Capabilities of monocentric objective lenses

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Outline:

- Motivation and latest applications of monocentric objective lenses
- How to get to top designs of monocentric lenses in simple geometries
- How to push the lens performance and do the designs even better
- Tradeoffs between spectral band, F/#, and lens complexity
Monocentric imager vs single flat-focus lens

SCENICC CEV imager design results:

\( f=12 \text{ mm} \) large NA lenses implemented with convention retro-telephoto vs monocentric lens

Monocentric lenses offer compact wide-angle imaging with extraordinary light collection...

*Given spherical image sensors with angle-selective coatings (or their equivalent).*
Monocentric imagers in the standard lens taxonomy

Field of view

- **Topogon Metrogon**
- **Hologon**
- **Distagon Flektogon**
- **Biogon**
- **Sonhar**
- **Cooke triplet**
- **Double-Gauss**
- **Petzval-Projection**
- **Fish-eye objective**
- **Monocentric**
- **SCENICC design virtual stop (F#1.7 160°)**
- **SCENICC design Aperture stop (F#1.7 130°)**
- **AWARE2 design (F#2.4 120°)**

Light collection

Conventional lenses fall into a standard lens taxonomy of field of view and F/#

Figure adapted from H. Gross, Handbook of Optical Systems 4 – Survey of Optical Instruments, Wiley 2008

Monocentric systems (large & small) can provide excellent wide-angle performance

Significant improvement in light collection and physical volume relative to single-aperture, flat image plane objective lenses
DARPA's "AWARE" Wide Field Imaging Project (MOSAIC)

Multi-scale monocentric imager: 2400 Megapixels per image at up to 10 fps

Lens design (UCSD)  Objective Lens  226 14 MPix microcams

Partial image captured Nov 2011

David Brady (PI & technical lead)

The Duke Imaging and Spectroscopy Program: www.disp.duke.edu
**Soldier-Centric Imaging with Computational Cameras**

**SCENICC Computer-Enhanced Vision**

<table>
<thead>
<tr>
<th>SCENICC Performance Metrics</th>
<th>3D Optics Approach</th>
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</thead>
<tbody>
<tr>
<td>Weight</td>
<td>&lt;25g</td>
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<tr>
<td>Battery Life</td>
<td>24 hours</td>
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<tr>
<td>%Shannon # Limit</td>
<td>&gt;90%</td>
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<tr>
<td>Resolution (foveal)</td>
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<tr>
<td>% Diffraction Limit MTF</td>
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<tr>
<td>Full / Zoom FOV</td>
<td>120° / 15°</td>
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<td>FOV Latency</td>
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</tbody>
</table>

Eye-Borne Optics (Hands-Free Zoom and CEV display)

- Precision eye tracking via optics embedded in scleral contact lens

**Computational Imaging**

- Foveated wide-field imager, 3D optics & multimodal focal planes

**Human Interface**

- Dual-HD Head-Mounted Display projecting on transflective lenses

(1) Eye-tracked object-of-gaze brightness/contrast enhancement
(2) Eye-tracked or object-tethered 3x-10x magnification
(3) High-level image processing

**3DOptics Research:**

- (1) 3D Optical elements using fully 3-D structures at the macro / micro / nano-scale
- (2) 3D Joint Optimization spanning the optical / electronic / computational domain.
- (3) Foveation & eye-borne optics to minimize data flow and reduce system SWaP.
- (4) Human Factors as the fundamental drivers of overall system interface & function.
Initial approach: Monocentric 2 glass symmetric (2GS) geometry (3λ UCSD global search algorithm)

1st step: 1st and 3rd order analysis

Exact raytracing analysis (3 wavelengths, multiple ray heights)

1st order approximation

\[ f = \frac{2}{r_1} \left( 1 - \frac{1}{n_2} \right) + \frac{2}{r_1} \left( 1 - \frac{1}{n_3} \right) \]

\[ B = \frac{1}{4} \sum_{i=1}^{4} h_i \left( \frac{\alpha_{i+1} - \alpha_i}{1 - n_i} \right) \left( \frac{\alpha_{i+1}}{n_i} \right) \]

\[ W_{602} = \frac{1}{4} Bp^3 = \frac{1}{8} \sum_{i=1}^{4} h_i \left( \frac{\alpha_{i+1} - \alpha_i}{1 - n_i} \right) \left( \frac{\alpha_{i+1}}{n_i} \right) \]

