Wide field-of-view imaging system using a liquid crystal spatial light modulator

George Curatu[a*], David V. Wick[b], Don M. Payne[c], Ty Martinez[d], Jamie Harriman[e], and James E. Harvey[a]

[a]University of Central Florida, 4000 Central Florida Blvd., Orlando, FL 32816
[b]Sandia National Laboratories, PO Box 5800, MS 1188, Albuquerque, NM 87185
[c]Narrascape, 3101 Hyder Ave. SE, Albuquerque, NM 87106
[d] Naval Research Laboratory, c/o AFRL/DEBI, 3550 Aberdeen Ave. SE, Kirtland AFB, NM 87117
[e]Boulder Nonlinear Systems, 450 Courtney Way, Lafayette, CO 80026

ABSTRACT

This paper presents the optical design and experimental demonstration of a compact, foveated, wide field-of-view (FOV) imaging system using two lenses and a liquid crystal spatial light modulator (SLM). The FOV of this simple doublet system is dramatically improved by the SLM, which can be programmed to correct all the geometrical aberrations at any particular field angle. The SLM creates a variation in the image quality across the entire FOV, with a diffraction-limited performance at the field angle of interest (similar to the foveated human vision). The region of interest can be changed dynamically, such that any area within the FOV of the system can be highly resolved within milliseconds. The wide FOV, compactness, and absence of moving parts make this system a good candidate for tracking and surveillance applications. We designed an f/7.7 system, with a 60° full FOV, and a 27 mm effective focal length. Only two lenses and a beam splitter cube were used along with a reflective SLM. The theoretical wavefront aberration coefficients were used to program the SLM, which was placed in the pupil plane of the system. A prototype was built and the system was experimentally demonstrated using monochromatic light and a CCD camera.

Keywords: foveated imaging, adaptive optics, imaging systems, aberration compensation, spatial light modulators, liquid crystal devices.

1. INTRODUCTION

Wide field-of-view (FOV) optical systems have always been a challenge for optical designers. Such systems generally require severe "bending" of the rays in order to form an image of the wide-angle object. To avoid this abrupt bending of rays, which introduces aberrations, wide-angle lenses tend to be complex designs, with multiple elements [1]. These systems end up being heavy, bulky, and expensive. A slower system (larger f/#) can minimize the complexity of the lens at the expense of less light hitting the detector or larger overall length. Currently there is an increasing demand for small, lightweight imaging systems with a wide FOV, with applications in tracking, surveillance, threat detection, and other areas that could benefit by using such systems.

2. FOVEATED IMAGING

Recent developments in systems that mimic human sensors inspired research on *foveated imaging*. The human visual acuity is highly resolved only within a few degrees around the part of the retina called the *fovea*, and decreases towards the peripheral FOV. However, humans can still detect objects or movement near the peripheral FOV, but in order to

[*] Now with LightPath Technologies, 2603 Challenger Tech Court, Orlando, FL, 32826
E-mail: gcuratu@lightpath.com; Tel: 407-382-4003 ext. 355

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highly resolve such objects, they would have to center their eyes such that the image of the object forms on the fovea. Our system mimics the human vision system, where a large FOV is covered with variable resolution across the FOV.

The idea behind the proposed wide FOV foveated imaging system is to use a liquid crystal spatial light modulator (SLM). SLMs are compact devices used to control optical wavefronts. They consist of a thin cell of birefringent liquid crystal material sandwiched between two pixilated transparent electrodes. Just like segmented deformable mirrors, SLMs can control the optical path seen by the wavefront. The optical path can be adjusted such that it would compensate for the optical path difference (OPD) in the aberrated wavefront. The OPD can be controlled at each pixel on the SLM by changing the refractive index of the liquid crystal ($OPD = \Delta n_z z$, where Δn_z is the index change in the direction of propagation, and z is the physical path length). The index of refraction is changed by applying a small voltage (typically less than 50 Volts) at each pixel across the liquid crystal. If the maximum wavefront error is larger than the maximum achievable OPD (dynamic range) of the SLM, correction can still be done modulo-λ [2,3].

