AO System Design in Vision Science

Donald T. Miller

http://www.opt.indiana.edu/people/faculty/miller.htm
Primary camera architectures

- Fundus camera (flood illumination)
- Scanning laser ophthalmoscope (SLO)
- Optical coherence tomography (OCT)
Camera parameters important for imaging single cells in the living human retina

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>1.</td>
<td>Lateral resolution</td>
</tr>
<tr>
<td>2.</td>
<td>Axial resolution</td>
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<tr>
<td>3.</td>
<td>Temporal resolution</td>
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<tr>
<td>4.</td>
<td>Sensitivity</td>
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<td>5.</td>
<td>Contrast</td>
</tr>
</tbody>
</table>
Point Spread Function vs. Pupil Size

- 1 mm
- 2 mm
- 3 mm
- 4 mm
- 5 mm
- 6 mm
- 7 mm

Perfect Eye

Typical Eye

AO

Courtesy A. Roorda
Transverse resolution (solid) and depth of focus (dashed) as a function of pupil size for an unaberrated eye

\[ \lambda = 0.83 \, \mu m \]

A. Roorda, D.T. Miller, J. Christou, “Strategies for High-Resolution Retinal Imaging,” Chapter 10 (Fig. 10.8) in Adaptive Optics for Vision Science (2006).
Adaptive Optics In Astronomy:

- Proposed in 1953 (Horace Babcock)
- First Implemented in mid-1970s

The laser emerging from the dome of the 120" Shane Telescope at the Lick Observatory is used for measuring atmospheric aberrations.
First Use of a Deformable Mirror In the Eye:

First use of wavefront sensing to correct higher order aberrations

First demonstration of retinal imaging and vision improvement by correcting higher order aberrations

Additional information on the content of this tutorial can be found in Donald T. Miller and Austin Roorda, "Adaptive optics in retinal microscopy and vision," chapter in *Handbook of Optics*, McGraw-Hill, New York (submitted).
Cartoon suggests adaptive optics for astronomy and vision science face very different challenges.
Eye speculum … not a patient-friendly solution.
How do I design an adaptive optics system that is tailored to the human eye?

- Permits large pupil (diffraction & NA)
- Increased lateral resolution
- Increased collection efficiency of reflected light
- Increased axial resolution (SLO)
Outline

1. Wavefront sensor
2. Wavefront corrector
3. Control system
4. Complete AO system
AO’s requirements to measure, correct, and track are dictated by the properties of the ocular aberrations:

1. **Spatial distribution** of the ocular aberrations.
2. **Magnitude** of the ocular aberrations.
3. **Temporal distribution** of the ocular aberrations.
4. **Field dependence** of the ocular aberrations. (isoplanatism)
Indiana’s flood-illuminated AO retina camera

- fiber light source
- retina CCD
- S-H WS
- Xinetics mirror
- Control computer
- Subject
Outline

1. Wavefront sensor
2. Wavefront corrector
3. Control system
4. Complete AO system
“... if an optician wanted to sell me an instrument which had all these defects, I should think myself quite justified in blaming his carelessness in the strongest terms, and giving him back his instrument.”

Hermann Von Helmholtz
(19th century)
Publication trend for use of wavefront sensors to measure the full wave aberrations of the human eye (PubMed)

Shack-Hartmann, spatially resolved refractometer, crossed-cylinder aberroscope, laser ray tracing, scanning slit refractometer, video keratography, corneal topography, phase retrieval, curvature sensing, and grating-based techniques

Liang, et al. SHWS JOSA 1994

J. Porter et al., Adaptive Optics for Vision Science (2006), Figure F.1 p. xviii.
Numerous types of objective wavefront sensors are available

- Common path interferometer
- Phasing shifting interferometer
- **Shack-Hartmann sensor**
- Shearing interferometer
- Pyramid sensor
- Curvature sensor
- Phase diversity
- Laser ray tracing
- Tscherning aberrometry
- Etc.
All major commercially-available aberrometers for the eye measure the wavefront slope*  

