MEMS and LC Adaptive Optics at the Naval Research Laboratory

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ABSTRACT

Adaptive Optics (AO) is an ensemble of techniques that aims at the remedial of the deleterious effects that the Earth's turbulent atmosphere induces on both imagery and signal gathering in real time. It has been over four decades since the first AO system was developed and tested. During this time important technological advances have changed profoundly the way that we think and develop AO systems. The use of Micro-Electro-Mechanical-Systems (MEMS) devices and Liquid Crystal Devices (LCD) has revolutionized these technologies making possible to go from very expensive, very large and power consuming systems to very compact and inexpensive systems. These changes have rendered AO systems useful and applicable in other fields ranging from medical imaging to industry. In this paper we will review the research efforts at the Naval research Laboratory (NRL) to develop AO systems based on both MEMs and LCD in order to produce more compact and light weight AO systems.

1.0 INTRODUCTION

The use of AO to improve imagery or signal gathering is now customary for large astronomical telescopes and defense systems. However, smaller telescopes and other imaging systems can benefit from the use of AO if these techniques could be brought to use at a lower cost or lower complexity or lower volumetric foot print. These were considerations that spurred various research groups in trying to use emerging technologies for Adaptive Optics purposes. Our group at NRL early on decided to investigate the use of MEMS and LC devices. The basic rationale was twofold: use of technologies that have a big market momentum behind for other applications, thus avoid costly development expenses; second technologies that are easily scalable to large number of corrective elements. Our group was the first to test both these technologies in real systems[1, 2]. In the past decade or so the advantages of using MEMS especially have become quite widely accepted and more and more programs have started with a wide variety of scopes and goals. The range of applications for these compact AO systems is wide including several fields of medical imaging, industrial applications etc. Spin offs of these technologies have also started moving in different directions. It is worth mentioning programs like the non-Mechanical Zoom at Sandia National Laboratories as an example of applications of AO techniques and hardware for a different type of application[3].

Furthermore, recent advances in manufacturing capabilities have resulted in many new electro optical devices being developed for use in Adaptive Optics (AO) systems like deformable secondary telescope mirrors[4] and emerging technologies using composite materials[5]. With so many of these systems coming available there is a significant need to be able to consistently evaluate and characterize the performance of these devices.

Traditionally the performance of an atmospheric compensation device is evaluated either as part of a full AO system using astronomical targets or in static, laboratory tests using lasers and fixed aberrations. What is desired is a system that can consistently and repeatably generate a phase screen similar to the atmosphere but under direct user control.

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It is also important that the system be able to support a wide range of atmospheric seeing conditions and be scalable to the aperture of the optical system being evaluated. Fried's parameter, also known as the coherence diameter of the atmosphere and represented by r_0, is a statistical description of the level of atmospheric turbulence at a particular site, related to wavelength. Fried's parameter ranges from under 5 cm with poor seeing conditions to more than 20 cm with excellent seeing conditions in the visible light spectrum[6-8].

2.0 THE NRL AO TEST-BED

As described in several publications, see for example[9], our test-bed is based on a flexible phase screen generator. The phase screen simulator is based on a Spatial Light Modulator (SLM) developed by the Holoeye Corporation. This device modulates light in amplitude and phase under computer control allowing the phase of the wavefront to be varied across the aperture.

This specific Liquid Crystal (LC) SLM was manufactured by Holoeye Photonics, AG. It is an 832 x 624 pixel 2π phase change device capable of operating at up to 33 Hz. It operates as a computer monitor, allowing software to be written to place an 'image' on the device. The images consist of a series of black and white bands that correspond to a phase of either 0 or 2π. This device creates a phase-only change allowing wavefront shaping. Fourier filtering is required to block the higher and lower order modes transmitted through the system. The SLM is shown below in Figure 1.

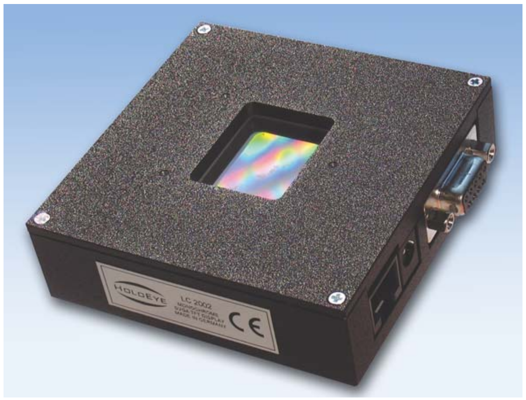

Figure 1 – Holoeye Liquid Crystal Spatial Light Modulator. The Liquid Crystal SLM used in this project is the LC2002 SLM.

