Silicon adaptive optics systems using micro-mirrors

Natalie Clark\textsuperscript{a}, John Comtois\textsuperscript{a}, Adrian Michalicek\textsuperscript{a}, Paul Furth\textsuperscript{b}, and Greg Whitfield\textsuperscript{c}

\textsuperscript{a}Air Force Research Laboratory, Kirtland AFB NM 87117
\textsuperscript{b}New Mexico State University, Las Cruces NM 88003
\textsuperscript{c}G. Whitfield, RDA Logicon, Albuquerque NM 87117

ABSTRACT

Many factors contribute to the aberrations induced in an optical system. Atmospheric turbulence between the object and the imaging system, physical or thermal perturbations in optical elements degrade the system’s point spread function, and misaligned optics are the primary sources of aberrations that affect image quality. The design of a non-conventional real-time adaptive optic system using a micro-mirror device for wavefront correction is presented. The adaptive optic system uses a VLSI circuit that can be reconfigured for use with many wavefront sensors including the Hartmann, shearing, and curvature wavefront sensors. The unconventional adaptive optic imaging systems presented offer advantages in speed, cost, power consumption, and weight. Experimental and modeling results that characterizes the performance of each wavefront sensor in the micro-mirror adaptive optic system are presented.

KEY WORDS: smart vision, adaptive optics, liquid crystals, and micro-mirrors, phase diversity, wavefront correction

1. Introduction

Image quality through the atmosphere is limited by the atmospheric blur due to turbulence [1-3]. Atmospheric turbulence is highly dynamic and requires compensation by deformable mirrors or phase modulating spatial light modulators with high bandwidth. This paper describes novel techniques using both analog and digital technologies to enhance the performance of an adaptive optic system. CMOS photodiodes are used in the wavefront sensor and for imaging. The CMOS photodiodes offer advantages in enabling massively parallel interfacing to the wavefront reconstructor as well as image processing. The wavefront reconstructor we present paper uses analog CMOS circuits to compute the wavefront aberrations. The analog nature of the reconstructor also drives the micro-machine electro-mechanical mirrors, which were fabricated using the Sandia National Laboratory Summit process. The micro-mirrors lend themselves to being integrated with CMOS circuits. Hence, the highly integrated nature of our silicon adaptive optic system offers advantages in speed, cost, size, and power consumption.

2. Wavefront Sensors

The analog wavefront reconstructor circuit described in section 3 can be used with several types of wavefront sensors. Our paper will describe our wavefront sensor and how the analog reconstructor is used to compute the aberrated wavefront. Once the aberrated wavefront is known it can be compensated for by the micro-mirrors described in section 4. Figure 1 illustrates the operation of the wavefront sensors discussed in this paper.

The Hartmann wavefront sensor is one of the most commonly used wavefront sensor in adaptive optic systems. The Hartmann sensor is known to be a very accurate wavefront measuring device used in many adaptive optic systems. The accuracy of measuring the wavefront is limited by not only the random noise...
sources associated with the Hartmann sensor apparatus but also is limited by the accuracy to which the shifted spot locations can be determined. For most applications, the overall system noise associated with the Hartmann sensors is very small in comparison to the amount of wavefront tilt that is to be measured. A schematic illustrating the operation of a Hartmann wavefront sensor system is shown in figure 1(a). Referring to figure 1(a), the Hartmann wavefront sensor system itself consists of an array of lenslets coupled to photo-detectors. Each lenslet focuses forms a spot whose centroid is offset by a distance $\Delta_i$ that is proportional to the average tilt (classically called distortion) of the aberrated wavefront impinging on the aperture. The centroid $(\bar{x}, \bar{y})$ is the first moment of the irradiance pattern $I(x,y)$ of the focused spot,

$$\bar{x} = \int \int I(x,y) x \, dx \, dy,$$

$$\bar{y} = \int \int I(x,y) y \, dx \, dy.$$  

The relationship between the average tilt across the lenslet and the focal spot deflection. The wavefront tilt induces a shift in the position of the centroid. Although other aberrations change the shape of the irradiance pattern, they do not alter the location of the centroid (or position of the maximum).

