# Distance measurement using an Optotune focus tunable lens

In the present paper we demonstrate that a focus tunable lens in conjunction with an autofocus algorithm is able to reliably measure distance to an arbitrary object in less than a second (depth from focus). The accuracy of the distance measurement is in line with the depth of field of the imaging system. No additional hardware is required apart from the imaging system comprising camera, objective lens and focus tunable lens. The fast and accurate focus and distance measurement enables and simplifies various applications ranging from robot vision to smart manufacturing control.

## Introduction

Many industrial and consumer applications rely on image analysis of objects placed at different distances, e.g. object recognition, 2D code reading and laser processing. In a conventional lens system, optical elements are mechanically moved with respect to each other to adjust the focus. In contrast, an electrically focus tunable lens from Optotune adjusts the focus by directly changing its shape. This allows for much faster response while saving space, as it replaces a series of optical elements and mechanics.

In the current work we have developed a software which enables automatic focusing of the whole system and calculates the distance of an object by relating the focus position to a set of calibration data. The autofocus works by evaluating the contrast values of images taken at sequential focus positions, collected by sweeping through the tuning range of the liquid lens (see figure 1). The relationship between focal power (in diopters) and contrast value follows a Lorentzian distribution. The best focus position is found at the diopter value corresponding to the maximum of the calculated fit. The beauty about this approach is that the best focus is found even if the corresponding picture was not part of the sequence recorded.

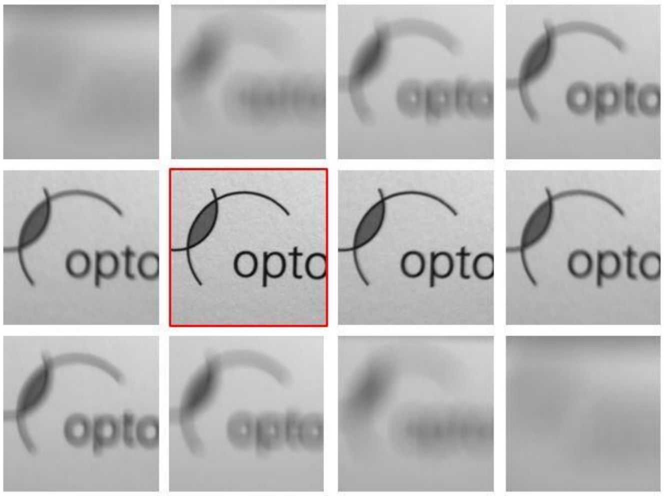

*Figure 1: A sweep through different diopter settings of the tunable lens to find the image in focus.*

Besides automatic focusing, many applications require knowledge about the distance to the object, too. For example, a laser marking system needs to know the exact position of an object to be able to focus the laser at the right distance. Therefore, oftentimes an additional distance sensor is inserted into the setup. The concept presented here allows for using the vision system as a distance sensor at the same time, which is generally reduces cost and space required.

In the following, we explain in detail the hardware and software components and provide an application example.

## Software

The autofocus algorithm operates as follows: The camera takes several images at different diopter values. The algorithm then calculates the contrast of a small area of interest. It subsequently fits a Lorentzian to the contrast values versus the optical powers as shown in figure 2. The sharpest image corresponds to the peak of the Lorentzian and defines the required diopter setting.

Figure 2 shows the autofocus program flow. The software starts to take an image at the smallest possible diopter value, which is at -2 diopters for Optotune's EL-16-40. In the first sweep an image is taken every 0.4 diopters until the largest possible diopter value is reached, which is at 3 diopters for the EL-16-40. At the same time the contrast value is calculated for each image. Afterwards the diopter setting corresponding to the (so far) largest contrast value is localized. To refine the autofocus, firstly a small interval is defined around this diopter setting. Secondly, the lens is set to the smallest possible diopter value within the interval and the second sweep starts, but this time with a much smaller step size of 0.04 diopters. After reaching the largest diopter value within the interval the data of the first and the second sweep are combined to fit a Lorentzian distribution $f_L = \frac{A}{\pi}\frac{\gamma}{(x-x_0)^2+\gamma^2} + c$. The peak position of the Lorentzian distribution indicates the diopter setting of the highest expected image contrast.

