Designing Adaptive Optics Systems

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Designing Adaptive Optics Systems

Outline

• The design process
• AO systems taxonomy
  – Commonalities and differences among systems
• Single-conjugate adaptive optics for astronomy
• Vision systems
• Communications systems
• Multi-conjugate adaptive optics
• Specific design examples
  – Lick laser guidestar
  – Keck laser guidestar
  – CELT MCAO
• Summary
The Design Process

• **Science Requirements and Conceptual Design**
  – Response to a need
  – Preliminary Proposal

• **Conceptual Design Review (CoDR)**
  – Establishes basic system architecture and scope of costs
  – Request funding for a detailed design phase

• **Preliminary Design Review (PDR)**
  – More details of design
  – Solved issues
  – Risk reduction plan
  – Project plan through CDR, scope overall project plan

• **Critical Design Review (CDR)**
  – Components & vendors identified
  – Completed design drawings
  – Build commences

• **Pre-ship Review**

• **Commissioning**
What do AO systems do?

- Correct aberrated wavefronts for sharper images
- **Astronomy**: compensate for the atmospheric distortions
- **Vision**: compensate for the aberrations in the lens, cornea, and vitreous volume
  - Image the retina at high resolution
  - Improve vision beyond 20/20
- **Communication**: keep the beam on the receiver’s detector, lower the bit error rate
- **Lasers**: confine the beam’s power onto a target
Specifying the Science Requirements

- Resolution $\lambda/D$ (imaging) $\Delta\lambda/\lambda$ (spectroscopy)
  - Strehl, bit error rate, power-in-the-bucket, ...
- Wavelength of correction $\lambda$
- Speed of operation $f_c, f_s$
- Field of view $\Theta$
- Throughput, Emissivity
- Sky coverage (astronomy)
AO Systems: common components

- Turbulent Volume
- Pupil
- Guide Star Source
- Reimaging Optics
- Wavefront Corrector
- Wavefront Controller
- Wavefront sensor
- Science detector or laser comm source
- User interface / system controller
- Operator
Differences among systems

- **Astronomy and imaging** may use the object itself as the reference source (“Natural” guide star, “scene-based” wavefront sensing)
- **IR-optimized** systems will avoid using reimaging optics
- **Vision systems** (and some LGS astronomy systems) project the reference beacon light through the receiving pupil
- **Communication systems** have several geometry variants:
  - Compensated receiver / conjugated link
  - T-R pair: it’s really 2 AO systems, one for each direction
Vision system geometry

- Pupil
- Guide Star Source
- Reimaging Optics
- Wavefront Corrector
- Wavefront Controller
- Eye chart or Retina imaging camera
- Wavefront sensor
- User interface / system controller
- Operator
Communication system geometry

Source

Wavefront Corrector

Wavefront Controller

Wavefront sensor

Transmitter Pupil

Turbulent Volume

Receiver Pupil

Guide Star Source

fiber

detector
Single-conjugate AO for astronomy

- Deformable mirror
  - Number of actuators \( \sim (D/r_0)^2 \)
  - \( r_0 \) is the Fried parameter: the transverse coherence length of turbulence
  - For Kolmogorov turbulence, the Mean Square Fitting Error is
    \[
    \sigma_{DM}^2 = \mu \left( \frac{d}{r_0} \right)^{5/3}
    \]
    - \( \sigma \) is in radians of wavefront
    - \( \mu \) depends on the particular DM (\( \approx 0.3-1.0 \))
    - \( d \) is the interactuator spacing

- Hartmann sensor
  - Usually 1:1 subaperture per DM actuator
  - Size of subaperture sets the limiting magnitude for a given wavefront sensing accuracy
    \[
    \sigma_{SNR}^2 = \left( \frac{2\pi d}{\lambda} \sigma_{spot} \frac{\eta}{\text{SNR}} \right)^2
    \]
    \[
    \text{SNR} = \left( \frac{\phi d^2 / f_s}{\sqrt{\phi d^2 / f_s + n_r^2}} \right)
    \]
    - \( \phi \) = guide star flux
    - \( f_s \) = sample rate
    - \( n_r \) = read noise
Single Conjugate AO for Astronomy (p.2)

