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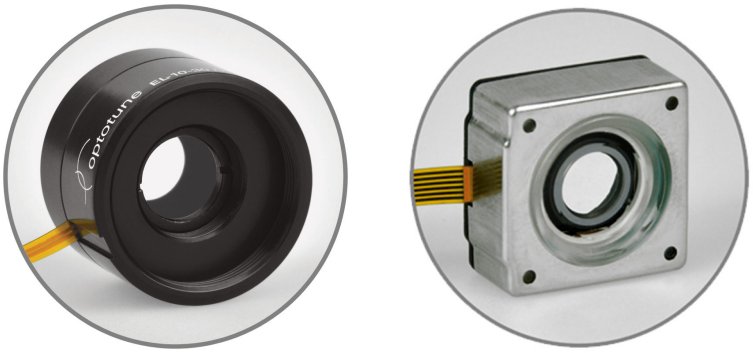

Application note

Fast focusing for machine vision applications

With Optotune's focus tunable lenses EL-10-30-C and EL-6-18

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Introduction

Flexible and fast focusing solutions with electrically tunable lenses are highly beneficial for machine vision applications, like e.g. quality control, packet sorting, bar code reading, etc. In traditional setups, the adjustment for objects at different working distances is realized mechanically. In contrast, with Optotune's shape-changing polymer lenses, refocusing can be achieved in milliseconds without any mechanical translation involved, enabling compact, robust and dust-free optical systems. Besides focusing solutions, focus-tunable lenses can also be used for adaptive illumination with highly flexible lighting parameters reducing the number of light sources and the overall power consumption.

Optotune offers two different-sized electrically tunable lenses: the EL-10-30-C with an aperture of 10 mm and the EL-6-18 with an aperture of 6 mm, respectively. The housing of the EL-10-30-C exhibits a C-mount thread compatible with standard industrial cameras. Furthermore, an offset lens can be integrated directly in the housing to adjust the focal length range to the desired values. The EL-6-18 with a built in offset lens enables very compact and fast solutions with a wide field of view. There are three main configurations:

1. **Front-lens configuration**: The tunable lens is placed in front of fixed-focus optics as a close-up lens. For such a configuration, the focal length range of the tunable lens has to include long focal lengths, especially infinity (zero diopters). The standard focal length range of the EL-6-18 already includes infinity. Also the EL-10-30-C can be placed in front with a diverging offset-lens, such that the focal length range is shifted to longer focal lengths including infinity (P/N EL-10-30-C-VIS-LD-MV). This configuration is recommended for high-quality imaging.
2. **High magnification configuration**: The tunable lens is placed between an infinity corrected objective lens and a tube lens. This configuration also requires the tunable lens to include infinite focal length.
3. **Doublet configuration**: In case of the EL-10-30-C, the focal length range can also be shifted to shorter focal lengths (typically 16 up to 35 mm) with a converging offset-lens. By doing so, the EL-10-30-C itself can be used as simple and compact focusing solution for C-mount or CS-mount cameras. As this is not an optimized optical design, it is only recommended for resolutions below 1 MP.

Offset lens

In the EL-10-30-C, the protective cover glass can be replaced by an offset lens of 12-mm or 12.7-mm diameter. This allows shifting the focal length range to any desired value. For example, the EL-10-30-C-VIS-LD with a normal planar cover glass has a standard focal range of +200 mm down to +80 mm. The integration of an offset lens with f = -150 mm will yield a focal length range of about -600 mm to infinity to +170 mm ($1/f_{res} = 1/f_{EL\text{-}10\text{-}30} + 1/f_{offset}$). The design of the EL-10-30-C is optimized for good alignment of the tunable lens and the offset lens. The maximally allowed thickness of the offset lens is 4.7 mm.

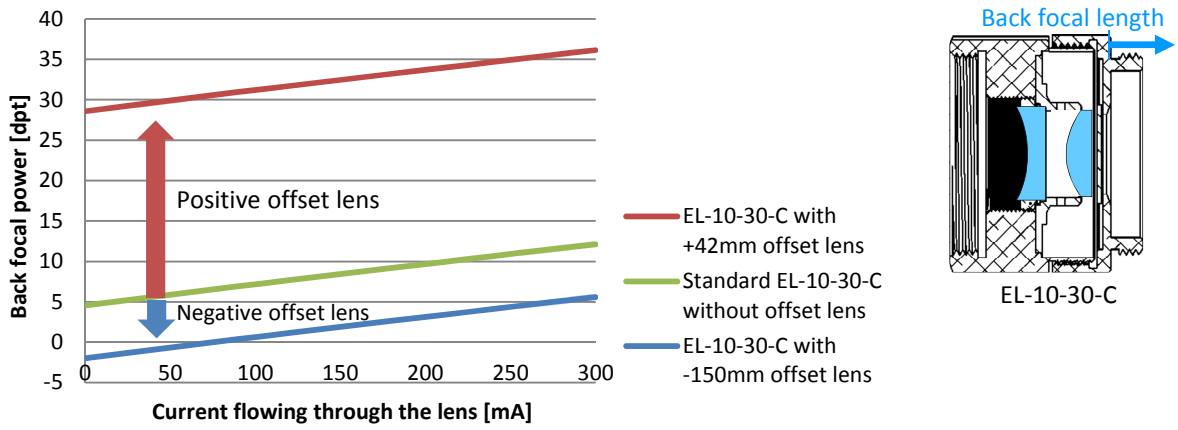

Figure 1: An offset lens can be used to shift the focal length range of the standard EL-10-30-C

