optotune

Optotune focus-tunable lenses for machine vision

Application note

August 2016

Bernstrasse 388 | CH-8953 Dietikon | Switzerland
Phone +41 58 856 3011 | www.optotune.com | info@optotune.com

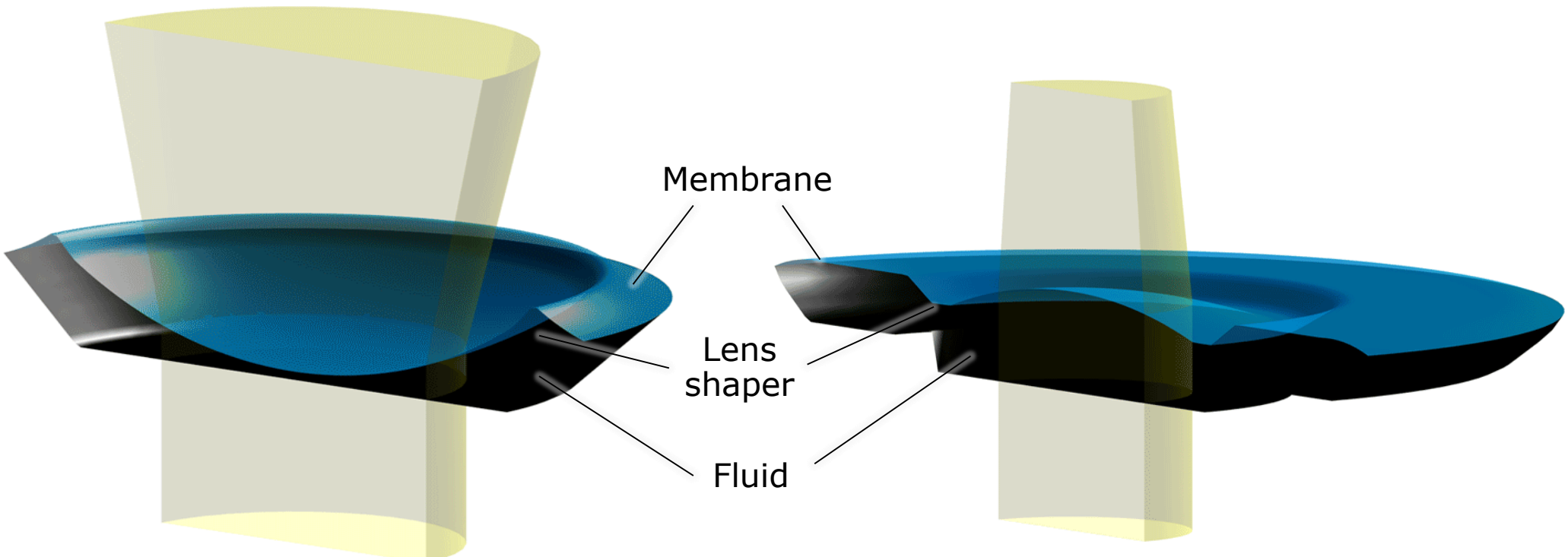
Agenda

- Introduction
- How to combine ELs with off-the-shelf optics
- Electrical integration
- Software
- Available products

Working principle based on membrane and fluid

Mechanically tunable lens

Electrically tunable lens

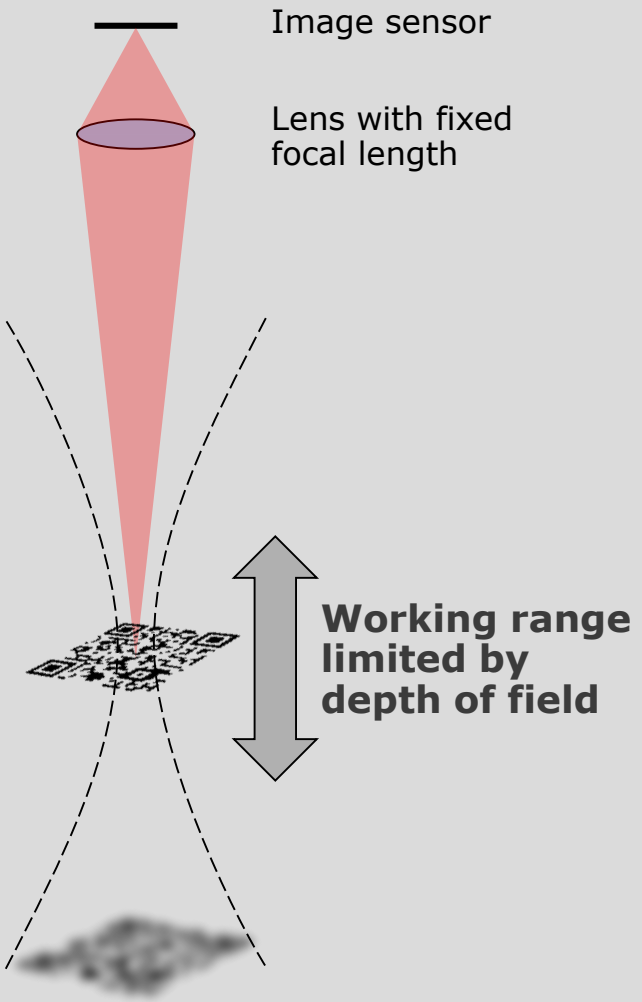


Videos available on www.optotune.com

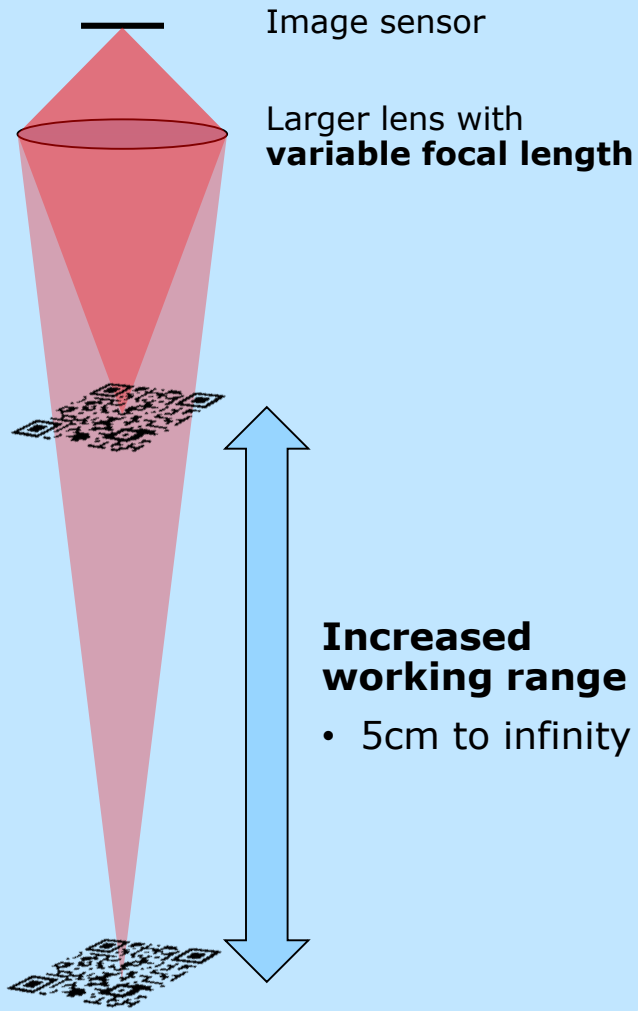
optotune

Tunable lenses offer a natural focusing solution

Fixed focus optics



Optotune approach



Benefits

- Larger working distance range
- Faster recognition
- Less lighting required thanks to smaller F#
- Easier installation

optotune

Focus tunable polymer lenses are fast

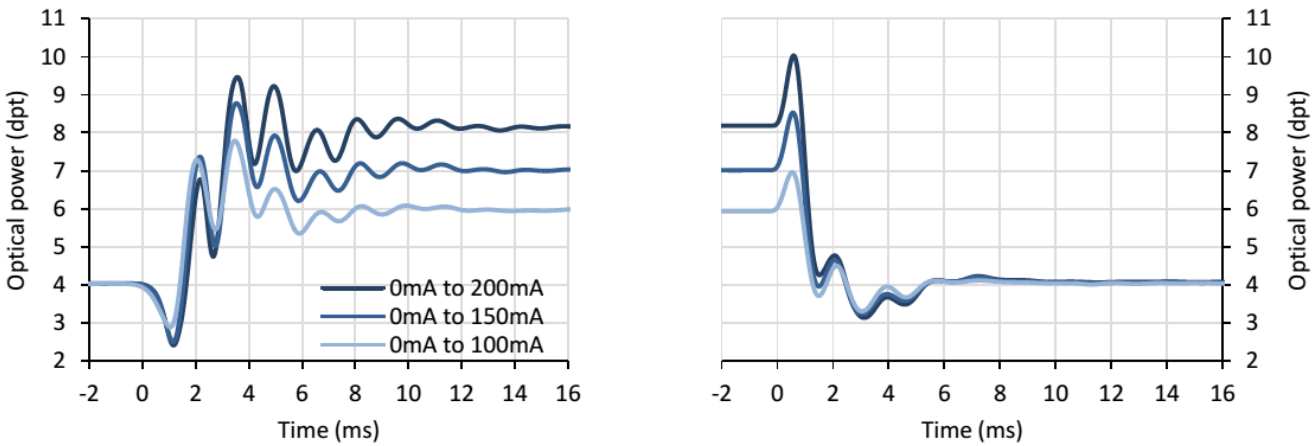


Figure 12: Typical optical response of the EL-10-30-C to a current step.

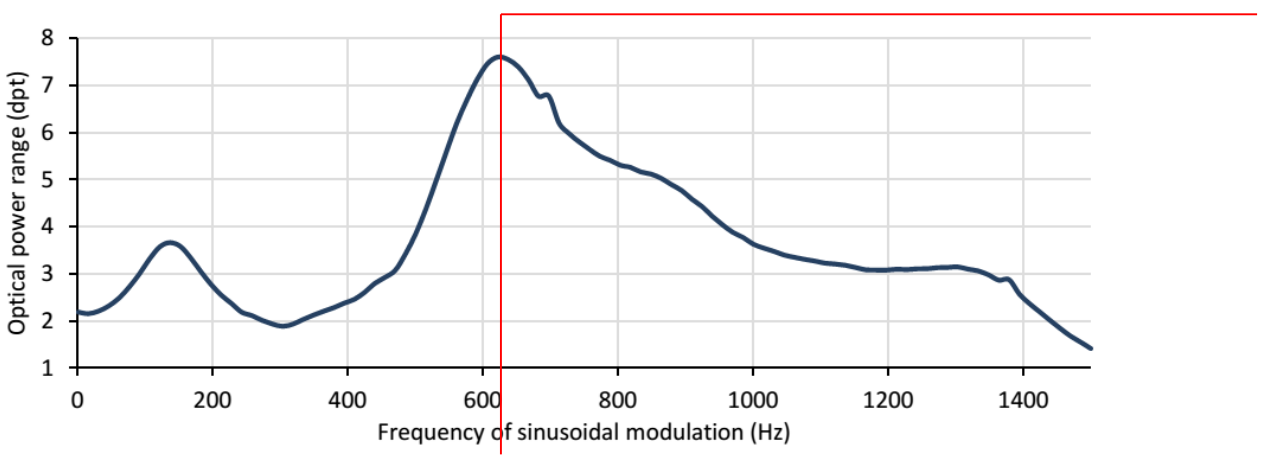
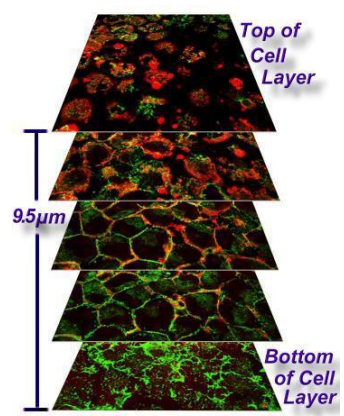


Figure 13: Typical frequency response of the EL-10-30-C with current oscillating from 50 to 150 mA.

