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Adaptive Imaging for ISR Applications

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Abstract: Imaging intelligence gathering is hindered by the diametrically opposed needs of high resolution and wide area surveillance. Multi-Gigapixel focal plane arrays are one solution, but we have successfully demonstrated adaptive optical systems as an alternative.
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1. Introduction

Persistent surveillance has become the hot area for current research efforts in military imaging. Imagery intelligence gathering has historically been hindered by the diametrically opposed needs of high resolution (for identification) and simultaneous wide area surveillance. Larger focal plane arrays continue to increase resolution over a wide field, but more and more pixels have created an unmanageable amount of data. The largest systems include DARPA's Autonomous Real-time Ground Ubiquitous Surveillance - Imaging System (ARGUS-IS), which use a 1.8 Gigapixel video sensor that is housed with an on-board processing unit in a 500 pound pod.

Conventional ball gimbals, such as the WESCAM MX-20, incorporate multiple sensors in a rotating housing to provide both wide field situational awareness and high resolution tracking. These systems are heavy (up to 200+ pounds) and require significant power (100s of Watts) to steer the instantaneous field-of-view (FOV). As platforms move to higher altitudes or require longer operational dwell times, such as the proposed 21-day on-station availability of the LEMV (Long Endurance Multi-Intelligence Vehicle), the size, weight, and power requirements (SWaP) of the sensor becomes even more important.

Sandia National Laboratories has led the development of active optical systems that use reconfigurable optical elements to improve the capability of an imaging system while reducing size, weight, and power. Active elements, such as phase-only spatial light modulators or variable focal length lenses or mirrors, are used to vary the optical properties (e.g. FOV, resolution, or spectral properties) of an imaging system in real-time. Foveated imaging, adaptive optical zoom and enhanced multispectral imaging are examples of reconfigurable imaging systems with reduced SWaP compared to comparable conventional systems.

2. Adaptive Optics

Adaptive optical (AO) systems have existed throughout history. The focus response of the eye when imaging objects at different distances is a biological example of active compensation based on real-time feedback from eye-brain imaging system. Although instances of manmade AO systems were documented as early as 215 B.C., when Archimedes supposedly used focused sunlight to ignite a Roman ship [1], the revolution in adaptive optics really started in the last half of the 20^{th} century when researchers looked at methods to correct atmospheric turbulence for ground-based telescopes [2].

Robert Tyson's book *Principals of Adaptive Optics*, and the references contained therein, provide an excellent history of AO [3]. In it, he defines AO as "a scientific and engineering discipline whereby the performance of an optical signal is improved by using information about the environment in which it passes." Usually, the environmental information is provided by a sensor that detects a specific aspect of the surrounding environment, such as a wavefront sensor. Data is collected and processed in real-time (phase reconstruction) in order to derive a correction. That correction is applied to an active element, such as a deformable mirror, spatial light modulator, or variable focal-length element, which must be updated at a rate faster than the changing environment. In the case of an astronomical telescope, this closed-loop architecture drives a deformable mirror at a kHz or more to remove the affects of turbulence in the atmosphere.

In addition to correcting the affects of turbulence or other dynamic aberrations (e.g. thermal distortions in high power lasers), adaptive elements have also been used or proposed to vary the focal position within an imaging system. Autofocus in cell phone cameras [4] and variable focus in confocal microscopy [5] have been achieved using active electrowetting lenses.

3. Adaptive Imaging for ISR

As adaptive optical devices continue to improve in size, wavefront quality, and dynamic range, the number of new applications that use or propose AO has significantly increased. Adaptive imaging does not use a wavefront sensor for real-time correction as is done in AO. Instead, the optical properties of the various configurations of the system are known a priori, and reconfiguration is done via a look-up table. By integrating electronically-controllable elements into conventional lenses or telescopes, researchers at Sandia and elsewhere have successfully increased performance and added flexibility to the imaging system while reducing size, weight, and power requirements. Specifically, they have demonstrated variable resolution [6-8], magnification [9-10], and spectral bandwidth [11]. In the case of adaptive optical zoom [10], variable focal length devices allow a user to increase the resolution over an area-of-interest in near real-time without the longitudinal motion associated with conventional zoom. By adding tilt to the active device, the system can "steer" the system anywhere within the wider field of view without slewing the entire optical system [11]. This may eventually reduce the need for gimbaled or multiple camera systems commonly used for acquisition and tracking.

This recent breakthrough in adaptive optical technology, done under funding from the Office of Naval Research (ONR) is shown in Figure 1, where an 8X change in magnification is achieved without using longitudinal mechanical motion, as is done in conventional zoom lenses. Instead of moving lenses along the optical axis, this adaptive optical zoom system used two variable focal length lenses from Holochip [12] to change the effective focal length and magnification of the system. Thus, optical zoom can be achieved very quickly with very little mechanical motion. The concept has also been demonstrated with adaptive mirrors from OKO Technologies [13] in reflective telescopes [14] and with pixilated spatial light modulators from Boulder Nonlinear Systems [11], where optical tilt and higher order correction were used to zoom off-axis without slewing the system.