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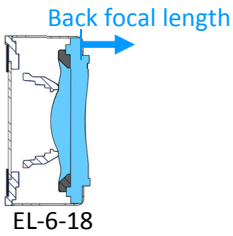
In case of the EL-6-18, the plano-concave offset lens with a focal length of -50 mm is built into the lens. The resulting total tuning range of the focal length is -500 to +50 mm (-2 to +20 dpt). For customized versions with a different tuning range, please contact sales@optotune.com.



Front-lens configuration: tunable lenses in combination with fixed optics

Both, the EL-10-30-C with an integrated plano-concave offset lens, as well as the EL-6-18, can be used as close-up lenses in combination with fixed focal length lenses to achieve electronically controllable focusing units exhibiting high optical quality.

Principle of a refocusing setup with a tunable lens

Figure 2 shows a comparison between a traditional focusing setup and a combination including a lens with variable focal length. In the traditional approach, one or several lenses have to be mechanically translated to achieve focusing for different working distances. In contrast, in combination with a tunable lens, all the elements stay at a fixed position. Only the curvature of the tunable lens and hence the focal length is varied to achieve focusing for different working distances.

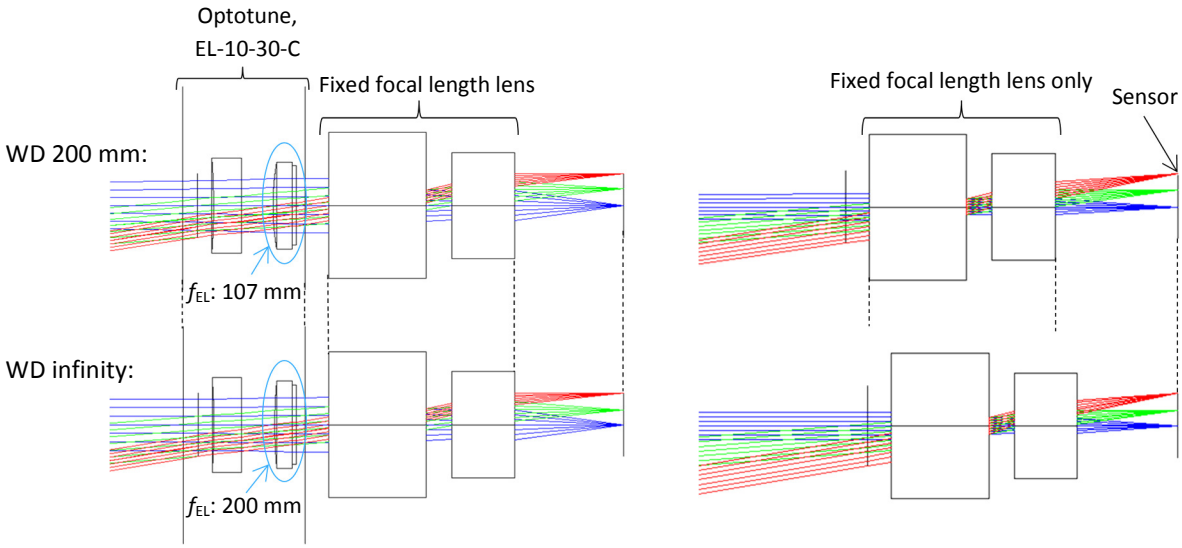


Figure 2: With a tunable lens, refocusing for different working distances (WD) is achieved by only changing electronically the focal length of the lens; without any translational movement

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Example EL-10-30-C with a 25-mm imaging lens

Figure 3 shows an example of a front-lens configuration with a standard C-mount machine vision lens with a focal length of 25 mm. The cover glass of the EL-10-30-C is replaced by a plano-concave (negative) offset lens with a focal length of -150 mm and orientated with the flat side facing the tunable lens. The EL-10-30-C is mounted in front of the fixed focal length lens. Depending on the filter thread of the fixed focal length lens, an adapter might be required.