600 Hz focus oscillation
→ fast image stacking



optotune

Agenda

- Introduction
- How to combine ELs with off-the-shelf optics
- Electrical integration
- Software
- Available products

Three main configurations for machine vision

Front-lens configuration

- Mounted on filter thread (adapter might be required)
- Working distances typically from infinity to 100mm

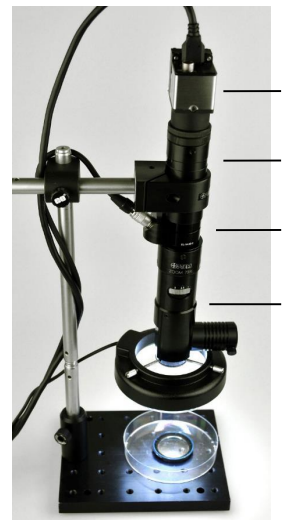
Most versatile configuration

Back-lens configuration

- Tunable lens acts like a distance ring
- Easy mechanical solution (C-mount)

Best quality for short working distances

High magnification



- Works best with infinity corrected lenses
- 1x to 40x magnification

Best for high magnifications

optotune

Front-lens configuration typically for large working distances

Front-lens configuration

Fixed focal length lens

EL-16-40-TC-VIS-5D-M27

Working distance ranges from infinity to about 100mm

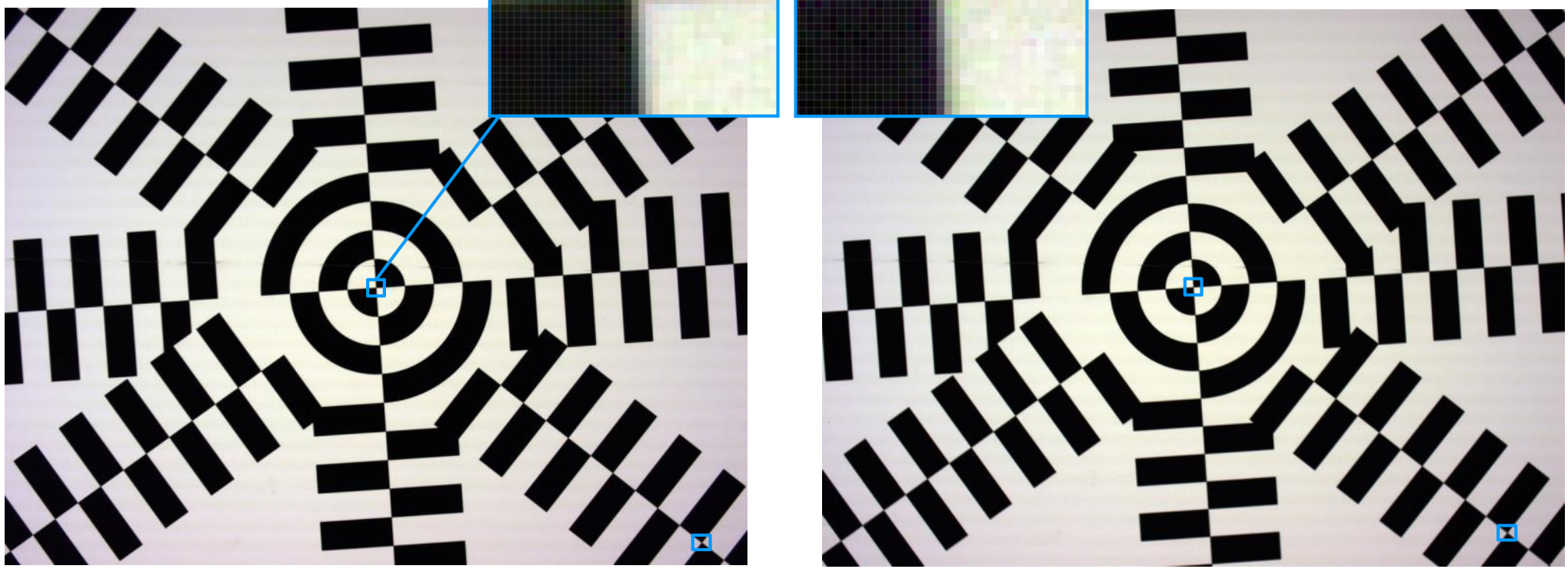
optotune

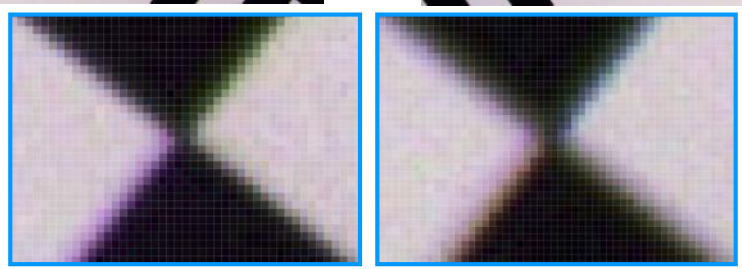
EL-10-30 well suited for board lenses

Front-lens configuration

12mm lens only

12mm lens + EL-10-30-C

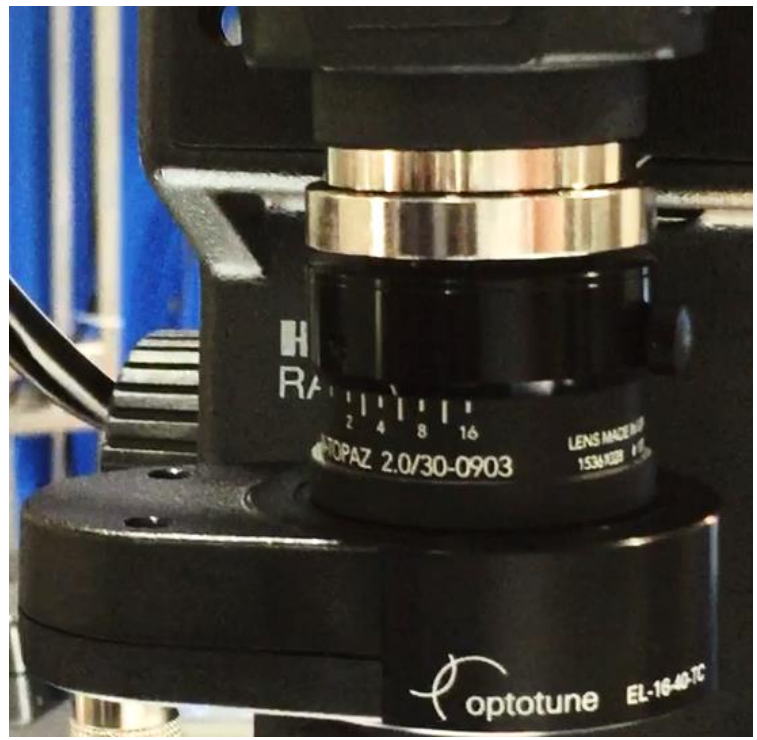




optotune

EL-16-40 on Schneider Topaz lenses is optimal for 1.1” 12MP sensors

Front-lens configuration



- 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

Lenses: http://www.schneiderkreuznach.com/industrial-solutions/objektive-und-zubehoer/produkte/11-oe176mm-objektive/

optotune

Back-lens configuration typically for macro imaging

Back-lens configuration

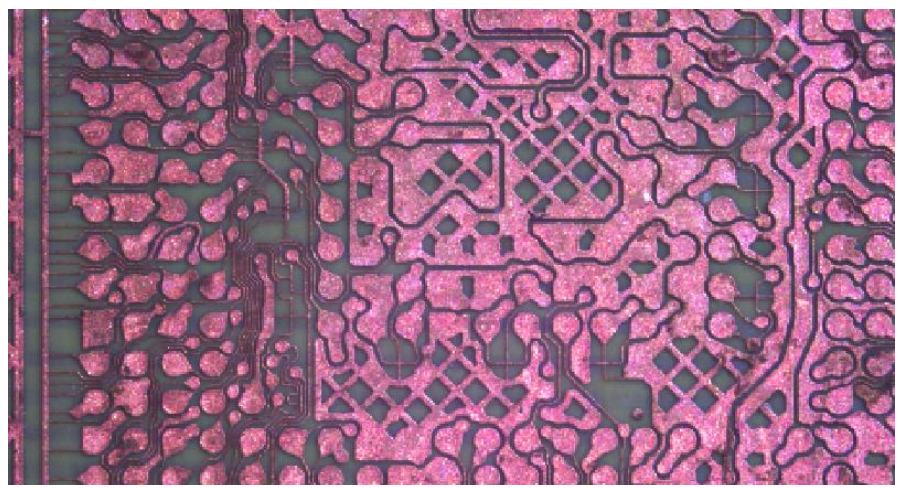
C-mount camera
½” 5MP sensor

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

Tamron 50mm lens
(23FM50SP)

Results:

Configuration	Large WD	Short WD
Magnification	0.4x	0.7x
Working distance	160mm	100mm
Z range	25mm	5mm
Z resolution	6.25µm	1.25µm
HFOV	16mm	9mm

