Focus tunable lenses
And how to use them in machine vision

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Agenda

- Introduction
  - How to combine ELs with off-the-shelf optics
    - Endocentric lenses
    - Telecentric lenses
    - Microscopy
  - Custom designs
  - Drivers & software
  - Optotune’s standard lenses
Founded 2008

Leader in tunable optics

29 sales partners in 33 countries

185 employees

HQ located in Zurich, Switzerland
Factory in Trnava, Slovakia

Privately owned
Working principle based on membrane and fluid

Mechanically tunable lens

Electrically tunable lens

Videos available on www.optotune.com
**Tunable lenses offer a natural focusing solution**

**Fixed focus optics**
- Image sensor
- Lens with fixed focal length

**Optotune approach**
- Image sensor
- Larger lens with **variable focal length**

**Benefits**
- Larger working distance range
- Faster recognition
- Less lighting required thanks to smaller F#
- Easier installation
Focus tunable polymer lenses are fast

**Figure 12:** Typical optical response of the EL-10-30-C to a current step.

**Figure 13:** Typical frequency response of the EL-10-30-C with current oscillating from 50 to 150 mA.

150 Hz focus oscillation → fast image stacking
Demonstration at VISION Stuttgart

https://youtu.be/PRQ5XjLPzfk
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  - Microscopy

- Custom designs

- Drivers & software

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## Four main configurations for machine vision

<table>
<thead>
<tr>
<th>Endocentric lenses</th>
<th>Telecentric lenses</th>
<th>Microscopy</th>
</tr>
</thead>
</table>

- **Endocentric lenses**
  - Mounted on filter thread
  - Working distances typically long (from 100mm to infinity)

- **Telecentric lenses**
  - Tunable lens acts like a distance ring
  - Working distances typically short (from 50mm to 500mm)
  - EL integrated close to aperture stop
  - Magnifications: from 0.13X to 4X

- **Microscopy**
  - Up to 100x magnification
  - Design options with or without mag change

### Position of tunable lens:
- **Front**
- **Back**
- **Middle**

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  – Microscopy
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Front-lens configuration typically for large working distances

- C-mount camera
- C- to S-Mount adapter
- 12mm board lens
- EL-10-30-C-VIS-LD-MV
- C- to S-Mount adapter
- 12mm board lens
- EL-10-30-C-VIS-LD-MV

Fixed focal length lens

EL-16-40-TC-VIS-5D-M25.5
- M27
- M30.5

Working distance ranges from infinity to about 100mm
EL-16-40 on Schneider Topaz lenses is optimal for 1.1” 12MP sensors

- Lumenera LT1265R camera
- 1” 12 mega pixel sensor
- 3.1um pixel size
- No vignetting

Schneider Xenon-Topaz lenses:
- 30, 38 & 50mm available
- 1.1” sensors & 3um pixel sizes
- M30.5 filter thread

Optical power is measured in diopters \( D = \frac{1}{f} \)

Optical power (dpt) is linear with current

- Vertical offset depends on liquid fill level
- Inclination depends on membrane stiffness

Optical power can be added arithmetically

### Thin lens equation:

\[
\frac{1}{f_{\text{res}}} = \frac{1}{f_1} + \frac{1}{f_2}
\]

\( D_{\text{res}} = D_1 + D_2 \)

Simple math in front lens configuration:

\[
\frac{1}{WD_{\text{res}}} = \frac{1}{WD_0} + D_{\text{EL}}
\]

**Examples:**
- \( WD_0 = \text{infinity}, \ D_{\text{EL}} = 5 \rightarrow WD_{\text{res}} = 1/5\text{m} \)
- \( WD_0 = 0.5\text{m}, \ D_{\text{EL}} = -2 \rightarrow WD_{\text{res}} = \text{infinity} \)
- \( WD_0 = 0.5\text{m}, \ D_{\text{EL}} = 3 \rightarrow WD_{\text{res}} = 1/5\text{m} \)
How to calculate working distance in front lens configuration

### Working distances for different lens settings (mm)

<table>
<thead>
<tr>
<th>Tunable lens optical power</th>
<th>Imaging lens WD (MOD setting, in mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>3</td>
<td>77</td>
</tr>
<tr>
<td>2</td>
<td>83</td>
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<tr>
<td>1</td>
<td>91</td>
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<tr>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>-1</td>
<td>111</td>
</tr>
<tr>
<td>-2</td>
<td>125</td>
</tr>
<tr>
<td>-10</td>
<td>∞</td>
</tr>
</tbody>
</table>

\[
\frac{1}{WD_{res}} = \frac{1}{WD_0} + D_{EL}
\]

A typical configuration would be to set the imaging lens to 0.5m so that the WD can range from infinity to 200mm with Optotune’s EL-16-40 going from -2 to +3 diopters, respectively.
The EL in front leads to vignetting at HFOV > 28°