<table>
<thead>
<tr>
<th>Aberrometer</th>
<th>Vendor</th>
<th>Sensing Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>LADARWave</td>
<td>Alcon</td>
<td>Hartmann-Shack</td>
</tr>
<tr>
<td>WaveScan</td>
<td>AMO/Visx</td>
<td>Hartmann-Shack</td>
</tr>
<tr>
<td>COAS</td>
<td>AMO/Wavefront Sciences</td>
<td>Hartmann-Shack</td>
</tr>
<tr>
<td>Zywave</td>
<td>Bausch &amp; Lomb</td>
<td>Hartmann-Shack</td>
</tr>
<tr>
<td>WASCA Analyzer</td>
<td>Carl Zeiss Meditec</td>
<td>Hartmann-Shack</td>
</tr>
<tr>
<td>ORK Analyzer</td>
<td>Schwind</td>
<td>Hartmann-Shack</td>
</tr>
<tr>
<td>iTrace</td>
<td>Tracey</td>
<td>Ray Tracing</td>
</tr>
<tr>
<td>Allegro Analyzer</td>
<td>WaveLight</td>
<td>Tscherning</td>
</tr>
</tbody>
</table>

* The one exception is the OPD-Scan by Nidek (based on the principle of sequential retinoscopy)
Conceptual layout of the Shack-Hartmann wavefront sensor

Video camera

Lenslet array

telescope

Collimated input beam ($\lambda = 800 - 900$ nm)

beamsplitter

Eye

Laser spot
Wavefront Sensor Design

Most important parameters:

- # of lenslets
- Sensitivity
- Dynamic range
- Signal-to-noise
Summary of aberrated wavefront reconstruction

1. Capture raw Shack-Hartmann spots

2. Centroid and determine displacement (reference) of Shack-Hartmann spots

\[ \Delta x_{l,a} = \frac{\sum_{i,j \in l} x_{i,j} I_{i,j,a}}{\sum_{i,j \in l} I_{i,j,a}} - x_{l,\text{ref}} \]

\[ s_{lax} = \frac{\Delta x_{l,a}}{f} \]

3. Calculate local wavefront slopes

4. Calculate coefficients of Zernike modes

\[ c_m = V D^{-1} U^T S_l \]

5. Reconstruct complete aberrated wavefront

\[ W(r, \theta) = W(R\rho, \theta) = \sum_{m=1}^{M} c_m Z_m(\rho, \theta), \]
Wavefront Sensor Design

Most important parameters:

- # of lenslets
- Sensitivity
- Dynamic range
- Signal-to-noise
Maximum number of Zernike modes that can be calculated reliably for a given number of sampling points.

### Ideal case:
No other effect, e.g., noise, partial occlusion of edge lenslets, pathology, dry eye

### Result:
Maximum lenslets

\[
= \text{Zernike modes to correct} \\
= (N+1)(N+2)/2 - 3,
\]

where \(N\) is order #.

### Example: Correct up through 10th order:
Maximum lenslets

\[
= (10+1)(10+2)/2 - 3 \\
= 63
\]

\[
W(R\rho, \theta) = \sum_{m=1}^{M} c_m Z_m(\rho, \theta)
\]
AO’s requirements to measure, correct, and track are dictated by the properties of the ocular aberrations:

1. **Spatial distribution** of the ocular aberrations.
2. **Magnitude** of the ocular aberrations.
3. **Temporal distribution** of the ocular aberrations.
4. **Field dependence** of the ocular aberrations. (isoplanatism)
Aberrations in two populations of 70 normal eyes for 7.5 mm pupil

Wavefront Sensor Design

Most important parameters:

- # of lenslets = # modes (221; 17 across 6.8 mm pupil)
- Sensitivity
- Dynamic range
- Signal-to-noise

# of pixels = \( \frac{(2.44\lambda F/d)}{\text{pix}_{\text{CCD}}} \) = \( \frac{(2.44 \times 0.78 \mu m \times 24 \text{mm} / 0.4 \text{mm})}{25.8 \mu m} \) = 4.4 pixels

\[ \theta_{\text{min}} = \frac{\Delta x_{\text{min}}}{F} \ll \frac{(25.8 \mu m/\text{pix})}{24 \text{mm}} \ll 1.1 \text{ mrad} \]

\[ 4.4 \text{pix} \times 25.8 \mu m/\text{pix} = 2.44\lambda F/d = 1.22\lambda/\text{NA} \]

\[ \lambda = 0.78 \mu m \]