We presented previously a theoretical concept for increasing the diffraction-limited FOV of a simple monochromatic doublet [4]. A pixilated liquid-crystal SLM placed at the pupil plane was used in transmission to correct for off-axis geometrical aberrations that would have otherwise limited the FOV. The computer-modeled system was compact (only two meniscus lenses), fast (f/2.4), and had a very large FOV (diffraction-limited over 90° full-field). We also demonstrated a foveated imaging system experimentally, using a 512 × 512 pixels reflective liquid crystal SLM and an off-the-shelf plano-convex lens [5]. The system was very simple, and it only covered a 15° FOV, but it proved the concept and its feasibility. Other applications were proposed where an SLM would be used along with conventional optics to create a zoom lens [6], or to correct off-axis aberrations and defocus in a telescope [7].

3. OPTICAL DESIGN

The goal of this project was to design and build a custom foveated imaging system with a larger FOV than the previous experiment. Although a transmissive SLM is preferable in order to simplify the optical setup, currently there are no commercially available transmissive devices that have sufficient resolution and dynamic range for this application. Therefore, we had to limit our design again to a reflective SLM. Furthermore, we limited our preliminary optical design to a doublet formed by a plano-concave and a plano-convex lens, with spherical surfaces. The use of such common lenses in the preliminary design made it easy to replace them with off-the-shelf lenses in the final design.

Figure 1 shows the optical layout of the final design. The f/7.7 system has a focal length of 27 mm, a full FOV of 60°, and includes a window, a polarizer, and a 633 nm narrowband filter (the system was optimized for 633 nm). The SLM limits the operation of the system to monochromatic polarized light, hence the use of the narrowband filter and the polarizer. A beam splitter cube was added to fold the system, and increase the usable FOV. The full image size to be captured on the CCD camera is 25 mm. The system was first optimized without SLM, in order to minimize the peak-to-valley wavefront error and the distortion across the entire FOV. Our goal was to achieve less than 35 waves peak-to-valley wavefront error (Figure 2) and less than 15% distortion across the FOV. There is no vignetting in the system.

The SLM was modeled as a *Zernike phase surface* - an infinitely thin phase plate, where the phase is described by a Zernike polynomial - placed at the pupil plane. The Zernike phase surface was optimized for each field of interest in order to minimize the wavefront error. For this demonstration, we chose to correct the aberrations at the 0° and 30° fields. In both cases, after the SLM correction was applied, the peak-to-valley wavefront error was reduced to less than 0.2 waves (Figure 3). The computer model of our foveated imaging system exhibited diffraction-limited performance at each point within the FOV where the OPD introduced by the SLM was optimized to correct the wavefront error.