\[ W_{604} = h_i \left( \frac{(n_i^2 - 3n_i^2 + n_i^2)}{32 f^2 (n_i - n_j)^2} - \frac{(n_i - 1)(n_i^2 - n_i)(n_i - 1)}{4n_i^2 (n_i - n_j)^2 r_i^2} \right) \]

\[ L_i = -2W_{605} = h_i \left( \frac{(n_i - 1)(2f(1-n_i) + n_i r_i)}{f(n_i - n_j) r_i n_j} \right) \]

\[ OE = S = \frac{h}{2 \left( \arcsin \left( \frac{h}{r_i} \right) - \arcsin \left( \frac{h}{r_i n_j} \right) + \arcsin \left( \frac{h}{r_i n_j} \right) - \arcsin \left( \frac{h}{r_i n_j} \right) \right) } \]

\[ \Delta S(h_i) = S(h_i) - f \]

\[ Q = \sum_{i=1}^{3} \sum_{j=4}^{6} \left( \Delta S(h_i, \lambda) - \Delta S(h_j, \lambda) \right) \]

\[ (\Delta \Phi)^2 = \Phi^2 - (\Phi)^2 = \frac{1}{2} \sum_{i=1}^{2} \left( \frac{C_{606}(\lambda)}{3} + \frac{C_{607}(\lambda)}{5} + \frac{C_{608}(\lambda)}{7} + \frac{C_{609}(\lambda)}{9} \right) \]

Brute force algorithm runs within minutes:
Computation of 312,000 glass combinations from existing catalogs.

LIMITATION: narrow wavebands with close to linear glass dispersion
Lens fabricated for SCENICC Y1 demo (3λ search algorithm)

470-650nm CEV F1.715 f=12mm, fused silica meniscus present for mounting purposes

<table>
<thead>
<tr>
<th>Surf:Type</th>
<th>Comment</th>
<th>Radius</th>
<th>Thickness</th>
<th>Glass</th>
<th>Semi-Diameter</th>
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<td>Infinity</td>
<td>S-LAH79</td>
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<td>7.15000 U</td>
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<td>Standard</td>
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<td>1.0000E-002</td>
<td>1.56,43.0</td>
<td>3.59900 U</td>
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<tr>
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<td>3.58900</td>
<td>3.58900 P</td>
<td>S-LAL13</td>
<td>3.58900 U</td>
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<tr>
<td>4</td>
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<td>Infinity</td>
<td>5.0000E-003</td>
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<td>2.41641 U</td>
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<td>STO</td>
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<td>Infinity</td>
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<td>Standard</td>
<td>Infinity</td>
<td>3.58900 P</td>
<td>S-LAH79</td>
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<tr>
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<td>S-LAH79</td>
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<tr>
<td>9</td>
<td>Standard</td>
<td>-7.15000</td>
<td>2.48990 V</td>
<td>-</td>
<td>6.60000 U</td>
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<tr>
<td>10</td>
<td>Standard</td>
<td>-9.63500</td>
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<td>F_SILICA</td>
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<tr>
<td>11</td>
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<td>-12.03400</td>
<td>0.00000</td>
<td>-</td>
<td>11.00000 U</td>
</tr>
<tr>
<td>IMA</td>
<td>Standard</td>
<td>final im</td>
<td>-12.03400 P</td>
<td>-</td>
<td>10.42840 U</td>
</tr>
</tbody>
</table>

Polychromatic MTF

Spot size

Chromatic focal shift
DARPA’s SCENICC Project: CEV camera

CEV: 12mm EFL F1.7 wide FOV imager

- 2-glass ball objective lens
- 12 mm radius meniscus lens (fiber bundle mounting surface)
- Optomechanical mount (with mechanical focus)

Canon F/4 "fisheye" lens -60° field

- Image taken with Canon DSLR Fisheye lens: low resolution, visible chromatic aberration and distortion.