Front-lens configuration

- **C-mount camera**
- **C-mount lens**
  - Filter threads: M25.5, M27, & M30.5

**EL-16-40-TC-VIS-5D**
- **M25.5**
- **M27**
- **M30.5**

<table>
<thead>
<tr>
<th>2/3” 1.4/12mm C</th>
<th>2/3”</th>
<th>1/1.8”</th>
<th>1/2”</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FOCAL LENGTH</strong></td>
<td>f=12mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>MAX. DIAMETER (RATIO)</strong></td>
<td>F=1:1.4~Close</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>PICTURE SIZE</strong></td>
<td>6.6x8.8mm</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>ANGLE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>VER. ANGLE</strong></td>
<td>29.1°</td>
<td>24.0°</td>
<td>21.4°</td>
</tr>
<tr>
<td><strong>HOR. ANGLE</strong></td>
<td><strong>38.3°</strong></td>
<td>31.7°</td>
<td><strong>28.3°</strong></td>
</tr>
<tr>
<td><strong>DIA. ANGLE</strong></td>
<td>46.8°</td>
<td>39.4°</td>
<td>35.0°</td>
</tr>
</tbody>
</table>
## Configuration table for endocentric lenses

<table>
<thead>
<tr>
<th>Sensor format &amp; camera</th>
<th>Imaging lens focal length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>&lt;6</td>
</tr>
<tr>
<td>1/4”</td>
<td></td>
</tr>
<tr>
<td>S-mount</td>
<td>30°</td>
</tr>
<tr>
<td>C-mount</td>
<td></td>
</tr>
<tr>
<td>1/3”</td>
<td>44°</td>
</tr>
<tr>
<td>S-mount</td>
<td></td>
</tr>
<tr>
<td>C-mount</td>
<td></td>
</tr>
<tr>
<td>1/2”</td>
<td>56°</td>
</tr>
<tr>
<td>S-mount</td>
<td></td>
</tr>
<tr>
<td>C-mount</td>
<td></td>
</tr>
<tr>
<td>2/3”</td>
<td>73°</td>
</tr>
<tr>
<td>C-mount</td>
<td></td>
</tr>
<tr>
<td>1”</td>
<td>74°</td>
</tr>
<tr>
<td>C-mount</td>
<td></td>
</tr>
<tr>
<td>30mm diag.</td>
<td>128°</td>
</tr>
<tr>
<td>M42-mount</td>
<td></td>
</tr>
</tbody>
</table>

**Front lens configuration only**

**Back lens configuration only**

- Not possible
- Possible with custom optics design
- Vignetting with off-the-shelf lenses
- Possible with OTS lenses
Large FOV for small sensors with 7.2mm S-mount lens & EL-16-40-TC

C-mount camera with up to 1/2.3” format sensor

Inside:
- S- to C-mount adapter AD04M
- Lensation B10M7224 7.2mm S-mount lens
- 15mm C-mount spacers
- EL-16-40-TC-VIS-5D-C

~160 lp/mm → Suitable for 2um pixel size!

53° HFOV with 1/2.5” sensor

Example for short WD

Working distance from lens (mm) vs. HFOV with 1/2.5” sensor (mm)
Typical applications for front lens configuration

Barcode reading

Robot vision

Package sorting

Bottle inspection
Back-lens configuration for C-mount lenses for macro imaging

C-mount camera

Optotune lens
EL-10-30-Ci-VIS-LD-MV or EL-16-40-TC-VIS-5D-C

50mm lens e.g. Tamron 23FM50SP

This only works for lenses with focal length >= 35mm

<table>
<thead>
<tr>
<th>Results</th>
<th>EL-10-30</th>
<th>EL-16-40</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>50mm lens focus</td>
<td>∞</td>
<td>∞</td>
<td>mm</td>
</tr>
<tr>
<td>Magnification</td>
<td>0.4x</td>
<td>0.4x</td>
<td>mm</td>
</tr>
<tr>
<td>WD @0dpt</td>
<td>160</td>
<td>200*</td>
<td>mm</td>
</tr>
<tr>
<td>Z range</td>
<td>25</td>
<td>40*</td>
<td>mm</td>
</tr>
<tr>
<td>HFOV @0dpt on 1/2” sensor</td>
<td>18</td>
<td>20</td>
<td>mm</td>
</tr>
</tbody>
</table>

*280-420mm WD possible with Schneider Kreuznach Topaz 50mm & custom adapter
Optimized back lens configuration with Xenon Topaz 50mm lens

- C-mount camera with 1” sensor
- 5mm C-mount spacer
- Optotune EL-16-40-TC-VIS-5D-C
- C-mount adapter from Xenon Topaz 38mm*
- Schneider Kreuznach Xenon Topaz 50mm

**WD range:** ~70mm

<table>
<thead>
<tr>
<th>Optical power</th>
<th>WD from lens</th>
<th>HFOV on 1” sensor</th>
<th>PMAG</th>
<th>Resolution on Object</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3.6 dpt</td>
<td>204mm</td>
<td>44mm</td>
<td>0.28X</td>
<td>17um</td>
</tr>
<tr>
<td>-2 dpt</td>
<td>186mm</td>
<td>42mm</td>
<td>0.30X</td>
<td>16um</td>
</tr>
<tr>
<td>0 dpt</td>
<td>166mm</td>
<td>40mm</td>
<td>0.31X</td>
<td>15um</td>
</tr>
<tr>
<td>3 dpt</td>
<td>138mm</td>
<td>36mm</td>
<td>0.34X</td>
<td>14um</td>
</tr>
<tr>
<td>4.7 dpt</td>
<td>128mm</td>
<td>35mm</td>
<td>0.35X</td>
<td>14um</td>
</tr>
</tbody>
</table>