NA = 0.0083 for individual lenslet
Wavefront Sensor Design

- **Most important parameters:**
  - # of lenslets = # modes
  - Sensitivity ≥ 4 pix / focal spot
  - Dynamic range
  - Signal-to-noise

- **Equations:**
  - \[ \theta_{\text{max}} = \frac{\Delta x_{\text{max}}}{F} = \frac{(d/2)}{F} = \text{NA} = 0.0083 \]
  - Diopters_{\text{max}} for 6.8 mm pupil
    - \[ \text{Diopters}_{\text{max}} = \frac{\Delta \theta_{\text{max}}}{\text{pupil radius}} = \frac{0.0083}{(6.8e-6 \text{ m} / 2)} = 2.44 \text{ diopters} \]

- Diagram showing:
  - \( \Delta x_{\text{max}} \)
  - \( \Delta x_{\text{min}} \) ≥ 4 pixels across 2.44\( \lambda F/d \)
Aberrations in two populations of 70 normal eyes for 7.5 mm pupil


Distribution of refractive error depends on many factors including population, age, education, and cycloplegia.

Reasonable goal: +/- 5 diopters covers a large percentage of the population

- Elderly (avg 74 yr) peak 0 to +2D
- Young adult peak 0 to +1D
- Young adult peak 0 to +1D
- 13 – 14 yrs cycloplegia most common 0 to +1D
- 12 – 16 yrs cycloplegia most common 0 to +1D
- 6 – 8 yrs cycloplegia vast majority 0 to +1D
- 5 – 7 yrs none vast majority 0 to +1D
- Infants (30 hrs) cycloplegia range -12 to +12 D

Refractive error (diopters)

Most important parameters:

- # of lenslets = # modes
- Sensitivity ≥ 4 pix / focal spot (θ_min << 1.1 mrad; 4.4 pix)
- Dynamic range = NA (8.3 mrad; 2.4 diopters)
- Signal-to-noise high

Noise sources:
- Photon noise, CCD read noise
- Photons/lenslet astron: ~100 to close loop
- Vision: >500,000

Symbols:
- Δx_max
- Δx_min
- F
- d
- x_max
- x_min
- NA
Typical SH sensor parameters for the eye

1. # of lenslets: ~200 (>1/2 million photons/lenslet for <8 μW entering eye.)

2. Lenslet array: lenslet diameter = 400μm (17x17 for 6.8 mm pupil) focal length = 24mm

3. # pixels across 4 to 14 dot core

4. Wavelength 633 to 850 nm
Indiana adaptive optics retina camera

1. SHWS wavefront sensor
   - 17x17 lenslets across 6.8 mm pupil
   - 4.4 pix across each focal spot
   - 2.4 diopter dynamic range
   - $\lambda = 0.78 \, \mu m$ SLD beacon
   - 6 $\mu W$ enters eye
   - Inexpensive areal CCD

2. Wavefront corrector

3. Control system

Laser beacon

Aberrated wavefront

Retina camera or Visual stimulus
Sampling geometry of the lenslets at the pupil plane of the eye

17x17 SHWS lenslets (0.4 mm spacing)

6.8 mm at eye
Outline

1. Wavefront sensor

2. Wavefront corrector

3. Control system

4. Complete AO system
Various types of wavefront correctors
(Which one is right for my application?)

a) Discrete Actuator

b) Segmented: Piston only and Piston/tip/tilt

c) Membrane

d) Bimorph
OKO membrane mirror

Xinetics deformable mirror

AOptix bimorph “fast, simple, & robust”

Hamamatsu LC-SLM

Imagine Eyes

Boston Micromachines Corp.