- **Controller**
  - Frame-rate + compute delays determine the closed loop bandwidth
  - $\tau_0$ is the coherence time of turbulence; $\tau_0 \approx r_0/v$ in the frozen-flow model
  - The bandwidth error is
    \[ \sigma_{BW}^2 = \kappa/(\tau_0 f_c)^{5/3} \]
  - $\kappa$ depends on the control algorithm
  - $f_c$ is the closed-loop controller bandwidth, $\sim f_s/10$

- **Optimization**
  - Minimize $\sigma^2 = \sigma_{DM}^2(d) + \sigma_{SNR}^2(d, f_c, \phi) + \sigma_{BW}^2(f_c)$
  - Optimum bandwidth and subaperture size can be found for a given flux and Hartmann spot size
  - In practice, bandwidth can be optimized on-line for a sub-optimal solution
Choice of deformable mirror

- **Physical actuator spacing**
  - Sets the beam size and path lengths in the AO relay optics
  - Lagrange invariant: \((\text{field angle}) \times (\text{aperture diameter}) = \text{constant}\!\)
- **Actuator stroke**
  - \(>1/2\) the peak to valley of the piston-removed phase aberration
    - atmosphere + all common-path optics
- **Actuator response time**
  - \(~10\times\) faster than the maximum AO closed-loop bandwidth
- **Surface roughness**
  - At spatial frequencies \(>1/d\) this is additional wavefront error
- **Cost**
  - PZT/PMN devices: \(~$1000/actuator including drive electronics\)
  - MEMS: presently \(~$100/actuator and dropping\)
Deformable mirror options

- Zonal mirrors, discrete PZT / PMN actuators
  - Continuous face sheet
  - Segmented
- Bimorph mirrors
- Micro electromechanical (MEM) devices
- Liquid crystal spatial light modulator (LQ-SLM)
Wavefront sensor options

- **Curvature sensors**  \[ c = \nabla^2 \varphi \]

- **Slope sensors**  \[ s = \nabla \varphi \]
  - Hartmann
  - Shearing
  - Pyramid

- **Direct phase sensors**  \[ \varphi \]
  - Mach-Zender (point-diffraction)
  - Holographic
Wavefront sensor camera

- Format (number of pixels across) X (number of pixels down)
  - Enough to measure phase at desired spatial resolution
- Sensor type
  - CCD
  - IR detector
  - APD and other amplified light approaches
- Sensitivity performance parameters
  - Quantum efficiency
  - Read noise
  - Dark current

\[ SNR = \frac{q_e \phi t_{\text{exp}}}{\sqrt{q_e \phi t_{\text{exp}} + n_{\text{pix}} n_r^2 + i_{\text{dark}} t_{\text{exp}}}} \]

- Pixel blur
Wavefront reconstructors / control computers

- Processing pipeline
  - Reasonable approximation of FLOPS:
    - \( O(\text{number of pixels}) \) to parse raw image
    - \( O(m) \) to centroid
    - \( O(m \times n) \) to calculate phase given slopes (matrix-multiply)
    - \( O(n) \) to calculate control compensation and update state vector
    - Do all this \( fc \) times/second, leaving a margin of cpu cycles for diagnostics streams, processing UI commands, etc.

- Possible architectures:
  - Parallel processor
  - DSP

- Real-time operating system (RTOS)
Wavefront reconstructors / control computers (p.2)

- **Diagnostics and Telemetry**
  - Bursts of data at full frame-rate for later diagnostic analysis
    - WFS pixels
    - Centroids, intensities
    - Actuator commands
  - Periodic status update for the user interface
    - Centroid & intensity display

- **User Interface / System Controller (UISC)**
  - Graphical user interface (GUI) controls
    - Open/close AO loops
    - Field-steering
    - Other optics bench support: ND filters, fiber calibration sources, etc.

