Designing Phase Diversity Wavefront Sensors for Ophthalmology

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Phase Diversity Wavefront Sensors (PDWS) offer a number of potential advantages when used in the ophthalmic field.

- Commonly known as “Curvature Sensors”
- Wavefront is connected to intensity via propagation physics

\[
k \left( \frac{I_{-1} - I_{+1} \delta I}{z_{-1} - z_{+1} \delta z} \right) = -i \nabla^2 \varphi - \nabla I \cdot \nabla \varphi
\]

- **Multi-plane imaging system (like a diffractive IOL for presbyopia!)**
- High spatial resolution
- Useful on scintillated beams with discontinuous wavefronts

- **Ophthalmic applications include:**
  - Aberrometry (implanted **multi-focal IOLs**)
  - **Multi-focal IOL** metrology
  - Cataract imaging
Modern PDWS function much like diffractive IOLs.

- **Essential hardware elements**
  - Lens or Lens System
  - Diffractive Optical Element
  - Camera

- **Optical configuration governs**
  - Location of sample planes
  - Magnification of images

\[
\frac{1}{f_m} = \frac{m}{f_g}
\]

*Blanchard and Greenaway*
Useful features of PDWS to exploit in ophthalmic applications:

- **Pupil Plane Imaging**
  - Provides a real image of the pupil
  - Accommodates variability in iris location, size and shape
  - May be critical to resolve phase on speckled beams

- **Telecentric Imaging**
  - Equally spaced sample planes with equal magnification on all images
  - Simplifies the sensor alignment, calibration, and data processing

- **Dynamic range and wavefront sensitivity are controlled by**
  - Sample plane spacing
  - Camera digitization bit depth
  - Unlike SHWS these are not coupled to the spatial resolution!
Ophthalmic aberrometer designs for SHWS and PDWS are optimized with different constraints.

Must we precondition the wavefront when using a PDWS?
The large dynamic range of PDWS can be used to simplify the design considerably.

Analytic Solutions with Pupil Plane and Telecentric Imaging and Static Optics

<table>
<thead>
<tr>
<th>$t=f_1$</th>
<th>$t=f$</th>
<th>$t=f=v$</th>
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</thead>
<tbody>
<tr>
<td>$s = 0$</td>
<td>$s = f - \frac{f^2}{f_1}$</td>
<td>$s = f - \frac{f^2}{f_1}$</td>
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<tr>
<td>$u_m = f_1 \left(1 - \frac{f_1}{f} + \frac{f_1}{v}\right) - \frac{m f_1^2}{f_g}$</td>
<td>$u_m = f^2 \left(\frac{f_1}{f^2 + (-f + v) f_1} - \frac{m}{f_g}\right)$</td>
<td>$u_m = f_1 - \frac{f^2 m}{f_g}$</td>
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<tr>
<td>Mag = $-\frac{v}{f_1}$</td>
<td>Mag = $1 - \frac{v}{f} - \frac{f}{f_1}$</td>
<td>Mag = $-\frac{f}{f_1}$</td>
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Design tradeoffs can be established by comparing design performance in a spreadsheet.

- General trends are easily established
- Design points can be established easily
- Non-viable designs can be eliminated without further consideration
Ray tracing shows this sensor can handle beams with +/-10 diopters of defocus.

- **System Values:**
  - \( f = 100 \text{mm} \), 25 mm dia
  - \( f_1 = 300 \text{mm} \), 38 mm dia
  - \( f_g = 500 \text{mm} \), 9 um period
- 300 mm stand off distance
- 20 \( \mu \text{m} \) spatial resolution
- <0.01 Diopter defocus resolution
- *No moving parts*
Conclusions

• PDWS work like a diffractive IOL—multi-plane imaging

• Identified important design features for ophthalmic PDWS
  – Pupil Plane Imaging
  – Telecentric Imaging

• Introduced a simple, effective design procedure for PDWS
  – Analytic solution of paraxial equations
  – Spreadsheet-based design tool

• Advantages
  – Complex optical systems are easily analyzed
  – Reduces design time
  – Improves performance

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