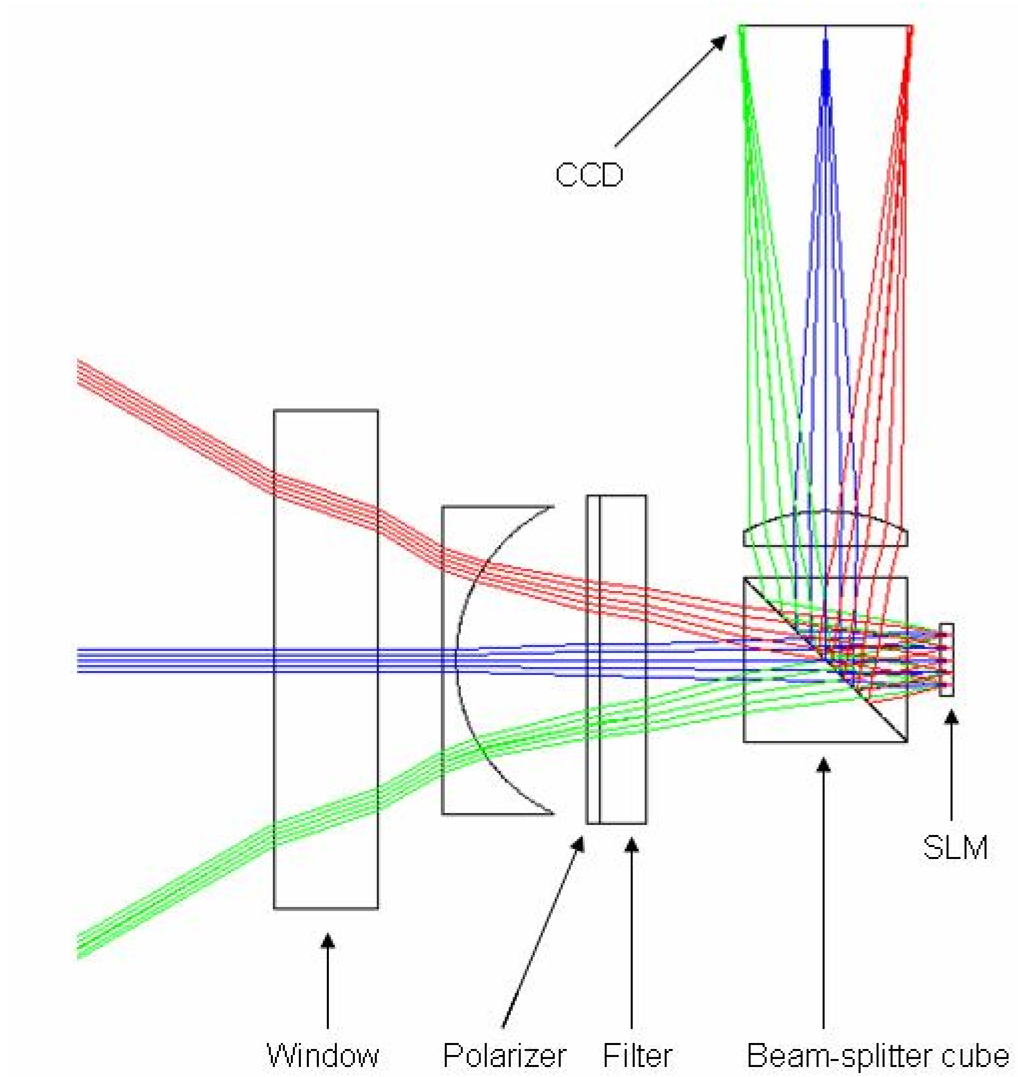

Figure 1: Optical layout of the final design (EFL = 27mm, f/7.7, FOV = 60°).

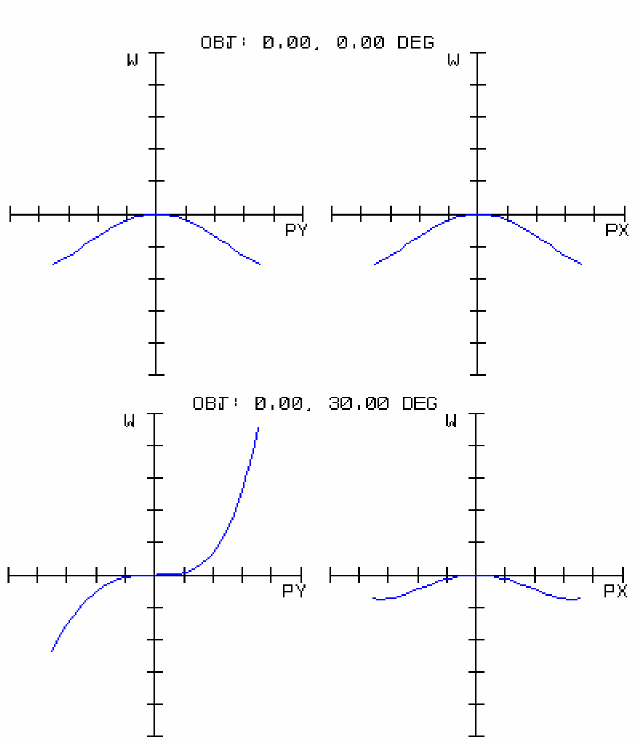

Figure 2: Wavefront error (OPD versus normalized pupil) without SLM correction at the 0° and 30° fields as a function of normalized pupil (maximum scale is ±25λ).