**Figure 1.** Wavefront Sensors. (a) Conventional Hartmann, (b) Correlation-based Hartmann-type for extended object, (c) Shearing, (d) Phase Diversity.
The wavefront sensor shown in Figure 1(b) is an extension of the Hartmann wavefront sensor for use on extended objects. The wavefront sensor is an extension of the classical Hartmann wavefront sensor. Analogous to the operation of the classical Hartmann wavefront sensor, each lenslet forms an image of the object, but shifted by an amount proportional to the average tilt across its subaperture. Once the location of each image formed by the lenslets is known, the analog reconstruction described in section 4 can be used to compute the aberrations. Another wavefront sensor that is commonly used is the shearing interferometer. Figure 1(c) illustrates the operation of the shearing wavefront sensor.

The phase diversity wavefront sensor can be used with extended objects. Figure 1(d) illustrates our integrated phase diversity based adaptive optic system. The difference between a well-focused and slightly defocused image contains information about the phase of the object. This section describes how to retrieve this phase information from images formed by an incoherent imaging system. The phase retrieval based on the irradiance transport equation offers advantages over other wavefront sensors. First, the transport equation is presented and its physical meaning is briefly discussed. Assume that a paraxial beam is propagating along the z axis as illustrated in figure 1. The complex amplitude can be expressed as $I(x,y;z) = \exp(ikW(x,y;z))$, where $I(x,y;z)$ is the irradiance, $W(x,y;z)$ is the phase term in terms of wavelength $\lambda$, and the wavenumber $k = 2\pi / \lambda$. According to Huygen’s principle the propagation of light from the plane $z=0$ to another plane $z \geq 0$ is described by the convolution of the amplitude $u(x,z=0)$ with spherical waves. In the paraxial approximation the spherical waves are replaced by parabolic waves. This approximation is quite good if the cone of emerging rays is narrow enough. Thus, based upon this the approximation of a parabolic equation yields the transport equation

$$
\nabla \cdot \nabla I + \nabla I + \frac{\partial I}{\partial z} = 0
$$

where $\nabla \equiv \frac{\partial}{\partial x} + \frac{\partial}{\partial y}$ is the gradient operator in the (x,y) plane which is normal to the direction of beam propagation [1-5].

The first term $\nabla \cdot \nabla W$ is often referred to as the prism term; it represents the irradiance variation induced by the transverse shift associated with the inhomogeneous beam to the local tilt of the wavefront in the direction of $\nabla W$. The second term, $I \nabla^2 W$ is often referred to as the lens term; it describes the convergence (or divergence) of the beam. The local focal length of the lens term is inversely proportional to the lens term. The third term, $\frac{\partial I}{\partial z}$ describes the propagation of the beam irradiance induced by the lens and prism term.

Assuming uniform illumination of $I_0$ over the pupil (and zero outside), then $\nabla I = 0$ everywhere except at the pupil edge where
\[ \nabla I = -I_0 n \delta_c, \tag{2} \]

where \( \delta_c \) is the Dirac delta distribution around the edge of the pupil and \( n \) is the unit vector orthogonal to the edge and pointing outward. Substituting into the transport equation (1) yields,

\[ \frac{1}{I_0} \frac{\partial I}{\partial z} = \frac{\partial W}{\partial n} \delta_c = P \nabla^2 W \tag{3} \]

where \( P(x,y) \) is the pupil function defined to be 1 inside the pupil and 0 outside the pupil. The wavefront derivative of the pupil edge in the outward direction is mathematically expressed as \( \frac{\partial W}{\partial n} = n \cdot \nabla W \).

Equation (3) shows that the fractional change in illumination is based upon two parts. For internal points the wavefront is governed by the Laplacian operator \( \nabla^2 W \). And for edge components the equation for wavefront radial slope \( \frac{\partial W}{\partial n} \) governs. Consequently it is possible to reconstruct the wavefront surface \( W \) by solving a Poisson equation with Neuman boundary conditions. The finite difference based approach that was used to characterize the system performance is described in section VI.

