Focus tunable liquid lenses
And how to integrate them in machine vision systems

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Agenda

• Introduction to Optotune
• Liquid lens working principle
• How to combine ELs with off-the-shelf optics
• Custom designs
• Optics configuration tools
• Drivers, software & standard liquid lenses
• Application examples
Established in 2008

Leader in tunable optics

27 sales partners in 30 countries

185 employees
• 118 in Switzerland
• 60 in Slovakia
• 7 in sales offices

Privately owned

InVision Top Innovations 2017 >
Vision Systems Innovator Award 2016 >
Swiss Economic Award 2014 >
No. 1 Startup in Switzerland 2011 >
Prism Award 2011 >
Swiss Technology Award 2010 >
Winner of Venture 2008 >
ETH Spin-off 2008 >
Optotune provides four core product lines

- Focus tunable lenses
- Laser speckle reducers
- Extended pixel resolution actuators
- 2D mirrors
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Working principle: membrane with fluid and actuator

**Human eye:**
Ciliary muscle actuates the lens curvature

**Optotune lens:**
Electromagnetic actuator controls the lens curvature

See also: [https://www.optotune.com/technology/focus-tunable-lenses](https://www.optotune.com/technology/focus-tunable-lenses)
The ideal focusing solution for machine vision

**Fixed focus optics**
- Image sensor
- Lens with fixed focal length
- Working range limited by depth of field

**Liquid lens approach**
- Image sensor
- Larger lens with **variable focal length**
- Variable working distance
The natural way to focus: Like your eyes but faster!

<table>
<thead>
<tr>
<th>Specification</th>
<th>Your benefit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apertures from 3 to 30mm</td>
<td>Sensor sizes from 1/3” to 40mm supported</td>
</tr>
<tr>
<td>Large working distance range</td>
<td>No need to increase F# for larger depth of field</td>
</tr>
<tr>
<td>Low dispersion (Abbe# V&gt;100)</td>
<td>No color aberrations introduced</td>
</tr>
<tr>
<td>&gt;10⁹ cycles</td>
<td>Long lifetime</td>
</tr>
<tr>
<td>High repeatability &lt;0.1 dpt (automatic temperature compensation)</td>
<td>Once calibrated, the system runs open loop</td>
</tr>
<tr>
<td>Response times of few millisecods</td>
<td>Increase your throughput!</td>
</tr>
</tbody>
</table>

**EL-3-10**
Response: 1ms
Settling: 4ms
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# Four main configurations for machine vision applications

<table>
<thead>
<tr>
<th>Conventional fixed focal length lenses</th>
<th>Telecentric lenses</th>
<th>Microscopes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Front-lens config.</strong></td>
<td><strong>Back-lens config.</strong></td>
<td></td>
</tr>
<tr>
<td>- C- or S-mount lens</td>
<td>- Fixed focal length lens $\geq 35\text{mm}$</td>
<td></td>
</tr>
<tr>
<td>- Working distances typically long (from 100mm to infinity)</td>
<td>- Working distances typically short (from 50mm to 500mm)</td>
<td>- Magnifications: from 0.13X to 4X</td>
</tr>
<tr>
<td>- Up to 100x magnification</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
# Four main configurations for machine vision applications

<table>
<thead>
<tr>
<th>Conventional fixed focal length lenses</th>
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<th>Microscopes</th>
</tr>
</thead>
</table>
| **Front-lens config.**  
Large WD | **Back-lens config.**  
Short WD | **Constant**  
magnification | **High magnification** |
| Package sorting | Contact lens  
inspection | Camera phone  
lens inspection | Particle counting  
in liquids |
| Robot vision | Electronics inspection | IC inspection | Microscopy |
Front-lens configuration typically for large working distances

C-mount camera

12mm board lens
C- to S-Mount adapter

3 cm

6.5 cm

Fixed focal length lens

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

Working distance ranges from infinity to about 100mm
Back-lens configuration with 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

Results

<table>
<thead>
<tr>
<th></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></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

This only works for lenses with focal length >= 35mm
Example of 2x telecentric lens with EL-16-40 integrated