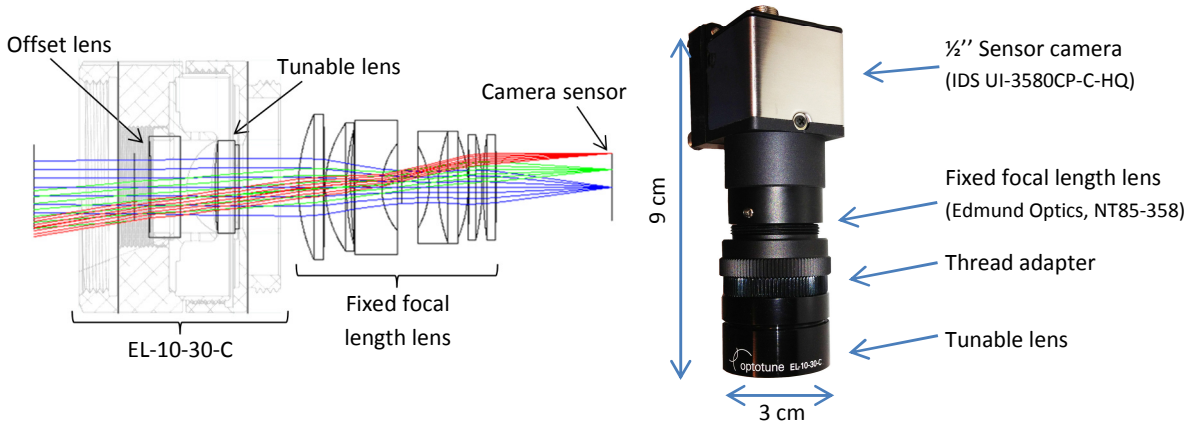

Figure 3: Example of an electrically controllable focusing unit: EL-10-30-C with an integrated plano-concave offset lens, a fixed focal length lens (focal length 25 mm) and a camera (1/2'' sensor)

Adding the EL-10-30-C preserves the high optical quality achieved with the fixed focal length lens. Figure 4 shows a comparison between images taken with the fixed focal length lens only (mechanical focusing) and in combination with the EL-10-30-C. The horizontal full field of view (FOV) of this configuration is 14.5° (for 1/2'' sensor sizes) and the f-number is 4.

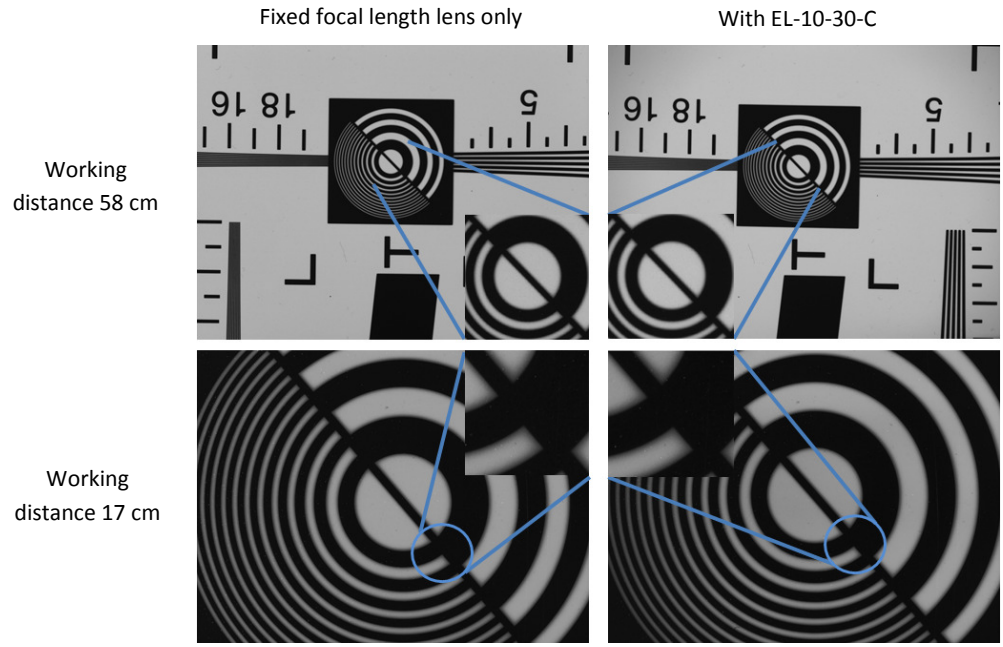

Figure 4: Close up configuration: comparison between the optical qualities achieved with a fixed focal length lens only (Edmund Optics, NT85-358) and in combination with the EL-10-30-C for different working distances

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Example EL-10-30-C with a 12-mm board lens

Figure 5 shows a very compact front-lens configuration with the EL-10-30-C using an M12 board lens with a focal length of 12 mm and an f-number of 2.8. The resulting horizontal full field of view (FOV) for a ½" sensor is 32.8°. This configuration is particularly well suited as the stop position of the board lens is in the very front (see discussion about vignetting below). Again, no loss of optical quality can be observed with a 5MP camera.

In the configuration shown below, the C-mount thread of the camera is long enough to both hold the C- to S-mount adapter as well as for mounting the EL-10-30-C by the male C-mount thread. For cameras with a shorter thread, a slightly different mounting is recommended: half of the C- to S- mount adapter is screwed into the camera housing, and the EL-10-30-C is screwed with the reversed orientation by the female C-mount thread to the other half of the adapter.