Optical leverage: 7-10mm/dpt

*The C-mount adapter of the Xenon Topaz 38mm lens is about 5mm shorter than the adapter of the 50mm lens. Hence the back flange distance of the 50mm lens is reduced, bringing it closer to the tunable lens and camera, which results in higher optical leverage of this configuration that with standard 50mm C-mount lenses.
Image circles of 30mm possible

- WD range: from 1100mm to 380mm @ -2Dpt to 3Dpt
- Distortion unchanged
- Resolution equally good
- No added vignetting

13mm of spacers M42x0.1
EL-16-40-TC-VIS-M42
8mm spacer
Apo-Componon
60mm lens

Without EL  
With EL-16-40

F4
F8

30mm

Test report available online: http://www.optotune.com/applications/machine-vision
Note: Infinite focus is possible by using only 8mm instead of 13mm of spacers at the back.
Low distortion 1x solution for large sensors

- Large z-range of 57mm achieved with +/-2 dpt
  - Optical leverage is ~14mm per diopter
- Magnification changes slightly with 0.5% per mm of WD change
- Slight vignetting at F4, no vignetting at F5.6 or higher
- No distortion measurable at 0 dpt and 1 dpt
- Nominal resolution of ~64lp/mm is maintained after adding EL-16-40 when optical axis is vertical
- In Horizontal optical axis a resolution of ~57lp/mm can be achieved by stopping the lens down to F11

95mm of M42 spacers
EL-16-40-TC-VIS-5D-M42
11m long M42 spacer
M39 to M42 adapter
Apo Rodagon D1x 75mm F/4 lens*

Test report available online: [http://www.optotune.com/applications/machine-vision](http://www.optotune.com/applications/machine-vision)
* by Linos (formerly Rodenstock)
Focal lengths of 150mm or 300mm with EL-16-40 are ideal for imaging via galvos in laser processing

Example: EL-16-40-TC-VIS-5D-M42 integrated behind aperture of Sill Optics S5LPJ9034 150mm lens

Example: EL-16-40-TC-VIS-5D-M42 integrated in Sill Optics S5LPJ0303 300mm lens

Drawing: http://www.silloptics.de/fileadmin/user_upload/Downloads/Outline/S5LPJ9034.PDF
Typical applications for back lens configuration

- Electronics inspection
- Laser processing
- Contact lens inspection
- Diamond inspection
Online lens configurator for endocentric lenses

http://configurator.optotune.com
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Telecentric lenses preferably integrate the EL to achieve large Z-ranges

Moritex MML1-ST150D with integrated EL-16-40
- 15mm Z-range
- <5% mag change

Moritex MML2-HR110 with integrated EL-16-40
- 5.5mm Z-range
- <8% mag change

Std back-lens configuration
\[ \text{OL} \approx 0.5 [\text{mm/dpt}] / \text{PMAG}^2 \]

EL above aperture stop

Optical leverage vs. Magnification chart

1x  2x  10x
Optimized 2X telecentric lens for large formats

Tubes:
- M42 tube required for large format sensors
- C-mount tube ok for sensors up to 20mm in diagonal (as shown)

Optotune EL-16-40-TC

Sill Optics Correctal T/2.0

- 30mm image circle
- Large WD range: 105 +/-5mm
  - EL tuning from -2 to +3 dpt
- 4.5% mag change over full range
  - 0.45% per mm
- Resolution close to diffraction limit reaching 90lp/mm