The test-bed allows us to test up to two simultaneous AO systems, to verify different hardware and/or software configurations, or to test individual components.

Using the continuously varying splining technique[9], the atmospheric turbulence generator is capable of producing aberrations at a refresh rate of up to 33 Hz, which is the fastest the SLM can update. Future efforts may include using faster and more capable devices.

Sample atmospheric conditions have been calculated and put on the SLM and then measured with an imaging camera. The simulated atmospheric turbulence was calculated for a 1.0 meter telescope with seeing conditions having a

r_0 of 20.0 cm, 10.0 cm and 5.0 cm. A sample of the results is shown in Figure 2, with the ideal unaberrated point spread function (PSF) on the far left. A sample of the time sequence of PSF obtained with a $D/r_0 = 20$ is shown in Figure 6. Furthermore, we can also analyze the Modulation Transfer Function (MTF) of the system and compare the measured and calculated MTFs. In Figure 3 is shown a sample of circularly integrated MTF for the unaberrated system and for the system in the presence of single aberrations.

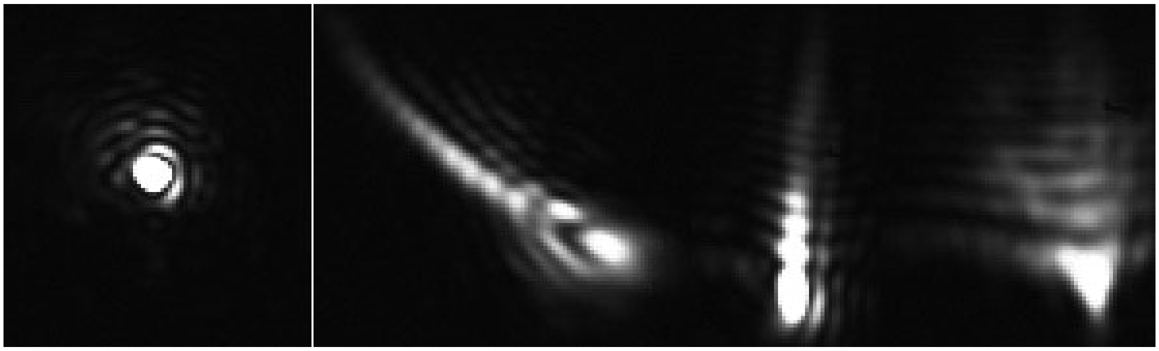

Figure 2: Sample of unaberrated PSF (left), and different time frames of PSF produced with a $D/r_0 = 20$.

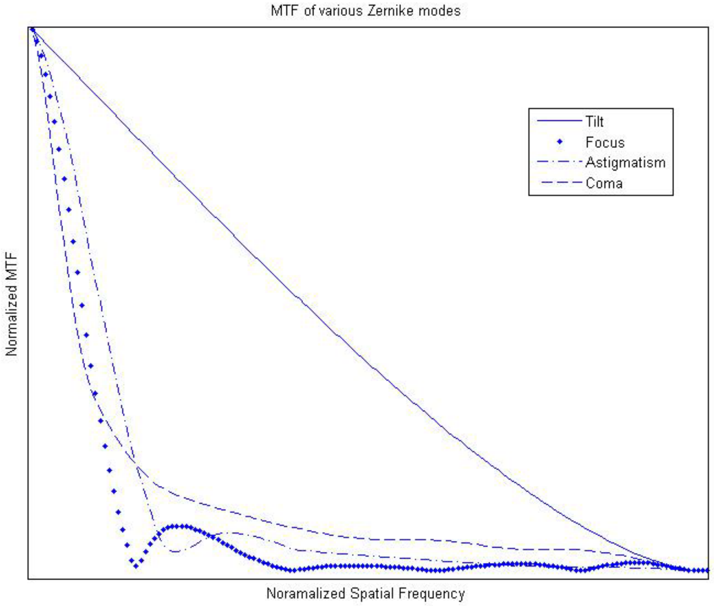

Figure 3 – Sample of circularly integrated Modulation Transfer Function of the system. Unaberrated system (solid line), only focus aberration (dotted line), only astigmatism (dashed line) and only coma (dashed and dotted line).