3. Wavefront Correction using micro-mirrors

Currently, adaptive optical systems are used on large earth-based telescopes to measure and compensate for rapidly fluctuating wavefront distortions due to turbulence in the atmosphere. All operational systems to date have made use of large opto-mechanical actuators. These systems are based upon the technology of elastic reflecting surfaces which are rapidly and continuously deformed by a closed loop feedback process involving a wavefront error sensing element. Often the wavefront sensing device that consists array of Hartmann sensors. While many of these systems are currently being used they suffer from many shortcomings. These systems are typically complex, very expensive, unreliable, and difficult to maintain, putting them out of reach of most astronomers and general commercial users. They are also very heavy and operate at low bandwidths, making them unsuitable for airborne applications. Recent advances in the development of SLM’s and in particular Liquid Crystal Display (LCD) devices, offer potential for low weight, low cost, and low power alternatives to the large opto-mechanical devices. Also, cost effective bulk manufacturing methods currently exist for these devices. However, current LCD devices suffer from limited bandwidth, low maximum phase modulation, and poor dynamic range. Bandwidth limitations will preclude the use of LCD’s for airborne or missile applications.

The recent advent of micro-electro-mechanical (MEM) technology offers an alternative technology for the construction of cost effective SLM’s. This technology is based upon the well established fabrication methods used in integrated circuit construction. Like LCD technology, it takes advantage of well established industrial investment in cost effective manufacturing methods already in use.
Micromachining offers an improvement in overall performance and reduction of cost of micro actuators for military, industrial, and commercial markets. This technology uses low voltage and is CMOS compatible. MEM devices offer low power consumption, large amplitude and phase modulation, digital control, large dynamic range and high bandwidth. Due to their small size, MEM devices can have extremely high speeds of operation (typically in the MHz region). MEM technology can provide devices with very low weight making them entirely suitable for ground based, airborne, and even hand-held wavefront correction applications. Figure 2 shows the details of an individual mirror design. This figure captures all of the advantages of the SUMMiT process for MOEMS. SUMMiT has a combination of features not found in other MEMS fabrication processes, such as a chemical-mechanically polished upper surface, 1 micron design rules, and four releasable layers. One of these layers is only 1 micron thick, allowing extremely low drive voltages. Current 4-flexure mirrors can be designed for actuation at less than 10V, making it possible to drive them with standard CMOS circuitry. The multiple releasable layers allow all of the wiring and flexures to be completely hidden under the polished optical surface, resulting in near-optimum active mirror area coverage. This is an important consideration not only for optical efficiency, but also in applications where stray light leakage into the mechanism limits power handling capability.

The multiple layers also allows us to shield the wiring so the optical surface can be metalized after the release etch. Thus the optical surface of choice can be deposited without concern over its survival through the harsh release etch. Another advantage of post-release metalization is that the entire active area is covered, unlike drawn metal which requires a margin between the edge of the metal and the edge of the polysilicon upper plate. These capabilities, coupled with the hidden-flexure/post metalization design techniques, give the 8x8 test array of 100 micron square mirrors an active area coverage of 97.7%. This high active area coverage offers unprecedented to diffraction-limited imaging with minimal light loss. Figure 3 shows an array of 50 micron square mirrors. Note that only mirror surfaces are visible, and the only area lost is due to the 1 micron gaps between the mirrors, the etch holes, and the anchor posts. This array has an active area coverage of 95.3%, and there are no topological effects from the underlying layers.

Figure 2. Details of a typical flexure beam piston micromirror which takes full advantage of the SUMMiT capabilities. These 50 micron square mirrors achieve 95.3% active mirror surface coverage. The layers left to right are: Poly0 layer used for wiring throughout the array; Poly1 used for the flexures because it is the thinnest layer, poly1 is also used for metalization gutters (square frames surrounding the spiral flexures) to prevent post-release metalization from shorting the wiring; Poly2 is used for the lower electrode of the electrostatic actuator; Poly3 forms the upper electrode and is also the planarized surface - note the total lack of topological effects at this level.
Figure 3. Array of 50 micron square mirrors showing the excellent active area coverage obtainable in the SUMMiT process. This array has 95.3% coverage. The coverage increases with mirror size, so an array of 100 micron square mirrors has 97.7% coverage. All wiring and actuator mechanisms are hidden, with no topological effect on the active mirror surface.