Without EL

With EL-16-40

USAF group element: 7/4
Lp/mm (object): 181
Lp/mm (image): 90

Sill Optics offers variable focus telecentric lenses from 0.13X to 3.0X

<table>
<thead>
<tr>
<th>part number</th>
<th>magnification</th>
<th>working distance [mm]</th>
<th>clear aperture [mm]</th>
<th>max. sensor size [mm]</th>
<th>wavelength [nm]</th>
<th>NA</th>
<th>max. distortion [%]</th>
<th>length [mm]</th>
<th>mount</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSVPJ1860</td>
<td>0.133</td>
<td>79.7 – 434.1</td>
<td>153</td>
<td>16.0 (1&quot;)</td>
<td>450 - 680</td>
<td>0.01</td>
<td>0.35</td>
<td>587.0</td>
<td>C-mount</td>
</tr>
<tr>
<td>SSVPJ5060</td>
<td>0.192</td>
<td>215.3 – 366.6</td>
<td>83</td>
<td>11.0 (2/3&quot;)</td>
<td>450 - 680</td>
<td>0.01</td>
<td>0.7</td>
<td>357.6</td>
<td>C-mount</td>
</tr>
<tr>
<td>SSVPJ1565</td>
<td>0.193</td>
<td>193.6 – 338.7</td>
<td>123</td>
<td>16.0 (1&quot;)</td>
<td>450 - 680</td>
<td>0.01</td>
<td>0.5</td>
<td>396.3</td>
<td>C-mount</td>
</tr>
<tr>
<td>SSVPJ6060 *</td>
<td>0.289</td>
<td>137.4 – 205.8</td>
<td>86</td>
<td>16.0 (1&quot;)</td>
<td>450 - 680</td>
<td>0.02</td>
<td>0.5</td>
<td>283.4</td>
<td>C-mount</td>
</tr>
<tr>
<td>SSVPJ1260</td>
<td>0.311</td>
<td>155.1 – 211.2</td>
<td>62</td>
<td>16.0 (1&quot;)</td>
<td>450 - 680</td>
<td>0.02</td>
<td>0.45</td>
<td>241.2</td>
<td>C-mount</td>
</tr>
<tr>
<td>SSVPJ3060</td>
<td>0.343</td>
<td>133.1 – 184.4</td>
<td>58</td>
<td>8.9 (1/1.8&quot;)</td>
<td>450 - 680</td>
<td>0.02</td>
<td>0.4</td>
<td>224.9</td>
<td>C-mount</td>
</tr>
<tr>
<td>SSVPJ2660 *</td>
<td>0.374</td>
<td>133.4 – 172.8</td>
<td>48</td>
<td>11.0 (2/3&quot;)</td>
<td>450 - 680</td>
<td>0.02</td>
<td>0.65</td>
<td>203.5</td>
<td>C-mount</td>
</tr>
<tr>
<td>SSVPJ2060</td>
<td>0.499</td>
<td>102.8 – 125.5</td>
<td>29</td>
<td>8.0 (1/2&quot;)</td>
<td>450 - 680</td>
<td>0.02</td>
<td>0.3</td>
<td>162.7</td>
<td>C-mount</td>
</tr>
<tr>
<td>SSVPJ2898 *</td>
<td>0.578</td>
<td>81.8 – 98.2</td>
<td>60</td>
<td>16.0 (1&quot;)</td>
<td>450 - 680</td>
<td>0.03</td>
<td>0.5</td>
<td>161.7</td>
<td>C-mount</td>
</tr>
<tr>
<td>SSVPJ1560</td>
<td>0.659</td>
<td>79.2 – 91.6</td>
<td>28</td>
<td>8.0 (1/2&quot;)</td>
<td>450 - 680</td>
<td>0.03</td>
<td>0.36</td>
<td>133.9</td>
<td>C-mount</td>
</tr>
<tr>
<td>SSVPJ0625 *</td>
<td>1.000</td>
<td>179.1 – 196.5</td>
<td>29</td>
<td>16.0 (1&quot;)</td>
<td>450 - 680</td>
<td>0.03</td>
<td>0.8</td>
<td>142.5</td>
<td>C-mount</td>
</tr>
<tr>
<td>SSVPJ0627</td>
<td>1.500</td>
<td>152.4 – 172.3</td>
<td>29</td>
<td>21.4 (1.25&quot;)</td>
<td>450 - 680</td>
<td>0.04</td>
<td>0.45</td>
<td>179.2</td>
<td>C-mount</td>
</tr>
<tr>
<td>SSVPJ0422 *</td>
<td>2.000</td>
<td>100.5 – 109.8</td>
<td>26</td>
<td>32.0</td>
<td>450 - 680</td>
<td>0.04</td>
<td>0.6</td>
<td>133.4</td>
<td>M42x1</td>
</tr>
<tr>
<td>SSVPJ0422/216</td>
<td>2.000</td>
<td>100.5 – 109.8</td>
<td>26</td>
<td>16.0 (1&quot;)</td>
<td>450 - 680</td>
<td>0.04</td>
<td>0.6</td>
<td>156.0</td>
<td>C-mount</td>
</tr>
<tr>
<td>SSVPJ0426</td>
<td>2.500</td>
<td>94.8 – 104.6</td>
<td>26</td>
<td>35.0</td>
<td>450 - 680</td>
<td>0.05</td>
<td>0.4</td>
<td>160.2</td>
<td>M42x1</td>
</tr>
<tr>
<td>SSVPJ0420</td>
<td>3.000</td>
<td>91.2 – 101.2</td>
<td>26</td>
<td>35.0</td>
<td>450 - 680</td>
<td>0.06</td>
<td>0.2</td>
<td>186.1</td>
<td>M42x1</td>
</tr>
</tbody>
</table>

* Lenses also supported by Coaxial illumination
Edmund Optics offers variable focus telecentric lenses from 0.15X to 0.75X

**MercuryTL™ Liquid Lens Telecentric Lenses**

- EL-10-30-Ci-VIS-LD-MV integrated behind aperture stop
- Demo video: [https://youtu.be/36qzwzmfCriM](https://youtu.be/36qzwzmfCriM)

