optical systems was greatly improved when the parallel alignment LCPM was used to modulate the distorted wavefront[8,9]. They got the depth of modulation up to 1.2π. More importantly, the LCSLM only functions with monochromatic linearly polarized light. Though it can make the system more compact, the useful area is limited. The deformable mirror is controlled by the voltages applied to the actuators and the OPD is adjusted by deflecting the mirror using actuators. It can be used not only to the reflective system, but also for the polychromatic light. Recently, Lü *et al.* presented their novel adjustable focal-length optical adaptive micro-mirror based on bi-mental effect[10]. The method had the advantages of low driving voltage and large driving force. Deformable mirror has unidirectional continuous deformation with maximum deformation of 15.8 μm, but it functions only experimentally not commercially available.

The technical parameters of the mirror we used are listed in Table 1. From the table we can see that the maximum OPD of the deformable mirror in the air is 8 μm, and the phase modulation depth is more than 30π

Table 1. Technical Parameters of the Used Deformable Mirror

Parameter	Value
Aperture Shape	Circular 30 mm in Diameter
Mirror Coating	Al
Actuator Voltages	$0 + 400$ V (with Respect to the Ground Electrode)
Number of Electrodes	19
Actuator Capacitance C_a	5 nF
Initial RMS Deviation from Reference Sphere	< 1 μm
Maximum Stroke	8 μm at +400 V
Actuator Pitch	7 mm
Main Initial Aberration	Concave Sphere with $r \sim 50$ m

RMS: root mean square.

for the wavelength of 633 nm, which is greater than the LCSLM's modulation depth.

In order to demonstrate the foveated imaging concept in broadband, we use a deformable mirror made by OKO Technologies to correct the deformed wavefront. The mirror consists of 19 piezoelectric column actuators bonded to the base holder. Reflective plate is bonded to the top of the actuator structure and Al is coated to form the mirror. The shape of the faceplate is controlled by the voltages applied to the actuators. The OPD is adjusted by deflecting the mirror. The laboratory demonstration includes common standard plano-convex and plano-concave lenses. So it is convenient to replace in the course of experiment. Figure 1 is the final optical system design plot. The f number, the effective focal length (EFL), and the FOV of the optical system are 6.1, 25 mm, and 60°, respectively. The system also includes a prism and a charge-coupled device (CCD) camera. The diameter of the CCD is 25 mm. Light from the object plane passes through the lens and the prism, and is reflected by the deformable mirror, and then, passes back through the prism and lens onto the CCD camera.

In experiment, we chose to correct imaging aberration of the 30° FOV. From Fig. 2, we can see that the initial wave aberration of the FOV of 0° is less than 10 waves, but for the FOV of 30° the maximum wave aberration is more than 40 waves. After correction, the wavefront aberration of the FOV of 30° has fallen down to less than 0.25 waves, as shown in Fig. 3. It is already below the diffraction limit. On the other hand, the wavefront aberration of the FOV of 0° has gone up to 30 waves. This is the characteristic of the foveated imaging system we mentioned. For an optical designer, it is the most difficult task to design a wide FOV imaging system while maintaining high image quality across the entire FOV. Utilizing multiple optics design can minimize off-axis aberrations, but even the best well-corrected systems have a limited FOV.

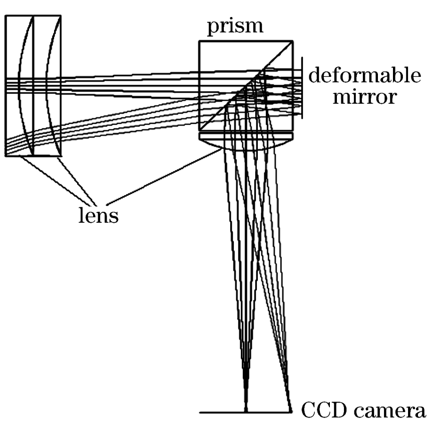

Fig. 1. Final optical system design.

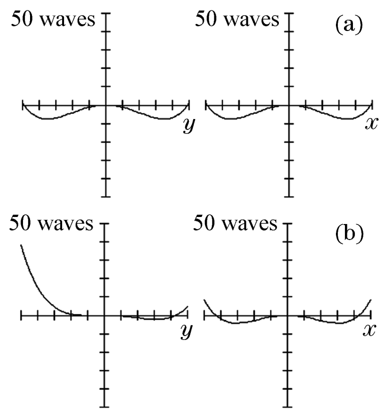

Fig. 2. Wavefront error (OPD versus normalized pupil) without correction at the FOVs of (a) 0° and (b) 30°.