Iris AO
Wavefront Corrector Performance

Input from Eye

Most important parameters:
- Actuator stroke
- Actuator number
- Actuator influence function

• Speed
• Reflectivity
• Diameter
• Cost!
AO’s requirements to measure, correct, and track are dictated by the properties of the ocular aberrations:

1. **Spatial distribution** of the ocular aberrations.
2. **Magnitude** of the ocular aberrations.
3. **Temporal distribution** of the ocular aberrations.
4. **Field dependence** of the ocular aberrations. (isoplanatism)
2. **Magnitude of the ocular aberrations.**

**Figure.** PV wavefront error that encompasses 95% of the population in the Rochester (black lines) and Indiana (gray lines) populations as a function of pupil diameter.

OKO membrane mirror

Xinetics deformable mirror

Hamamatsu LC-SLM

Iris AO

Peak-to-valley wavefront correction available for defocus:
2*stroke = 8 \mu m

(32 \mu m)

AOptix bimorph
“fast, simple, & robust”

(11 \mu m)

Boston Micromachines Corp.

(70 \mu m)

(16 \mu m)
Wavefront Corrector Performance

Input from Eye

Most important parameters:
- Actuator stroke
- Actuator number
- Actuator influence function

actuators push & pull on mirror surface

- Speed
- Reflectivity
- Diameter
- Cost!
AO’s requirements to measure, correct, and track are dictated by the properties of the ocular aberrations:

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Aberrations in two populations of 70 normal eyes for 7.5 mm pupil


Indiana population: Log$_{10}$ of the wavefront variance after a conventional refraction using trial lenses is plotted as a function of Zernike order and pupil size (4.5, 6.0, and 7.5 mm). Diamonds and corresponding dashed curves represent the mean and mean ± two times the standard deviation of the log$_{10}$(wavefront variance), respectively, for a 7.5 mm pupil. Star and open circle correspond to 4.5 mm and 6.0 mm pupils.
Various types of wavefront correctors
(Which one is right for my application?)

a) Discrete Actuator

b) Segmented: Piston only and Piston/tip/tilt

c) Membrane

d) Bimorph
1. Discrete actuator deformable mirrors

Diff lim result: >14 (Roch), 11-14 (Ind)

Predicted Strehl ratio

Actuators across 7.5 mm pupil

\( \lambda = 0.6 \, \mu m \)
2. Piston segmented correctors

Diff lim result: >90 (Roch), 45-85 (Ind)

Meadowlarks 127 segments

Actuators across 7.5 mm pupil

\( \lambda = 0.6 \, \mu m \)
3. Piston/tip/tilt segmented correctors

Diff lim result: 12-19 (Roch), 9-10 (Ind)

IrisAO
37 actuator

Predicted Strehl ratio vs. Actuators across 7.5 mm pupil

$\lambda = 0.6 \mu m$
Various types of wavefront correctors
(Which one is right for my application?)

a) Discrete Actuator

b) Segmented: Piston only and Piston/tip/tilt

c) Membrane

d) Bimorph
Simulated residual RMS error (µm)

Number of modes used for correction

- 6 mm pupil
- Indiana Aberration Study of 100 eyes
- Includes finite stroke of mirrors

## Desired parameters for the wavefront corrector

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification and Notes</th>
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</thead>
<tbody>
<tr>
<td>Temporal Bandwidth</td>
<td>1-6 Hz fluctuations in the eye</td>
</tr>
<tr>
<td>Reflectivity</td>
<td>&gt;90% (400-900 nm)</td>
</tr>
<tr>
<td>Physical size</td>
<td>4 - 8 mm</td>
</tr>
<tr>
<td>Mirror Stroke</td>
<td>10-53 μm (Rochester)</td>
</tr>
<tr>
<td>(7.5-mm pupil, 95% population)</td>
<td>7-11 μm (Indiana)</td>
</tr>
<tr>
<td># of actuators or segments</td>
<td>&gt; 14 (Roch), 11-14 (Ind)</td>
</tr>
<tr>
<td>across 7.5 mm pupil</td>
<td>Discrete actuator</td>
</tr>
<tr>
<td>(for 80% Strehl at λ = 0.6 μm)</td>
<td>&gt; 90 (Roch), 45-85 (Ind)</td>
</tr>
<tr>
<td></td>
<td>Piston-only segmented</td>
</tr>
<tr>
<td></td>
<td>12-19 (Roch), 9-10 (Ind)</td>
</tr>
<tr>
<td></td>
<td>Piston/tip/tilt segmented</td>
</tr>
<tr>
<td>Specific correctors evaluated</td>
<td>OKO37 membrane</td>
</tr>
<tr>
<td></td>
<td>AOptix35</td>
</tr>
<tr>
<td></td>
<td>OKO19 piezoelectric</td>
</tr>
<tr>
<td></td>
<td>BMC140</td>
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<tr>
<td></td>
<td>MIRAO52</td>
</tr>
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Conventional fundus image