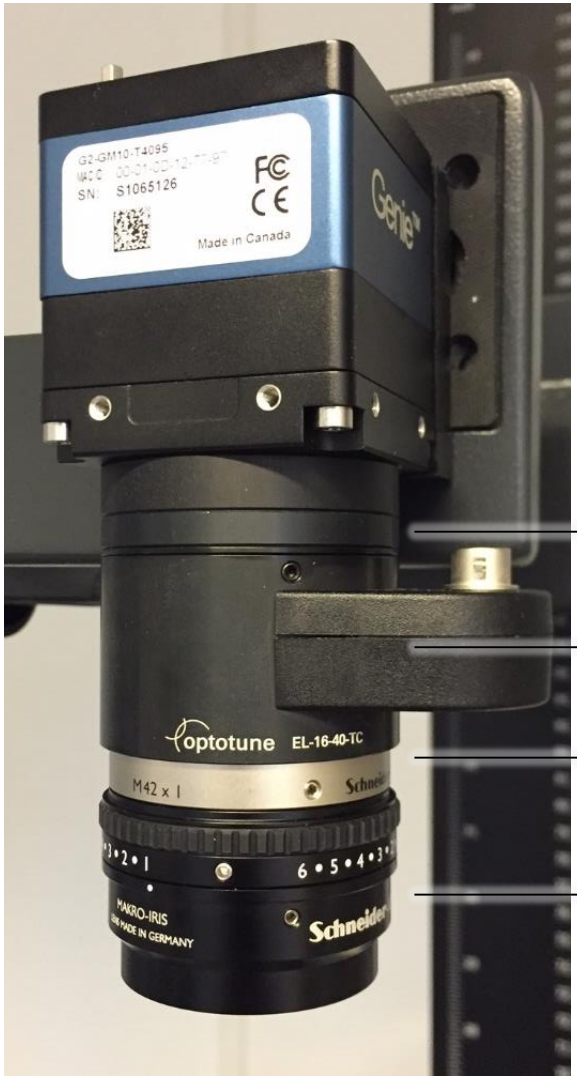


This only works for lenses with focal length >= 35mm

optotune

Image circles of 30mm possible

Back-lens configuration



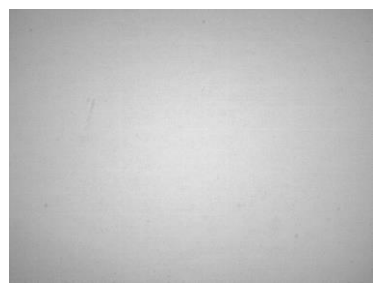
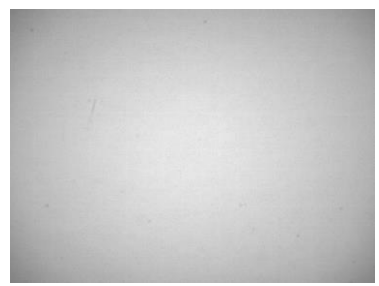
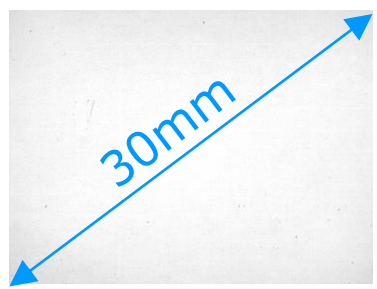
- WD range: from 1100mm to 380mm @ -2Dpt to 3Dpt
- Distortion unchanged
- Resolution equally good
- No added vignetting

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		

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.

optotune

Telecentric lenses preferably integrate the EL to achieve large Z-ranges

Moritex MML1-ST150D
with integrated EL-16-40

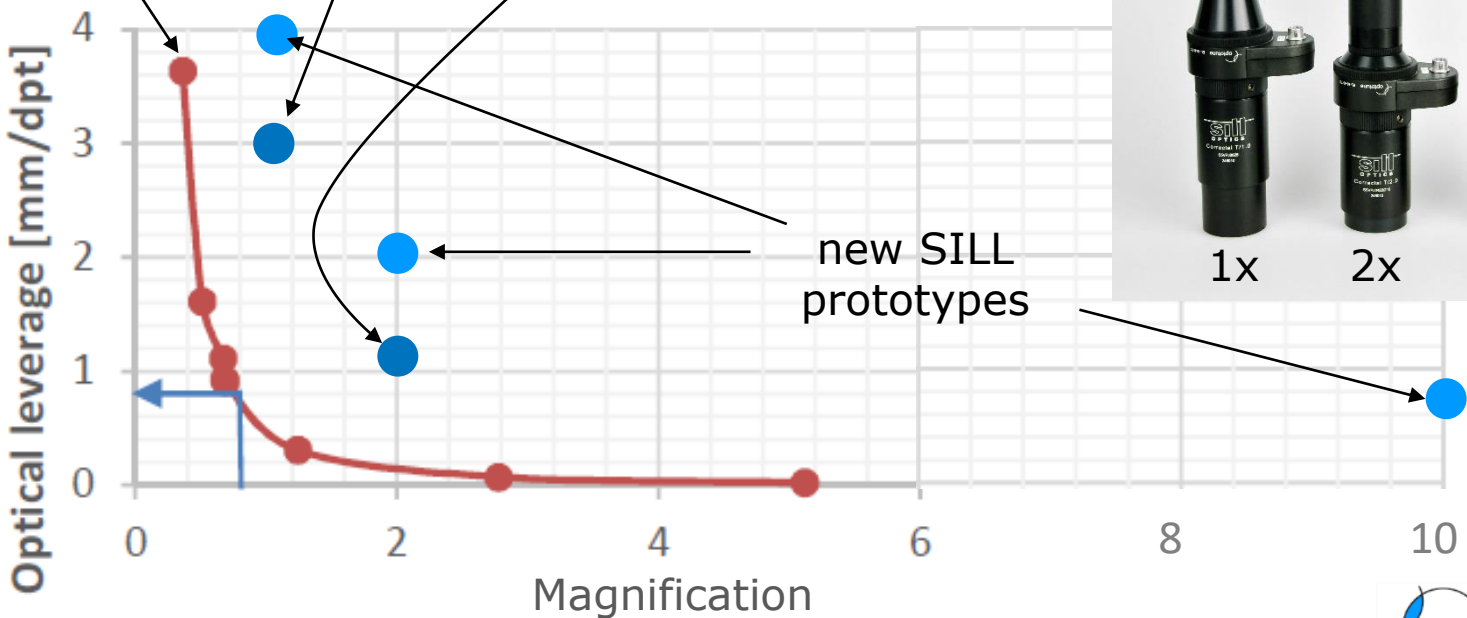
- 15mm Z-range
- <5% mag change

Moritex MML2-HR110
with integrated EL-16-40

- 5.5mm Z-range
- <8% mag change

Std back-lens configuration

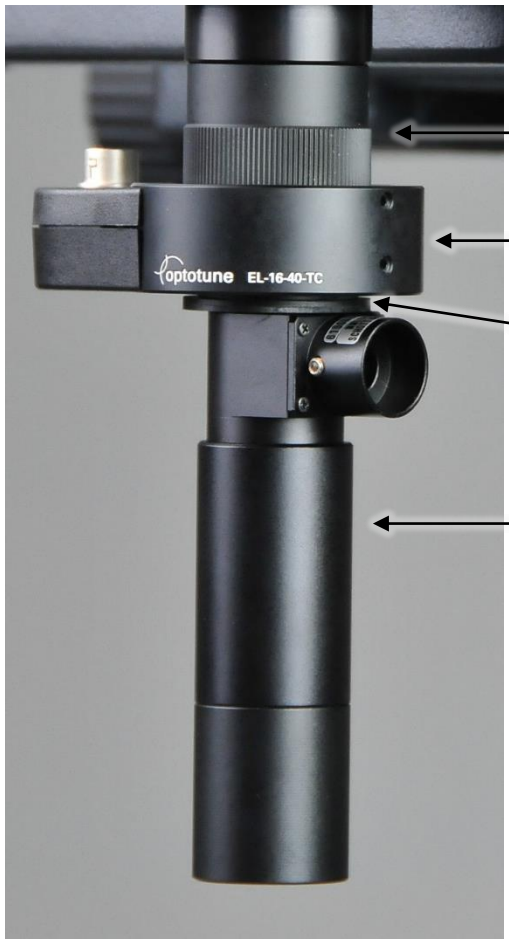
$\mathbf{OL} \approx 0.5[mm/dpt] \ / \ PMAG^2$



optotune

EL in off-the-shelf Moritex telecentric lenses

Many Moritex telecentric lenses can be taken apart
→ Integration of Optotune EL requires only one adapter



30mm C-Mount spacer

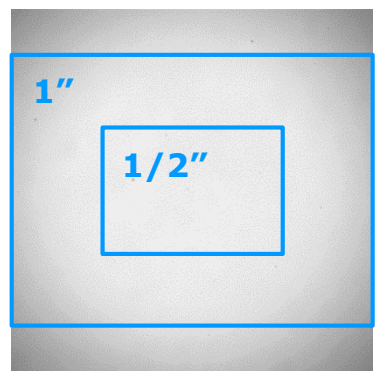
Optotune EL-16-40-TC

C-Mount to Moritex adapter

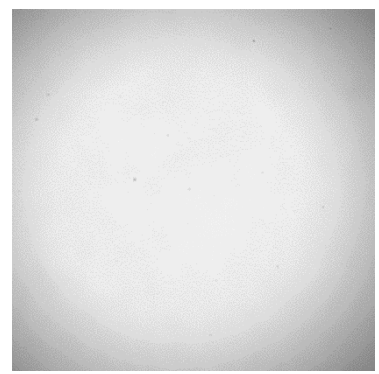
Moritex MML1-ST150D

- 2/3” camera sensors
- 15mm z-range at 1X mag
- <5% mag change
- Resolution unchanged

Without EL



With EL-16-40



optotune

Optimized 2X telecentric lens for large formats

Tubes:

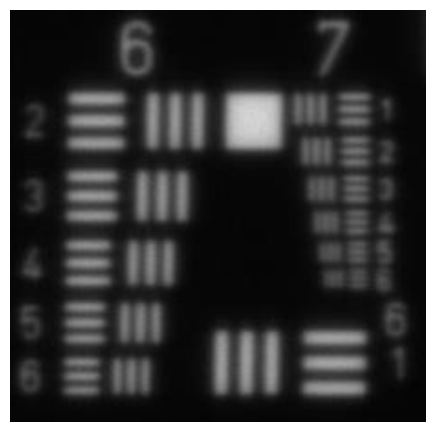
- M42 tube required for large format sensors
- C-mount tube ok for sensors up to 20mm in diagonal (as shown)

Optotune EL-16-40-TC

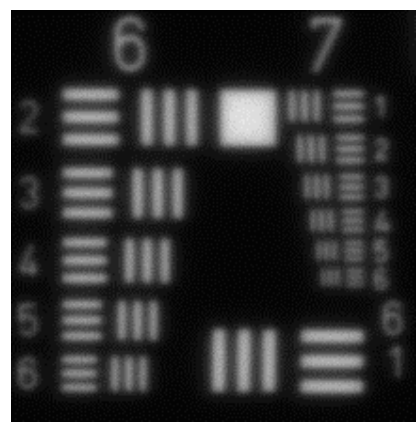
Sill Optics Correctal T/2.0

- 30mm image circle
- Large WD range: 105 +/-5mm
  - EL tuning from -2 to +3 dpt
- 4.5% mag change over full range
- 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