SCENICC F/2 CEV: -60° field

- Microscope imaging of monocentric lens image surface indicates high resolution even at full 60° field at 10X smaller weight and volume with 4X light energy collection.
1st improvement: 2&3-glass global optimization algorithm (5λ)

Symmetric 2 glass geometry

Exact raytracing analysis (5 wavelengths, multiple ray heights)
Modified 3λ algorithm with aim to address wider wavebands.

\[ n_1 = 1 \quad n_2 = n_4 \quad n_5 = 1 \]

1st order approximation

\[ \frac{1}{f} = \frac{2}{r_1} \left( \frac{1}{n_2} - \frac{1}{n_3} \right) + \frac{2}{r_2} \left( \frac{1}{n_2} - \frac{1}{n_3} \right) \]

\[ \bar{OE} = S = \frac{h}{\sin \left[ \frac{\arcsin \left( \frac{h}{r_1} \right) - \arcsin \left( \frac{h}{r_2} \right)}{n_2} + \arcsin \left( \frac{h}{r_1} \right) - \arcsin \left( \frac{h}{r_2} \right) \right]} \]

\[ \frac{\Delta S(h_i)}{S(h_i)} = f \]

\[ Q = \sum_{i=1}^{\lambda} \sum_{\lambda=1}^{\lambda} \text{Abs} \left[ \Delta S(h_i, \lambda) \right] \]

\[ (\Delta \phi)^2 = \phi^2 - (\phi)^2 = \frac{1}{2} \sum_{i=1}^{\lambda} \left[ \frac{C_{20}^m(\lambda)}{3} + \frac{C_{40}^m(\lambda)}{5} + \frac{C_{44}^m(\lambda)}{7} + \frac{C_{54}^m(\lambda)}{9} \right] \]

(runs 8min on 12 physical CPU cores) (2 x Intel 3.1GHz Xeon E5-2687W)

Symmetric 3 glass geometry

Exact raytracing analysis (5 wavelengths, multiple ray heights)
Extension of 2 glass global search algorithm as an attempt to improve designs over large scales and broader wavebands.
Air is one of the materials consider -> 2-glass symmetric air gap.

\[ n_1 = 1 \quad n_2 = n_6 \quad n_3 = n_5 \quad n_4 = 1 \]

1st order approximation

\[ \frac{1}{f} = \frac{2}{r_1} \left( \frac{1}{n_2} - \frac{1}{n_3} \right) + \frac{2}{r_2} \left( \frac{1}{n_2} - \frac{1}{n_3} \right) + \frac{2}{r_3} \left( \frac{1}{n_2} - \frac{1}{n_3} \right) \]

\[ \bar{OE} = S = \frac{h}{\sin \left[ \frac{\arcsin \left( \frac{h}{r_1} \right) - \arcsin \left( \frac{h}{r_2} \right) + \arcsin \left( \frac{h}{r_3} \right)}{n_2} + \arcsin \left( \frac{h}{r_1} \right) - \arcsin \left( \frac{h}{r_2} \right) + \arcsin \left( \frac{h}{r_3} \right) - \arcsin \left( \frac{h}{r_4} \right) \right]} \]

One radius is predeterminded by the focal length. For a viable glass choice other two form a close to linear ravine in merit function optimization space.

(runs 24h on 32 physical/64 logical CPU cores) (4 x Intel 2.7GHz Xeon E5-4650)
Extended Spectrum operation of CEV (f=12mm F1.7 120° FOV)
Symmetric geometries (2GS, 3GS)

<table>
<thead>
<tr>
<th>Layout</th>
<th>Polychromatic MTF</th>
<th>Spot size</th>
<th>Chromatic focal shift</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fabricated 2G VIS</td>
<td><img src="image1" alt="MTF Graph" /></td>
<td>20um</td>
<td>650nm</td>
</tr>
<tr>
<td>Top 2GS VIS</td>
<td><img src="image2" alt="MTF Graph" /></td>
<td>20um</td>
<td>650nm</td>
</tr>
<tr>
<td>Top 2GS extended VIS</td>
<td><img src="image3" alt="MTF Graph" /></td>
<td>20um</td>
<td>470nm</td>
</tr>
<tr>
<td>Top 3GS extended VIS</td>
<td><img src="image4" alt="MTF Graph" /></td>
<td>20um</td>
<td>470nm</td>
</tr>
</tbody>
</table>

RMS values:
- 2G VIS: 2.41um
- 2GS VIS: 1.11um
- 2GS extended VIS: 1.92um
- 3GS extended VIS: 1.69um

Focal shift values:
- 2G VIS: 50um
- 2GS VIS: 435-850nm
- 2GS extended VIS: 435-850nm
- 3GS extended VIS: 435-850nm
Extended Spectrum operation of CEV (f=12mm F1.715 120° FOV)
Symmetric geometries (2GS, 3GS)

