Long-Range Adaptive Passive Imaging Through Turbulence

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Overview of Talk

• Outline Problem
  ➢ Comparison to Standard Methods
  ➢ Turbulence Image Effects
  ➢ Annular Aperture Short-Exposure Modulation Transfer Function
  ➢ Variable Aperture Responses to Turbulence

• Generalized Proposed Solution
  ➢ Zernike Expansion and Hufnagel Theory
  ➢ Solution Components

• Solution Phase Control
  ➢ Adaptive Aperture, Modes, Deformable Mirror Control
  ➢ Decorrelation Issues, System Speed, Camera

• Conclusions
Most Adaptive Optics Systems are Active

- Receiver w/ Feedback & Wavefront Sensor
- Specialized Target Scene Required
- Guide Star Active Beacon

Examples:
- LASER COMS ASTRONOMY
- Active SWIR HEL Beam Control

- Laser Illuminator
- Non-Stealthy
- Reflective “Glint” Target

Examples:
- Active SWIR HEL Beam Control

Or use only Post-Processing

- Passive Imager
- No Optical Correction (No Feedback)
- Natural Target

Examples:
- Lucky Patch De-Warping Segmentation

We Propose Combining a Passive Imager with Adaptive Elements = Passive Adaptive

- Adaptive Imager
- Optical Correction to Remove Blur Prior to Imaging
• Distortion effects divide into long-exposure (>100 s) and short-exposure (~1ms) cases based on pixel integration times. Short-exposure blur effects are caused by smaller scale turbulence distortions.

• Larger scale turbulent distortions cause the short-exposure image of a point source to wander as a function of time within the overall long-exposure blur envelope.

• The short-exposure blur patch size is wavelength, path length, and turbulence strength dependent.
Initially, turbulent distortions dominate. As turbulence strength increases, blur effects dominate. Short-exposure blur is weighted most strongly at receiver.
Annular Aperture MTFs

\[ M_S(\omega) = M_0(\omega, C) M_{SA}(\omega, S, Q, C) \]

\[ \omega = \Omega / \Omega_0, \quad \Omega_0 = D / \lambda \]

\[ C = D_1 / D_2 \]

\[ S = D_2 / \rho_o \]

\[ Q = D_2 / (\lambda L) \]

\[ \rho_o = 1.437 (k^2 L C_n^2)^{-3/5}, \quad k = 2\pi / \lambda \]
\[ M_S(\omega) = M_0(\omega, C) \cdot M_{SA}(\omega, S, Q, C) \]

- Net atmosphere plus system MTF is monotonically decreasing.
- Short-exposure influences produce a plateau region at mid-band spatial frequencies.

\[ M_{SA}(\omega, S, Q, C) = \exp \left\{ -S^{5/3} \left[ \omega^{5/3} - V(\omega, S, Q, C) \right] \right\} \]

Function \( V(w, S, Q, C) \) reflects removal of phase tilt, dominated by a tilt-phase correlation term.
Consider turbulence effects as a function of aperture size (1/2” to 5”) measured using Fried’s Resolution function, the volume under MTF:

\[ R = \int \pi \omega M_S(\omega) \, d\omega \]

- Smaller apertures outperform larger by factors up to 3 under increasing turbulence strength.
- Suggests aperture control key to improved image quality.
Aperture reduction can reduce the number of active modes, but what about additional mode corrections?
Figure from Hufnagel [1989]

\[ D = \text{Aperture Diameter} \]

\[ r_o = \text{Coherence Diameter} \]

**Basic “Lucky Patch”**

Blur DOFs Removed

Improved Range Capability:

- Tip/Tilt: 2X
- Sph/Astig: 3X
- Coma/Clover: 4X

Increasing Turbulence

- \[ \frac{D}{r_o} \]

Lucky Image Probability

0.1
0.2
0.5
1.0
Aperture Control both simplifies the problem (fewer modes) and provides a means of sub-sampling the aperture. Camera sub-aperture images analyzed to determine phase correction to apply.
Prototype System

System Camera

Adaptive Aperture

System Light Path

Spatial Light Modulator

Main Mirror
Phase Decomposition

First, model inner and outer radius height functions:

\[ \Phi_{\text{inner}} = A_0 + A_1 \cos(1\theta) + A_2 \cos(2\theta) + B_1 \sin(1\theta) + B_2 \sin(2\theta) \]
\[ \Phi_{\text{outer}} = C_0 + C_1 \cos(1\theta) + C_2 \cos(2\theta) + D_1 \sin(1\theta) + D_2 \sin(2\theta) \]

AzCurl is unrealizable, reflecting the inaccuracy of the current size of the outer and inner diameters of the system vs. turbulent state.

The resulting model can be expressed using eight “modes”. Of these, two are the tip and tilt linear terms that do not affect image quality. The remaining terms are shown at left.
In the current prototype version, four subaperture images are collected using a flywheel apparatus.

The four sample images are collected, then a full aperture image is collected.

Image shifts are calculated via a cross-correlation procedure to determine the relative tilt of the incoming light in each portion of the aperture.
Use cross correlation techniques to determine angle-of-arrival shifts:

- For computational speed:
  - Sum both in Vertical and Horizontal Dimensions
  - Correlate to determine pixel shift

Based on observed shift sequences, derive decorrelation information… 90+% @ <20ms
• Layout of underlying threading design
  • GUI
  • Thread Controller
    • Sync all threads and GUI
    • Control flow of incoming images
    • Control SLM and Motor Controllers

• Correlation Thread
  • Handles reduction and correlation to output pixel shifts

• Mirror Modes Thread
  • Models mirror shape according to 4 image shifts
  • Generates shape array to be applied to SLM
Conclusions

- System testing awaiting completion of software checkout.
- Preliminary results indicate near linearity of phase across annular rings.
- Timing of the system dependent on maintaining adequate cross-correlation between full frames & image exposure.

Aperture size dictated by photon availability.

- Turbulence strength also controlled by relative light level.
- Improved performance through additional innovations needed.