<table>
<thead>
<tr>
<th>Primary Magnification PMAG</th>
<th>Camera Sensor Format recommended &amp; maximum</th>
<th>FOV @ 1/2&quot; Sensor Format</th>
<th>Aperture (f/#)</th>
<th>Working Distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.15X</td>
<td>1/2&quot;</td>
<td>41.2 x 30.9</td>
<td>f/10</td>
<td>169 – 265</td>
</tr>
<tr>
<td>0.24X</td>
<td>1/2&quot;</td>
<td>26.5 x 19.9</td>
<td>f/10</td>
<td>91 – 173</td>
</tr>
<tr>
<td>0.37X</td>
<td>1/2&quot; (2/3&quot;)</td>
<td>17.3 x 13.0</td>
<td>f/10</td>
<td>84 – 101</td>
</tr>
<tr>
<td>0.75X</td>
<td>1/2&quot; (2/3&quot;)</td>
<td>8.7 x 6.5</td>
<td>f/10</td>
<td>85 – 99</td>
</tr>
</tbody>
</table>

VST offers variable focus telecentric lenses from 1x to 4x

- EL-16-40-TC-VIS-5D-C integrated behind aperture stop

<table>
<thead>
<tr>
<th>Primary Magnification PMAG</th>
<th>Model</th>
<th>Camera Sensor Format</th>
<th>FOV @ 2/3&quot; Sensor Format</th>
<th>Aperture (f/#)</th>
<th>Resolution on object (um)*</th>
<th>Working Distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1X (0.9–1.0)</td>
<td>VS-THV1-110_S-LQL1</td>
<td>1”</td>
<td>7.5 x 8.8</td>
<td>f/10</td>
<td>5.5</td>
<td>106.1 – 120.2</td>
</tr>
<tr>
<td>2X (1.8–2.0)</td>
<td>VS-THV2-110_S-LQL1</td>
<td>1”</td>
<td>3.8 x 4.4</td>
<td>f/9.6</td>
<td>TBD</td>
<td>105.4 – 115.6</td>
</tr>
<tr>
<td>2X (1.91–2.03)</td>
<td>VS-TCH2-65-LQL1</td>
<td>2/3”</td>
<td>3.8 x 4.4</td>
<td>f/13.5</td>
<td>TBD</td>
<td>63.5 – 66.1</td>
</tr>
<tr>
<td>4X (3.7–4.0)</td>
<td>VS-TCH4-65CO-LQL1</td>
<td>2/3”</td>
<td>1.9 x 2.2</td>
<td>f/17.5</td>
<td>TBD</td>
<td>64.7 – 65.3</td>
</tr>
</tbody>
</table>


* Resolution is measured using red light with USAF target at a contrast of about 30% contrast
Linkhou offers variable focus bi-telecentric lenses from 0.36x to 2.0x

- EL-16-40-TC-VIS-5D-C integrated in front of aperture stop

<table>
<thead>
<tr>
<th>Primary Magnification (PMAG)</th>
<th>Model</th>
<th>Camera Sensor Format</th>
<th>FOV @ max Sensor Format</th>
<th>Aperture (f/#)</th>
<th>Resolution on object (um)*</th>
<th>Working Distance (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.36X</td>
<td>TCPLP23-036-115</td>
<td>2/3”</td>
<td>23.5 x 19.6</td>
<td>f/4.5</td>
<td>8.7</td>
<td>115 +/- 15</td>
</tr>
<tr>
<td>0.6X</td>
<td>TCPLP23-06-115</td>
<td>2/3”</td>
<td>14.1 x 11.8</td>
<td>f/4.5</td>
<td>6.9</td>
<td>115 +/- 10</td>
</tr>
<tr>
<td>1.0X</td>
<td>TCPLP23-1.0-110</td>
<td>2/3”</td>
<td>8.5 x 7.1</td>
<td>f/10</td>
<td>5.9</td>
<td>106 – 116</td>
</tr>
<tr>
<td>2.0X</td>
<td>TCPLP23-2.0-110</td>
<td>2/3”</td>
<td>4.2 x 3.5</td>
<td>f/16</td>
<td>5.0</td>
<td>108 – 112</td>
</tr>
</tbody>
</table>

* Resolution is measured using white light with USAF target at a contrast of about 30% contrast
Typical applications for telecentric lenses

Camera phone lens inspection

IC inspection
Agenda

• Introduction

• How to combine ELs with off-the-shelf optics
  – Endocentric lenses
  – Telecentric lenses
  – Microscopy

• Custom designs

• Drivers & software

• Optotune’s standard lenses
Two most typical microscopy configurations

<table>
<thead>
<tr>
<th>Non-telecentric</th>
<th>Telecentric</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Tunable lens right above objective lens (infinity corrected lenses are preferred)</td>
<td>• Tunable lens at intermediary pupil position of a relay</td>
</tr>
<tr>
<td>• Largest Z-range, but with mag change</td>
<td>• Smaller Z-range, but no mag change</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Z-range (typical)</th>
<th>Mag change</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>10x</strong></td>
<td>2560 μm (20D: 10240 μm)</td>
<td>7.5 %</td>
</tr>
<tr>
<td><strong>20x</strong></td>
<td>640 μm (20D: 2560 μm)</td>
<td>12.2%</td>
</tr>
<tr>
<td><strong>40x</strong></td>
<td>160 μm (20D: 640 μm)</td>
<td>23.7%</td>
</tr>
</tbody>
</table>
Optem Fusion industrial microscope with EL-16-40-TC autofocus module

- The zoom is parfocal as the EL is placed BELOW the zoom.