One of the most customary parameters used to assess the performance of an AO system is the measurement of the Strehl ratio[6-8]. In Figure 4 is shown a comparison between the measured Strehl ratio with open and closed loop.

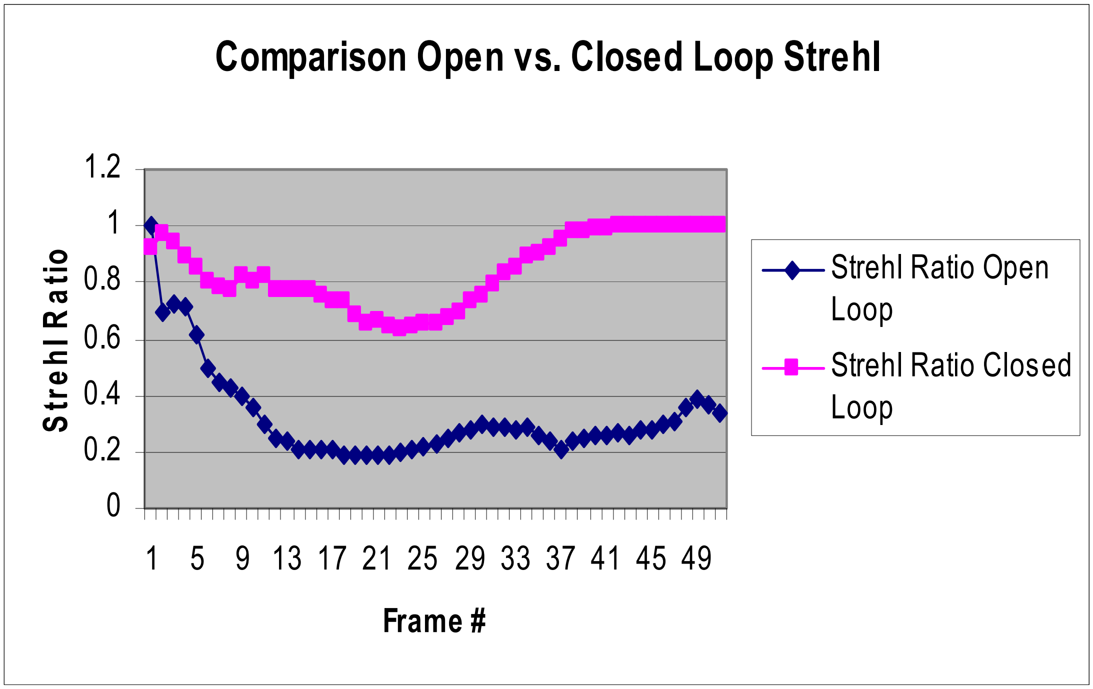

Figure 4: Comparison of Strehl Ratios with open and closed loop.

3.0 Use of MEMS and LC for Horizontal Path AO

Another advantage in using MEMS and LC for AO applications, as mentioned before, is the fact that now AO systems can be made very compact. This allows to start testing and design AO systems for horizontal propagation where even modest apertures, 10 cm for example, are affected by the atmospheric turbulence. A new program at NRL has been started with twofold goals, characterize atmospheric turbulence along a horizontal path, and then develop a compact AO system that can be used in conjunction with these smaller apertures mentioned before. The key for such a program to be successful is the ability of creating an ultra-compact AO system with very low power consumption.

The experimental set-up consists of a 5” commercial Celestron telescope mounted on a bread-board that is mounted on a tripod. The Celestron feeds a couple of high-speed DALSA CCD cameras and the corrective element is a 37 actuators OKO MEM deformable mirror. In figure 5 is shown a picture of the set-up with a close-up of the DM. The imagery collected by the telescope is shown in figure 6 where two different targets were acquired, a tag on a building roughly 200 meters away and a set of antennas on top of the Sandia Mountains, roughly 30 Km away. The image degradation, especially in the second case, is quite evident.

