Liquid crystal lens focusing in monocentric multiscale imagers

Igor Stamenov¹, Eric Tremblay², Katherine A. Baker¹, Paul McLaughlin³
and Joseph E. Ford¹

¹University of California San Diego Jacobs School of Engineering, ²Ecole Polytechnique Fédérale de Lausanne, ³RPC Photonics, Rochester

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Wide field of view surveillance

Standard approach:
Mechanical sweep over full scene
Time / resolution tradeoff

Reverse telephoto or Fisheye lens:
Limited angular resolution / sensitivity

Multi aperture + image stitching system:
Physical volume / resolution tradeoff
First monocentric panoramic lenses

(1859) Thomas Sutton
Water filled Panoramic ball lens

(1942) Baker ball lens (U2 spy plane)

100-110° F#/10-30

120° F#/3.5

DARPA's "AWARE" Wide Field Imaging Project (MOSAIC)

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

Lens design (UCSD)
Objective Lens
226 14 MPix microcams
Optomechanics (Jungsang Kim)
Microcamera
1st (partial) image, August 2011

David Brady (team lead)

The Duke Imaging and Spectroscopy Program: www.disp.duke.edu
- Up to 226 microcameras on a spherical image plane
- Each with a 14MPix focal plane, full scene is stitched
- Focusing via servo motor translation of sensor

Independent focusing challenge
AWARE2 focusing mechanism

Original fabricated MC0 design (mechanical focusing)

"Electronic" focus option (Liquid crystal lens)

70μm sensor movement (∞÷15m object distance)

LC optical power needed for refocus
“Electronic” focus options

Liquid Lens

Membrane (e.g., Optotune):
- Full 10 mm aperture in available products
- Liquid reservoir adds bulk
- Good option for larger microcameras

Liquid crystal

Liquid crystal (e.g., LensVector):
- Dielectric layer over planar LC (E-field shaping)
- Limited ~2.5mm aperture of available products
- Ideal for wafer-scale integration
- Potential for higher-level aberration correction

[Diagram of Optotune liquid lens and LensVector liquid crystal]
Research goal is multiscale system integration

Large scale MMC using thousands of (cheap) WLC: ~10GPix
Miniaturized MMC hundreds of (small) WLC : ~100MPix

This talk:
Characterization of wafer-level LC focus in monocentric multiscale optics
LensVector liquid crystal lens focusing

**Lens Vector**
**Auto Focus**
crystal lens

LV5830 with USB controller board
0-5dP range
(1dP=1/m)
AWARE2 focusing mechanism

Original fabricated MC0 design (mechanical focusing)

6.4mm stop

70μm sensor movement (∞/15m object distance)

"Electronic" focus option (Liquid crystal lens)

2.3mm stop

Vignetting from 2.3 mm LVAF aperture

Partial image

Full image

LC optical power needed for refocus

2.3mm stop

6.4mm stop

L1 L2 L3 L4

L1 L2 L3 L4

Focus distance (m)

LV power (dP)
- For focal distances $>2F_{\text{min}}$ spherical aberration can be compensated efficiently.

- LC lens affects only one polarization component of light; combination of two LC lenses can be used to make a polarization-independent device.

- Calibrated lens with calibration data for a function generator driving is available.

http://www.okotech.com/lclenses

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength region</td>
<td>0.44...2 $\mu$m</td>
</tr>
<tr>
<td>Transmittance (without antireflection)</td>
<td>about 70%</td>
</tr>
<tr>
<td>Reflection range</td>
<td>below 10 V, typically 3...6 V</td>
</tr>
<tr>
<td>Geometry</td>
<td>cylindrical or spherical</td>
</tr>
<tr>
<td>Geometry</td>
<td>1...50 kHz</td>
</tr>
<tr>
<td>Switching speed</td>
<td>780 ms from 1 to 2 m focal distance, 860 ms from 2 to 1 m</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Configuration</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
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<tbody>
<tr>
<td>LC thickness ($d$, $\mu$m)</td>
<td>40</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Aperture diameter ($D$, mm)</td>
<td>5</td>
<td>5</td>
<td>7.8</td>
<td>5</td>
</tr>
<tr>
<td>External diameter, mm</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>$F_{\text{min}}$, cm</td>
<td>27.9</td>
<td>22.3</td>
<td>60.2</td>
<td>22.3</td>
</tr>
<tr>
<td>Type</td>
<td>spherical</td>
<td>spherical</td>
<td>spherical</td>
<td>cylindrical</td>
</tr>
</tbody>
</table>
LVAF characterisation