- 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

**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**

**Without EL**
- USAF group element: 7/4
- Lp/mm (object): 181
- Lp/mm (image): 90

**With EL-16-40**

Integration of liquid lenses in microscopes

Non-telecentric

- Tunable lens right above objective lens (infinity corrected space)
- Largest Z-range, but with mag change

<table>
<thead>
<tr>
<th>Z-range (typical)</th>
<th>Mag change</th>
</tr>
</thead>
<tbody>
<tr>
<td>10x 2560 μm (20D: 10240 μm)</td>
<td>7.5 %</td>
</tr>
<tr>
<td>20x 640 μm (20D: 2560 μm)</td>
<td>12.2 %</td>
</tr>
<tr>
<td>40x 160 μm (20D: 640 μm)</td>
<td>23.7 %</td>
</tr>
</tbody>
</table>

Telecentric

- Tunable lens at intermediary pupil position of a relay
- Smaller Z-range, but no mag change

<table>
<thead>
<tr>
<th>Z-range (typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10x 500 μm (20D: 2000 μm)</td>
</tr>
<tr>
<td>20x 125 μm (20D: 1000 μm)</td>
</tr>
<tr>
<td>40x 30 μm (20D: 120 μm)</td>
</tr>
</tbody>
</table>
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  - Drivers, software & standard liquid lenses
  - Application examples
Rapidly increasing number of custom designs allow for optimized performance

In collaboration with our lens partners:

- Edmund Optics
- VS Technology
- Sill Optics
- Kowa
- QIOPTIQ
- chance 4 change GmbH & Co. KG
- EVETAR
- optotune
Example: 12 mm lens with integrated EL-16-40

High resolution and large field of view (FOV)
- Ideal for code reading and OCR, e.g. in logistics

Working distance (WD) range from 250mm to infinity
- Best MTFs in the range of 500 to 1000mm
- High optical leverage (1.13 m/dpt)

Resolution for 3.45um pixels (e.g. Sony IMX253/304 1.1” sensors)
- In the center over the WD range: at 145 lp/mm = Nyquist limit

Image quality
- No vignetting
- Barrel distortion, which can be corrected digitally
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# Configuration table for entocentric lenses

<table>
<thead>
<tr>
<th>Camera sensor</th>
<th>Mount</th>
<th>Imaging lens focal length (mm)</th>
<th>&lt;6</th>
<th>6</th>
<th>8</th>
<th>12</th>
<th>16</th>
<th>25</th>
<th>35</th>
<th>50</th>
<th>75</th>
<th>100</th>
<th>&gt;100</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4&quot;</td>
<td>S</td>
<td>30° HFOV</td>
<td>23°</td>
<td>15°</td>
<td>11°</td>
<td>7°</td>
<td>5°</td>
<td>4°</td>
<td>2.5°</td>
<td>2°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/3&quot;</td>
<td>S</td>
<td>44°</td>
<td>33°</td>
<td>23°</td>
<td>17°</td>
<td>11°</td>
<td>8°</td>
<td>6°</td>
<td>4°</td>
<td>3°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1/2&quot;</td>
<td>S</td>
<td>56°</td>
<td>44°</td>
<td>30°</td>
<td>23°</td>
<td>15°</td>
<td>10°</td>
<td>7°</td>
<td>5°</td>
<td>4°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2/3&quot;</td>
<td>C</td>
<td>73°</td>
<td>58°</td>
<td>40°</td>
<td>31°</td>
<td>20°</td>
<td>14°</td>
<td>10°</td>
<td>7°</td>
<td>5°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1&quot;</td>
<td>C</td>
<td>74°</td>
<td>77°</td>
<td>56°</td>
<td>44°</td>
<td>29°</td>
<td>21°</td>
<td>15°</td>
<td>10°</td>
<td>7°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30mm diag.</td>
<td>M42</td>
<td>128°</td>
<td>114°</td>
<td>91°</td>
<td>75°</td>
<td>52°</td>
<td>39°</td>
<td>28°</td>
<td>19°</td>
<td>14°</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Front lens configuration only**

