Arc-Section Annular Folded Imagers

Eric Tremblay & Joseph Ford, UCSD Photonics Systems Integration Lab

Ronald Stack & Rick Morrison, Distant Focus Corporation
1) Ultra-Thin Imaging Systems: Motivation & Approach
   The Montage Program
   Annular folded optics concept
   Annular folded optics in general

2) 8-Fold Prototype Imagers
   Symmetric 8-fold imager for UAV/Surveillance
   Arc-Section 8-fold for portable devices

3) Current work: 4-Fold Imager
   Symmetric 4-fold design, fabrication and test
   Long-range imaging with an arc-section (masked) 4-fold

4) Conclusion
Motivation: Ultra-Thin Imagers

Goal: Fit imager into wing or hull of micro-UAV aircraft for long-range surveillance
Constraint: 10x thinner imagers with uncompromised resolution and sensitivity

Conventional Miniature F/1 Lens
5 mm focal length: OK for wide angle images

5 mm thickness (max allowed)

Solution?: Miniature cameras readily available – just look on your cellphone
Problem: Light collection & resolution: blurred “electronic zoom” images
Traditional design:
- Lenses
- Detection
- Post-processing

MDO approach:
- Optics
- Detection
- Post-processing

Montage Phase 1 Targets
- 5 mm thickness (1st surface to sensor)
- 0.1 (5.7°) radian field of view
- 0.1 mrad resolution
- 1000 x 700 pixel image
- Color imaging
- 35 mm diameter effective aperture

Montage Phase 2 Targets
- Same 5 mm thickness (1st surface to sensor)
- Same 0.1 mrad resolution
- 5x larger (500mrad) field of view
- Same sensitivity as 35 mm diameter lens
- Color imaging

MDO: Multi-Domain Optimization

University of Arizona
Mark Neifeld (lead)
Ray Kostuk, UAZ

Distant Focus Corp.
Ron Stack,
Rick Morrison

MIT
George Barbastathis
Daniela Pucci de Farias

CDM Optics
Paulo Silveira,
Joel Rutkowski

UCSD
Shaya Fainman,
Joe Ford
Annular Folded Optics

Refractive Lens

object

10x less length/weight/volume

Folded Optic Imager

object

Annular input aperture

Concentric zone reflectors

New in 1672: Cassegrain Telescope
Wide field reflective telescopes?

A simplified look at the geometrical properties of annular folded optics

4-fold example: assume all power at the first reflection (thin, paraxial mirror).
Fixed thickness (t = 5 mm), fixed focal length F = 4t = 20 mm

Small FOV, aperture limited at 2nd mirror

Knee point: Limited at 2nd and 2nd to last mirrors

Large FOV, aperture limited by 2nd to last Mirror only

Small FOV (before knee):

\[ w = \frac{D}{2N} - \tan\left(\frac{FOV}{2}\right) \cdot F \cdot \left(\frac{2 - \frac{1}{N}}{N}\right) \]

Large FOV (after knee):

\[ w = \frac{D}{2} - \tan\left(\frac{FOV}{2}\right) \cdot F \cdot \left(N - 1 + \frac{1}{N}\right) \]

Field of View (deg)

Width of Annulus (mm)

D = 28 mm

D = 32 mm

D = 24 mm
**Diffraction Limit of Annular Apertures**

**Incoherent point spread function:**

\[ I(r) = \left( \frac{1}{\lambda z} \right)^2 \left( \frac{2J_1(ka_r/z)}{ka_r/z} \right)^2 - \left( \frac{2J_1(ka_r/z)}{ka_r/z} \right)^2 \]

**Resolution cut-off**

\[ f_o = \frac{2a_s}{\lambda z} \] (unchanged)

**Point Spread Function**

- 0% obscured
- 50% obscured
- 70% obscured
- 90% obscured

3 micron pixel sampling: 167 lines/mm
1) Ultra-Thin Imaging Systems: Motivation & Approach
   The Montage Program
   Annular folded optics concept
   Annular folded optics in general

2) 8-Fold Prototype Imagers
   Symmetric 8-fold imager for UAV/Surveillance
   Arc-Section 8-fold for portable devices

3) Current work: 4-Fold Imager
   Symmetric 4-fold design, fabrication and test
   Long-range imaging with an arc-section (masked) 4-fold

4) Conclusion
An 8-Fold All-Reflective Telephoto Lens

Montage program design goals
- 5 mm thickness (1st surface to sensor)
- 0.1 (5.7°) radian field of view
- 0.1 mrad resolution
- 1000 x 700 pixel image
- Color imaging
- 35 mm diameter effective aperture

