Adaptive optical zoom for space-based imaging

Mirror Technology Days
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David Wick, Ty Martinez, Brett Bagwell, Gary Peterson, Bill Cowan, Bill Sweatt, Olga Spahn, Sergio Restaino, Don Payne, Jonathan Andrews, Christopher Wilcox, Robert Romeo, and Robert Martin
ZEMAX Layout
Conventional 2.5X Zoom

Wide field-of-view

Narrow field-of-view – ON AXIS
Optical Zoom vs. Electronic (Digital) Zoom

Electronic (Digital) Zoom

4X Optical Zoom
Adaptive Optical Zoom vs Conventional Zoom

Small changes in the individual focal lengths of individual elements (lenses or mirrors) yield much larger changes in effective focal length and magnification of the system.

• Power consumption can be greatly reduced …deflection of a membrane vs. moving glass.
Why Adaptive Optical Zoom?
NONMECHANICAL

• **Optical magnification**
  - Switch between wide area surveillance mode and high-resolution identification/tracking mode in milliseconds
  - Higher resolution over **ANY** area-of-interest within wide field of view – Do **NOT** have to be pointed at area (i.e. on-axis) as in conventional zoom system

• **Gimballess tracking and rapid retargeting**
  - Track targets without mechanical gimbals or steering mirrors
  - Zoom-in on **multiple** targets without steering optics in milliseconds
  - Optimize centroid tracking for improved tracking/laser comm performance

• **NO macroscopic moving parts – Very Fast (20 Hz – 1 kHz)**
  - No moving lens elements, gears or cams for optical zoom
  - No gimbals or steering mirrors for redirecting ‘gaze’
  - Low power consumption (mW)
  - No inertia, doesn’t require momentum compensation on platform

U.S. Patent #6,977,777
Current experimental results for 3.3X zoom
Uses two liquid crystal SLMs as active lenses

Note: Magnification is NOT on axis.
Adaptive Optical Zoom vs Digital (Electronic) Zoom

Digital Zoom is simply larger: no increase in resolution.

Active Optical Zoom accomplished by changing the voltages that were applied to the two SLMs. NO MOVING PARTS
4.5X Adaptive Optical Zoom System
4.5X Adaptive Optical Zoom System
Adaptive Optical Zoom

Increase in resolution by almost 2X from 17.95 lp/mm to 32 lp/mm

Adaptive Optical Unzoomed

Adaptive Optical Zoomed

Sponsored by NRO/DII program and Sandia LDRD NP&A SMU
Large Aperture Composite Mirror Development

Prototype 16” CRFP telescope. This prototype is being developed for testing and capability demonstrations.

1.4 m design. This telescope is being developed for the upgrade of the Naval Prototype Optical Interferometer (NPOI) in Flagstaff, AZ.
Carbon Fiber Reinforced Polymer Mirrors

We are developing a variety of active and adaptive optics control systems for ground- and space-based applications.

- Using a 1-arm actuator warping harness to eliminate astigmatism
- Using the 8-arm moment actuator system to correct an optic from 1.24 rms to 0.18 rms (@632.8nm)

1.5 kg/m²

8-Arm Moment Actuator System

Sparse Array of Force Actuators

Square Grid Force Actuator Array
Why do we need large stroke?

Mirror deformations from unzoomed to zoomed are related by

\[ \Delta s_2 = \frac{H(r - 1)}{2r} + \frac{(4\Delta s_1)^2 + H^2(r - 1)^2}{16\Delta s_1 r} \]

Mirror #1 is closest to detector, and is the aperture stop
Mirror #2 is closest to the object.
\( \Delta s_2 \) is measured in the zoomed configuration.