**Back lens configuration only**

- Not possible
- Possible with custom optics design
- Custom design available
- Vignetting with off-the-shelf lenses
- Possible with off-the-shelf lenses

** Customized lens in development
Online lens configurator for entocentric lenses
http://configurator.optotune.com
Lens selector tool to get specific part numbers
http://www.optotune.com/Optotune_lens_selector.xlsx

1) Enter FOV and WD
2) Angular FOV is calculated
3) Click on a field in the matrix
4) Recommended imaging lenses and the matching Optotune product are listed

Note: Only for entocentric lenses
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Three drivers available off-the-shelf

<table>
<thead>
<tr>
<th></th>
<th>Optotune Lens Driver 4i</th>
<th>Gardasoft TR-CL180</th>
<th>Gardasoft CL191</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Applications</strong></td>
<td>R&amp;D, portable systems</td>
<td>Industrial 24/7 operation</td>
<td>OEM</td>
</tr>
<tr>
<td><strong>Current range</strong></td>
<td>-290 to +290 mA</td>
<td>-400 to +400 mA</td>
<td>-250 to +250 mA</td>
</tr>
<tr>
<td><strong>Interfaces</strong></td>
<td>USB</td>
<td>GigE, RS232, Analog 0-10 V</td>
<td>I2C, UART, Analog 0-10 V</td>
</tr>
<tr>
<td><strong>SDKs</strong></td>
<td>C#, LabVIEW</td>
<td>Triniti SDK, C#, C++, VB</td>
<td>C#, C++, VB</td>
</tr>
<tr>
<td><strong>Supply voltage</strong></td>
<td>5 V</td>
<td>24 V</td>
<td>3.3 or 5 V</td>
</tr>
</tbody>
</table>
Stable focus control with temperature feedback

Liquid lens stability
- Temperature drift of 0.02 - 0.06 diopters / °C (depending on lens model) is compensated by the driver
- Typical accuracy ± 0.1 diopter, which is usually within depth of field
Lens control by camera removes the need for external drivers

Lens controlled by external driver

Driver SDK

USB or Ethernet

or

Lens current & I2C

Lens controlled via camera

Camera SDK

Any interface

Power & Serial interface

Integrated driver

To do: Provide serial interface & firmware for focus control
# Optotune’s liquid lenses for machine vision

<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></td>
<td>+5 ... +10 Dpt</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>Response time</strong></td>
<td>4 / 9 / 20 ms</td>
<td>2.5 / 6 / 15ms</td>
<td>5 / 12 / 25ms</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>Typical use case</strong></td>
<td>Microscopy</td>
<td>Small &amp; mid size sensors</td>
<td>Large sensors</td>
</tr>
</tbody>
</table>

* 10-90% of step / settling time of a controlled step / settling time of rectangular step
** vertical / horizontal optical axis
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Application example:  
**Package sorting – focus on different box sizes**

- Code reading and OCR on boxes of different heights
- Sensor size: 40mm (line scan)
- Tunable lens: EL-16-40-TC-VIS-5D-M42
- Imaging lens: 60mm M42-mount
- Angular FOV: 37°
- WD range: 800 – 1500mm

### Close focus

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length f:</td>
<td>60 mm</td>
</tr>
<tr>
<td>Sensor height v:</td>
<td>40 mm</td>
</tr>
<tr>
<td>Working distance D:</td>
<td>800 mm</td>
</tr>
<tr>
<td>Pixel pitch</td>
<td>5 um</td>
</tr>
<tr>
<td>Field of view:</td>
<td>37 °</td>
</tr>
<tr>
<td>Object height H:</td>
<td>533 mm</td>
</tr>
<tr>
<td>Magnification:</td>
<td>0.08</td>
</tr>
<tr>
<td>Resolution on object:</td>
<td>67 um</td>
</tr>
</tbody>
</table>