Specification flowdown
- Image field = 1000 x 700 pixels
  Choose Omnivision CMOS color sensor w/ 3.18 µm pixels
  \( \rightarrow \text{Image field diameter} = 3.90 \text{ mm} \)
- Optical Invariant: image height = \( \tan(\text{semi-FOV}) \times \text{EFL} \)
  (eg. \( h = 1.59, 0.1 \text{ rad FOV} \rightarrow \text{EFL} = 32 \text{ mm} \))
8-Fold Optic Design: Single Sided Structure

- 38 mm effective focal length folded into 5mm track
- 60mm diameter, effective circular aperture = 27.3 mm (20% aperture efficiency)
- Image NA = 0.71
- Single-side features
- Back focal length ~0.5mm

Field Angles
- 0 deg
- 3.3 deg
- -3.3 deg

- FOV = 0.12 rad
- 1280 x 960 pixel
- F/#_{eff} = 1.40
8-Fold Design: Simulated Performance

**Monochromatic MTF**

- Diffraction limited monochromatic performance

- Almost achromatic: Refraction at flat input face
  - ~8 µm lateral color over visible band (CaF2)
  - (Hollow air gap version totally achromatic)

**Monochromatic spot diagram**

- 5 field positions shown (center, mid-way, and corner of imager)
- 3.2 um pixels for size reference
- Monochromatic design diffraction limited (geom. spots misleading)

**Broadspectrum spot diagram**

- 100 nm spectral bandwidth
  - 486 nm, 588 nm, 656 nm

Visible spectra: +/- 1 pixel lateral color from refraction at input face
  - (slight wavelength-dependent magnification)
8-Fold Prototype Fabrication

(1) **Diamond-turn Calcium Fluoride lens blank**
Fresnel Technologies standard process, except that
Entire surface roughed and blackened before fine turning
Key spec is thickness, 5 microns

(2) **Patterned double-sided reflector coating**
Silver metal mirrors done at UCSD plus outside vendor
Dielectric coating from Iridian Spectral Tech is IR cold mirror
Total light throughput is 30% w/o AR coatings and 8 bounces

(3) **Active alignment of CMOS sensor**
Optical bench alignment; key spec is axial (3 microns)
Hard UV adhesive for fixed focus camera
Index matching to CMOS sensor to disable microlenses

(4) **Fully functional fixed-focus camera**
Rigiflex PCB holds all electronics under 1 mm
Strain relief with soft UV epoxy & silicone adhesive
Ready to mount into plastic case

**Fully-packaged prototype**
Including USB interface to PC
Montage Folded Optic Imager Performance Comparison

Conventional Lens
F = 43 mm, F/1.9: >50mm deep
Full 1024x1024 field

Conventional Mini-Cam
1.3 Mpix, f=3.9mm lens: ~5mm deep
Electronic zoom (~80x80 pixels)

Montage 8-Fold Imager
Phase 1 WF-coded: 5mm deep
Full 1024x1024 field

Refractive: Tradeoff magnification for aperture & depth
Folded: Thin cameras with large aperture & magnification

Scene: diorama @ 2.8 m
Compact Surveillance Lens:
Fixed focus at infinity
High resolution at focal plane
Not designed for close range
Depth of Focus / Depth of Field

**Depth of Focus** (Geometrical)

\[
depth \text{ of focus} = \frac{D_{\text{blur}}}{\tan\left(\sin^{-1}\left(\frac{NA}{n}\right)\right)} \approx \frac{D_{\text{blur}} \cdot n}{NA}
\]

Large NA & long focal lengths mean short depth of field

→ Fine for long range (i.e. surveillance) applications

→ Not for nearby/deep object fields (i.e. cellphones)

We want depth of field AND an ultra-compact package!
“Stopping Down” Annular Apertures

Refractive lens  
(35mm, F/1.4)

Off-axis aperture mask  
(same diffraction results)

70% obscured  
(D = 60mm, F = 35 mm)

90% obscured  
(D = 60mm, F = 35 mm)

“Arc-section” aperture mask

Arc-Sectioning: increased depth of field, reduced volume

- 1D loss of resolution w/ very large obscuration
Arc-Sectioned Folded Optic Imager

Modeled performance:
- 38 mm focal length, F/#_{eff} = 3.76
- Asymmetrical PSF and MTF due to diffraction
- Trade light collection and 1D resolution for depth of field and compactness

Geometrical Depth of Field

40 mm, F/1.9 lens (for reference)

