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
  → Image field diameter = 3.90 mm

- Optical Invariant: image height = tan (semi-FOV)*EFL
  (eg. h = 1.59, 0.1 rad FOV → EFL ≈ 32 mm) …in 5mm track?

Solution Concept: Obscured, Folded Telephoto Lens
Eight-Reflection Lens Design

- 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
- FOV = 0.12 rad
- 1280 x 960 pixel
- F/#eff = 1.40

Top Award, Optical Research Associates’ Student Optical Design Competition (2005)
Simulated Performance

• 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)
Lens Fabrication and First Results

(1) **Diamond-turn 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 by 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
Hard UV adhesive for fixed focus camera
Index matching to CMOS sensor to disable microlenses

**Results:**

- PMMA Test
- 1st CaF₂ Lens (thickness errors)
- 2nd CaF₂ Lens
- Zemax Prediction
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

Thickness comparison with equivalent conventional camera

Measured Modulation Transfer Function

- Conventional Comparison Lens
- CaF$_2$ 8-Ref. Lens

Spatial Frequency (lp/mm)
- 0
- 20
- 40
- 60
- 80
- 100
- 120

lp/mm
- 0
- 0.1
- 0.2
- 0.3
- 0.4
- 0.5
- 0.6
- 0.7
- 0.8
- 0.9
- 1

Fully-packaged prototype
Including USB interface to PC
(package by DFC)
Deep Color Test Scene
- Stacked resolution targets
- 2.5m distance with 7 cm steps
- Plus color textbook
- Fluorescent illumination

Conventional imager for comparison
- Tokina F/1.2 zoom 12.5-75mm, set to 40 mm
- Aperture constrained to 35 mm diameter
- Identical CMOS sensor and interface board
Resolution and Color Image Comparison

Conventional Tokina lens

Unprocessed 8-Reflection Lens

+7cm

Focus (250 cm)

-7cm

-14cm

Spatial resolution: Similar at ~120 lines/mm

Color fidelity: Identical (following standard post-detection color balancing)

Depth of field: CMR lens (right) is revealed by defocus (NA = 0.7)
Thermal testing

Thermal test setup:
- Same stepped target & lighting as resolution & depth of field test
- Images taken through uncoated oven door window
- Camera heated from 77°F to 140°F, and cooled to about 50°C with ice.

25°C (before heating)  
After 90 minutes at 60°C  
23°C (after cooldown)

Results from testing lab prototype camera
- Minor lens defocus (~1% closer) from initial position, plus slight tilt due to plastic hinge.
- CMOS imager has strong color variation (images shown corrected by autobalancing in photoshop)
- No apparent damage to camera after testing