Example: 40 deg fundus image would require collection of $\pi(40/2)^2 = 1,257$ one-degree AO images.
Indiana adaptive optics retina camera

2. Xinetics wavefront corrector
   37 actuators fill 6.8 mm pupil
   4 µm stroke
   Predicted Strehl = 0.2-0.4 (7.5 mm)

1. SHWS wavefront sensor
   17x17 lenslets across 6.8 mm pupil
   4.4 pix across each focal spot
   2.4 diopter dynamic range
   λ = 0.78 µm SLD beacon
   6 µW enters eye
   Inexpensive areal CCD

3. Control system

Aberrated wavefront
Retina camera or Visual stimulus
Eye
Sampling geometry of the actuators and lenslets at the pupil plane of the eye

**Xinetics:**
- 37 elements,
- 4 µm stroke

Pupil size for retinal imaging (6 mm)

37 Xinetics actuators (1.12 mm spacing)

17x17 SHWS lenslets (0.4 mm spacing)

6.8 mm at eye
Deformable mirrors used in the AO woofer-tweeter system

**BMC MEMS:**
- 140 elements (12x12),
- 3.7 $\mu$m stroke,
- used for higher order aberrations

**AOptix Bimorph:**
- 35 actuators + guard ring + front face electrode,
- 16 $\mu$m stroke available for defocus,
- used for lower order aberrations

Actuator geometry

12x12

36 total
Sampling geometry of the actuators and lenslets at the pupil plane of the eye

**AOptix Bimorph:**
- 36 elements,
- 15 µm stroke

**BMC MEMS:**
- 140 elements (12x12),
- 3.7 µm stroke
Outline

1. Wavefront sensor
2. Wavefront corrector
3. Control system
4. Complete AO system
AO system has distinct spatial and temporal control characteristics

1. $\phi_{\text{ocular}}(x,y)$ → Spatial control, $\phi_{\text{correct}}(x,y)$ → $\phi_{\text{ocular}}(x,y)$

2. $\phi_{\text{ocular}}(t)$ → Temporal control, $\phi_{\text{correct}}(t-\tau)$ → $\phi_{\text{ocular}}(t)$
1. Spatial control of the adaptive optics system

<table>
<thead>
<tr>
<th>$S_l$</th>
<th>$F_{l,a}$</th>
<th>$M_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measured sensor slopes $(2l,1)$</td>
<td>Response matrix for the mirror-sensor system $(2l, a)$</td>
<td>Mirror Voltages $(a,1)$</td>
</tr>
</tbody>
</table>

**Problem:** $F^{-1}$ typically does not exist as $F$ needs to be singular.

**Solution:** Determine pseudo-inverse, $F^*$, using for example singular value decomposition.
1. Spatial control of the adaptive optics system

Direct slope reconstruction method:

\[ S_l = F_{l,a} M_a \]

Measured sensor slopes \((2l,1)\)

Response matrix for the mirror-sensor system \((2l, a)\)

Mirror Voltages \((a,1)\)

\[ F_{l,a} = U D V^T \]

Singular value decomposition

\[ F_{l,a}^* = V D^{-1} U^T \]

Least squares inverse
1. Spatial control of the adaptive optics system

Direct slope reconstruction method:

\[ S_l = F_{l,a} M_a \]