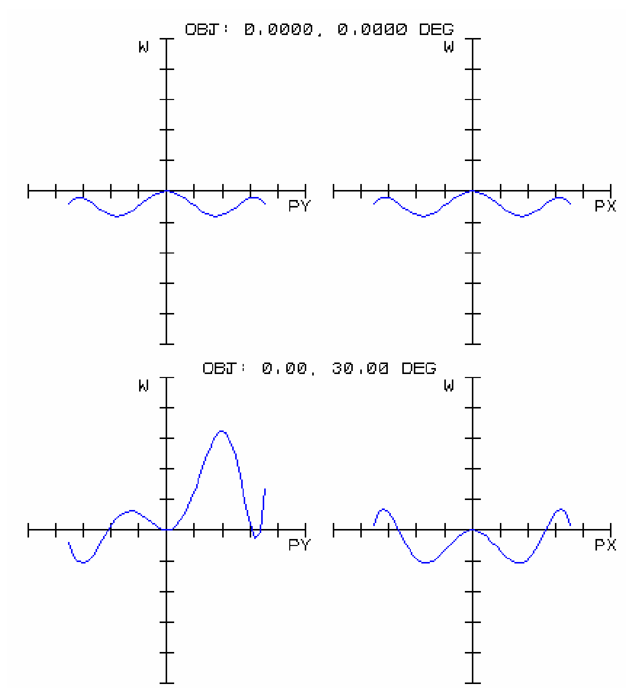

Figure 3: Wavefront error with SLM correction at the 0° and 30° fields as a function of normalized pupil (maximum scale is ±0.25λ).

4. EXPERIMENTAL DEMONSTRATION

Figure 4 shows on the left a picture of the prototype built following the lens prescription from the final optical design. The SLM is a 7.68 × 7.68 mm reflective device with 512 × 512 pixels (15 × 15 µm pitch), and a response time of 10 ms. The dynamic range of the SLM was given by the thickness of the liquid crystal cell (2.5 µm used in double-pass), and the maximum change in the refractive index (0.39). Although the high-birefringence liquid crystal used in the SLM provided a fairly wide dynamic range, it was not enough to correct for the maximum wavefront error (35 waves). The optical path correction had to be done modulo-λ.