Spot at Best focus

Blur at 4% defocus @ 2.5 m

Phase 1 8-Fold Imager

RRMS 0.5 μm

RRMS 20.7 μm (unacceptable)

Arc-Section 8-Fold Imager

RRMS 0.5 μm

RRMS 5.2 μm

PSF

MTF
Prototype Arc-Section Imager

Fabrication:
- Diamond section 50° from round diamond-machined optic
  Aperture is 7.2x smaller than full ring
- Replace metal mirrors w/ dielectric stacks
  Transmission increases from 12% to ~50% (4.2x)

Image sensor:
- Forza/Sunplus 2.1Mpix sensor with 3 μm pixels
- IBM Copper-CMOS process: Thinner
  interconnects & larger sensor area
  → 70% greater energy collection at edge

Optomechanics & package:
- USB interface on sensor PCB
- On-board focus adjustments
## Camera Performance Comparison

<table>
<thead>
<tr>
<th>Camera Type</th>
<th>Lens Details</th>
<th>Image Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conventional Lens</strong></td>
<td>$F = 43, \text{mm}, F/1.9: &gt;50, \text{mm deep}$</td>
<td>Full 1024x1024 field</td>
</tr>
<tr>
<td><strong>Conventional Mini-Cam</strong></td>
<td>1.3 Mpix, f=3.9mm lens: ~5mm deep</td>
<td>Electronic zoom (~80x80 pixels)</td>
</tr>
<tr>
<td><strong>8-Fold Imager</strong></td>
<td>Phase 1 WF-coded: 5mm deep</td>
<td>Full 1024x1024 field</td>
</tr>
<tr>
<td><strong>Arc-Sectioned Imager</strong></td>
<td>Phase 2A raw image: 5mm deep</td>
<td>Full 1024x1024 field</td>
</tr>
</tbody>
</table>

- **Best Focus:** 8% Defocus @ 2.5 m
Resolution Over a 30% deep field: Images

Conventional
Tokina F/1.9
f = 40 mm

-15% ← In focus (2.6 m) → +15%

Full 8-Fold

-15% ← -3.8% In focus (2.72 m) +5.5% → +15%

Arc-Section 8-Fold

-15% ← In focus (2.6 m) → +15%
Resolved Not resolved

**USAF resolution target:**
Measure object space resolution (lp/mm)
Measured both horizontal and vertical resolution

**Imagers:**
- Tokina F/1.9, f = 40 mm
- Montage full 8-fold
- Montage arc-section 8fold

### Horizontal Resolution

![Graph of Horizontal Resolution](image)

### Vertical Resolution

![Graph of Vertical Resolution](image)
Comparison: Canon SD-30 to the Arc-Section Prototype

Canon SD-30 (jpeg!)  Arc-Section Folded Optic (raw)

Canon SD30  Montage Nano

<table>
<thead>
<tr>
<th>Optical track</th>
<th>~30mm</th>
<th>5mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light collection</td>
<td>&lt; 20mm²</td>
<td>80mm²</td>
</tr>
<tr>
<td>Resolution (2.2m range)</td>
<td>~30 lp/mm</td>
<td>100 lp/mm</td>
</tr>
<tr>
<td>Focal length</td>
<td>6.3 – 14.9mm</td>
<td>38mm</td>
</tr>
<tr>
<td>Lens design</td>
<td>Multi-element refractor</td>
<td>Single element folded reflector</td>
</tr>
</tbody>
</table>

Spatial Frequency in object space (cycles/mm)

Horizontal MTF

Montage Folded Optic

- Canon SD30 Compact Camera
- Montage Nano
- Phase 1 Montage 8-Fold
1) Ultra-Thin Imaging Systems: Motivation & Approach
   - The Montage Program
   - Annular folded optics concept
   - Annular folded optics in general

2) 8-Fold Prototype Imagers
   - Symmetric 8-fold imager for UAV/Surveillance
   - Arc-Section 8-fold for portable devices

3) Current work: 4-Fold Imager
   - Symmetric 4-fold design, fabrication and test
   - Long-range imaging with an arc-section (masked) 4-fold

4) Conclusion
8-Fold vs 4-Fold Imagers

8-fold f = 38mm optic

- 6.7° full angle field of view
- Input Aperture
- Planar Mirror
- Omnivision OVT-3610 color CMOS sensor
- Diamond Machined Aspheric Reflectors
- 2 plano-aspheric elements: Dia-machined aspheric reflectors (top and bottom)
- Cross-section