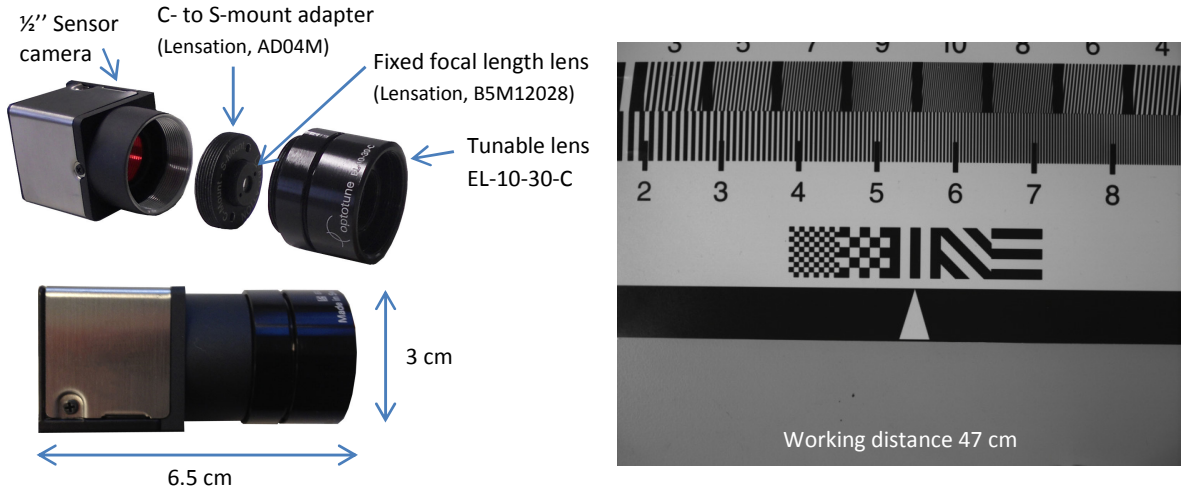

Figure 5: Very compact wide field configuration with the EL-10-30-C and a compact fixed focal length lens (Lensation, B5M12028 (with IR-cut filter: B5M12028C) with a field of view of 32.8° (for ½'' sensor) and high optical quality

Recommended off-the-shelf combinations with the EL-10-30-C lens

In Table 1, recommended fixed focal length lenses with different field of views ranging from 6° up to 56° are listed, which are suited to be combined with the EL-10-30-C lens. The field of view corresponds to the horizontal full field of view for a standard 4:3, ½'' sensor format. For certain configurations (e.g. with Schneider-Kreuznach, 1068908), the EL-10-30-C can be directly mounted to the filter threading of the fixed focal length lens. In case of compact fixed focal length lenses (S-Mount, M12 lenses), the EL-10-30-C can be mounted to the housing of the camera (e.g. with Lensation, B5M12028). It is indicated in the overview table if a customized thread adapter is required to mount the EL-10-30-C.

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Field of view[#1]	Product	Focal length	Working distance[#2]	Aperture (f/#)	Adapter	Customized adapter required	Maximum sensor size
56°	Lensation, B5M8428 B5M8448 B5M8480	8.4 mm	30 mm – infinity	Fix, 2.8 4.8 8	Lensation, AD04M	no	1/1.8”
32.8°	Lensation, B5M12028 B5M12040 B5M12056	12 mm	30 mm - infinity	Fix, 2.8 4 5.6	Lensation, AD04M	no	1/2’’
19.6°	Qioptiq, 101185910	18.5 mm	25 mm - infinity	Fix, 3.5		yes	2/3’’
14.6°	Qioptiq, 101250910	25 mm	30 mm - infinity	Fix, 3		yes	2/3’’
14.6°	Tamron, 23FM25SP	25 mm	70 mm - infinity	Variable, 2.2 up to 22		yes	2/3’’
14.5°	Schneider-Kreuznach, 1068908	25.2 mm	50 mm - infinity	Variable, 2.2 up to 16		no	1/1.8’’
14.5°	Edmund, NT85-357 NT85-358 NT85-359 NT85-360	25 mm	20 mm - infinity	Fix, 2.8 4 5.6 8		yes[#3]	2/3’’
14.5°	Edmund, NT59-871	25 mm	20 mm - infinity	Variable, 2.8 up to 17		yes	2/3’’
13.3°	Edmund, NT58-207 NT69-266 NT83-955	25 mm	60 mm - 1200 mm	Fix, 2.5 4.0 8.0	Edmund, 53-675 and 54-630	no	1/2’’
13.2°	Qioptiq, 101277910	27.7 mm	40 mm - infinity	Fix, 3		yes	2/3’’
10.4°	Edmund, NT85-365 NT85-366 NT85-367	35 mm	50 mm - infinity	Fix, 4 5.6 8		yes	2/3’’
10.4°	Edmund, NT59-872	35 mm	50 mm - infinity	Variable, 4 up to 22		yes	2/3’’
10.2°	Qioptiq, 101360910	36 mm	45 mm - infinity	Fix, 4		yes	2/3’’
8.6°	Qioptiq, 101425910	42.5 mm	50 mm - infinity	Fix, 4.5		yes	2/3’’
8.2°	Edmund, NT54-689	35 mm	90 mm - infinity	Variable, 4 up to closed		yes	1/2’’
7.3°	Tamron, 23FM50SP	50 mm	90 mm – infinity	Variable, 5 up to 32		yes	2/3’’
6.2°	Edmund, NT59-873	50 mm	100 mm - infinity	Variable, 5 up to 22		yes	2/3’’