- **Analysis support**
  - $r_0$ and wind speed calculator
  - Closed-loop point spread function (PSF) estimation
Vision adaptive optics systems

- Is there an $r_0$ for the eye?
- Beacon (guide star)
  - Coherence. Broad bandwidth superluminescent diode reduces speckle in the Hartmann subapertures
  - Corneal reflection (ghost)
  - Collimation/focus
  - Light budget
    - Maximum eye exposure
    - Wavelength
    - Choice of beam splitters
- Eye motion / Pupil tracking
- Deformable mirrors
  - Conventional
  - MEMS
  - LQ-SLM
Population statistics of eye aberrations
Communications systems

• Characteristics
  – Objective is to minimize bit error rate (BER) in free-space point-to-point communications
    • Equivalent to maximizing power in the bucket
    • Minimum BER allows higher communications bandwidth
  – Turbulence is spread out along path
  – Narrow field of view

• Design (DARPA/CCIT)
  – Pre-compensation at transmitter end
  – Holographic wavefront sensor
    • Direct phase measuring
  – Piston-only segmented DM
  – Massively parallel control algorithm

• Design (AOptix)
  – Curvature sensing
  – Curvature MEMS
Multiconjugate Adaptive Optics

- **Science need**
  - Wide field imaging - beyond the isoplanatic patch
  - Uniform PSF, high Strehl over the field

- **Problem**
  - Turbulence is distributed in altitude
  - Cone beam from single laser guidestar fails to probe the entire volume.

- **Approach**
  - Multiple laser beacons for tomographic measurement of all the atmosphere above the telescope plus field angle
  - Multiple deformable mirrors at conjugate heights corresponding to atmospheric layers
Multi-conjugate adaptive optics

Turb. Layers

#2

#1

Telescope

DM1

DM2

WFS

Atmosphere

UP
MCAO Performance Summary
Early NGS results, MK Profile

No AO  |  Classical AO  |  MCAO
1 DM / 1 NGS  |  2 DMs / 5 NGS

320 stars / K band / 0.7” seeing

Stars magnified for clarity

March 31, 2000
SPIE CONFERENCE 4007, MUNICH
Cone effect and resolution with multiple guide stars
The cone effect is more severe the larger the telescope.
MCAO design parameter space

- Number and placement of laser guide stars
- Number of DMs, and their conjugate locations
- Number of actuators per DM
- Brightness of guide stars
- Controller bandwidth
Tomographic reconstruction error

Tokovinin & Viard, JOSA-A, 18, 4, 2001

\[
\sigma^2 \approx \left( \frac{\Theta \delta}{r_0} \right)^{5/3} e(\theta)
\]

- \(\Theta\) = constellation radius
- \(r_0\) = transverse coherence distance (Fried’s parameter)
- \(\delta\) = effective layer thickness
- \(e\) = field-dependent factor (\(\leq 1\) inside constellation)

150 nm rms: entire CELT AO error budget

8/13/03  CfAO Summer School August 2003
Fourier interpretation of tomographic wavefront reconstruction

- Each wavefront sensor measures the integral of index variation along the ray lines.
- The line integral along z determines the $k_z=0$ Fourier spatial frequency component.
- Projections at several angles sample the $k_x, k_y, k_z$ volume.

**Fourier slice theorem in tomography (Kak, 1988)**

- Each wavefront sensor measures the integral of index variation along the ray lines.
- The line integral along $z$ determines the $k_z=0$ Fourier spatial frequency component.
- Projections at several angles sample the $k_x, k_y, k_z$ volume.

Adequate sampling in Fourier space: $k_x \theta < \Delta k_z = 1/\Delta z$ when $k_x < 1/r_0$
MCAO $k_x < 1/[\Delta z (\theta - \theta_{gs})]$ requirement interpreted spatially

\[ \theta \Delta z < r_0 \]
Selecting optimum conjugate planes for the finite number of DMs

Generalized anisoplanatism
Tokovinin & LeLouarn, JOSA-A, 17, Oct 2000

\[ \langle \epsilon^2 \rangle = (|\theta|/\theta_M)^{5/3} \]

\[ \theta_M^{-5/3} = 2.905(2\pi/\lambda)^2(\sec z)^{8/3} \int_0^{h_{\text{max}}} C_n^2(h)F_M(h)dh \]
MCAO fitting error

- **Problem:**
  - We have chosen the total number of DMs and their multi-conjugate locations using the previous techniques so as to minimize anisoplanatism.
  - Now, how many actuators do we need per DM to achieve adequate fitting of the wavefront at each altitude?