### Far focus

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length f:</td>
<td>60 mm</td>
</tr>
<tr>
<td>Sensor height v:</td>
<td>40 mm</td>
</tr>
<tr>
<td>Working distance D:</td>
<td>1500 mm</td>
</tr>
<tr>
<td>Pixel pitch</td>
<td>5 um</td>
</tr>
<tr>
<td>Field of view:</td>
<td>37 °</td>
</tr>
<tr>
<td>Object height H:</td>
<td>1'000 mm</td>
</tr>
<tr>
<td>Magnification:</td>
<td>0.04</td>
</tr>
<tr>
<td>Resolution on object:</td>
<td>125 um</td>
</tr>
</tbody>
</table>
Application example:

**Bottle inspection – refocus for different sizes**

- Inspection of bottle bottom, variable sizes
- Sensor size: 2/3”
- Imaging lens: 35mm C-mount
- Tunable lens: EL-16-40-TC-VIS-5D-M27
- Angular HFOV: 14°
- WD range: 150 to 550mm

![Graph showing horizontal FOV vs. working distance with Z-range: 400 mm and Lens tuning range: -2.0 to 3.0 dpt]
Application example:
**Robot vision – refocus as you get closer to zoom in**

- Camera mounted on robot arm
- Benefit: Focused images can be taken at any distance resulting in variable magnification. E.g. reducing WD from 1m to 0.2m + refocusing results in a 5X zoom!
- Sensor size: 1/2”
- Imaging lens: 12mm S-mount
- Tunable lens: EL-10-30-Ci-VIS-LD-MV
- Angular HFOV: 30°
- WD range: 170 to 1000mm

Application example:

**Contact lens inspection – scan along the curves**

- Inspection of contact lenses (defects, read imprinted codes)
- Sensor size: 2/3”
- Tunable lens: EL-16-40-TC-VIS-5D-C
- Imaging lens: 50mm C-mount
- Resulting 3D FOV: 28x21x45mm

![Graph showing working distance and FOV relationship]

**Z-range:** 45 mm  
**Lens tuning range:** -2.0 to 3.0 dpt
Application example: Electronics inspection – fast autofocus

- Inspection of electronics, EL allows for continuous focusing
- Sensor size: 1”
- Tunable lens: EL-16-40-TC-VIS-5D-C
- Imaging lens: 50mm C-mount
- Resulting 3D FOV: 40x30x45mm
Application example:
Jewel inspection – scan through to find defects

- Inspection of jewels (z-scan to find defects)
- Sensor size: 1"
- **Distance rings: 20mm**
- Tunable lens: EL-16-40-TC-VIS-5D-C
- Imaging lens: 50mm C-mount
- Resulting 3D FOV: 24x18x21mm

![Diagram showing camera setup and specifications](image-url)
Application example:
**Camera lens inspection – step through the stack**

- Inspection of dust & scratches in a stack of molded plastic lenses
- Sensor: 1.1” 12MP
- Imaging lens: 1.0X telecentric VS-THV1-110_S-LQL1
- Tunable lens: EL-16-40-TC-VIS-5D-C (integrated)
- Resulting 3D FOV: 14.2x10.4x**14.3**mm
Application example:
**IC inspection – image five sides with one camera**

- Inspection of ICs, top and side views (via mirror) have different working distances
- Sensor: 1/2"
- Imaging lens: 0.15X telecentric lens
- Tunable lens: EL-10-30-Ci-VIS-LD (integrated)
- Resulting 3D FOV: 41.2x30.9x50+mm
Application example:

**Industrial microscopy – automated zoom & focus**

- Lens control fully integrated into system software
- Tunable lens: EL-16-40-TC-VIS-5D-C
- Video: [https://youtu.be/ZZFe3hg9JwM](https://youtu.be/ZZFe3hg9JwM)
Application example:
**Blood analysis – portable microscope**

- Cell counting & analysis
- Sensor: 2/3"
- Empty tube: 50mm
- Tunable lens: EL-10-30-Ci-VIS-LD-MV
- Imaging lens: inverted 16mm lens (e.g. Edmund Optics 85350)
- Magnification: 6X
- Resulting 3D FOV: 1.4x1.1x0.8mm
Thank you!

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