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</thead>
<tbody>
<tr>
<td><strong>Fabricated 2G VIS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1=7.15mm R2=3.58mm</td>
<td></td>
<td>20um</td>
<td>650nm</td>
</tr>
<tr>
<td><strong>Top 2GS VIS</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1=9.07mm R2=3.79mm</td>
<td></td>
<td>20um</td>
<td>650nm</td>
</tr>
<tr>
<td><strong>Top 2GS extended VIS @ 400-1000nm</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1=8.52mm R2=3.72mm</td>
<td></td>
<td>20um</td>
<td>1000nm</td>
</tr>
<tr>
<td><strong>Top 3GS extended VIS @ 400-1000nm</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R1=9.37mm R2=6.50mm R3=3.95mm</td>
<td></td>
<td>20um</td>
<td>1000nm</td>
</tr>
</tbody>
</table>

Note: The RMS values are provided for each setup to indicate the spread of data points.
Towards extended waveband and larger aperture: exploration of monocentric lens geometries

Glass only design space

Preferred designs

Glass + airgap design space

Degrees of freedom: 1 2 3 4 5 6 7 8 9 10
470-650nm CEV F1.7 f=12mm top design 2GS candidate

Longitudinal aberration

Push F number & optimize

Spherochromatism & zonal aberration

Pupil Radius: 3.4907 Millimeters

Aperture zone

F1.7

Distance around focus

0.1mm

Pupil Radius: 4.6093 Millimeters

Aperture zone

F1.3

Distance around focus

0.1mm

2GS optimization for F/1.3 on 470-650nm spectral band leads to glass L-BBH2 + LAH80 core candidate, but still unsatisfactory result - more degrees of freedom are needed.

Example: Spherochromatism compensation method, introduce air gap between crown & flint glass
Asymmetric air gap lens

Optimization process 1 (fast)
- Start from the best 2-glass candidate(s)
- Split the right shell and introduce airgap
- Do hammer optimization with glass substitution, but keep the core glass fixed

Optimization process 2 (in progress)
- Start from the best 2-glass candidate core
- Perturbate the glass adjacent to the core and try all glasses for the meniscus material.
  (5-dimensional systematic (not global) search)

470-650nm CEV F1.3 f=12mm seed 2GS candidate

470-650nm CEV F1.3 f=12mm 4 glass + air gap (4GA) candidate

Longitudinal aberrations
- Distance around focus 0.1mm

CEV (f=12mm F1.715 120° FOV) optimized candidates comparison
Asymmetric geometries (3GA, 4GA) derived from 2GS

**Layout**
- 3GA 400-1000nm
  - R1=7.17mm
  - R2=2.82mm
  - R3=4.04mm
  - R4=4.16mm
  - R5=7.65mm

- 4GA 400-1000nm
  - R1=7.07mm
  - R2=3.05mm
  - R3=4.32mm
  - R4=4.67mm
  - R5=7.49mm

- 4GA 400-1000nm
  - R1=7.37mm
  - R2=3.01mm
  - R3=4.28mm
  - R4=4.61mm
  - R5=7.44mm

- 4GA 400-1400nm
  - R1=7.40mm
  - R2=3.00mm
  - R3=4.27mm
  - R4=4.60mm
  - R5=7.40mm

**Polychromatic MTF**
- 400-1000nm
- 200cyc/mm

**Spot size**
- RMS = 1.61μm

**Chromatic focal shift**
- 1000nm
- 400nm

**VNIR Candidate**

- RMS = 1.18μm
- 1400nm
- 50μm
- 400nm
Lens complexity vs F/# for visible light

Optimal solutions found by global search
Ill chosen geometries which converge to simpler ones.
Specific results of hammer/systematic optimization

Increasing degrees of freedom
Define performance constraint: MTF at least 70% of diffraction limit @ 200lp/mm & RMS spot radius <1.5 Airy
- Continuous function of lens F/# (energy collection) and physical scale (focal plane area)
- Three selected wavelength ranges: VIS, Extended VIS and Visible to NIR
- Field of view from 120° (conventional aperture) to 160° (image-surface filtering)

Asymmetric 4-glass air-gap lens (8 DOF)
Specific results of hammer optimization
Asymmetric 3-glass air-gap lens (7 DOF)
Specific results of hammer optimization
Symmetric 3-glass lens structure (5 DOF)
Optimal solutions found by global search
Symmetric 2-glass lens structure (3 DOF)
Optimal solutions found by global search

* AWARE prototype objectives alone (not including relay optics) were not designed to satisfy MTF performance constraint
Thank you for your attention