Ocular Shack-Hartmann sensor resolution

Dan Neal
Dan Topa
James Copland
Outline

• Introduction
  – Shack-Hartmann wavefront sensors
  – Performance parameters
  – Reconstructors

• Resolution effects
  – Spot degradation
  – Accuracy
  – Dynamic range
  – Wavefront sampling

• Conclusions
A practical Shack-Hartmann wavefront sensor is based on a microlens array

Wavefront Analysis
1. Locate position of focal spot $x_{ij}$
2. Compute wavefront slope $\frac{\hat{x}_{ij} - \hat{x}_{io}}{f} = \left( \frac{\partial \phi_j}{\partial x} \right)_i$
3. Recover wavefront $\phi_j$ by integrating.

Photomicrograph of discrete level lens array fabricated in fused silica using binary optics technology; lenslets are 250 μm in diameter.
The wavefront analysis process consists of three steps

- Find the focal spot centroids
  - Each spot assigned unique Area of Interest (AOI)
  - Typically uses a thresholded centroid algorithm
  - Errors from pixelization, camera noise, and spot Strehl ratio
- Compare to reference to produce slope map
  - Absolute or relative reference acquired during instrument calibration
  - Other instrument calibrations may be taken into account
    - Magnification
    - Telescope focus
- Reconstruct wavefront
  - Zonal: point by point integration of 2D slope map
  - Modal: Fit to polynomials such as Zernike or Taylor
WFS design parameters

- Lenslet Fresnel number: \( N_{Fr} = \frac{d^2}{f\lambda} \)

- Focal spot size: \( \rho = \frac{f\lambda}{d} \) or \( \rho = \frac{d}{N_{Fr}} \)

- Angular dynamic range: \( \theta_{\text{max}} = \frac{d/2 - \rho}{f} \)

- Total wavefront dynamic range: \( \frac{w_{\text{max}}}{\lambda} = \frac{N_i N_{Fr}}{4n} \)
Ocular SH WFS system

- Guide star system
  - Injected spot
  - Measured scattered light
- Measured by Shack-Hartmann wavefront sensor
- Resolution limited by
  - Lenslet array
  - Retina spot size
  - Camera sensitivity/injected power
- Additional elements:
  - Fixation target
  - Alignment camera
  - Optomechanics/cover
  - Chin rest/XYZ base
  - Electronics
  - Software
  - Etc., Etc.
Complete Ophthalmic Analysis System

- Complete system for optical metrology of the eye
- High resolution/high dynamic range wavefront sensor
- Variable position optical system uses active optics to maximize performance
- Experiments with laser vision correction are underway
- The COAS G200 is already a second generation product
COAS Measurement results

- Sphere: -12 to +5 d
- Cyl: 5 d
- Measurement time: 5 sec autorefract, 13 ms measurement
- Zernike polynomial to arbitrary order
- Accuracy: +/- 0.1 diopter
Wavefront sensor image from Human Eye
Why does the measurement resolution matter?

- **Spot degradation**
  - For larger lenslets, the wavefront aberration across the lenslet may be significant
  - With aberration, the focal spots are degraded
  - Poor focal spots lead to inaccurate measurements, or perhaps no measurement at all
  - This ultimately limits the dynamic range
  - Smaller lenslets intercept a smaller portion of the wavefront aberration

- **Dynamic range**
  - Depends on number of lenslets, and lenslet Fresnel number
  - Larger lenslets have reduced response for rapidly varying aberrations

- **Accuracy**
  - Each slope measurement determined from small, high quality focal spot
  - More points in reconstructor lead to higher accuracy for each term
  - Rapidly varying features may be accurately measured
The SHWFS wavefront is a piecewise linear approximation

- Shack-Hartmann sensors measure only average tilt
- Focal spot irradiance distribution depends upon total incident wavefront
- Low resolution SHWFS measurements tend to UNDERPREDICT the actual wavefront
- Residual WFE error is the RMS difference between the linear approximation and the actual wavefront
Focal spot degradation

• Small lenslets
  – Sample small portion of the wavefront
  – Sampled wavefront matches well to linear approximation

• Large lenslets
  – May have large residual wavefront error
  – Reduced Strehl may affect centroid location
Residual wavefront error depends strongly on resolution

- Linear approximation fit error
- In practice, this fit error reduces the lenslet Strehl ratio
Excellent images can be obtained from a normal eye

- Good focal spots can usually be obtained even at low resolution
- Focus/cylinder result in pattern spread
- Higher order terms usually have limited wavefront error

- 210 \( \mu \text{m} \) resolution
- 44 X 33 samples
- 3.8 mm pupil
- 25 \( \mu \text{W} \) input power

- 400 \( \mu \text{m} \) resolution
- 18 x 18 samples
- 6.8 mm pupil
- 6 \( \mu \text{W} \) input power
- Salmon et al, JOSA A 1998
With high resolution, good focal spots are obtained even from a badly damaged eye

- 210 μm resolution
- RK patient with poor correction
- Damaged regions scatter light badly
- Patient has poor BCVA
However, with lower resolution, the focal spots are degraded

- 400 µm lenslets
- 6.5 mm pupil
- 16 X 16 samples
- Poor focal spots are difficult to locate
- Blurry, fuzzy spots give inaccurate results
- Strehl reduction reduces signal to noise
You *do* need more incident power with more focal spots