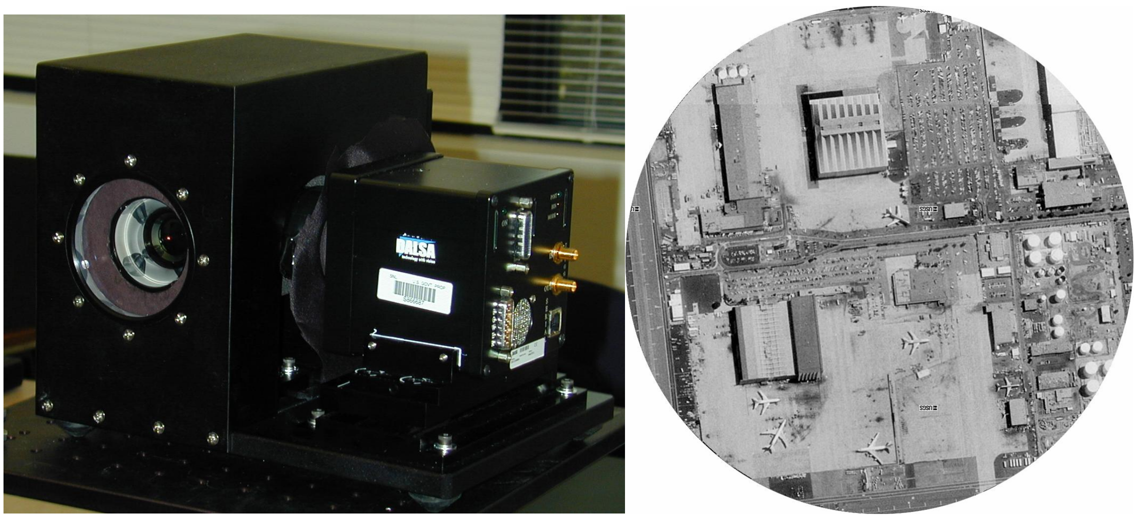

Figure 4: Left – foveated imaging system prototype. Right – aerial picture used for experimental and simulated imaging.

Using the computer model, Zernike phase surfaces were determined for each field angle such that the OPD introduced by the SLM would minimize the wavefront error at that particular field angle. We calculated thirty different Zernike phase surfaces to correct the wavefront error from 0° to 30°, in increments of 1°. Since our imaging system is rotationally symmetric, it is sufficient to map only half of the FOV in one direction. For each field angle, the two dimensional array of voltages to be applied to the pixels was calculated from the corresponding Zernike phase surface using modulo-2π phase-wrap.

To demonstrate the wavefront correction capabilities of our foveated imaging system, an 8 by 8 ft print of an airport was placed in the object plane. The narrowband filter filtered out everything but the 633 nm light. The aerial image of the airport shows various structures and planes located on a tarmac (Figure 4, on the right). The SLM was first addressed to correct the wavefront error at the field angle corresponding to the position of the two planes at the left-bottom of the image (Figure 5). The targeted planes are highly resolved, while other planes and structures around the target planes are clearly visible. However, the structures in the upper part of the image are not resolved. Figure 6 shows the image with the SLM being readdressed to correct the wavefront error at the field angle corresponding to the position of the structures in the upper part of the image. The targeted structures are now highly resolved. The experiment was simulated using the computer model of our imaging system, with the same aerial picture as object. For the simulation, the SLM correction was applied at the same field angles as for the experiment. The simulated images are shown on the right side of Figures 5 and 6.

