Holographic Adaptive Laser Optics System (HALOS): Fast, autonomous aberration correction

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1. ABSTRACT

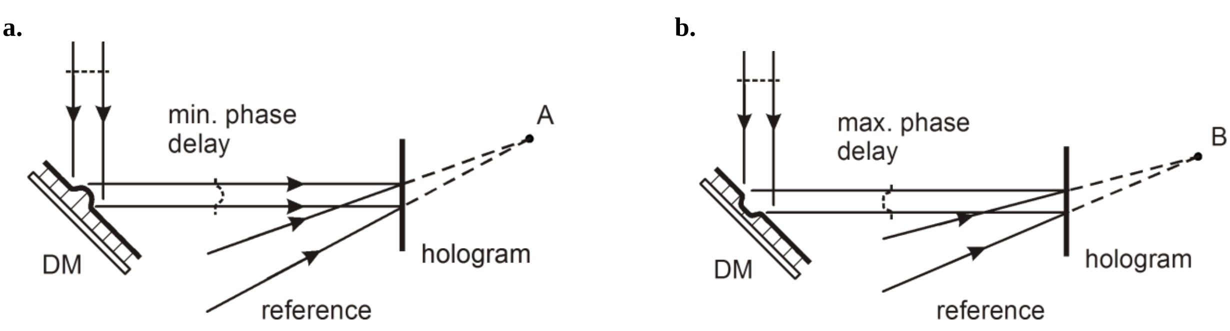
We present a Holographic Adaptive Laser Optics System (HALOS) that uses a multiplexed hologram to deconvolve the phase aberrations in an input beam. This wavefront characterization is extremely fast as it is based on simple measurements of the intensity of focal spots and does not require any computations. Furthermore, the system does not require a computer in the loop and is thus much cheaper, less complex and more robust than conventional methods. A fully functional, closed-loop prototype incorporating a 32-element MEMS mirror has been constructed. The unit has a footprint no larger than a laptop but runs at a bandwidth of 10kHz. Additionally, since the sensing is based on parallel, all-optical processing, the speed is independent of actuator number – running at the same bandwidth for one actuator as for a million.

2. INTRODUCTION

Ground-based space surveillance can greatly benefit from adaptive optics systems to remove the distorting effects of atmospheric turbulence. Improved performance can be achieved with increases in speed and actuator number (spatial resolution) but with conventional techniques this comes with an increase in complexity and cost. For example, the typical sensing method uses a Shack-Hartmann sensor which breaks a wavefront into subapertures created by a lenslet array. The local slope of each subaperture is then measured as the displacement of the foci compared to their ideal locations previously calibrated using a flat wavefront. A complete picture of the wavefront is generated by stitching together all the subapertures – usually with a further step of rendering the result in terms of Zernike polynomials. Correction can then be applied to the wavefront by deconvolving the Zernike-based wavefront error into actuator motions for a deformable mirror. Each of these steps requires many complex calculations and the process is greatly slowed as the spatial resolution is increased. Here we present an approach that uses a multiplexed hologram that, in effect, acts as an all-optical processor, removing the need for a complex computer.

3. HALOS

The operation of the holographic adaptive laser optics system (HALOS) is best understood in terms of how it is constructed. We begin with a deformable mirror with an actuator that is driven to its maximum extent in one direction. A localized plane wave reflecting off this subaperture will experience a phase shift. A hologram is recorded using this object beam and a reference beam focused to some distant point A (Fig. 1a). It is important to note here that on reconstruction, if the actuator were set to the same position, the input beam would reconstruct a focused beam to point A.



c.

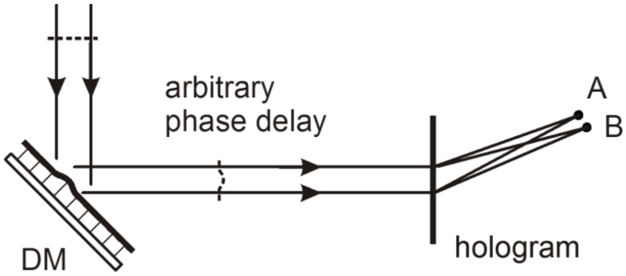


Fig. 1. Recording. A hologram is recorded with the minimum (**a.**) and maximum (**b.**) phase shift against beams focused to distant points A and B respectively. Replay. With an arbitrary input phase, two focused beams are reconstructed (**c.**).

