FAST AUTONOMOUS HOLOGRAPHIC ADAPTIVE OPTICS

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Abstract
We present an adaptive optics system incorporating a holographic wavefront sensor with the autonomous closed-loop control of a MEMS deformable mirror. Our Holographic Adaptive Laser Optics System (HALOS) incorporates a multiplexed holographic recording of the response functions of each actuator in a deformable mirror. On reconstruction with an arbitrary input beam, multiple focal spots are produced. By measuring the relative intensities of these spots a full measurement of the absolute phase can be constructed. Using fast photodiodes, direct feedback correction can be applied to the actuators.

1. Introduction
We present the results from an all-optical, ultra-compact system that runs in closed-loop without the need for a computer. The 32-actuator HALOS runs at a 100kHz bandwidth, but the speed is independent of the number of actuators and should run equally fast with one million. Additionally, the system is largely insensitive to obscuration unlike the more conventional Shack-Hartmann WFS. We also show how HALOS can be used for image correction and beam propagation as well as several other novel applications.

2. Theory
The operation of HALOS is best described in terms of how it is constructed. We begin by having a plane wave reference beam illuminate an actuator on a deformable mirror which is set to the maximum push position (Figure 1a). The reflected beam is made to interfere with a reference beam focused to some distant point A. The recording of this interference pattern constitutes the hologram. This hologram has the property that if the original input beam reflected from the actuator is present it will reconstruct a beam focused to point A.

A second hologram is then recorded on the same medium in the same location. This multiplexing of holograms is a fairly straightforward process and retains the properties of each individual hologram (though with a slight loss in efficiency). In this case though, the hologram is recorded with the actuator set to its maximum pull position, and the reference beam is focused to a different point B (Figure 1b).
If we now set the actuator to some intermediate position between maximum push and pull, the reflected beam does not perfectly match either recording condition. As such, the phase matching condition is such that both focused beams are reconstructed. If we place pinholes at locations A & B we can measure the transmitted power, which is directly proportional to the absolute phase of the input beam over that particular actuator. In essence, the holographic wavefront sensor operates as a subaperture-based curvature sensor. The key, though, is that the spots do not move, so long as global tip/tilt is removed – something which is routinely performed in most adaptive optics systems.

Figure 1: a. A hologram is recorded between a beam with minimum phase delay and a reference focused to point A. b. A second hologram is multiplexed with a maximum phase delay object beam and reference beam focused to point B. c. On replay, a beam with intermediate phase delay reconstructs two focused beams.
The text above describes the way in which the phase can be determined for a patch over a single actuator. For a useful adaptive optics system, however, the phase has to be determined over a number of actuators which is simply a matter of repeating the recording process to produce a pair of holograms for each actuator. The resultant wavefront sensor is shown in Figure 2. Here we also add an array of pinholes to provide better discrimination between the two curvatures.

![Figure 2: A holographic wavefront sensor works by reconstructing a pair of beams for each actuator. A pinhole plate is placed at the focal plane, followed by a detector array.](image)

By placing an array of photodiodes at each focal spot we can use intensity measurements of focal spots to determine the phase error over the entire wavefront. Since no major calculations are required, this can be accomplished using a simple circuit at speeds of upwards of MHz or even GHz rates. In practice we use the fractional energy difference of the photodiode voltage outputs \(\frac{(V_a-V_b)}{(V_a+V_b)}\) which makes it possible to generate a more stable error function and one that is largely insensitive to background light. Furthermore we can use this method for a simple closed-loop correction we call the Holographic Adaptive Laser Optics System (HALOS).

We begin by introducing a plane wave into the HALOS system with the mirror flattened. The spot intensities are measured and the error function for each pair of detector outputs is recorded. These values represent the target values for a closed-loop system. With a simple feedback control we can use the difference between the calibrated and measured error functions to drive each actuator into a condition such that a flat wavefront is always maintained. The advantage to this system is that all the measurements and correction is made in parallel – so the speed is largely unchanged no matter how many actuators are used. We can use a very simple microcontroller to do all the calculations and control the actuators in feedback to speeds of kHz or greater.

**3. Experiment**

We conducted a test of HALOS using a 32-element MEMS deformable mirror (mini-DM). 64 holograms were recorded using 460nm laser light on dichromated gelatin film on glass. After processing a single input generated 64 diffracted beams incident on a SensL 144-element photodiode array (Figure 3). The outputs from 64 “pixels” were used to generate 32 error functions using an X莫斯 microcontroller. The same basic circuit was also capable of performing the feedback control over each of the 32 MEMS DM actuators at a full-frame closed-loop bandwidth of ~8kHz.
We designed and constructed the control software and graphical user interface in-house. As well as being very straightforward in construction, the entire control system could be run autonomously – that is to say, we could upload the entire control routines onto the microcontroller and have it run without a computer in the loop. This makes the entire HALOS system very compact, simple, rugged and inexpensive.

HALOS is initially calibrated with a flat wavefront to set the target error function values. If a single actuator is now cycled from maximum to minimum we can see that that particular channel registers a very clear, singly determined output, while the neighboring channel stays relatively free of influence. This changes depending on the extent of the influence function affecting cross-talk between actuators, but the main point is that we do have a signal to lock to (Figure 4, left).
With the set values stored, we can activate the closed-loop control to control the actuators in order to maintain a particular desired error function value in each channel. A demonstration of this in practice is shown in Figure 4 (right). In this case we had a wavefront initially flat, which was aberrated using a phase plate. With the feedback control activated the wavefront is returned to flat in a single clock cycle.

4. Conclusion
We have presented a holographic adaptive laser optics system (HALOS) that can provide a scalable adaptive optics correction operating at kHz speeds with any number of actuators. We have constructed a working prototype and are currently improving the performance and characteristics to test the fully capabilities.

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