Measured sensor slopes \((2l,1)\)

Response matrix for the mirror-sensor system \((2l, a)\)

Mirror Voltages \((a,1)\)

\[ M_a = V D^{-1} U^T S_l \]

\( F_{l,a}^* \), least squares solution to inverse

\[ \hat{M}_a = F_{l,a}^* (S_l - \overline{S}_l) - \overline{M}_a \]

remove mean slope and piston
Response matrix for the mirror-sensor system \((m,n)\)

Least squares solution to inverse

Influence function

Reconstructor (svd)

Note: axes should be flipped
AO system has distinct spatial and temporal control characteristics

1. \( \phi_{\text{ocular}}(x,y) \rightarrow \text{Spatial control,} \quad \phi_{\text{correct}}(x,y) \rightarrow \phi_{\text{ocular}}(x,y) \)

2. \( \phi_{\text{ocular}}(t) \rightarrow \text{Temporal control,} \quad \phi_{\text{correct}}(t-\tau) \rightarrow \phi_{\text{ocular}}(t) \)
How fast does my AO need to go?
AO’s requirements to measure, correct, and track are dictated by the properties of the ocular aberrations:

1. **Spatial distribution** of the ocular aberrations.
2. **Magnitude** of the ocular aberrations.
3. **Temporal distribution** of the ocular aberrations.
4. **Field dependence** of the ocular aberrations. (isoplanatism)
Temporal fluctuations in the eye’s PSF
(viewing distant target, 6.8mm pupil, 780nm monochromatic light)

Video represents wave aberration measurements taken at 21 Hz during a 4 second interval.
Figure. Temporal traces of the total rms wave-front error and Zernike terms: defocus, astigmatism, coma, and spherical aberration for one subject when accommodating on a target at 2 D. A trace of the total rms wave-front error for an artificial eye is also shown.

**Result:** Fluctuations are found in all of the eye’s aberrations, not just defocus.

Fluctuations in higher-order aberrations share similar spectra and bandwidth, dropping at $f^{-4/3}$, (4dB/octave).

All spectra have measurable power out to ~5-6 Hz.

Figure. Comparison of the power spectrum of the fluctuations in the total rms wave-front error for an artificial eye and for a human subject with paralyzed accommodation. Aberrations were computed for a 4.7-mm pupil size.

**Result:** A closed-loop bandwidth of an ideal AO system of 1-2 Hz can correct ocular aberrations well enough to achieve Strehl > 0.8.

Figure. Time-averaged Strehl ratio versus bandwidth for a perfect adaptive optics system, calculated for a 5.8-mm pupil for paralyzed accommodation and for natural accommodation on a far target.

Figure. Comparison of the power spectrum of the fluctuations in the total rms wave-front error for an artificial eye and for a human subject with paralyzed accommodation. Aberrations were computed for a 4.7-mm pupil size.

Result (not shown): Fluctuations in higher-order aberrations share similar spectra and bandwidth, dropping at f^{-4/3}, (4dB/octave).

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>Average Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.7 mm pupil</td>
<td></td>
</tr>
</tbody>
</table>

Total rms for subject

Total rms for model eye

All spectra have measurable power out to ~5-6 Hz.

**Method:** AO system with a 240 Hz sampling rate and 0 to 25 Hz closed-loop bandwidth.

**Result:** Aberration power spectra show same slope as in Hofer et. al paper, but extended up to 30 Hz.

Fig. 2. Dynamics of ocular aberrations. (a) Wavefront rms measured at 240 Hz over approximately 4 s. (b) Power spectrum of the signal in (a) showing dynamic behaviour in excess of 30 Hz.

Result: Increase in the closed-loop bandwidth above 2Hz may offer a marginal benefit in corrected Strehl for real AO systems.

Fig. 4. System’s performance as a function of bandwidth

Figure. Comparison of the power spectrum of the fluctuations in the total rms wave-front error for an artificial eye and for a human subject with paralyzed accommodation. Aberrations were computed for a 4.7-mm pupil size.