[#1]Horizontal FOV on standard 4:3, ½’’ sensor format [#2]Distance between object and front of the tunable lens [#3]available from Optotune

Table 1: Recommended fixed focal length lenses for combinations with the EL-10-30-C for different field of views, focal lengths and f-numbers

Example EL-6-18 with a 12-mm board lens

Figure 6 shows a very compact front-lens configuration with the EL-6-18 using an M12 board lens with a focal length of 8.4 mm and an f-number of 2.8. The resulting horizontal full field of view (FOV) for a ½” sensor is 56°. This configuration is particularly well suited as the stop position of the board lens is in the very front (see discussion about vignetting below). A good optical quality can be observed with a 5MP camera.

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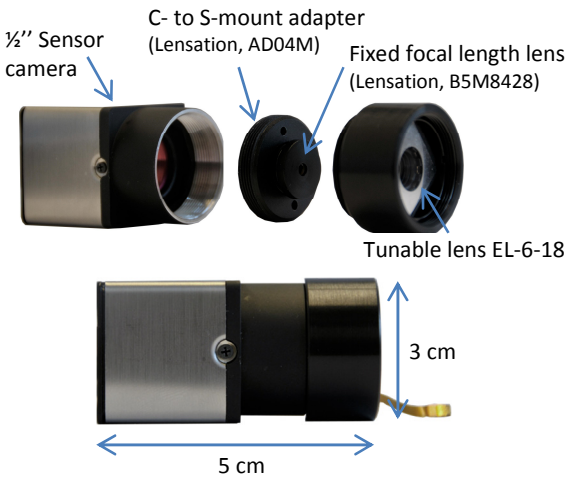

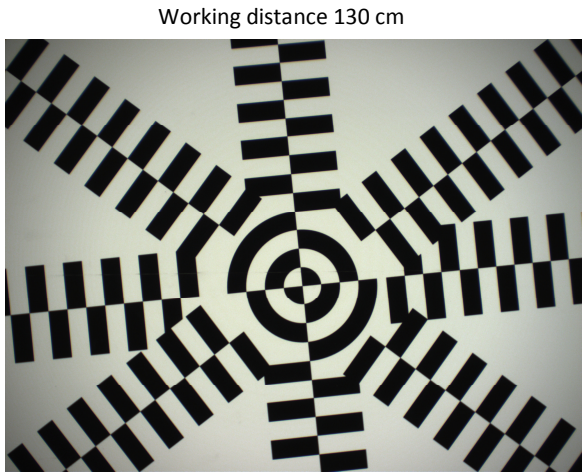

Figure 6: Compact wide field configuration with the EL-6-18 mounted in a C-mount tube and a compact fixed focal length lens (Lensation, B5M8428 (with IR-cut filter: B5M8428C)) with a field of view of 56° (for ½'' sensor) and high optical quality

As illustrated in Figure 7, the EL-6-18 can be mounted in a C-mount extension tube (e.g. Edmund 54-630) with a retainer ring (e.g. Edmund 58-740). The retainer ring should not be screwed too tightly, as this can destroy the lens (max. 8 N normal to surface). For good mechanical precision, an adapter plate with an inner diameter of 13.8 mm is used to align the EL-6-18 concentrically via the extruding reference ring to the C-mount tube. A slot is milled in the C-mount extension tube, for guiding the flex cable from the lens (distance between the slot and the edge of the tube: ca. 4 mm).

The orientation of the EL-6-18 should be such that the extruding reference ring faces the sensor.

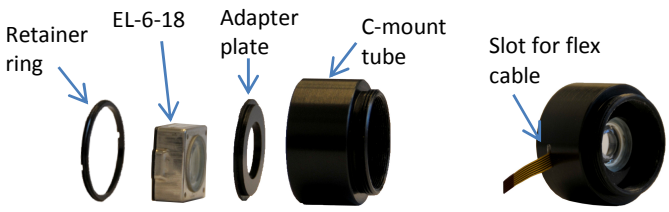

Figure 7: Mounting possibility of the EL-6-18 with a C-mount extension tube

Recommended off-the-shelf combinations with the EL-6-18 lens

In Table 2, recommended fixed focal length lenses with different field of views ranging of 33° and 56° are listed, which are suited to be combined with the EL-6-18 lens. The field of view corresponds to the horizontal full field of view for a standard 4:3, ½'' sensor format.