http://www.qioptiq.com/optem-fusion-lens, Optem® is a registered trademark of Qioptiq, Inc
Mvotem industrial microscope with EL-16-40-TC autofocus module

- The zoom is parfocal as the EL is placed BELOW the zoom
- Lens driver fully integrated into system software
- Video: https://youtu.be/ZZFe3hq9JwM

High mag
Edmund optics dynamic focus VZM with the EL-10-30-Ci-VIS-LD-MV integrated

- Very large focus range as EL is placed close to aperture stop
- The zoom is NOT parfocal, however, as the EL is placed above the zoom

<table>
<thead>
<tr>
<th>Magnification setting</th>
<th>0.75X</th>
<th>1X</th>
<th>2X</th>
<th>3X</th>
<th>4X</th>
<th>4.5X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnification range</td>
<td>0.65X - 1.15X</td>
<td>0.9X - 1.2X</td>
<td>1.5X - 2.0X</td>
<td>2.4X - 3.0X</td>
<td>3.2X - 4.0X</td>
<td>3.7X - 4.6X</td>
</tr>
<tr>
<td>Working distance (mm)</td>
<td>20 - 101</td>
<td>20 - 100</td>
<td>54 - 90</td>
<td>75 - 90</td>
<td>82 - 90</td>
<td>84 - 90</td>
</tr>
<tr>
<td>Horiz. FOV (1/2” sensor)</td>
<td>9.8 - 5.6</td>
<td>7.1 - 5.3</td>
<td>4.3 - 3.2</td>
<td>2.7 - 2.1</td>
<td>2.0 - 1.6</td>
<td>1.7 - 1.4</td>
</tr>
</tbody>
</table>
Low cost AF microscope with fixed mag

<table>
<thead>
<tr>
<th>Tube length</th>
<th>40mm</th>
<th>60mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnification*</td>
<td>3X</td>
<td>4X</td>
</tr>
<tr>
<td>Z-range:</td>
<td>~3mm</td>
<td>~2mm</td>
</tr>
<tr>
<td>Resolution:</td>
<td>3.7um</td>
<td>2.8um**</td>
</tr>
<tr>
<td>Image circle</td>
<td>25mm</td>
<td>25mm</td>
</tr>
</tbody>
</table>

* 5-6X can be achieved with a reversed 16mm lens
** Line width of group 7 element 4

C-mount camera

Empty C-mount tube, 40-60mm long

Optotune lens EL-10-30-Ci-VIS-LD

M22 to C-mount adapter

25mm lens (reversed!) Edmund Optics 85358

Working distance: ~20mm
Compact variable focus 2X and 5X lenses offered by Edmund Optics

- EL-10-30-Ci-VIS-LD-MV integrated

<table>
<thead>
<tr>
<th>TECHSPEC® TUNABLE COMPACT OBJECTIVE LIQUID LENS ASSEMBLIES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnification:</strong></td>
</tr>
<tr>
<td>--------------------</td>
</tr>
<tr>
<td>Numerical Aperture NA:</td>
</tr>
<tr>
<td>Working Distance (mm):</td>
</tr>
<tr>
<td>Focus Tunable Range (typical) (mm):</td>
</tr>
<tr>
<td>Maximum Sensor Size:</td>
</tr>
<tr>
<td>Field of View, ¾&quot; Sensor (mm):</td>
</tr>
<tr>
<td>Field of View, ½&quot; Sensor (mm):</td>
</tr>
<tr>
<td>Mount:</td>
</tr>
<tr>
<td>Liquid Lens Type:</td>
</tr>
<tr>
<td>Stock No.</td>
</tr>
<tr>
<td>1-5</td>
</tr>
<tr>
<td>6-10</td>
</tr>
<tr>
<td>+11</td>
</tr>
</tbody>
</table>

Typical applications for high magnifications

**LCD & PCB inspection**

**Particle counting in liquids**

Stack of images

Depth of field
Agenda

• Introduction
• How to combine ELs with off-the-shelf optics
  − Endocentric lenses
  − Telecentric lenses
  − Microscopy
• Custom designs
• Drivers & software
• Optotune’s standard lenses
Kowa 35mm lens for 1” sensors with great MTF

Optimized optical design provides top performance

• 1” camera sensors
• F5.6 to F32 (lower F# achievable with EL-16-40-TC)
• WD range: 250 – 500mm (250 – infinity achievable with EL-16-40-TC)
• MTF50 @ 80 – 120lp/mm
• No orientation dependence

Test report: [www.optotune.com/images/products/Optotune_35mm_imaging_lens_for_1inch_sensors.pdf](http://www.optotune.com/images/products/Optotune_35mm_imaging_lens_for_1inch_sensors.pdf)
50mm lens for 1.1” sensors with integrated EL-16-40

- Optimal performance due to integration of the EL-16-40 lens close to the aperture stop

- Main specs:
  - Working distances: 285mm to infinity
  - Resolution: 140lp/mm (also with optical axis horizontal)
  - F-number: F/2.8 with some vignetting, F/4 without vignetting

- Test:

  WD1 @ 3 Dpt:
  Resolution 104 LP/mm (image)
  10 mil barcodes very well resolved

  WD2 @ -2 Dpt:
  Resolution 114 LP/mm (image)
  10 mil barcodes still well resolved