3. Analog Wavefront Reconstructor

The PDE (partial differential equation) reconstructor chip can then be used in virtually all wavefront sensors to sense phase aberrations. The technical challenge for the hybrid vision processor is to further develop the general purpose, reconfigurable partial differential equation solver chip. The chip has programmable boundary conditions which can be altered to solve a wide variety of partial differential equations. Thus, each cell can be programmed as to what partial differential equation governs it and if it is a boundary cell, and what type of boundary condition (Dirichlet or Neumann) governs it. Figure 4 is a schematic illustrating the operation of the chip. Referring to Figure 4a, the chip acts as a programmable resistive grid. Transistors operating in the ohmic mode act as programmable resistors. The transistor implementation of a single cell in the resistive grid is shown in figure 4b. Each cell can be programmed to be either a resistive cell, a boundary cell or an empty cell. This allows the chip to become a programmable partial differential equation solver. For adaptive optics applications, the processor chip can be programmed to be utilized in virtually any wavefront sensor including the ones developed under this proposed effort. When used to control the micro-mirror array so that it behaves as a deformable lens, the system becomes a miniature adaptive optics system on a chip which we refer to as our AFRL silicon eye.

The processor architecture is based on neuromorphic processing associated with the human eye. The parallel processing aspect of the human visual system allows it to do complex image processing more rapidly than any digital computer. A digital computer is extremely effective at producing precise answers to well defined problems. The nervous system, on the other hand, accepts fuzzy, poorly conditioned input and performs computations that are ill defined, producing an approximate output. Digital and nervous system are different in fundamentally irreconcilable ways. Past and current efforts with digital computers and digital signal processing algorithms have taught us how neural computation is not done.

Part of the reason for this failure is that a large proportion of neural computation is done in an analog rather than a digital manner. This is especially true of many vision problems, including the proposed adaptive optics system using phase diversity. As is true for phase diversity, vision problems are very expensive in terms of computer cycles. A color CCD camera, sampling its visual field using a 1024 x 1024 pixel grid will generate approximately 100 million bytes of information each second that need to be transmitted and further processed. For some image processing algorithms, such as edge detection or filtering, on the order of 10 to 100 elementary operations must be performed for each pixel in the image, requiring a
computational throughput of about $10^8$ to $10^9$ operations per second. Numerically solving the transport equation at bandwidths exceeding 10Hz is very difficult. For typical adaptive optic system bandwidths of 1000 Hz are desired in order to keep up with the turbulence effects. It is difficult for even supercomputers to handle the load imposed by typical visions systems. Moreover, speed is not the only constraint. For many applications it is neither practical nor cost efficient to carry around a ton of silicon and steel to perform the necessary computations required in a vision system.

![Figure 4](image)

Figure 4. Smart Vision Processor chip, (a) shows the schematic of one node of the processor in a hexagonal grid; (b) shows the circuitry of a single node for a processor built on a rectangular grid.

5. Experimental Results

An optical system used for evaluating the performance of the Hartmann wavefront sensor is illustrated in figure 5. Referring to figure 5b, the second lens was displace by an amount $dz$ which in turn induced defocus aberration on the wavefront sensor. The centroids from the hartmann wavefronts sensor were computed and the resulting information fed into a spice simulation of the PDE reconstructor chip. The radius of curvature of the defocus aberration vs the displacement amount is shown in figure 5(b). These results demonstrate that the reconstructor chip accurately computes the wavefront aberration comparable to that of a digital system. Preliminary results show that the wavefront sensors/reconstructor system is capable of detecting 1/100 or a wave of defocus aberration.
Figure 6 shows some experimental results for the phase diversity wavefront sensor. From the best-focus and diverse image the wavefront aberrations were computed by a circuit simulation of the PDE reconstructor chip. A spatial light modulator (liquid crystal device) consisting of 69 actuators was used to compensate for the aberration induced. The PDE chip is able to compute the aberrations comparable to that associated with digital systems. These results are preliminary and more detailed quantitative analysis is currently being performed.

Figure 5. Noise equivalent tilt angle of a Hartmann Wavefront sensor.
6. References