Test report available

Autofocus for high magnification

High mag

C-mount camera
½” 5MP sensor

1.5x mini tube lens
P/N 29-90-28-000

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

Optem 70XL zoom (0.75x-5.25x)
P/N 399510-309

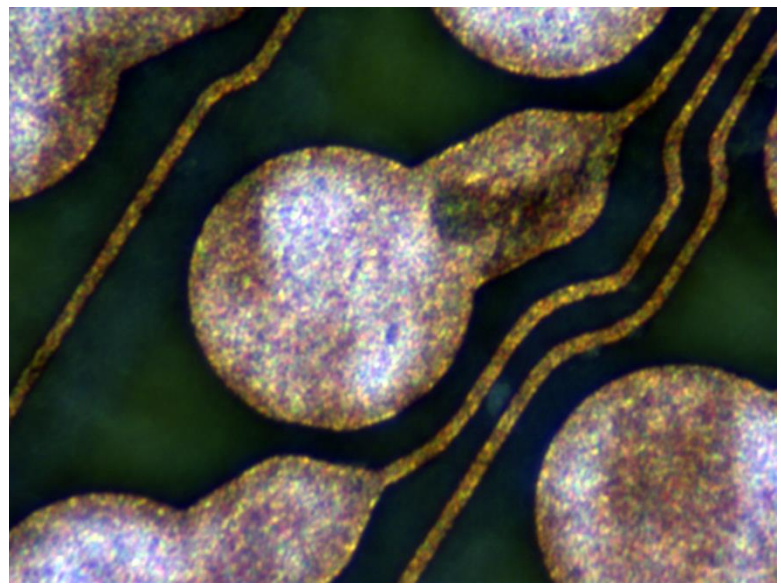
Coaxial lighting unit with lens
P/N 296515-310

LED ring light (used instead)

Working distance: ~90mm

Results:

Magnification	1.1x	3.5x	7.9x
Z range	400mm	40mm	8mm
Z resolution	100µm	10µm	2µm
DOF (approx.)	1mm	0.3mm	0.1mm
HFOV	4.5mm	1.4mm	0.65mm



- No vignetting
- Off-the-shelf components

optotune

Low cost AF microscope with fixed mag

High mag

C-mount camera

Empty C-mount tube,
40-60mm long

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

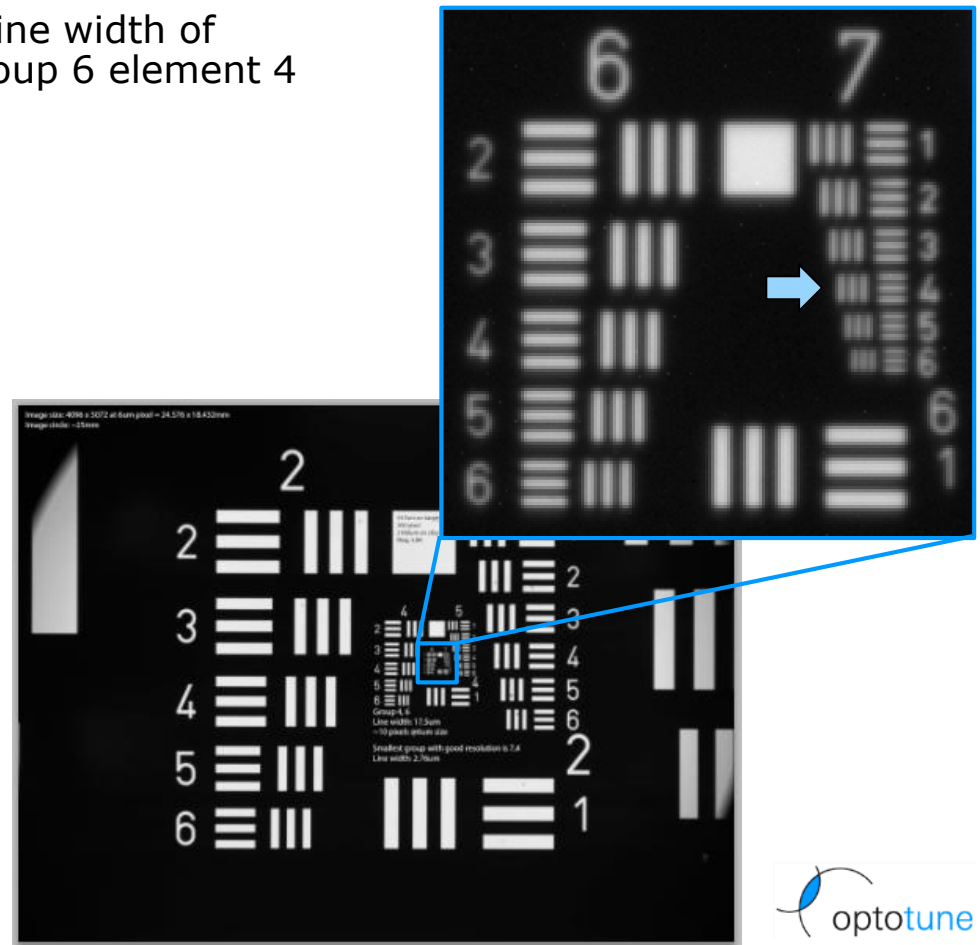
M22 to C-mount adapter

25mm lens (reversed!)
Edmund Optics 85358

Working distance: ~20mm

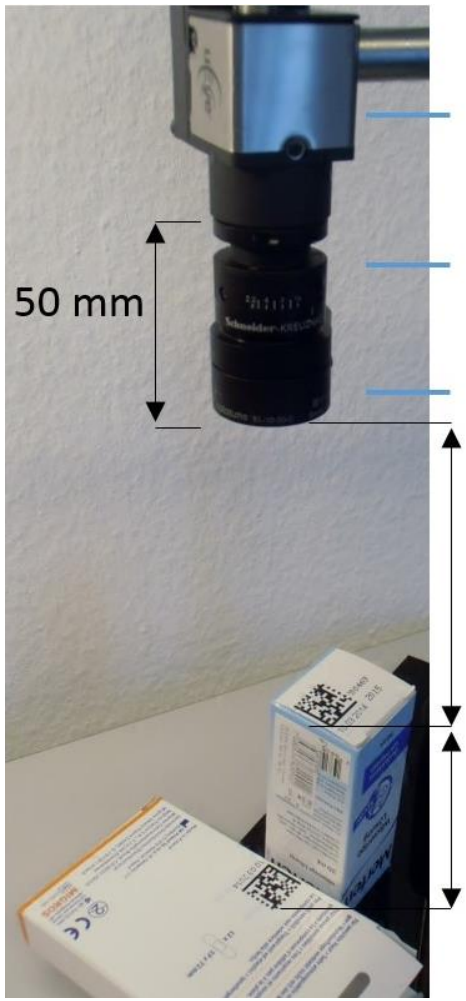
Tube length	40mm	60mm
Magnification	3X	4X
Z-range:	~3mm	~2mm
Resolution*:	3.7um	2.8um
Image circle	25mm	25mm

*Line width of
group 6 element 4



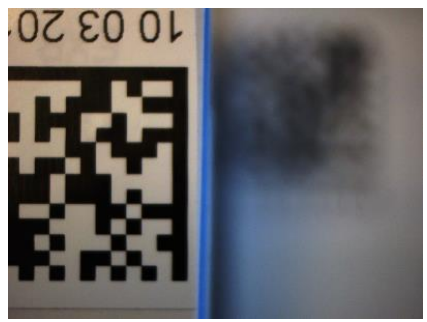
optotune

Frequency mode allows for multiple working distances within one image



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

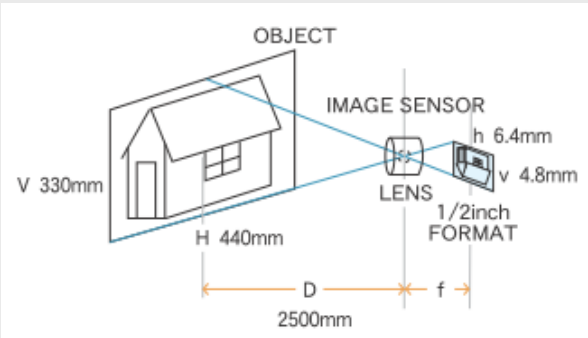
The working distance is modulated with a frequency of 35 Hz. Both the lower and the upper barcode are readable.

Note: Contrast is reduced as the two images are added/overlaid during exposure. A fast camera that acquires both images separately and image processing can be used avoid this effect.

optotune

What we need to make a recommendation

Customer requirement



1. Field of view (FOV) on object
2. Minimum and maximum working distance (WD)
3. Z-range on object (distance to focus over)
4. Target sensor size

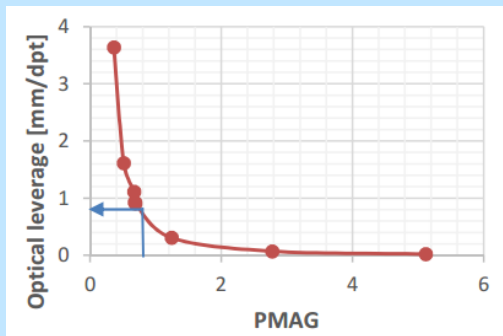
Calculations

Overall focal length:

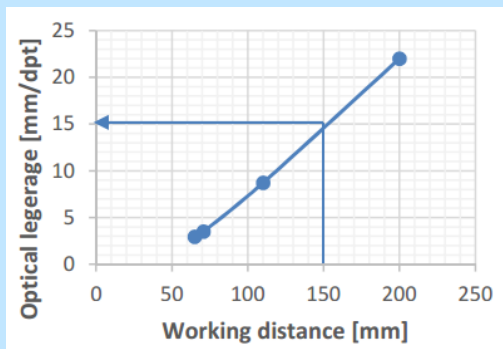
$$f = v \times \frac{D}{V}$$

Optical leverage of EL:

Back lens



Front lens



Recommendation

- From MV appl. note:

Qioptiq, 101 250 910	25 mm
Tamron, 23FM25SP	25 mm
Schneider-Kreuznach, 1068908	25.2 mm
Edmund, NT85-357	25 mm

- Optotune EL selection
- Estimate of required current range
- Thread adapters

optotune

Online lens configurator for endocentric lenses

http://configurator.optotune.com

Optotune Lens Configurator

optotune

REQUIREMENTS

Please enter details about the objects you want to inspect.