Test report: https://www.optotune.com/images/products/181213%20c4c_50mm_1p1inch%20%20EL-16-40.pdf
Agenda

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  – Endocentric lenses
  – Telecentric lenses
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• Custom designs

• Drivers & software

• Optotune’s standard lenses
Two drivers available off-the-shelf

<table>
<thead>
<tr>
<th></th>
<th>Optotune Lens Driver 4i</th>
<th>Gardasoft TR-CL180</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current range</strong></td>
<td>-290 to +290 mA</td>
<td>-400 to +400 mA</td>
</tr>
<tr>
<td><strong>Current resolution / accuracy</strong></td>
<td>0.07 / 0.5 mA</td>
<td>0.1 / 0.5 mA</td>
</tr>
<tr>
<td><strong>Latency in current mode</strong></td>
<td>1-2 ms</td>
<td>Focal power mode only</td>
</tr>
<tr>
<td><strong>Latency in focal power mode</strong></td>
<td>2-4 ms</td>
<td>1 ms</td>
</tr>
<tr>
<td><strong>Interfaces</strong></td>
<td>USB 2.0 (UART &amp; analog 0-5 V the PCB)</td>
<td>GigE, RS232, Analog 0-10 V</td>
</tr>
<tr>
<td><strong>Firmware features</strong></td>
<td>Oscillation modes with trigger out</td>
<td>Oscillation modes &amp; custom waveforms with trigger-in</td>
</tr>
<tr>
<td><strong>SDKs</strong></td>
<td>C#, LabVIEW</td>
<td>Triniti SDK, C#, C++, VB</td>
</tr>
<tr>
<td><strong>Supply voltage</strong></td>
<td>5 V</td>
<td>24 V</td>
</tr>
</tbody>
</table>

* Analog input only mapped to current, not focal power
Compact embedded driver CL191 by Gardasoft

-250mA to +250mA in 0.07mA steps

- Compatible with all Optotune electrical lenses

- Similar features as the TC-CL180 incl.
  - “Focal Power Mode” with automatic temperature compensation
  - Oscillation modes & custom waveforms with trigger-in
  - Analog mode with look-up table

- Interfaces:
  - I2C
  - UART
  - Analog 0-10V
**Focal power mode for good reproducibility**

- **Why it is important:**
  - The focal power of our lenses drifts with temperature by 0.02 - 0.06 diopters / °C (depends on lens model)
- **Typical accuracy achieved:** +/- 0.1dpt

“I need a lens with f=125mm (8 diopters)”

Use focal power mode to set lens to 8 diopters

Lens calibration table and temperature read by lens driver

Temperature compensated control current to adjust lens to 8 diopters

Temp sensor with EEPROM

f=125mm (8 diopters)

Lens calibration curve stored on lens internal memory

Lens characterization f vs T vs I
Up to 20m of combined cable length tested

- **USB 2.0 cable**
  - 1.8m included
    - Ships with Lens Driver 4
  - 5m specified
    - According to USB 2.0 standard
  - 10m tested
    - Full performance verified
    - High quality cable required

- **Hirose cable**
  - 1m Optotune standard
    - P/N: CAB-6-100
  - 3m specified
    - According to I2C standard
  - 10m tested
    - Full performance verified
    - I2C enters clock stretching mode
    - High quality, shielded cable required
How to find the right focus

**Image based autofocus**
- Multiple images are acquired to find the best focus by algorithm
- Typically 10-15 frames required → 0.5 to 1 sec focus time

**Preset lookup tables**
- Focus positions are stored in a lookup table during calibration (teaching)
- Only one focus step required → 15ms focus time

**Using a distance sensor**
- Multiple distance vs focal power points are saved during calibration
- Only one focus step required → 15ms focus time

**Product Focus**
- A 2 dpt
- B 1 dpt
- C 3 dpt

**Distance Focus**
- 100mm 1 dpt
- 200mm 2 dpt
- 300mm 3 dpt

**Cheap, flexible but not 100% reliable**
**Inflexible, as reliable as the focal power mode (~0.1dpt)**
**Flexible, quite reliable but expensive**
Optotune’s autofocus algorithm

Parameters can be set in Lens Driver Controller:
Example with distance sensor & Gardasoft driver

• Distance sensor signal is mapped to optical power
• Stand-alone system using Gardasoft TR-CL180 lens controller
• Each package is in focus within 20ms → at 5m/s packages can be placed with 100mm gaps

Videos available online: https://youtu.be/83mTQu9dPc8 and https://youtu.be/h5BUzn4UTNU
Serial protocol can be implemented by customers

- Optotune’s Lens driver is a serial device in Windows, Linux or using RS232
  - COM port in Windows
  - /dev/ttyACM0 in Linux
- Example commands are:
  - “Start” → “Ready” (works in ASCII)
  - SetCurrent
  - SetFocalPower
  - GetTemperature
- Implementation of a 16bit CRC is required
- Optotune provides sample code in C#, Labview, Python and Halcon
# Software partners