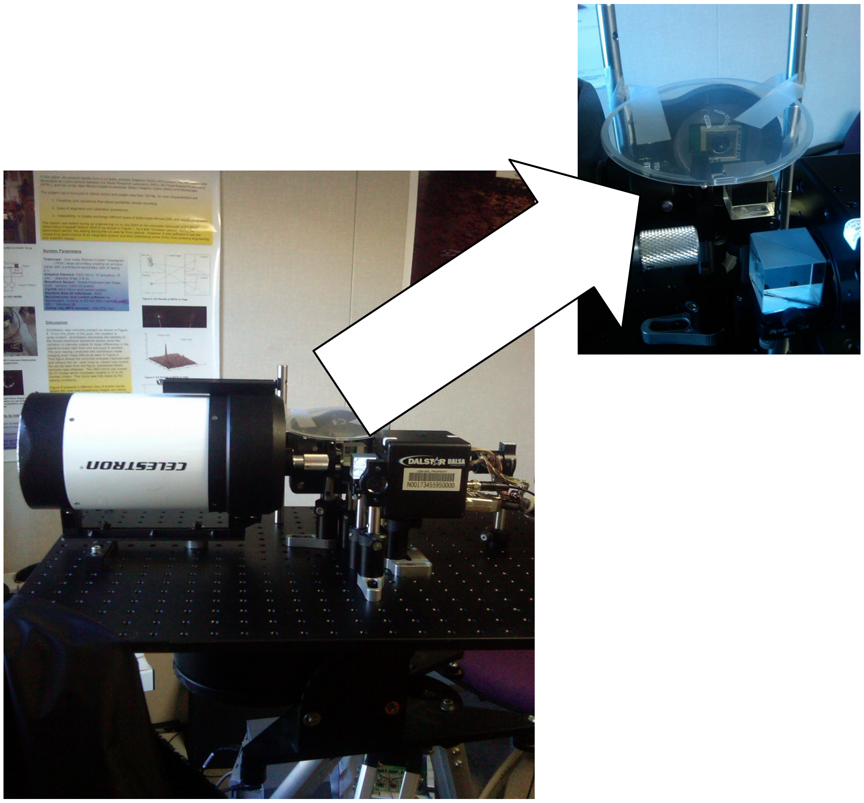

Figure 5: Experimental set up with a view of the MEMS deformable mirror in the inset.

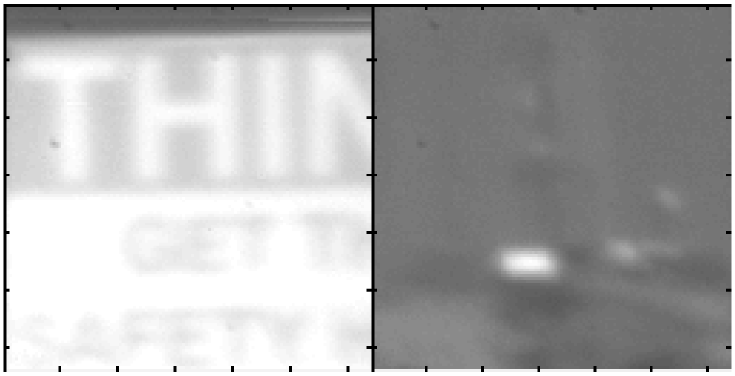

Figure 6: Example of images collected with the small telescope. On the left a small tag that is on a building 200 meters away and on the right a series of antennas and a small building at 30 Km of distance.

The current set up is aimed at implementing tip/tilt stabilization only. We use the DM to perform the tip/tilt correction instead than having a separate Fast Steering Mirror (FSM). The full AO system will be implemented as the results of the test-bed, for both the wavefront sensor and the control algorithm, become well established. In Figure 7 and 8 are shown a plot of the tilt, in one axis, with and without tilt correction for the target at 200 m and 30 Km. respectively.