- Scattered light is collected by smaller area lenslets
- Spot size should be similar for good accuracy
- Improved Strehl keeps light level high even for aberrated systems
- Near IR measurement improves patient comfort
- Extremely accurate lenslet array with 100% fill factor maximizes the efficiency

<table>
<thead>
<tr>
<th>Resolution (7 mm pupil)</th>
<th>Focal spots</th>
<th>Lenslet area (µm)</th>
<th>Power (µW)</th>
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<tbody>
<tr>
<td>33 X 33</td>
<td>800</td>
<td>210 X 210</td>
<td>22</td>
</tr>
<tr>
<td>18 X 18</td>
<td>254</td>
<td>400 X 400</td>
<td>6</td>
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<tr>
<td>10 X 10</td>
<td>78</td>
<td>700 X 700</td>
<td>2</td>
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</table>

But not much!
With higher resolution, you get better dynamic range AND accuracy

- **Dynamic range**
  - For smaller lenslets, the focal length is shorter for the same spot size
    - Larger angular dynamic range per lenslet
  - More focal spots divide the aberration into smaller samples
    - Spots are unlikely to collide with neighbor because they measure similar wavefronts
- **Accuracy**
  - Strehl ratio is high, even for aberrated pupils
  - Uniform brightness gives better centroids
  - Short focal length is less important than centroid estimation error
  - Larger number of samples approximate wavefront better
  - Reconstructor error is reduced
There are two basic types of reconstructor

- **Modal**
  - Fits to polynomials
  - Typically Zernikes
  - Polynomials have optical meanings
  - Quantitative understanding of results
  - Expansion yields point by point wavefront map
  - Interpolation functions in place
- **Zonal**
  - Numerical integration of slope grid
  - Yields point by point phase
  - Further fitting needed to produce sphere, cylinder, coma or other terms
  - Produces high spatial frequency results
Zernike polynomials allow quantitative display of the data

- RK patient
- 4\textsuperscript{th} Order Zernike reconstructor
- High RMS values and odd mix of higher orders
- 4\textsuperscript{th} order fit does not really resolve wavefront
For a normal eye, high resolution may not be needed

- Normal eye
- Low higher order terms
- Small pupil
- Zonal and Modal produce similar results
Unless you’re interested in the detailed structure

- Tear film
- Scratches
- Edema
- Unusual structures

Various wavefront maps with 4\textsuperscript{th} order terms removed
There are also many “abnormal” eyes

- RK patients
- Large pupils
- LASIK
- PRK
- Damaged
- Wrinkled flap
- Scratched/edema
- Dry eye
- Kerataconus
A pure Zernike viewed at different resolutions

- “Simulated” RK patient
- “Perfect” reconstruction
Conclusions

• High resolution ocular wavefront sensing is a desirable and practical solution
  – High Strehl ratio spots, even with aberrated systems
  – Safe, comfortable power levels maintained

• Larger aberrations may be measured, more accurately
  – Better focal spots
  – Larger dynamic range and accuracy
  – Reduced fitting error

• Fine detail allows observation of important phenomena
WFS Precision

- Zero Tilt Centroid Estimation Error
  \[
  \sigma_{j,0} = \frac{\sum_{i=1}^{N} (\rho_i - \rho_i^{REF})^2}{N} \quad \bar{\sigma}_0 = \frac{\sum_{j=1}^{M} \sigma_{j,0}}{M}
  \]
- Tilt precision:
  \[
  \theta_{RMS} = \frac{\bar{\sigma}_0}{f}
  \]
- Wavefront precision (RMS)
  - Per lenslet
    \[
    w_{0}^l = \theta_{RMS} \cdot d
    \]
  - Total across aperture
    \[
    w_{0}^{Tot} = K_R w_{0}^l
    \]
WFS Accuracy

- **Pixelization Error**
  - Threshold dependent
  - Depends strongly on pixels/focal spot
  - Is sometimes limiting performance metric
  - Pixelization factor $K_p$
WFS Accuracy, cont…

- Wavefront error
  - PV
  - RMS
- Reconstructor factor $K_p$ depends on type and options for reconstructor
- Total wavefront error is given by:

$$w_{RMS} = K_r \cdot K_p \cdot \theta_{RMS} \cdot d$$
Typical WFS design process

• Specify key design parameters
  – Lenslet size in pixels
  – Lenslet Fresnel number
  – Total size of array

• Estimate performance parameters
  – Angular dynamic range, $\theta_{\text{max}}$
  – Total wavefront dynamic range ($n=1, 2$)
  – Precision:
    • Scale $\sigma_0$ from measurements to new design point
    • Compute $\theta_{\text{rms}}$, and $w_{\text{rms,l}}$
  – Accuracy
    • Compute $W_{\text{rms,tot}}$ using $K_p$ and $K_r$
Measuring WFS performance

• Precision
  – 100 Frame statistical average of focal spots
  – Average RMS Tilt values produce $\theta_{rms}$
  – $\overline{\sigma_0} = \theta_{rms} f$

• Accuracy
  – Vary tilt, focus or other parameter
  – Measure residual WFE

• Dynamic range
  – Increase tilt while monitoring spot centroid
  – Dynamic range exceeded when non-linearity is induced