Field of view[#1]	Product	Focal length	Working distance[#2]	Aperture (f/#)	Adapter	Max. sensor size
56°	Lensation, B5M8428 B5M8448 B5M8480	8.4 mm	30 mm – infinity	Fix, 2.8 4.8 8	Lensation, AD04M	1/1.8"
32.8°	Lensation, B5M12028 B5M12040 B5M12056	12 mm	30 mm - infinity	Fix, 2.8 4 5.6	Lensation, AD04M	1/2''

[#1]Horizontal FOV on standard 4:3, ½'' sensor format [#2]Distance between object and front of the tunable lens

Table 2: Recommended fixed focal length lenses for combinations with the EL-6-18 for different field of views, focal lengths and f-numbers

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What kind of combinations do not work?

The front-lens configuration does not work well with certain types of fixed focal length lenses. Depending on the lens used, vignetting of the outer fields can occur due to light that is being cut off by the aperture of the tunable lens. This can particularly be an issue for wide field lenses (focal length < 12 mm or fields of view > 35°). In general, it is recommended to use a fixed focal length lens with a short distance between the stop position and the front of the lens (see Figure 8).

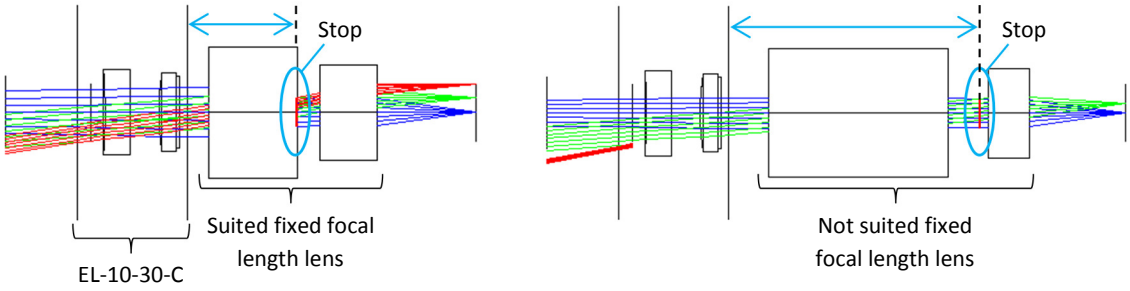


Figure 8: Long distances between the stop and the front of the fixed focal length lens are unfavorable because of vignetting

High magnification configuration: EL-10-30-C for microscopes

When high magnification is required, the tunable lens is typically placed between an infinity corrected objective lens and a tube lens. The following example outlines an off-the-shelf system combining the EL-10-30-Ci with Optem micro-inspection lenses by Qioptiq. All parts offer C-mount threads and thus fit together perfectly. The table below outlines the Z-ranges and resolution achieved.

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

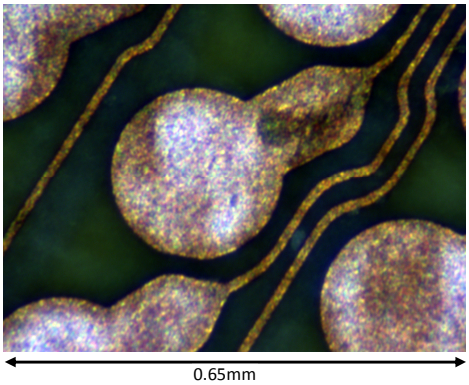
Optem 70XL zoom (0.75x-5.25x)
P/N 399510-309

Coaxial lighting unit with lens
P/N 296515-310

LED ring light (used instead)

Working distance: ~90mm

Optem® is a registered trademark of Qioptiq, Inc



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

Figure 9: Example of a high-magnification inspection system with off-the-shelf components. The image shows a PCB at 7.9x magnification (track width is 10 µm)

For magnifications above 10x, please consider our application note for microscopy.

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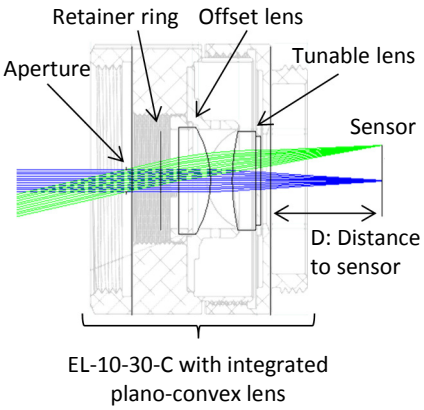
Doublet configuration: EL-10-30-C for camera objectives

The EL-10-30-C with an integrated plano-convex (positive) offset lens can be used as a doublet configuration directly in combination with standard industrial cameras. Focal lengths as short as 16 mm and reasonably good optical quality are achieved for sensor sizes up to ½''. Figure 10 shows the setup with recommendations on offset lenses for different distances between the EL-10-30-C and the camera sensor. An aperture defining the stop of the object is added in front of the lens. The cover glass is replaced by a plano-convex offset lens orientated with the curved side facing the tunable lens. By changing the current applied to the tunable lens, refocusing for different working distances from 100 mm to infinity can be achieved.