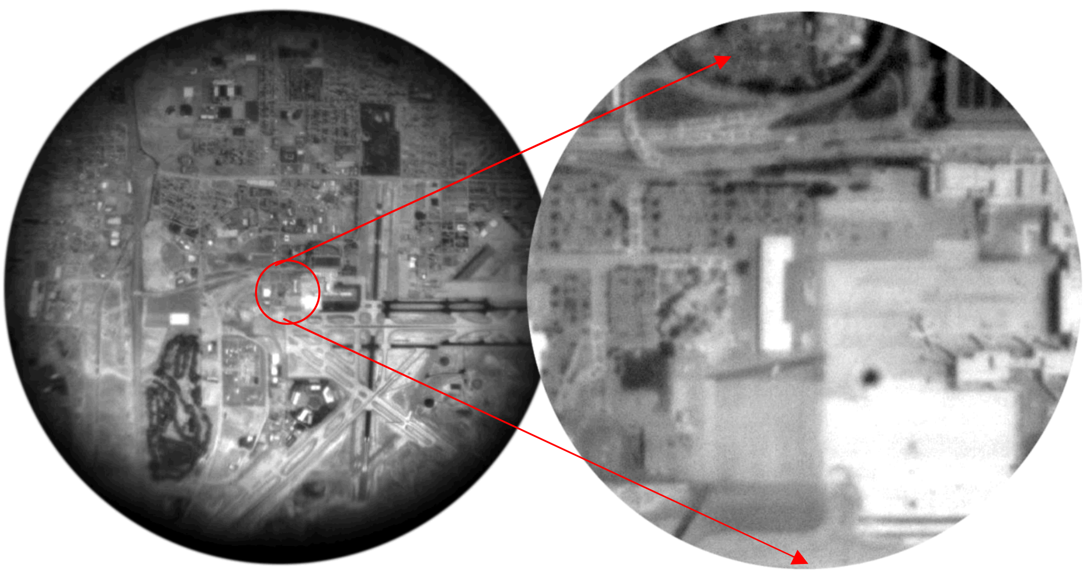

Figure 1: 8X zoom system using adaptive focal length lenses. There is no longitudinal motion or additional optics flipped into the optical train, as is currently done in conventional zoom systems.

Foveated imaging uses active elements to replace bulky fisheye lenses with compact, lightweight, wide field-of-view optical systems. These systems have been developed for small unmanned aerial systems (UASs), where the size and weight of conventional "fish-eye" lenses are too great. Sandia National Labs, working under the DARPA Bio-Optic Synthetic Systems (BOSS) program, developed a foveated imaging system that significantly reduces the size of the imaging system. By placing a pixilated spatial light modulator in a pupil plane, off-axis aberrations, which would normally be corrected by adding additional lenses, can be dynamically corrected for any given area of interest. This foveal, high-resolution area can be moved within the full field of view in 1-50 milliseconds, depending on the correction element. The DARPA BOSS foveated imaging system developed by Sandia with partners Boulder Nonlinear Systems, the Naval Research Laboratory, and the University of Central Florida, is shown in Figure 2.

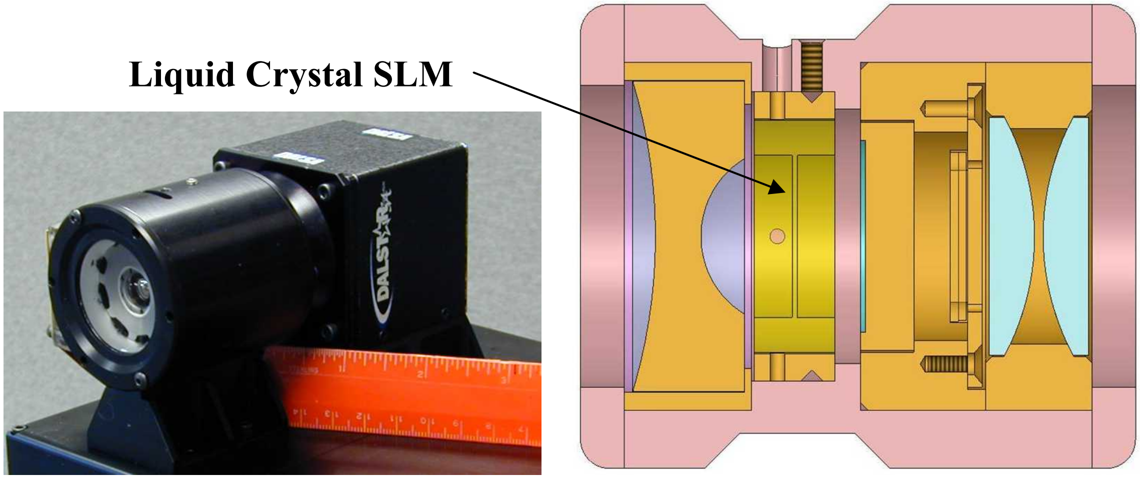

Figure 2: Foveated imaging lens developed under the DARPA BOSS program. The foveated lens is 40% the length of a comparable conventional wide angle lens. The lens houses a custom liquid crystal spatial light modulator, developed by Boulder Nonlinear Systems, Inc. and the University of Central Florida, to dynamically correct aberrations at any field point.

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