Maximum object size

350 mm x 250 mm

Required working distance range

1000 mm to 3000 mm

OPTICAL CONFIGURATION

Camera sensor size: 1/2" - 6.4mm width

Optotune Lens: EL-16-40-TC-5D

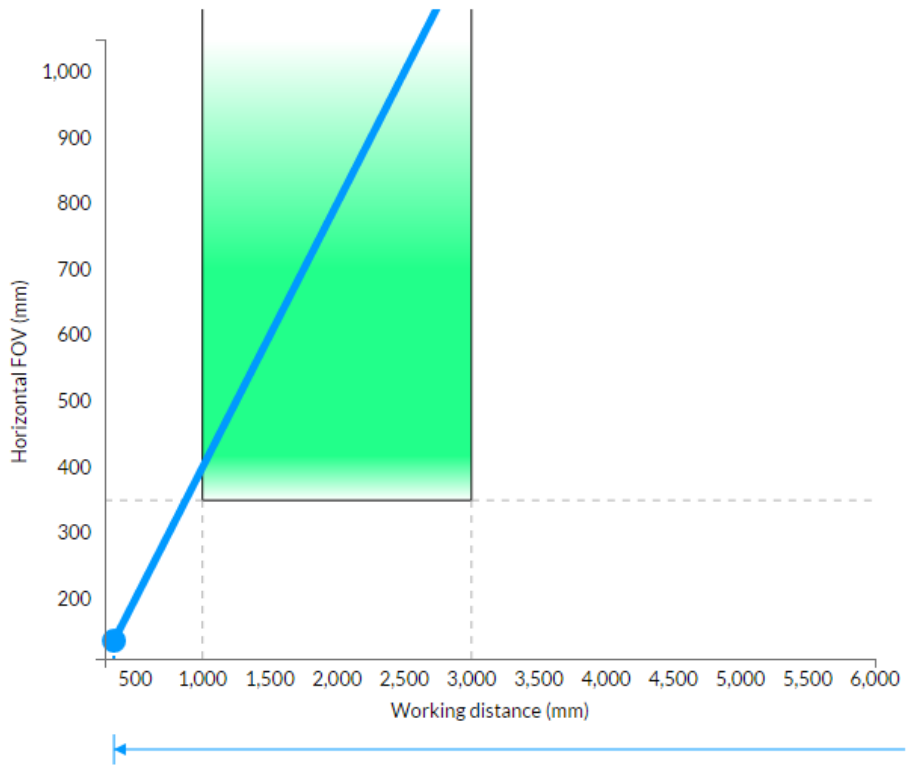
Camera Lens: 16mm: Tamron 23FM16SP

Lens Configuration

- (•) Frontlens
- ( ) Backlens

Spacer

Millimeters 0 − +



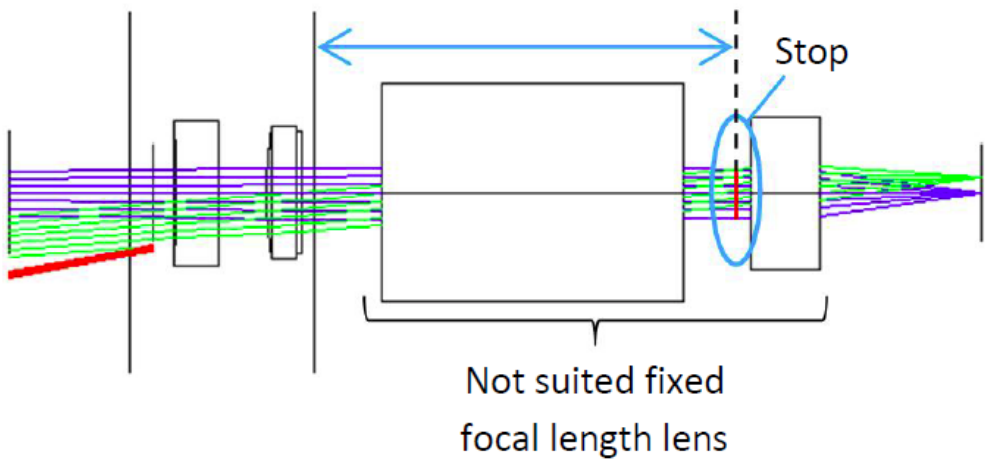
Z-range: **Infinite**
Lens tuning range: **-2.0** to **3.0 dpt**

optotune

Where are the limits?

The main limitations of Optotune's lenses for machine vision are:

Aperture size

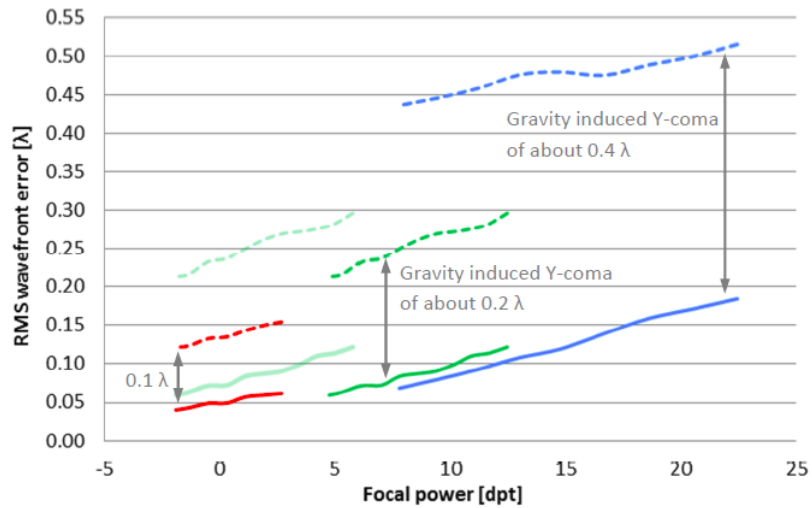


- Aperture currently limited to 16mm

Sensors limited to 30mm diagonal

Wide angles are problematic (f=8mm or less)

Wavefront error influenced by gravity



- Optical axis vertical: 0.05–0.15 λ RMS
- Optical axis horizontal: 0.15–0.25 λ RMS

Most applications work well in all orientations

Few applications require the optical axis to be vertical

Note: Wavefront error measured at 525nm over 80% of clear aperture

optotune

EL-10-30-Ci in back lens configuration can produce a ghost image

Back-lens configuration

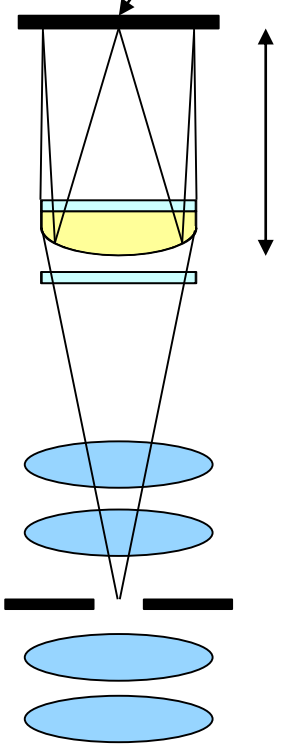
C-mount camera

EL-10-30-C

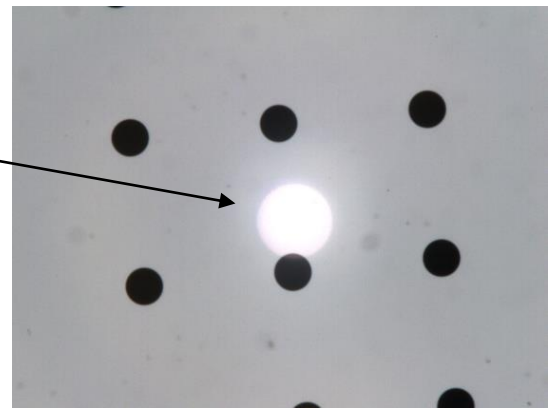
C-mount lenses

telecentic or FL>30mm

Aperture of imaging lens is imaged onto the sensor when EL-10-30-C is at ~65mA



17.5 + 5.3 = 22.8mm



Behavior very similar for different kinds of imaging lenses

Solution:

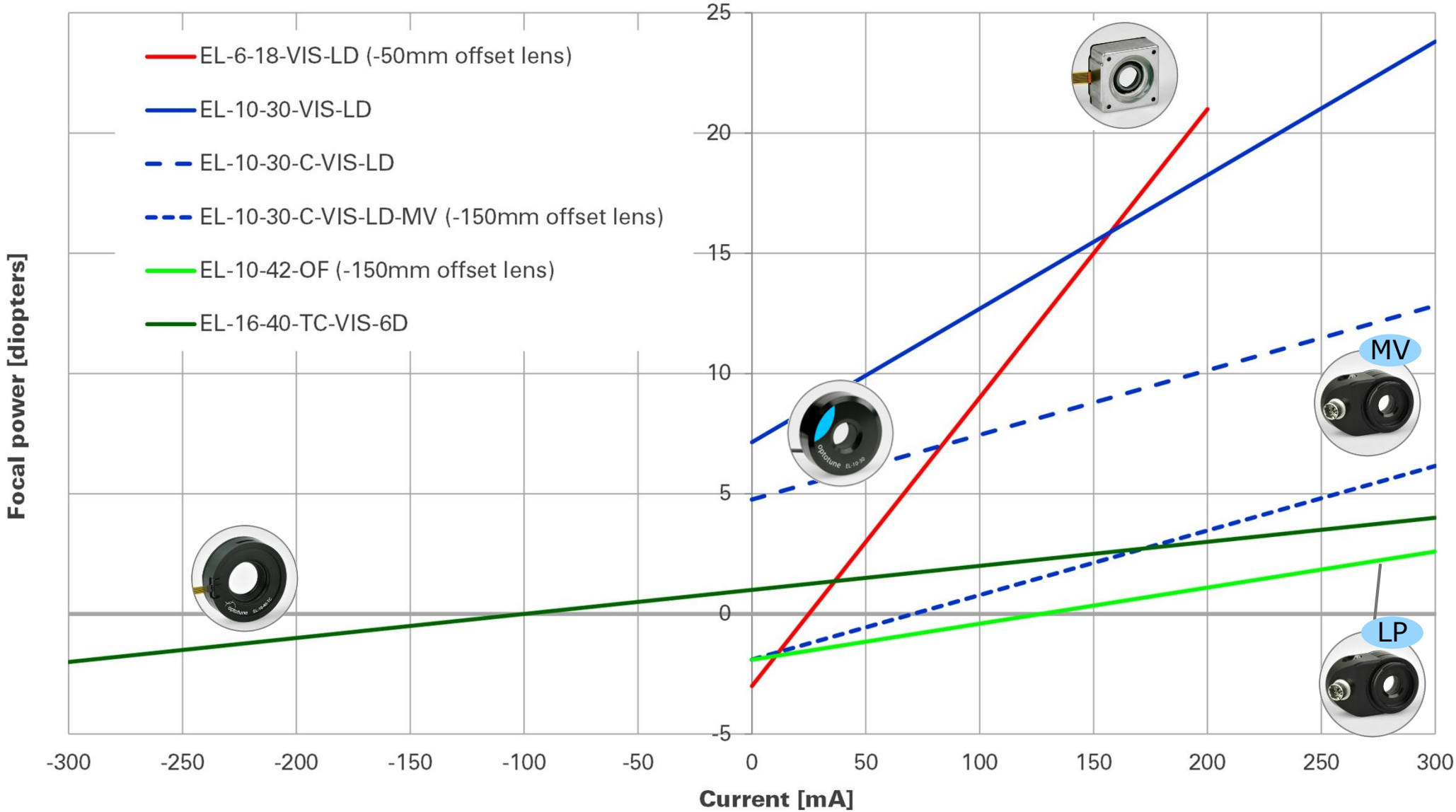
1. Insert distance ring between camera and EL-10-30 to change the current at which the ghost image is in focus

   With 10mm spacer:
   Aperture of imaging lens is imaged onto the sensor when EL-10-30-C is at 0mA
2. Use EL-16-40-TC instead
   (no ghost images within +/-5 dpt)

Agenda

- Introduction
- How to combine ELs with off-the-shelf optics
- Electrical integration
- Software
- Available products