\( r = \) zoom ratio
\( H = \) Lagrange invariant = \( \frac{1}{2}D \sin \theta = \frac{w}{4f} \)
\( D = \) Entrance pupil diameter
\( \theta = \) half field of view
\( w = \) image height (full)
\( f\# = f\text{-number} = \text{focal ratio} \)

Note: this relationship is independent of design details, and cannot be altered by using intermediate (fixed) lenses and mirrors.
Required mirror deformation

Primary mirror deformation as a function of secondary mirror deformation for a zoomed entrance pupil diameter of 1 m, a zoom ratio of 3X, and a FFOV of 1 degree.
Sandia (Bill Cowan and Olga Spahn) currently has only MEMS development with piston-tip-tilt analog control and 26.7 μm stroke.
Large throw MEMS

Veeco
Mag: 5.2 X
Mode: PSI

Surface Data

Surface Statistics:
Ra: 23.79 nm
Rq: 29.73 nm
Rz: 211.83 nm
Rt: 226.07 nm

Set-up Parameters:
Size: 736 X 480
Sampling: 1.62 um

Processed Options:
Terms Removed: Tilt
Filtering: None

Title: H850_L1 ctr Al
Note: id6436 std P4
3D images of AO Zernikes on Current 61 Element Mirror

All images are on the same scale

Note: Mirrors are uncallibrated: all actuators controlled using a single voltage to deflection curve
Potential Applications: Space-based SSA

- Surveillance/
  - Situational Awareness
- Identification
Potential Applications: Airship or Satellite Surveillance

Single, wide field-of-view or multiple receivers may be used to cover wide areas. Nonmechanical zoom allows receiver(s) to adjust magnification in real-time as necessary for target identification/tracking.

4X optical Zoom
↓
4X increase in resolution.
A typical tracking system has a fixed field-of-view and system magnification. We believe that tracking could be enhanced if the magnification could be adjusted in real time to optimize signal-to-noise on the detector. Also, reacquisition could be more easily accomplished (say after loss of tracking due to “jerk” motion) without having to switch back to acquisition mode. Simply increase the field-of-view iteratively until reacquisition is possible.
Adaptive Optical Zoom for laser comm
variable FOV to optimize Signal/Noise

Conventional
Fixed field-of-view system

Transmitter

Receiver

Variable field-of-view
With nonmechanical Zoom can improve the S/N ratio

2X miles – S/N reduced by 4X

X miles

2X miles
Harbor Surveillance and ship-to-ship secure communication

The Nonmechanical Zoom concept would use active optics to quickly zoom in on areas of interest with high spatial resolution interlaced with low spatial resolution wide field of view from the SAME sensor.

The technology proposed could scan between the four (and more) image contexts presented at speeds of at least video frame rates (30 Hz).
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Back Up Slide
Demonstration Design

Three spherical mirrors, $f = 1.0, 0.2, 1.0$ m
$F/# = 40-80$
$FOV = 0.12^\circ$
Experimental Layout

CCD

OKO

Deformable Mirrors

Object – AF
Bar Chart

Static Mirrors
Correcting 37 Channel to $f = 2.5m$

No Voltage  Bias Voltage  Corrected

\[
\text{Sag} \approx \frac{y^2}{2R} \\
R = 5m \approx \frac{(7.5\text{mm})^2}{2} (10*0.532\text{\mu m})
\]
Same system with Diffraction-Limited Static Mirrors
Unzoomed comparison

Diffraction Limited MTF < 10% at Group 4/ Element 3 (20.16 lp/mm) in Unzoomed

Adaptive Optical Unzoomed

Static Optical Unzoomed
Zoomed Comparison

Diffraction Limited MTF < 10% at Group 5/ Element 2 (36 lp/mm) in Zoomed

Adaptive Optical Zoomed

Static Optical Zoomed
Conclusions – Preliminary Study of Adaptive Optical Zoom Design Tradespace

- To preserve system numerical aperture (f-number) the entrance pupil must be stopped down by the ratio of the zoom in the unzoomed case.

- The second active mirror must be at an image of the aperture stop.

- For 1m class telescope with 1° FOV, > 1 mm of throw is necessary on primary to maintain high image quality for both zoomed and unzoomed states IF we maintain the numerical aperture.

- For only 2 active mirrors, changing the numerical aperture between states sacrifices both illumination and image quality in the zoomed configuration and does not simply reduce the irradiance and image quality FOR THE UNZOOMED CASE ONLY as was hoped. Adding more active elements needs to be investigated.

- Auxiliary optics can reduce the overall length of the system, but cannot reduce the magnitude of the mirror deformations.

- Possible to use a fixed primary and place smaller active mirrors within a reimager to zoom the system – needs to be investigated.