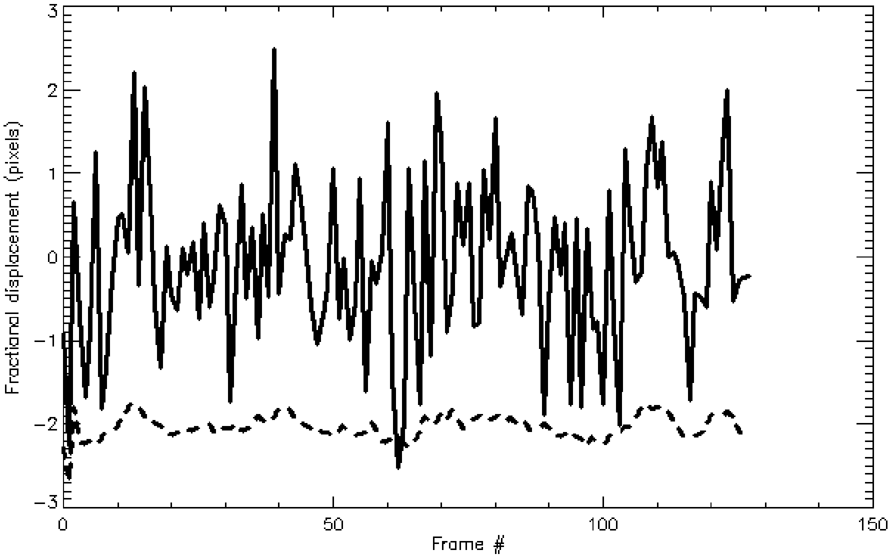

Figure 7: Plot of the measure tilt in one axis (solid line) and the residual after correction (dashed line). The data is for the target at 200 yards of distance. Note that the dashed line has been displaced from the 0 mean position for sake of better displaying the plot.

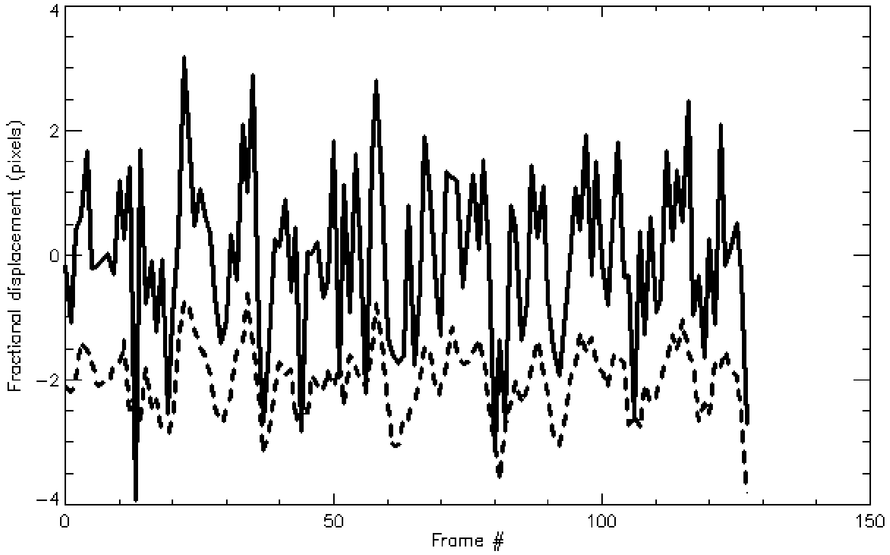

Figure 8: Plot of the measure tilt in one axis (solid line) and the residual after correction (dashed line). The data is for the target at 30 Km of distance. Note that the dashed line has been displaced from the 0 mean position for sake of better displaying the plot.

The first thing to notice is that the tilt correction of the distant target is not as effective as the close target. This is, obviously, an expected result and it is mostly related to the signal level from the distant target and the presence of high order aberrations.

Remembering that the overall residual tilt error is the sum of several terms, the most important of which are the residual errors due to the sensor SNR, the tilt anisoplanatism and the finite bandwidth of the closed loop system (we are ignoring the effect of higher order aberrations). Estimations of each term have been made based on measured performances or theoretical considerations for both cases. The measured residual tilt error for both cases is of ~ 1μrad and ~10 μrad respectively. The calculated residual error due to the Signal-to-Noise is of 0.8 μrad and 9.8 μrad respectively. This once again shows that the bulk of the residual errors are due to the SNR and this becomes totally dominant in the far case. This also demonstrates that the use of the DM for tilt correction is not a dominant issue with respect to the sensing part of the problem.

5.0 CONCLUSIONS

In the past several years NRL has been at the forefront of demonstrating the use of MEMS and LC devices for AO applications. Our laboratory test-bed and experimental results are now ranging from the use of AO for vertical and horizontal propagation problems. The use of a well calibrated test-bed allows us to measure and determine performance parameters of individual components and/or entire systems. In this paper we have reported some of the results attained in our almost decade long effort to bring these technologies to the forefront of Adaptive Optics applications.

6. REFERENCES

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