Lens Vector LV Driver Demo V3.5 suite

LVAF interferograms and measured optical power

<table>
<thead>
<tr>
<th>Interferogram</th>
<th>Fringe Count</th>
<th>Nominal lens power [dP]</th>
<th>Measured power [dP]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 – 0.00dP</td>
<td>5</td>
<td>10.75</td>
<td>5.4</td>
</tr>
<tr>
<td>2 – 0.25dP</td>
<td>4</td>
<td>8.75</td>
<td>4.3</td>
</tr>
<tr>
<td>3 – 0.50dP</td>
<td>3</td>
<td>6.50</td>
<td>3.2</td>
</tr>
<tr>
<td>4 – 0.75dP</td>
<td>2</td>
<td>4.50</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1.75</td>
<td>1.0</td>
</tr>
<tr>
<td>44 – 10.75dP</td>
<td>0-1(?)</td>
<td>1.50</td>
<td>0-0.75 (?)</td>
</tr>
<tr>
<td>44 – 10.75dP</td>
<td>1</td>
<td>1.00</td>
<td>-1(?)</td>
</tr>
<tr>
<td>44 – 10.75dP</td>
<td>2</td>
<td>0.75</td>
<td>-2.2</td>
</tr>
<tr>
<td>44 – 10.75dP</td>
<td>2+</td>
<td>0.50</td>
<td>-2.3 (?)</td>
</tr>
<tr>
<td>44 – 10.75dP</td>
<td>2+</td>
<td>0.00</td>
<td>-2.2 (?)</td>
</tr>
</tbody>
</table>
Exploded MC0 lens system

Keyence VHX-1000 digital microscope

MC lens

Collimator

Imatest test reticle

Collimated LED light source

Results obtained by Imatest Master 3.6
AWARE2 + LVAF exploded lens setup

Exploded MC0 lens system

Results obtained by Imatest Master 3.6

Object at ∞ / without LVAF

MTF50 = 79.1 Cy/mm
MTF30 = 113 Cy/mm
MTF10 = 228 Cy/mm

MTF: Vertical

Object at ∞ / with LVAF at 0dP

MTF50 = 74.8 Cy/mm
MTF30 = 111 Cy/mm
MTF10 = 193 Cy/mm

MTF: Vertical

Results obtained by Imatest Master 3.6
MC0 slotted lens barrel
# AWARE2 + LVAF setup indoors results

MTF falloff with object distance decrease (LVAF focused to infinity)

![Graph showing MTF50 and MTF30 as a function of object conjugate](image)

MTF value change when LC refocusing (LVAF at best focus)

![Graph showing MTF50 as a function of object conjugate](image)

## LC optical power needed for refocus

- **ZEMAX simulation**
- **Experimental results**

<table>
<thead>
<tr>
<th>Object distance</th>
<th>Measured lens power [dP]</th>
<th>MTF50 [C/μm]</th>
<th>MTF30 [C/μm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infinity (no LVAF)</td>
<td>-</td>
<td>83.8</td>
<td>121</td>
</tr>
<tr>
<td>Infinity</td>
<td>1.13</td>
<td>62.2</td>
<td>107</td>
</tr>
<tr>
<td>30m</td>
<td>1.25 (+0.12)</td>
<td>63</td>
<td>105</td>
</tr>
<tr>
<td>15m</td>
<td>1.38 (+0.25)</td>
<td>63.9</td>
<td>107</td>
</tr>
<tr>
<td>8m</td>
<td>1.63 (+0.50)</td>
<td>63.3</td>
<td>106</td>
</tr>
<tr>
<td>4m</td>
<td>2.38 (+1.25)</td>
<td>57.4</td>
<td>97.8</td>
</tr>
<tr>
<td>3m</td>
<td>2.88 (+1.75)</td>
<td>50.3</td>
<td>90.3</td>
</tr>
<tr>
<td>2m</td>
<td>3.25 (+2.12)</td>
<td>36.4</td>
<td>61.8</td>
</tr>
<tr>
<td>1.7m</td>
<td>4.63 (+3.50)</td>
<td>35.4</td>
<td>57.4</td>
</tr>
</tbody>
</table>

MTF performance data of refocused system for different object distances.
MTF falloff with object distance decrease (LVAF focused to infinity)

MTF value change when LC refocusing (LVAF at best focus)

MTF percent increase with LVAF refocusing

AWARE2 + LVAF setup indoors results

Object @ ≈3m (lens 1.13dP) NOT FOCUSED

Object @ ≈3m (lens 2.88dP (+ 1.75dP) FOCUSED
Top of the CALIT2 building, Jacobs School of Engineering, UCSD.
AWARE2 + LVAF setup outdoors results

Focus at 500m (LVAF @1.13dP)

Focus at 14m (LVAF @1.38dP (+0.25dP))

Focus at 2m (LVAF @3.38dP (+2.25dP))
Next steps

2.5mm stop
Smaller AWARE2
secondary optics
aperture

AWARE2 all glass design
(Dan Marks at Duke, with Rochester Photonics and Moondog Optics)

Smaller MMC+WLC
integrated systems
Conclusions

• Liquid crystal tunable lens are a viable option for focus of monocentric multiscale imagers.

• Monocentric imagers integrating WLC with LC focusing is an attractive future research direction.

This work was done in collaboration with the AWARE research team, lead by David Brady of Duke University, including Dan Marks, Jungsang Kim, Ron Stack, and many others, and supported by DARPA MTO through contract HR0011-10C-0073.