<table>
<thead>
<tr>
<th>Partner company</th>
<th>Software</th>
<th>Integration features</th>
</tr>
</thead>
<tbody>
<tr>
<td>Common Vision Blox</td>
<td>- Lens Driver</td>
<td>- Lens Driver integrated in custom release</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Slider for Focal Power Mode</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Auto focus function</td>
</tr>
<tr>
<td>EyeVision</td>
<td>- Lens Driver</td>
<td>- Lens Driver built in through plugin interface</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- User friendly integration of current mode</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Auto focus function</td>
</tr>
<tr>
<td>Halcon</td>
<td>- Lens Driver</td>
<td>- Lens Driver integrated via HDevelop procedure library</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Source code can be edited</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Image stacking &amp; 3D reconstruction</td>
</tr>
<tr>
<td>Matrox</td>
<td>- C++ project</td>
<td>- C++ project compatible with MIL10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Auto focus implementation incl. “continuous mode”</td>
</tr>
<tr>
<td>Modular X</td>
<td>- Lens control</td>
<td>- Lens control via DLL calls</td>
</tr>
<tr>
<td></td>
<td>via DLL calls</td>
<td>- Several autofocus functions incl. “continuous mode”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Image stacking &amp; 3D reconstruction</td>
</tr>
<tr>
<td>NeuroCheck 6.1</td>
<td>- Lens control</td>
<td>- Lens control via plugin-DLL</td>
</tr>
<tr>
<td></td>
<td>via plugin-DLL</td>
<td>- Optical power mode</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Parallel use of several lenses</td>
</tr>
<tr>
<td>nVision</td>
<td></td>
<td>- Complete integration of all Driver features</td>
</tr>
</tbody>
</table>
Frequency mode allows for multiple working distances within one image

½” 5MP C-mount camera (IDS UI-3580CP)

25 mm lens (Schneider Kreuznach 1068968)

Tunable lens (EL-10-30-C-VIS-LD-MV)

120 mm

50 mm

80 mm

Lower plane in focus
The visible barcode corresponds to the lying package.

Upper plane in focus
The visible barcode corresponds to the upright package.

Frequency feature applied
The working distance is modulated with a frequency of 35 Hz.
Both the lower and the upper barcode are readable.

Note: Contrast is reduced as the two images are added/overlaid during exposure. The more advanced technique of focus stacking is shown on the next page.
Focus stacking enables “hyper-focus” images and “depth from focus”

Z-stack of e.g. 10 to 30 images*

Rendered hyper-focus image**

*Ideally the number of frames to acquire is = Z-range / DoF  **Rendered with Helicon Focus 6.7.1 software from 15 pictures (offline)
Focus stacking in real-time using FPGA

- 20 images per stack in 50ms
- Scaled & combined in FPGA with zero latency
- 1MP extended depth image @20fps
- The bottle neck is now the camera & camera interface

See demo video: https://youtu.be/-NBXIMhB1UQ
Agenda

- Introduction
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  - Endocentric lenses
  - Telecentric lenses
  - Microscopy
- Custom designs
- Drivers & software
- Optotune’s standard lenses
# Optotune’s electrically focus tunable lenses

<table>
<thead>
<tr>
<th></th>
<th>EL-10-30-TC</th>
<th>EL-10-30-C(i)</th>
<th>EL-16-40-TC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Focal power range</strong>*</td>
<td>8 ... 22 Dpt</td>
<td>-1.5 ... +3.5 Dpt</td>
<td>-2 ... +3 Dpt</td>
</tr>
<tr>
<td></td>
<td>+5 ... +10 Dpt</td>
<td></td>
<td>-10 ... +10 Dpt</td>
</tr>
<tr>
<td><strong>Clear aperture</strong></td>
<td>10mm</td>
<td>10mm</td>
<td>16mm</td>
</tr>
<tr>
<td><strong>Outer diameter</strong></td>
<td>30mm</td>
<td>30mm</td>
<td>40mm</td>
</tr>
<tr>
<td><strong>Wavefront quality RMS @525nm</strong></td>
<td>&lt;0.25 / 0.5 λ</td>
<td>&lt;0.15 / 0.25 λ</td>
<td>&lt;0.25 / 0.5 λ</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;0.25 / 1.5 λ</td>
</tr>
<tr>
<td><strong>Absolute focal power accuracy (typical)</strong></td>
<td>&lt; 0.1 dpt</td>
<td>&lt; 0.1 dpt</td>
<td>&lt; 0.05 dpt</td>
</tr>
<tr>
<td><strong>Applications</strong></td>
<td>Microscopy OCT</td>
<td>Machine vision</td>
<td>Machine vision Ophthalmology</td>
</tr>
</tbody>
</table>

* Depends on membrane parameters

**vertical / horizontal optical axis
EL-16-40 with versatile configurations

- Two optical configurations:
  
  | Thin membrane (+/ - 10 diopters) | EL-16-40-TC-VIS-20D |
  | Thick membrane (-2 to 3 diopters) | EL-16-40-TC-VIS-5D |

- Push/pull design (convex/concave lens)
  - No need for offset lens

- Several mechanical configurations:
  - C-mount (male & female)
  - M42-mount
  - Filter threads (M25.5, M26, M27, M30.5)

Connector at 0°

Adapter threads can rotate freely and be locked