The focal power (D = 1/f) of Optotune's lenses is controlled by current



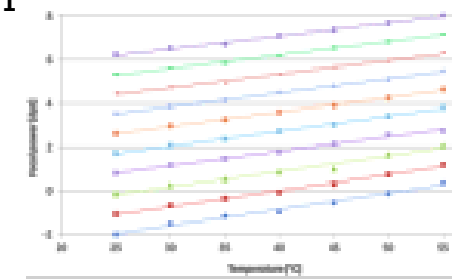
Note: This curve varies from lens to lens. However, it is reproducible once calibrated

optotune

Focal power mode for good reproducibility

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

Lens characterization f vs T vs I



Lens calibration curve stored on lens internal memory

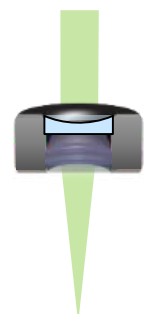
"I need a lens with f=125mm (8 diopters)"

Use focal power mode to set lens to 8 diopters

Temperature compensated control current to adjust lens to 8 diopters

Lens calibration table and temperature read by lens driver

Temp sensor with EEPROM

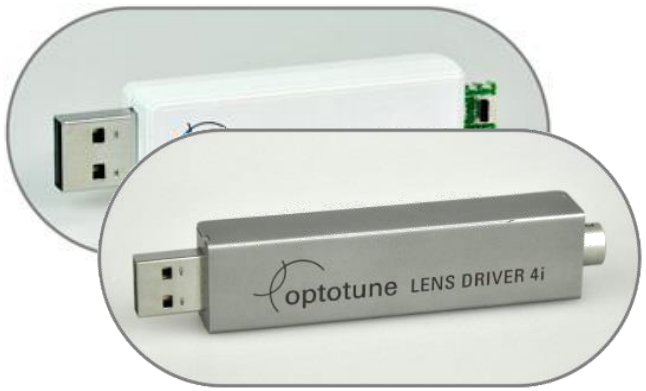


f=125mm (8 diopters)

optotune

Three options to drive Optotune's lenses

Optotune Lens Driver



- Currently only USB based
- RS232 & analog interface possible for R&D (connections on PCB)
- Responsibility for performance with Optotune

Best for R&D and low volume

Our circuit on customer PCB

- FW shared in compiled form only
- All interfaces can be used
- Responsibility for performance with Optotune

Fast implementation for high volumes

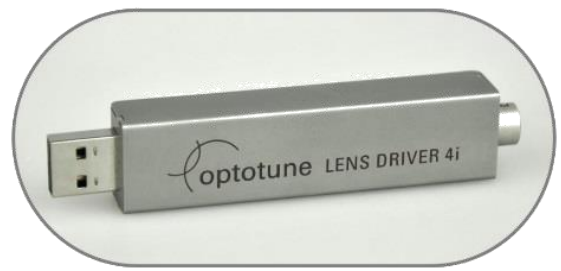
Customer's own circuit

- Only very limited FW support provided
- Implementation of focal power mode is not simple
- Responsibility for performance with customer!

Optimized for cost & performance

optotune

Industrial driver with GigE interface by Gardasoft

	Gardasoft TR-CL180	Optotune Lens Driver 4i
		
Current range	-400 to +400 mA	-290 to + 290 mA
Current resolution	0.1 mA	0.07 mA
Current accuracy	0.5 mA	0.5 mA
Latency in current mode	NA	1-2 ms
Latency in focal power mode	1 ms	2-4 ms
Interfaces	GigE, RS232, Analog 0-10 V	USB 2.0 (UART & analog* 0-5 V on the PCB)
Supply voltage	24 V	5 V

* Analog input only mapped to current, not focal power

optotune

Up to 20m of combined cable length tested

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

- 1m Optotune standard
  - P/N: CAB-6-100
- 3m specified
  - According to I2C standard
- 10m tested
  - Full performance verified
  - I2C enters clock stretching mode

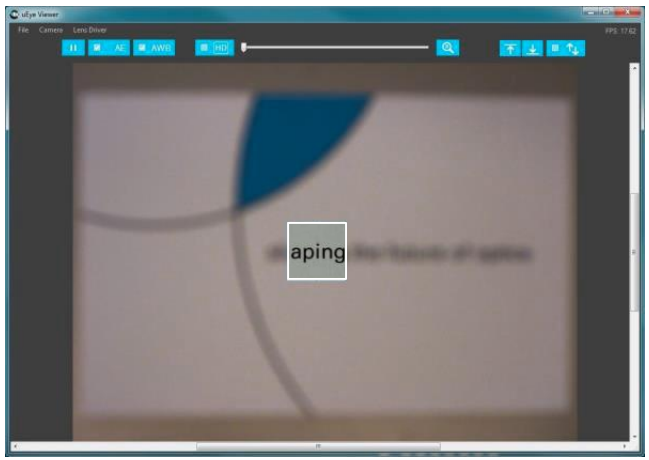
optotune

Agenda

- Introduction
- How to combine ELs with off-the-shelf optics
- Electrical integration
- Software
- Available products

How to find the right focus

Image based autofocus

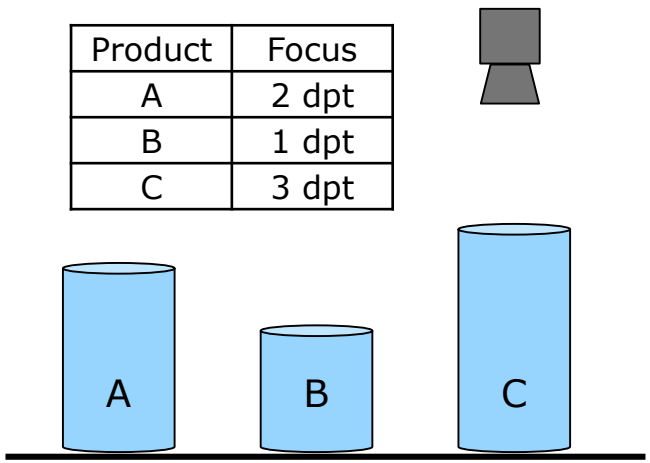


- Multiple images are acquired to find the best focus by algorithm
- Typically 10-15 frames required
  → ~1sec focus time

Cheap, flexible but not 100% reliable

Preset lookup tables

Product	Focus
A	2 dpt
B	1 dpt
C	3 dpt

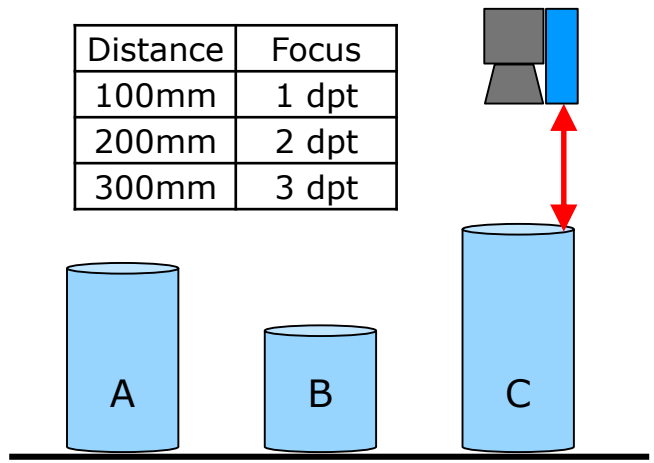


- Focus positions are stored in a lookup table during calibration (teaching)
- Only one focus step required
  → 15ms focus time

Inflexible, as reliable as the focal power mode (~0.1dpt)

Using a distance sensor

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

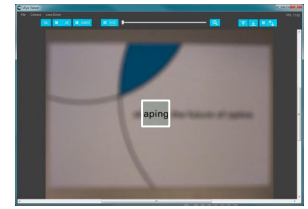


- Multiple distance vs focal power points are saved during calibration
- Only one focus step required
  → 15ms focus time

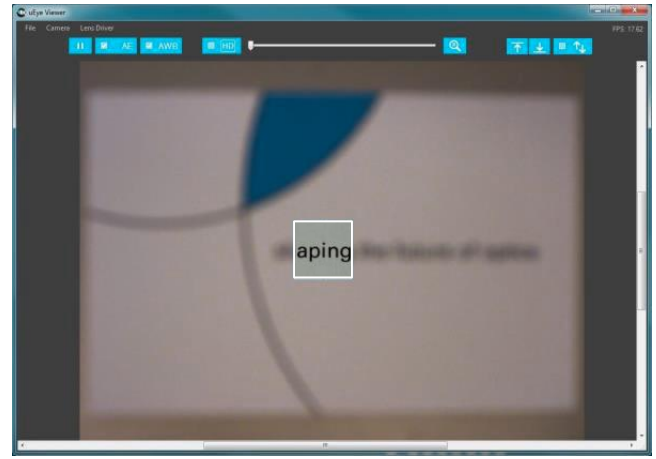
Flexible, quite reliable but expensive

optotune

Image based autofocus

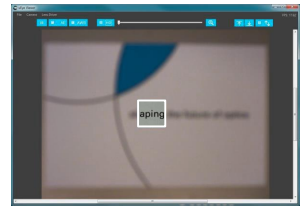


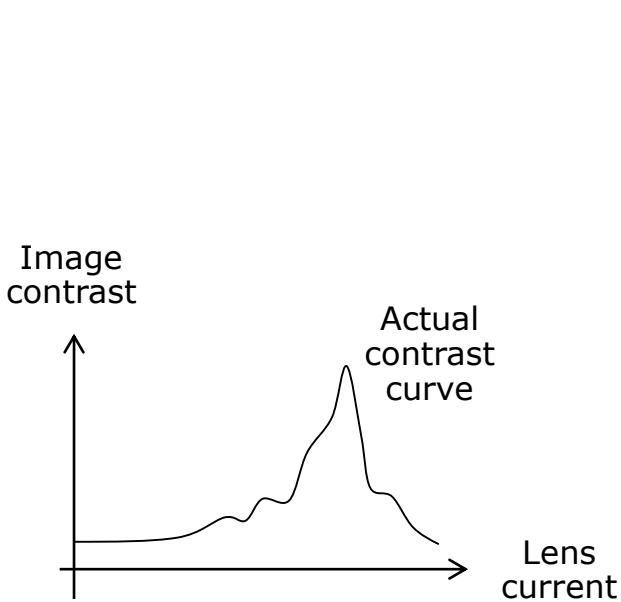
- In order to increase the framerate >30 fps it is recommended to use a small ROI
- We recommend doing AF in current mode and switch back to focal power mode afterwards
- Optotune has implemented AF in C# and shares the source code
  - Very limited support for customer SW