Result (not shown): Fluctuations in higher-order aberrations share similar spectra and bandwidth, dropping at $f^{-4/3}$, (4dB/octave).

All spectra have measurable power out to ~5-6 Hz.

Temporal power spectra of the wavefront disturbance without and with dynamic correction

- No Correction
- 10% Gain
- 30% Gain
- 50% Gain
- Unstable (30% Gain)
Power rejection magnitude = power spectra with AO
                          / power spectra w/o AO
Schematic of a closed-loop AO system

Aberrations, $X(s)$

Mirror, $M(s)$

Residual, $R(s)$

$H_{openloop}(s)$

$H_{OL}(s) = \frac{M(s)}{R(s)}$

$s = \imath 2\pi f$

Goal: find $H_{\text{closedloop}}(s)$

$H_{CL}(s) = \frac{R(s)}{X(s)} = \frac{1}{1 + H_{OL}(s)}$

$R(s) = X(s) - M(s)$

$M(s) = H_{OL}(s) R(s)$

$R(s) = X(s) - H_{OL}(s) R(s)$
Schematic of a closed-loop AO system

- **Residual, \( R(s) \)**
- **Aberrations, \( X(s) \)**
- **Mirror, \( M(s) \)**
- **Zero-order hold**
  - \( H_{zoh}(s) = \frac{1-e^{-sT_2}}{sT_2} \)
- **Compensator**
  - \( H_{comp}(s) = \frac{1}{1-e^{-sT_2}} \)
- **Readout & Computational delay**
  - \( H_{delay}(s) = e^{-st} \)
- **SHWS exposure**
  - \( H_{exp}(s) = H_{OL}(s) = \frac{1-e^{-sT_1}}{sT_1} \)

- \( T_2 = 100 \text{ ms} \)
- \( T_1 = 50 \text{ ms} \)
- \( t = 118 \text{ ms} \)
- \( \text{Gain} = 0.3 \)
- \( G = \frac{1}{1-e^{-sT}} \)

\( s = i2\pi f \)
Timing diagram of Indiana’s AO system

10 Hz, 0.3 Gain

- **SHWS exposure**
  - $T_1 = 50$ ms
  - 1 (integrate) 2 (integrate) 3 (integrate)...

- **Readout**
  - $t_1 = 50$ ms
  - 1 (delay) 2 (delay) 3 (delay)...

- **Reconstruct**
  - $t_2 = 68$ ms
  - 1 (delay) 2 (delay) 3 (delay)...

- **apply & hold voltage on corrector**
  - $T_2 = 100$ ms
  - 1 (integrate) 2 (integrate) 3 (integrate)
Schematic of a closed-loop AO system

Aberrations, \( X(s) \)

\[ + \]

\[ T_2 = 100 \text{ ms} \]

\[ \text{Zero-order hold} \]

\[ H_{zoh}(s) = \frac{1 - e^{-sT_2}}{sT_2} \]

\[ \text{Compensator} \]

\[ H_{comp}(s) = \frac{G}{1 - e^{-sT_2}} \]

\[ \text{Readout & Computational delay} \]

\[ H_{delay}(s) = e^{-st} \]

\[ \text{SHWS exposure} \]

\[ H_{exp}(s) = H_{OL}(s) = \frac{1}{1 - e^{-sT_1}}, s = i2\pi f \]

\[ \sqrt{\text{Power rejection curve}} = \frac{\text{Error transfer function}}{X(s)} = H_{CL}(s) = \frac{R(s)}{X(s)} = \frac{1}{1 + H_{OL}(s)} \]
Predicted and measured power rejection magnitude of the Indiana AO retina camera

Temporal frequency (Hz)

Power rejection magnitude

10 Hz
$T_1 = 50$ ms
$t = 118$ ms
$T_2 = 100$ ms
Gain = 0.3
Predicted and measured power rejection magnitude of the Indiana AO retina camera

- **10 Hz**
  - $T_1 = 50$ ms
  - $t = 118$ ms
  - $T_2 = 100$ ms
  - Gain = 0.3

- **50 Hz**
  - $T_1 = 20$ ms
  - $t = 40$ ms
  - $T_2 = 20$ ms
  - Gain = 0.3

Graph with temporal frequency (Hz) on the x-axis and power rejection magnitude on the y-axis.
Schematic of a closed-loop AO system