4-fold “Quad” f = 18mm optic

- 16.6° full angle field of view
- 2 elements: Diamond-machined aspheric reflectors (top and bottom)
- 16.6° full angle field of view
- Forza Cu-CMOS 3.0 µm pixel sensor
- Variable gap (focus)

Montage “Quad” imager lens:
- 2 plano-aspheric elements with index-matched gap
- Variable gap focus adjustment
- Pupil phase coding & smaller focal length for increased depth of field

Result: 75% smaller, 38% aperture eff., 7x solid angle
4-Fold Adjustable Focus “Quad” Imager

- Input aperture (38% of surface area)
- "Squeeze" Focus (gap control +/- 20um)
- 5.5 mm
- 28 mm OD, 22mm ID
- “Quad” imager:
  - f = 18 mm, F/#eff = 1.04, NA = 0.7, 16.6° FOV
  - 2.1 megapixel Forza Sensor with 3 μm pixels
  - Adjustable “squeeze” focus from 3m to 10m
  - 11 μm of lateral color (→ remap RGB planes)

Diamond turned parts
Top (input)
Bottom (sensor)

Simulated monochromatic MTF

8/29/2007
PHOTONIC SYSTEMS INTEGRATION LABORATORY – UCSD JACOBS SCHOOL OF ENGINEERING
Quad Prototype: Optomechanics and Electronics

8.9mm overall package depth

Threaded for focus adjuster.

Focus adjuster (120 pitch 168 tooth 303 stainless steel spur gear)

All components on inside of PCB with sensor to minimize overall thickness.

12 tooth Focusing pinion

Ribbon connector high-speed signaling supports full-res video

Connects to USB interface PCB (shown) or multi-camera board

DFC Interactive Camera Environment custom software interface
Full-Quad Imager Performance: Refocus

Quad Imager 3.75 m Quad Imager 2.6 m Quad Imager 0.95 m Scene

Range: 3.75 m
0.63 lp/mm res
Exp: 40.1 ms, Gain: ~2

Range: 2.6 m
0.80 lp/mm
Exp: 40.1 ms, Gain: ~2

Range: 0.95 m
2.0 lp/mm
Exp: 28.7 ms, Gain: ~2

Color & depth scene
Res targets: 7 cm steps
Folded Imagers: Common Scene @ 2.6m Range

4-Fold vs 8-Fold Summary
- Half Diameter
- 2.5x field of view
- 4x depth of field
- Better sensitivity
- ~Half resolution (due to EFL)

Full 8-Fold (Montage Phase 1)
- 6.7° field of view
- EFL = 38 mm
- Omnivision sensor
- Distance: 2.75 m (1.8 lp/mm)
- Exp: 967 ms w/ gain 10
- Depth of Field: ~30 mm

4-fold “Quad”
- 16° field of view
- EFL = 18 mm
- Forza Sensor
- Distance: 2.6 m (0.8 lp/mm)
- Exp: 40 ms w/ gain ~2
- Depth of Field: ~120 mm (4x)
Folded Optics Graduates from the Lab

Scenes from UCSD campus: 2 ms exposure on a cloudy day (full input aperture w/ killflash glare shield)
4-Fold Imager arc-sectioned down to 35 deg

Optical volume: 0.5 cm³

Range: 288 meters

Imager 1: Tripod-mounted
Air temp 46° (115°F)

Imager 2: Camouflaged
Ground temp 53° (127°F)
Field test – 473 meters

4-Fold Imager arc-sectioned down to 35 deg

Imager 1: Tripod-mounted
Air temp 46° (115°F)

Optical volume: 0.5 cm³

Range: 473 meters

Imager 2: Camouflaged
Ground temp 53° (127°F)
1) Ultra-Thin Imaging Systems: Motivation & Approach
   The Montage Program
   Annular folded optics concept
   Annular folded optics in general

2) 8-Fold Prototype Imagers
   Symmetric 8-fold imager for UAV/Surveillance
   Arc-Section 8-fold for portable devices

3) Current work: 4-Fold Imager
   Symmetric 4-fold design, fabrication and test
   Long-range imaging with an arc-section (masked) 4-fold

4) Conclusion
Conclusions

Annular folded imagers

Arc-Section 8-fold

“Quad” 4-fold

8-fold

Full-aperture Annular Folded Optics

• Extremely thin form
• High resolution
• Large light collection

Long-range applications
(e.g., visible & IR surveillance)

Arc-Sectioning of Annular Folded Optics

• Extremely thin & compact
• Large magnification
• Broad depth of field

Miniature general purpose imagers
(mid-range surveillance, cell-phone cameras?)