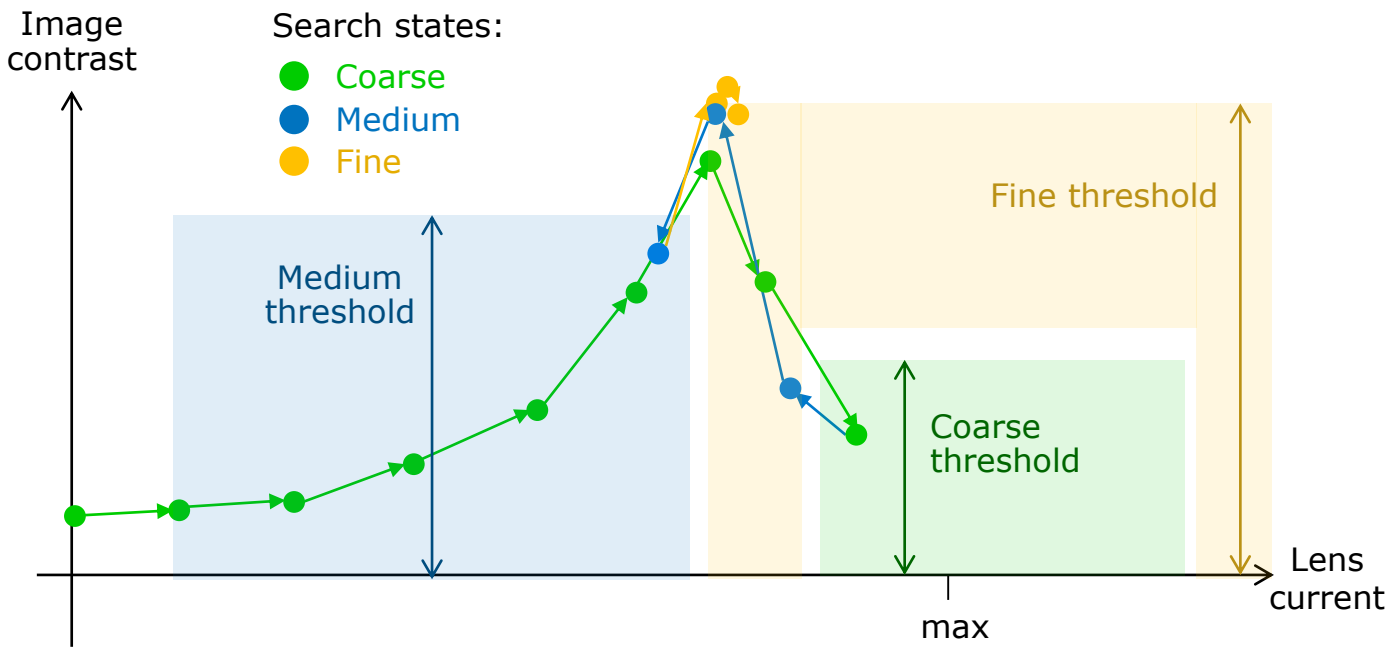


Pros	Cons
• No additional HW cost • No teaching required • Works without focal power mode • Good for demos • Usually works well for code reading	• Focus is not always found (depending on target) • Quite slow (~1 sec) • SW development required

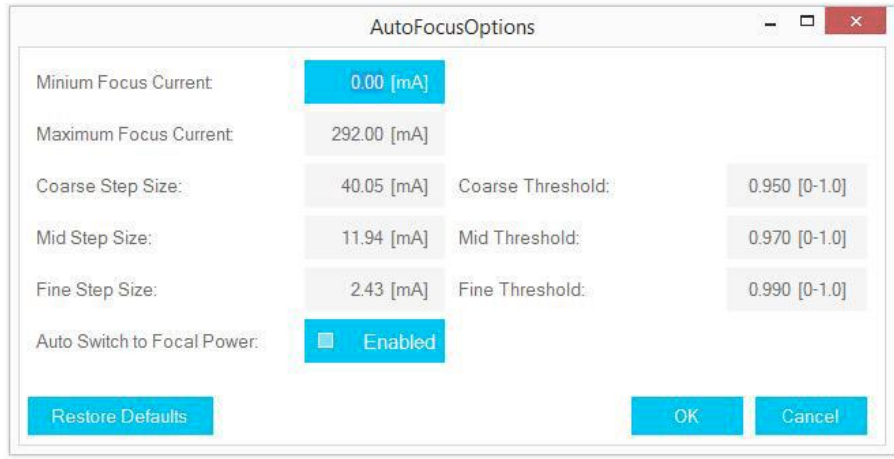
Optotune's autofocus algorithm





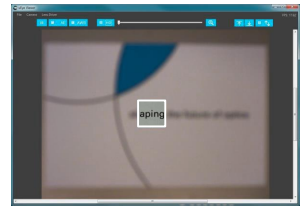


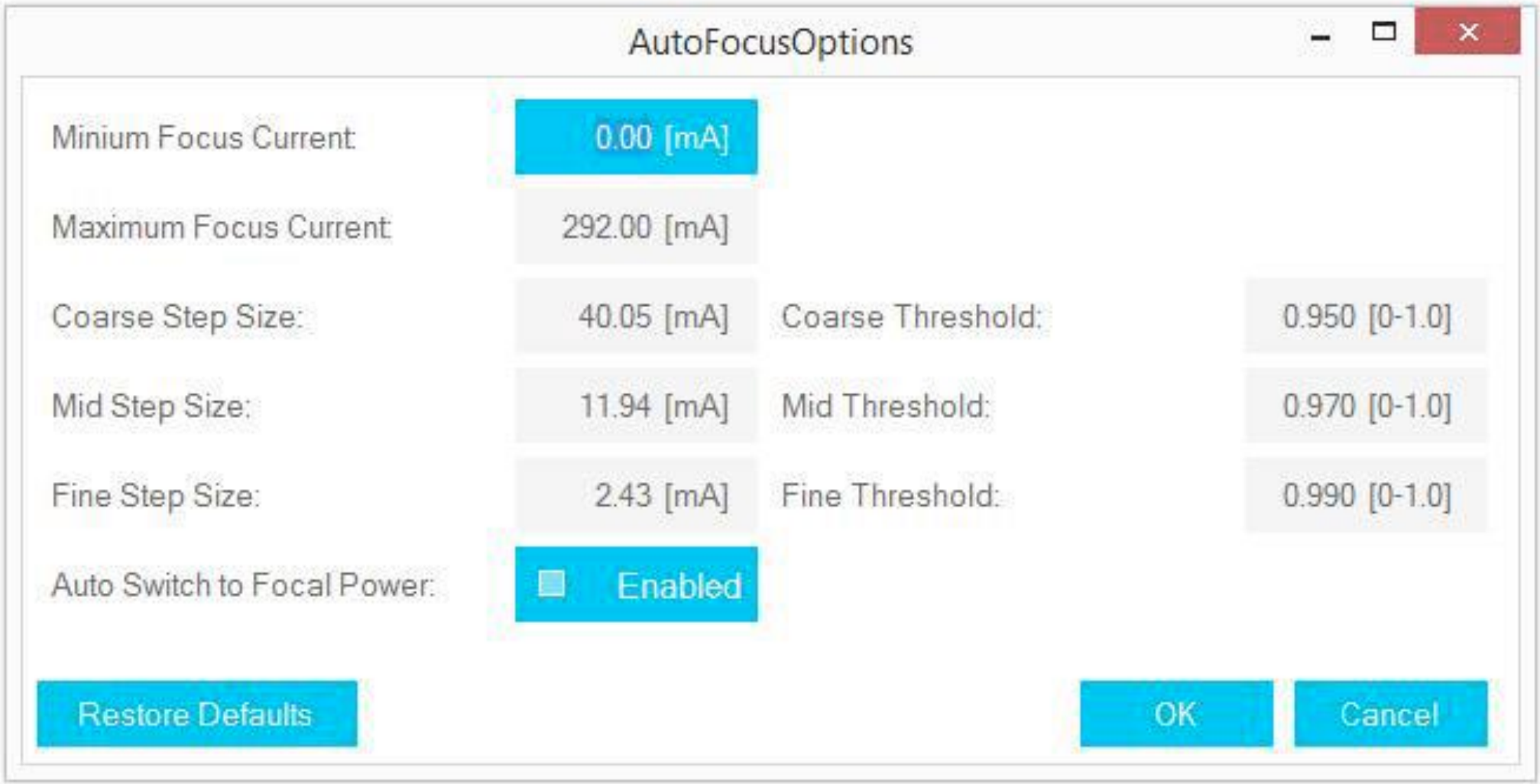
Parameters can be set in Lens Driver Controller:



optotune

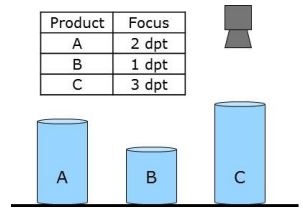
Optotune’s autofocus algorithm



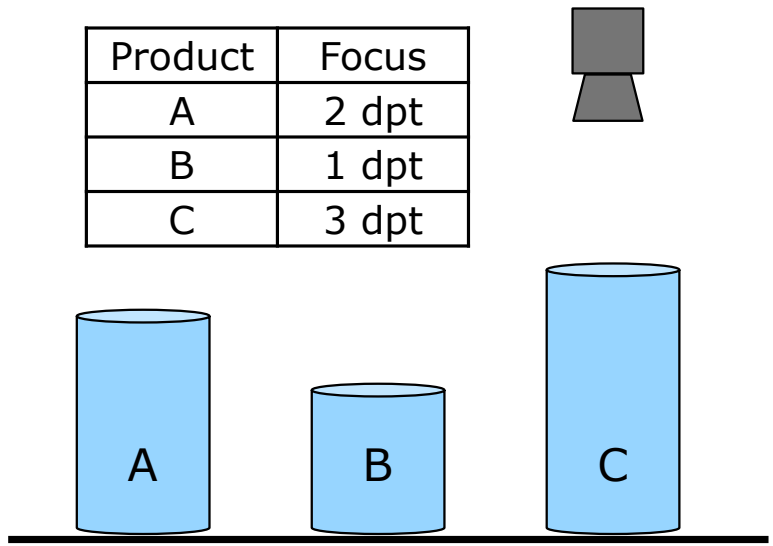


optotune

Preset “focus lookup table”



- Once the system is installed, the customer saves the focal power values for each product or inspection step (teaching)
- The customer SW sends a single focal power command per inspection step
  → 15ms focus time with EL-10-30



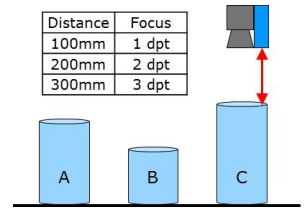
Pros

- Fastest way to focus
- No additional HW cost
- Deterministic focus method
- Minimal SW development required

Cons

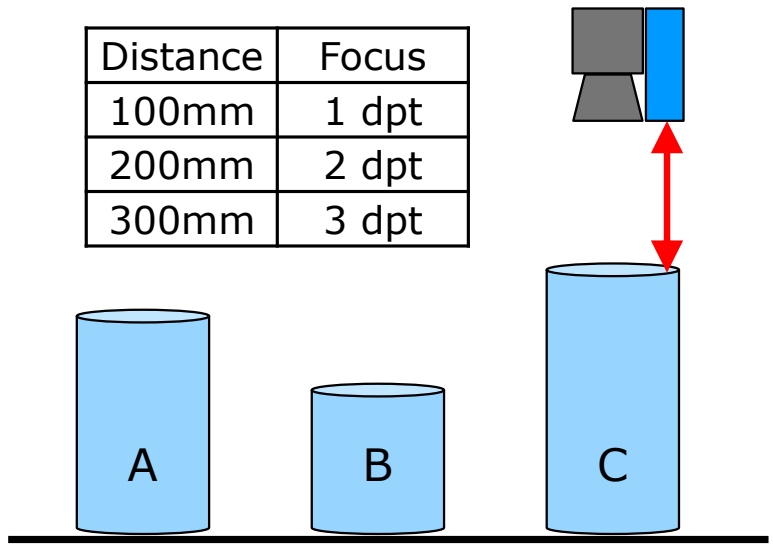
- Teaching required (may have to be repeated from time to time)
- Only works for limited pre-set positions
- Only as accurate as focal power mode (~0.1 dpt)