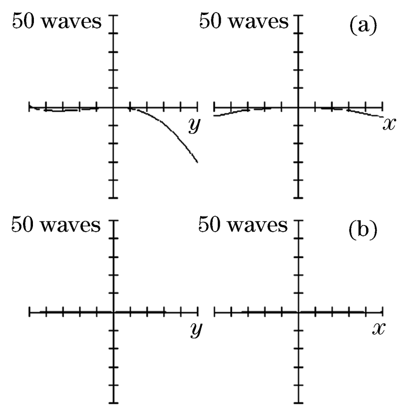

Fig. 3. Wavefront error with correction at the FOVs of (a) 0° and (b) 30°.

By using the image analysis functions of ZEMAX software, we put the "airport" picture on the object plane of the system. Figure 4 is the output surface image

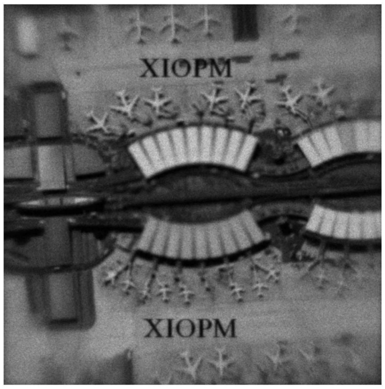

Fig. 4. Uncorrected output image.

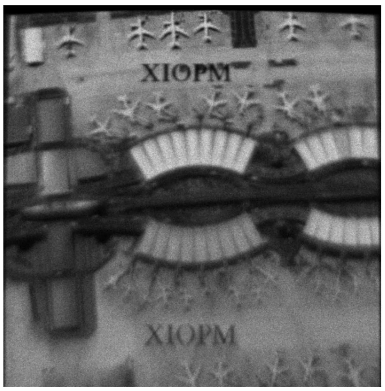

Fig. 5. Corrected image at the FOV of 45°.

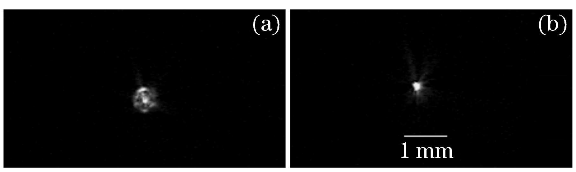

Fig. 6. (a) Uncorrected and (b) corrected images of a 20-μm pinhole at a 25° field angle.

without using phase modulation. The images of on-axis points are very clear, and with the expanding of FOV, the images of off-axis points become increasingly blurred. Figure 5 is the 45° FOV corrected output image. The top airplanes are very clear, and the remaining FOV becomes blurred, but we can still make out the general goal different. Our imaging system creates an image with a limited region of interest that is well corrected and appears in focus, while peripheral areas are aberrated and appear blurred. The variable spatial resolution mimics the operation of the human eye, where the limited area within a few degrees of the point gaze is highly resolved, but the resolution of other areas falls off rapidly with increasing field angle. This is the reason why the spatial resolutions of the top and underside in Fig. 5 are different.

Figure 6 shows the correction of a point source, a 20-μm pinhole, at a field angle of 25°. The source we used is white light. In Fig. 6(a), with no voltages applied to the deformable mirror, the image of the pinhole is completely smeared out due to the aberration in the system. When we applied the correction for 25°, the image of the pinhole is dramatically improved, as shown in Fig. 6(b). This further demonstrated the function of the foveated imaging system.

As seen from the experiment, we can use the deformable mirror to correct the area we are interested in and do not care much about the region we are not concerned about. It is very important when the data transmission is very large, which is often difficult to overcome in many critical areas.

In conclusion, we successfully demonstrated a 60° FOV imaging system by using deformable mirror to change wavefront and correct the arbitrary FOV aberration. We can improve arbitrary high-resolution imaging points of interest at the entire FOV. Besides, we can reduce data transmission to meet the bandwidth requirements. Compared with the traditional optical systems, this system is very simple and compact, and even we can use a plastic lens in the system. The smaller and lighter optical system is very important in the future in many applications including surveillance, remote navigation of unmanned vehicles, target acquisition and tracking. Compared with other work[1−5], the deformable mirror has the wider phase modulation depth and wider bandwidth. We believe that with the development of low-light-level devices, the wide FOV imaging system will certainly be promoted greatly.

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