Distance D	Focal length offset lens	Offset lens	Field of view*	Resulting focal length range
12.5 mm	20 mm	Edmund Optics, NT49-917	¼'': 11.2° ½'': 22.3°	16 to 18 mm
17.5 mm	30 mm	Edmund Optics, NT45-484	¼'': 8.8° ½'': 17.4°	22 to 26 mm
25 mm	42 mm	Edmund Optics, NT45-485	¼'': 6.6° ½'': 13.1°	28 to 35 mm

*Full horizontal field of view on standard 4:3 sensor format

Figure 10: Doublet system with EL-10-30-C with recommended plano-convex offset lenses for different distances between EL-10-30-C and sensor

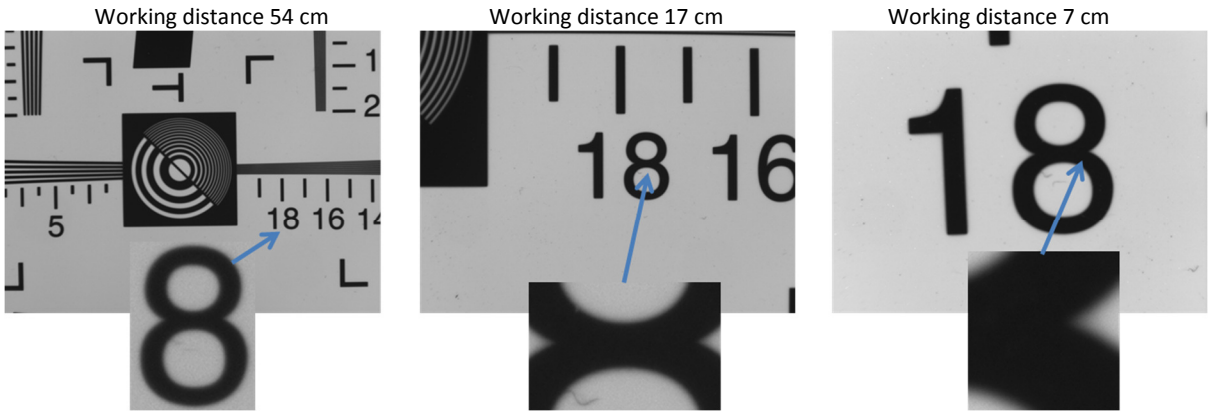


Figure 11: Doublet configuration: images for different working distances with the EL-10-30-C with an integrated plano-convex offset lens (focal length 30 mm), with an f-number of 5 and a C-mount camera with a ½'' sensor size

Wavefront quality dependent on orientation and focal length range

In principle, Optotune's focus tunable lenses exhibit a spherical lens shape (the nominal parameters can be found in the ZEMAX package, which is available for download on www.optotune.com).

As the membranes used are elastic, the lens shape is influenced by gravity. With the lens lying horizontally (optical axis vertical), the RMS wavefront error of the EL-10-30 Series lenses is currently in the order of 0.1 λ (measured at 525 nm), allowing for high quality imaging e.g. in microscopy. With the lens standing upright (optical axis horizontal) a Y-coma term must be added. Furthermore, as can be seen in the graph below, the lens exhibits a smaller wavefront error when it is less curved corresponding to longer focal lengths. Therefore, it is recommended to set the position of the fixed focal length lens such that the tunable lens can be operated in the long focal length range corresponding to low current values.

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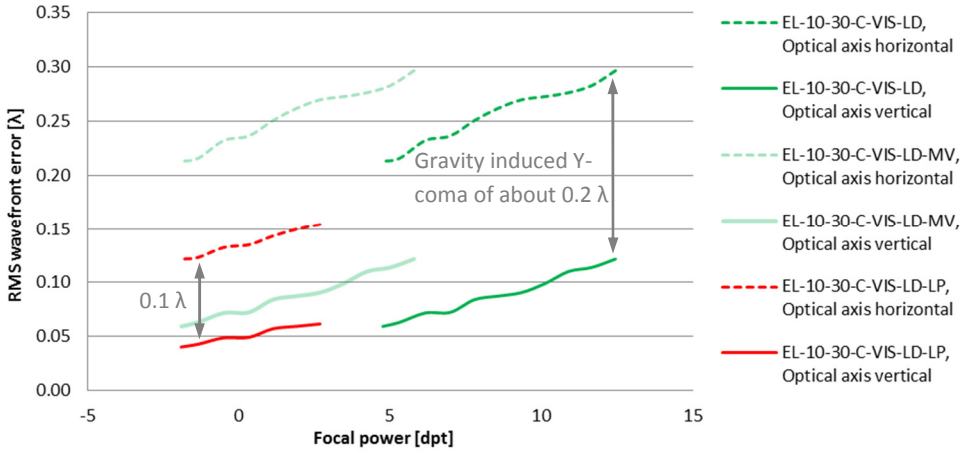