Aberrations, \( X(s) \)

\[ + \]

Zero-order hold

\[ H_{zoh}(s) = \frac{1}{1 - e^{-sT_2}} \]

Gain = 0.3

Compensator

\[ H_{comp}(s) = \frac{G}{1 - e^{-sT_2}} \]

Readout & Computational delay

\[ H_{delay}(s) = e^{-st} \]

SHWS exposure

\[ H_{exp}(s) = H_{OL}(s) = \frac{1}{1 - e^{-sT_1}} \], \( s = j2\pi f \)

Error transfer function

\[ H_{CL}(s) = \frac{R(s)}{X(s)} = \frac{1}{1 + H_{OL}(s)} \]

Power rejection curve

\[ = \sqrt{\text{Power rejection}} \]

Residual, \( R(s) \)
Outline

1. Wavefront sensor
2. Wavefront corrector
3. Control system
4. Complete AO system
Indiana adaptive optics retina camera

2. Xinetics wavefront corrector
37 actuators fill 6.8 mm pupil
4 μm stroke
Predicted Strehl = 0.2-0.4 (7.5 mm)

3. Control system
Zonal reconstructor (direct slope)
0.5 Hz cutoff frequency

1. SHWS wavefront sensor
17x17 lenslets across 6.8 mm pupil
~4 pix across each focal spot
λ = 0.78 μm SLD beacon
6 μW enters eye
Inexpensive areal CCD
Sampling geometry of the actuators and lenslets at the pupil plane of the eye

**Xinetics:**
- 37 elements,
- 4 µm stroke

**37 Xinetics actuators** (1.12 mm spacing)

**17x17 SHWS lenslets** (0.4 mm spacing)

**Pupil size for retinal imaging** (6 mm)

**6.8 mm at eye**
Dynamic correction in one subject’s eye as revealed by sensor-measured PSF

Before correction:
- 1.6 μm RMS

After correction:
- 0.16 μm RMS

- λ = 0.78 μm
- 6.8 mm pupil
- 10% Gain
- 21 Hz

27 frames to converge

80 frame video
Dynamic correction in one subject’s eye as revealed by sensor-measured PSF

- $\lambda = 0.78 \, \mu m$
- 6.8 mm pupil
- 30% Gain
- 21 Hz

**Before correction:**
1.6 $\mu m$ RMS

**After correction:**
0.16 $\mu m$ RMS

- 6 frames to converge

80 frame video
Dynamic correction in one subject’s eye as revealed by measured total RMS

Wavefront error (μm)

Time (frames)

10% Gain

20% Gain

30% Gain

0 sec

3.8 sec
Indiana adaptive optics retina camera

2. Xinetics wavefront corrector
   37 actuators fill 6.8 mm pupil
   4 μm stroke
   Predicted Strehl = 0.2-0.4 (7.5 mm)

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   Zonal reconstructor (direct slope)
   0.5 Hz cutoff frequency

1. SHWS wavefront sensor
   17x17 lenslets across 6.8 mm pupil
   ~4 pix across each focal spot
   λ = 0.78 μm SLD beacon
   6 μW enters eye
   Inexpensive areal CCD
Turning on the AO during a 10 Hz video of the cone mosaic

- Video rate: 10 fps
- 2° FOV
- 1° ecc.
- AO correcting at 15 Hz
- 6.0 mm pupil
Cone images in one subject's eye

No AO correction  AO correction

1° field of view; 1.25° eccentricity
Summary

1. Wavefront sensor
   - **Type:** Shack-Hartmann is used exclusively.
   - **Performance:** Lenslet #, sensitivity, dynamic range, and noise.

2. Wavefront corrector
   - **Type:** Many types are used.
   - **Performance:** Actuator #, stroke, and influence function.

3. Control system
   - **Type:** Direct slope reconstruction
   - **Performance:** Spatial and temporal properties

4. Complete AO system