A second hologram is now recorded on top of the first, with the actuator set to the minimum extent, and a beam focused to point B (Fig. 1b). The ability to record more than one grating in the same location (multiplexing), while retaining the information content of both, is a key property of holograms. If we now set the actuator position to some arbitrary configuration between one of the two extremes, we can now generate an object beam incident on the hologram that will reconstruct two focused beams A and B (Fig. 1c). The reason for the two beams is that the phase matching condition does not perfectly correlate with either recording case. As such, the degree to which each beam is recreated depends on how closely the input phase matches the recorded phase – i.e. the ratio of spot intensities is directly proportional to the absolute phase of the input beam.

The above procedure describes how the phase of the wavefront can be determined over a single actuator location. For an entire wavefront the process is simply repeated – with a multiplexed hologram recorded for each actuator over the entire aperture (Fig. 2). The pairs of holograms can be isolated or overlapped on the same medium, but the foci they produce are configured to be spatially separate. A single input wavefront encompassing the entire aperture will now reconstruct a number of foci - two for each actuator location. A full prescription of the wavefront phase is now simply built up from the individual measurements based on each subaperture.

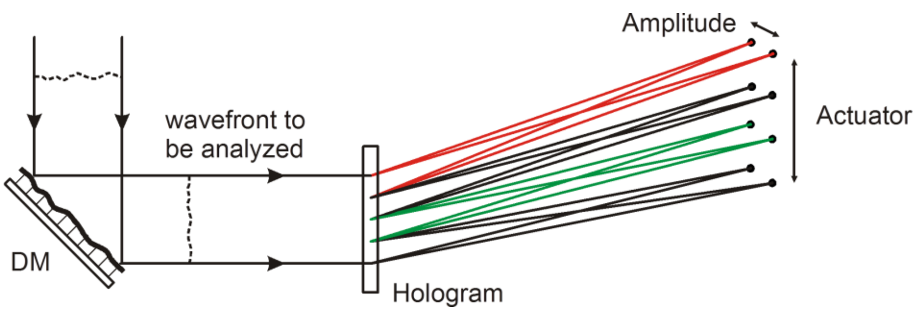


Fig. 2. HALOS. A single input beam reconstructs one pair of beams for each actuator. An array of detectors can then be used to analyze the entire wavefront.

In the HALOS concept, the phase is determined simply by a ratio of beam intensities – something which can be accomplished at MHz rates or beyond using two photodiodes and a simple circuit. No reduction of data by complex computers is required. Furthermore, by using an array of detectors we can make all of the required measurements in parallel, so a complete wavefront analysis can be made independent of actuator number. In other words, in principle the system will run as fast for one actuator as it will for one million.

While HALOS breaks the requirement of complex computers it also results in a sensing method orders of magnitude faster than Shack-Hartmann, pyramidal or curvature sensors. Furthermore, the very nature of the design lends itself to a simple closed-loop methodology. Since the detection is based on the phase at a particular actuator location, there is no need to translate the wavefront phase to or from any basis set such as Zernike polynomials. Instead, once the phase is determined for a given subaperture, a one-to-one feedback control over the corresponding actuator can be made to guarantee any particular phasefront (typically zero phase error).

4. EXPERIMENT

We have constructed a prototype of HALOS using a 32-element MEMS deformable mirror (DM) as shown in Fig. 3. The 64 holograms were recorded sequentially on the same piece of dichromated gelatin film using a blue laser (460nm). On replay, a single input beam reconstructs the 32 pairs of beams focused onto individual elements of a SensL 4p9 avalanche photodiode array. The sensor is, in fact, positioned slightly beyond the foci, with a pinhole plate located at the focal plane itself. The pinholes serve to isolate background light, but more importantly improve the discrimination between foci by increasing signal to noise.

a. **b.**

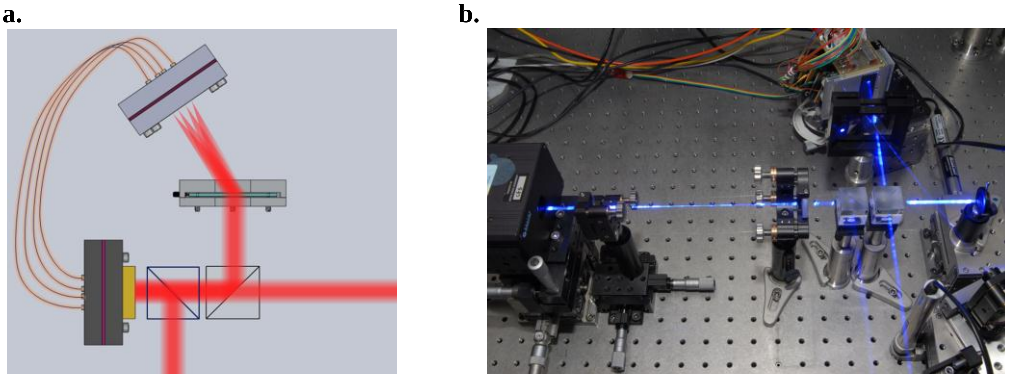


Fig. 3. a. A schematic of the feedback scheme with deformable mirror (left), hologram (center) and sensor array (top). **b.** A photo of the actual HALOS system with 460nm laser light.