“Always in focus” with a distance sensor



- Once the system is installed, the customer calibrates multiple pairs of distance vs. focal power
- Suitable sensors (e.g. Keyence, με, Sick)
  - Time of flight (~1mm resolution, ~400EUR)
  - Confocal (~10um resolution, >1000 EUR)
- The Lens Driver’s analog input can be used

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



Pros

- Focus in 20ms
- Can work as stand-alone system (without PC)

Cons

- Calibration required (may have to be repeated from time to time)
- Only as accurate as focal power mode (~0.1 dpt)
- Not all surfaces work well
- Additional hardware cost

optotune

Fast focusing with the EL-10-30

optotune

shaping the future of optics

Continuous focus with Optotune's EL-10-30-C using a distance sensor

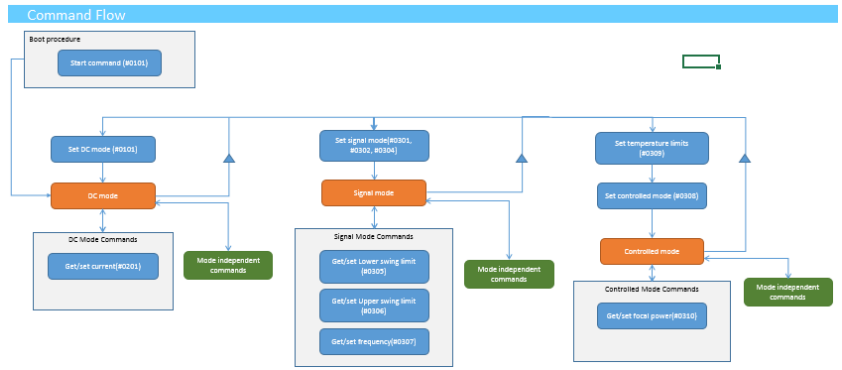
Video available on www.optotune.com

optotune

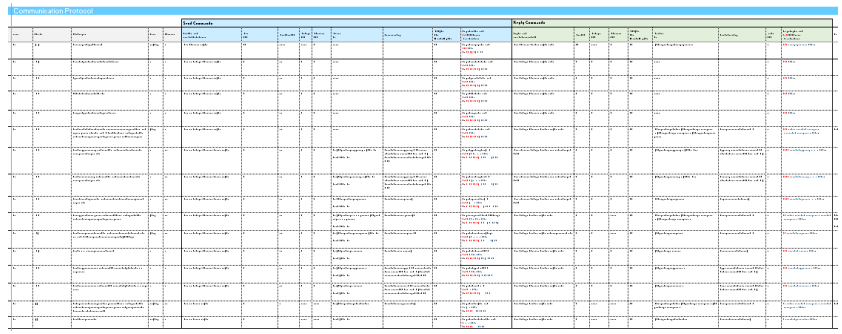
Serial protocol can be implemented by customers

- 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

Command flow:



Serial protocol:



optotune

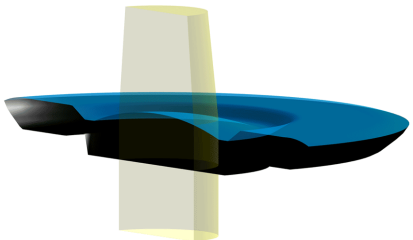
Software partners

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

Agenda

- Introduction
- How to combine ELs with off-the-shelf optics
- Electrical integration
- Software
- Available products

Optotune's electrically focus tunable lenses

	EL-10-30	EL-10-30-C(i)	EL-16-40
			
Focal power range*	8 … 22 Dpt	-1.5 … +3.5 Dpt	-2 … +3 Dpt -10 … +10 Dpt
Clear aperture	10mm	10mm	16mm
Outer diameter	30mm	30mm	40mm
Wavefront quality RMS @525nm**	<0.25 / 0.5 λ	<0.15 / 0.25 λ	<0.25 / 0.5 λ <0.25 / 1.5 λ
Absolute focal power accuracy	N/A	< 0.1 dpt	< 0.1 dpt
Built-in sensors	None	Temperature	Temperature
Applications	Microscopy	Machine vision	Machine vision Ophthalmology

* Depends on selected optical fluid

** vertical / horizontal optical axis

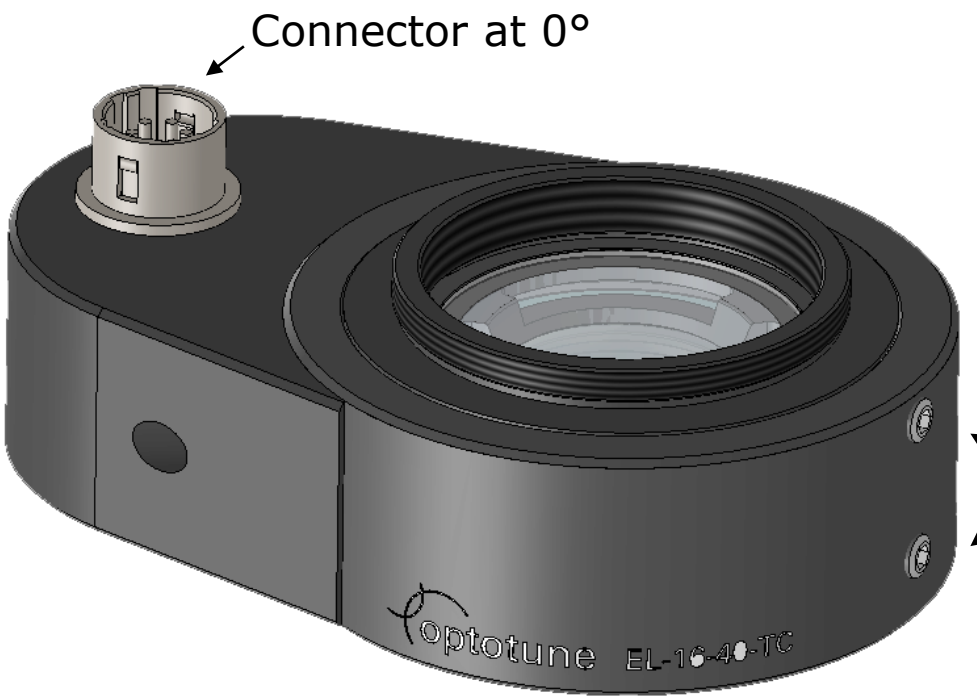
***Qualification is ongoing

optotune

New 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, M27, M30.5)

optotune

EL-16-40 configurations for machine vision

Front-lens configuration

C-mount camera

C-mount lens
filter threads
M25.5 M27 & M30.5

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

Typical WD range: **200mm to infinity**

Back-lens configuration

C-mount camera

M42-mount camera

EL-16-40-TC-VIS-5D-**C**

EL-16-40-TC-VIS-5D-**M42**

C-mount lenses

telecentric or FL>30mm

M42-mount lens

WD <200mm, Range depends on magnification

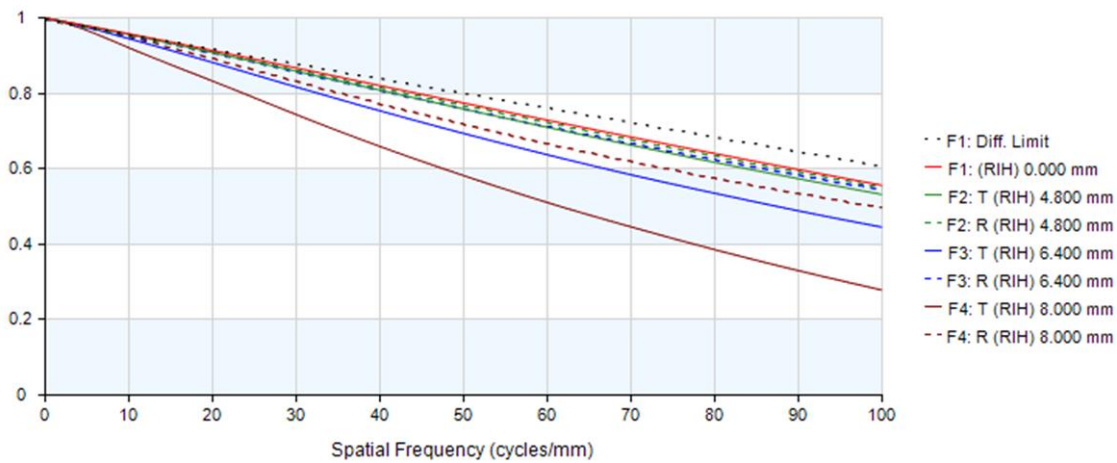
300mm to infinity

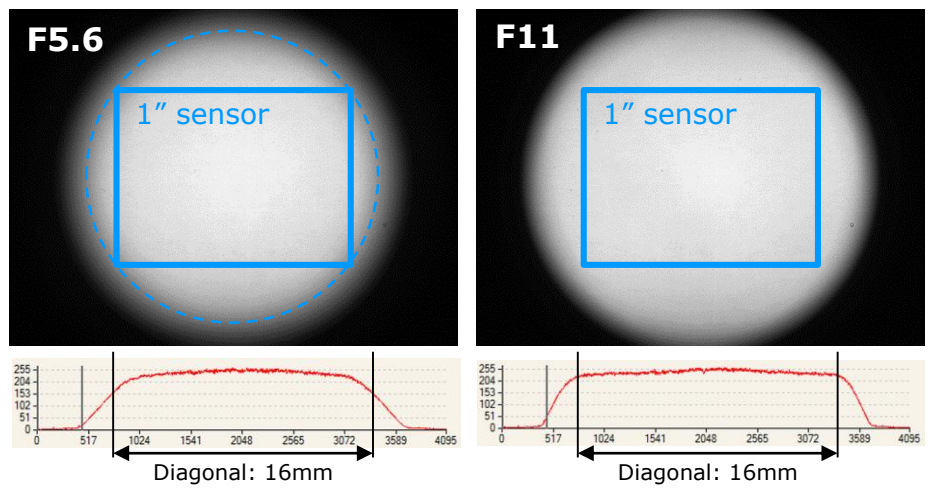
optotune

Kowa 35mm lens with integrated EL-10-30-Ci

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





Spec sheet: www.optotune.com/images/products/Optotune-Kowa 35mm lens S10-469 spec sheet.pdf
Test report: www.optotune.com/images/products/Optotune 35mm imaging lens for 1inch sensors.pdf

optotune

Optotune Switzerland AG
Bernstrasse 388
CH-8953 Dietikon
Switzerland

Phone: +41 58 856 3000 | Fax: +41 58 856 3001

www.optotune.com | info@optotune.com