- **Solution Approach:**
  - Pick an error budget for the fitting error.
  - Pick a total number of actuators.
  - Distribute the actuators “parato-optimally” - i.e. so that total fitting error is not improved by taking an actuator from one DM and putting on another.
  - Adjust the total number of actuators and repeat until the specified total fitting error is achieved.
  - This approach solves a dual problem:
    - Minimum number of actuators to achieve a given fitting error.
    - Minimum fitting error with a given number of actuators.
Minimum number (and optimal distribution) of actuators on multiple DMs to achieve a given fitting error

Wavefront fitting error at each layer

\[ \sigma_i^2 = \mu \left( \frac{d_i}{r_{0i}} \right)^{5/3} \]

Optimality Conditions:

\[ \frac{\partial \sigma_i^2}{\partial N_i} = \frac{\partial \sigma_j^2}{\partial N_j} \quad \forall i, j \]

\[ \delta_i^{5/3} N_i^{-11/6} = \delta_j^{5/3} N_j^{-11/6} \quad \forall i, j \]

\[ \delta_i = \frac{D_i}{D_1/r_0} \]

Solution

\[ N_1^* = \left[ \sigma^{-2} \alpha \sum_{i=1}^{M} \delta_i^{10/11} \right]^{6/5} \]

\[ N_i^* = \delta_i^{10/11} N_1^* \quad i = 2K \quad M \]

\[ \sigma_i^{*2} = \alpha \delta_i^{5/3} N_i^{*-5/6} \]

Optimality conditions (all equal)

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5 DMs

30,000 actuators
Specific AO designs

- Lick laser guidestar system
- Keck laser guidestar system
- CELT MCAO multi-laser guidestar system
Lick laser guide star

3 m primary
0.8 m secondary

- 40 subabertures, d=43cm
- 61 actuators, hex grid, \( d_a = 50 \text{ cm} \)
- Max sample rate: 1000 Hz
- Sodium layer LGS
- IR Cam: \( 256^2 \) HgCdTe, 0.076 arcsec/pixel (Nyquist sampled in K)
Keck laser guide star

- 10 meter equivalent area telescope aperture
- 349 Actuator DM (rectangular grid)
- 50 cm subapertures
- 20 watt laser beacon
  - Sodium dye laser
  - Projected from the side of the telescope (spot elongation)
- Science camera (NIRC-II) Nyquist sampled in H ($\lambda=1.6\mu$)
Waffle modes
on Keck and other rectilinear geometry AO systems

Fried geometry, Hartman sensor subapertures with actuators at the corners on a rectilinear grid

A simple transformation shows that two grids can be independently pistoned, and result in zero Hartmann sensor output.

Waffle mode: global over the deformable mirror (circular aperture)

Another kind of “wafflish” behavior

PSF with least squares reconstructor

PSF with the actuator penalty method reconstructor
CELT MCAO

• Requirements
  – 30 Meter aperture concept (Future Giant Telescope)
  – Needs multiple laser guidestars just to overcome cone effect
  – 2 arcminute field of view desired
  – Strehl of 0.5 at $\lambda=1\mu$ desired (113 nm error budget)

• Design Concept
  – 4 conjugate DMs, 20-30 thousand total actuators
  – 7 sodium laser guidestars in a configurable constellation
  – 7 wavefront sensors in the tomographic reconstruction configuration
  – Sodium LGS spot size mitigation
  – Several NGS tip/tilt sensors - to break LGS ambiguous modes - these will be IR detectors to take advantage of AO correction of dimmer stars to allow higher sky coverage
Summary

• Building an adaptive optics system is a complicated multidisciplinary project. Adequate reviews at critical phases of the design process are important.

• AO wavefront correction systems for a wide variety of applications have many of the same design considerations.

• Multi conjugate adaptive optics is very similar in concept to tomography.

• A concept for a 30 meter telescope AO system is in the initial study phase