The signals from corresponding pairs of sensor elements are combined to give a first moment error signal: $(V_a-V_b)/(V_a+V_b)$. Ideally, for a hologram with 50% efficiency in each multiplexed grating, this quantity will be zero for zero phase error. In practice the actual value will be non-zero due to imperfect matching of the gratings and beam intensities, but this is not important as we perform a one-time calibration by flattening the mirror and sending in a known plane wave. The values for the 32 error signals are recorded as the target values. Closed-loop control can now be initiated by adjusting the voltage to the mirror actuators in order to hold a particular error value.

A plot of the error function for a particular actuator (19) is shown in Fig. 4a. Note that in the correct detector channel (19) we obtain a singly-defined function as we drive an actuator from maximum pull to maximum push. Meanwhile, the recorded signal from a neighboring sensor channel (20) is virtually flat, indicating minimal cross-talk. This is significant, as there is some degree of influence function for the continuous facesheet deformable mirror, but this is not reflected in the sensed output.

a. **b.**

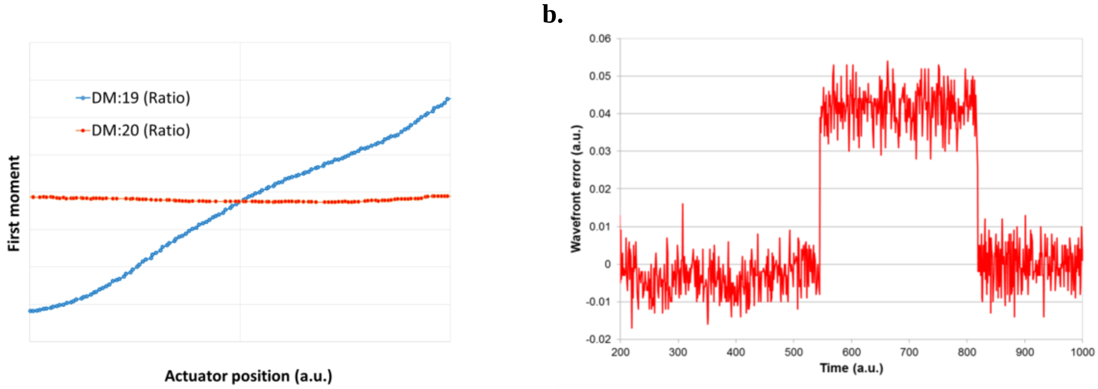


Fig. 4. a. The response function from varying a single actuator (19) as measured in sensor channels 19 (blue) & 20 (red). **b.** A plot of the wavefront error as an aberration is introduced then removed by closing the correction loop.

Once the calibration is completed, we can now activate the closed-loop correction with feedback control over the actuators. Fig. 4 b shows a plot of the wavefront error measured as an aberrator is introduced into the input wavefront and the loop is closed. We have constructed a basic circuit using an XMOS microntroller that can handle the detection, calculations, calibration and feedback control autonomously – i.e. without a computer in the loop. The system is currently running at 10kHz but could run to MHz or faster with a more advanced microcontroller. With the avalanche photodiode sensors, HALOS is extremely sensitive at low light levels, but because of the nature of the error function, the system operates equally well (and without noticeable interruption) whether the room lights are on or off.

The entire HALOS system, including optics, drivers, power supplies and control electronics is no larger than a 2'x3'breadboard and we are currently working on constructing a next-generation system that is designed to be hand-held. Because of the compact, ruggedized nature of HALOS it is ideally suited to applications such as aerial surveillance where it can be configured to fit within a UAV. Meanwhile, the high bandwidth capability makes the concept well suited for directed energy projection through extreme turbulence.

5. CONCLUSION

We are developing the HALOS technology with a view towards next-generation surveillance systems for extreme adaptive optics applications. These include imaging, lidar and free-space optical communications for unmanned aerial vehicles and SSA. The small volume is ideal for UAVs, while the high speed and high resolution will be of great benefit to the ground-based observation of space-based objects. We have demonstrated a working system with 32 actuators that operates autonomously at a 10kHz update rate.

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