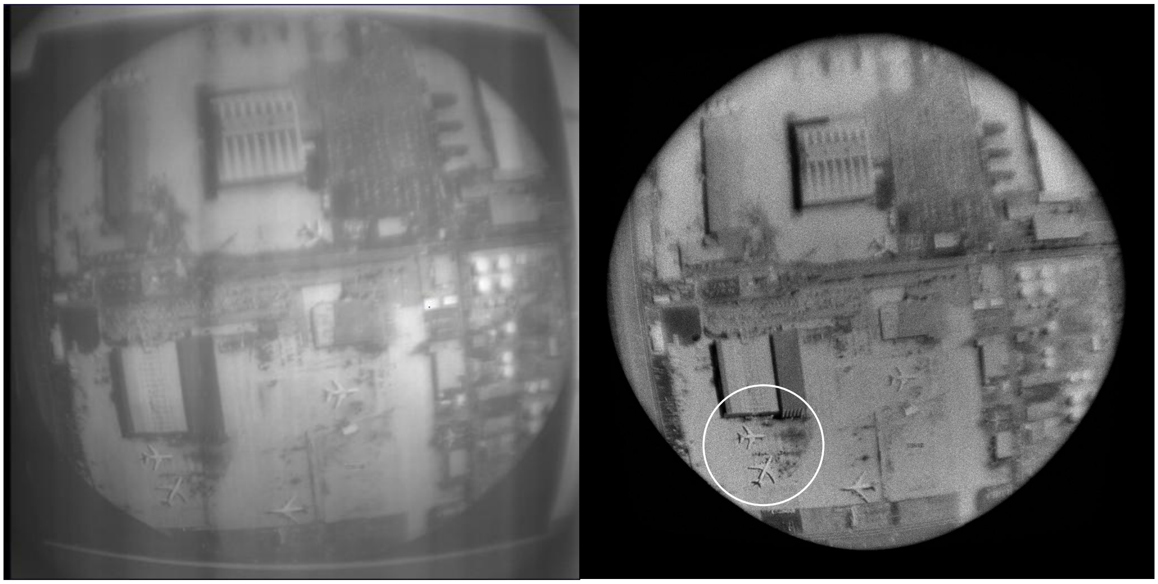

Figure 5: Image with the SLM correction applied to resolve the two planes at the left-bottom.
Left –image obtained experimentally. Right – simulated image.

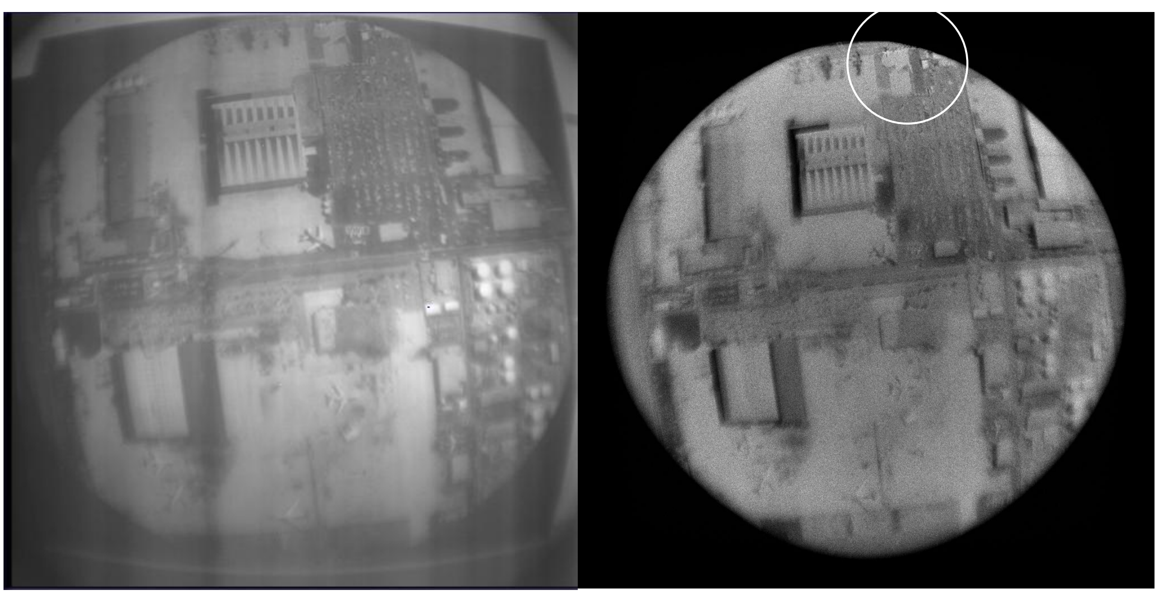

Figure 6: Image with the SLM correction applied to resolve the structures at the top.
Left –image obtained experimentally. Right – simulated image.

5. CONCLUSION

We have successfully designed, built, and demonstrated a 60º FOV foveated imaging system using a 512 × 512 reflective SLM and commercial off-the-shelf optical components. The liquid crystal SLM corrected off-axis aberrations that would have otherwise limited the FOV. Our lens is simple and more compact than conventional wide FOV lenses. However, the SLM limits the operation of our foveated imaging system to monochromatic polarized light.

The new developments in high-birefringence liquid crystal materials along with technological advances in high-resolution transmissive SLM devices will facilitate the design and development of new, more compact foveated imaging systems, with larger FOV.

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