Figure 12: Wavefront measurement of typical EL-10-30-VIS-LD and EL-10-30-C-VIS-LD lenses (at 525 nm and 80% of clear aperture, defocus, tilt & sphere excluded)

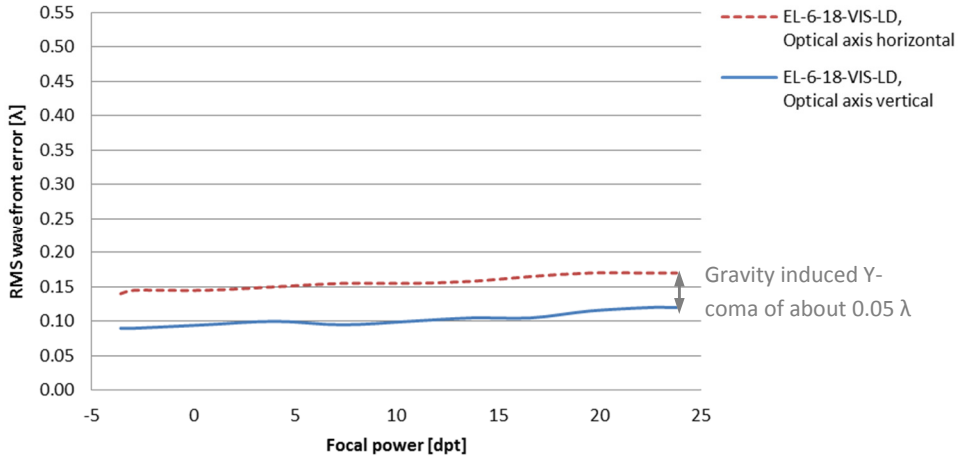

Figure 13: Wavefront measurement of a typical EL-6-18 lens (at 525 nm and 80% of clear aperture, defocus, tilt & sphere excluded)

The gravity induced Y-coma term depends on the size of the lens, the density of the liquid and the mechanical properties of the membrane. While it is insignificant with lenses of apertures below 5 mm, it accounts for about 0.1 λ for the C-mount LP-version and 0.2 λ for the C-mount MV-version of the EL-10-30. The difference between the different variations of the EL-10-30 lenses is the design of the membrane. The stronger membrane of the EL-10-30-C (with the LP version having the strongest membrane) reduces the gravity effect, however at the expense of focal tuning range (4 diopters for the EL-10-30-C-LP and 7.5 diopters for the EL-10-30-C and EL-10-30-C-MV). The EL-6-18 with an aperture of 6 mm and a tuning range of 22 diopters exhibits a gravity induced coma of only 0.05 λ.

Response time

In case of the EL-10-30-C, the rise time on a current step is about 2.5 ms. However, it takes about 15 ms until the lens has fully settled. Please refer to the EL-10-30-C datasheet for detailed information including a graph with the optical response of the EL-10-30-C to a current step. The smaller electrical lens EL-6-18 exhibits a shorter response time with a rise time <2 ms and a settling time <10 ms (detailed information can be found in the datasheet).

Coating options

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The deformable surface of Optotune's focus tunable lenses cannot be coated with standard processes as it needs to remain flexible. This means about 3-4% of reflection at the air/membrane interface must be expected. The cover glasses, however, can be coated adequately. The EL-10-30-C and EL-6-18 are available with two standard broadband coatings for VIS and NIR, but also narrow band coatings are available (e.g. for 355 nm or 1064 nm, see EL-10-30-C datasheet for detailed transmission curves).

Temperature effects

When heating up the lens, the fluid expands in volume reducing the focal length of the lens. However, this temperature effect is systematic and reproducible. This means the focal length can be controlled if the temperature is known. The EL-10-30-C and EL-6-18 have a built-in temperature sensor (SE97B). The compact EL-10-30 does not have that sensor, but measuring the resistance of the coil (voltage divided by current) can serve as a proxy for the temperature in the lens. Please refer to the corresponding datasheets for more detailed information.

Controlling the electrically tunable lenses

The EL-10-30-C and EL-6-18 are current controlled (0 – 300 mA and 0-200 mA, respectively). Optotune offers a high-precision USB driver, EL-E-4, with a resolution of 0.1 mA. It includes the I^2C readout of the integrated temperature sensor and temperature compensation functionality. Please refer to the data sheets for more advice on a variety of available driver options.

Publication using Optotune's lenses

- D. Miau, O. Cossairt, and S. K. Nayar, "Focal Sweep Videography with Deformable Optics," in *IEEE International Conference on Computational Photography (ICCP)* (2013). (http://www1.cs.columbia.edu/CAVE/publications/pdfs/Miau_ICCP13.pdf)

Further information & Support

Our applications engineers are happy to help you with the integration of our products in your design. Don't hesitate to contact us at sales@optotune.com or to call us at +41 58 856 3000.

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