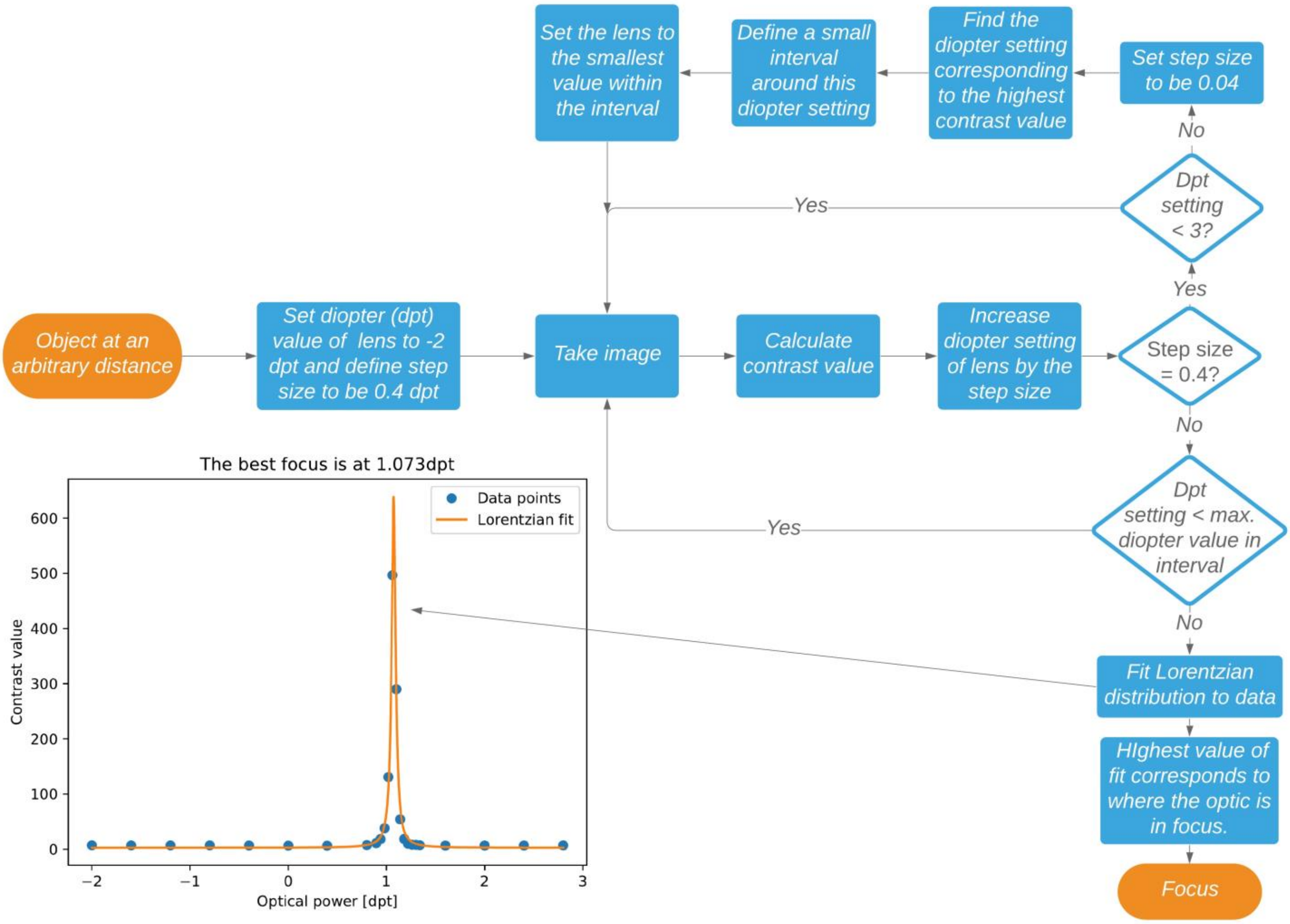

*Figure 2: Program flow of the autofocus algorithm. The software collects the contrast value of the image at different diopter settings. The first sweep through the diopter range has a relatively large step size, the second sweep has a smaller step size and collects the contrast values around the maximum. A Lorentzian distribution is fit to the data points. The peak indicates at which optical power the best focus is located.*

To calculate the object distance the diopter value of the best focus is inserted into a model derived from calibration data (see figure 3). While simple interpolation techniques could be use we find that a well fit mathematical model produces best results.

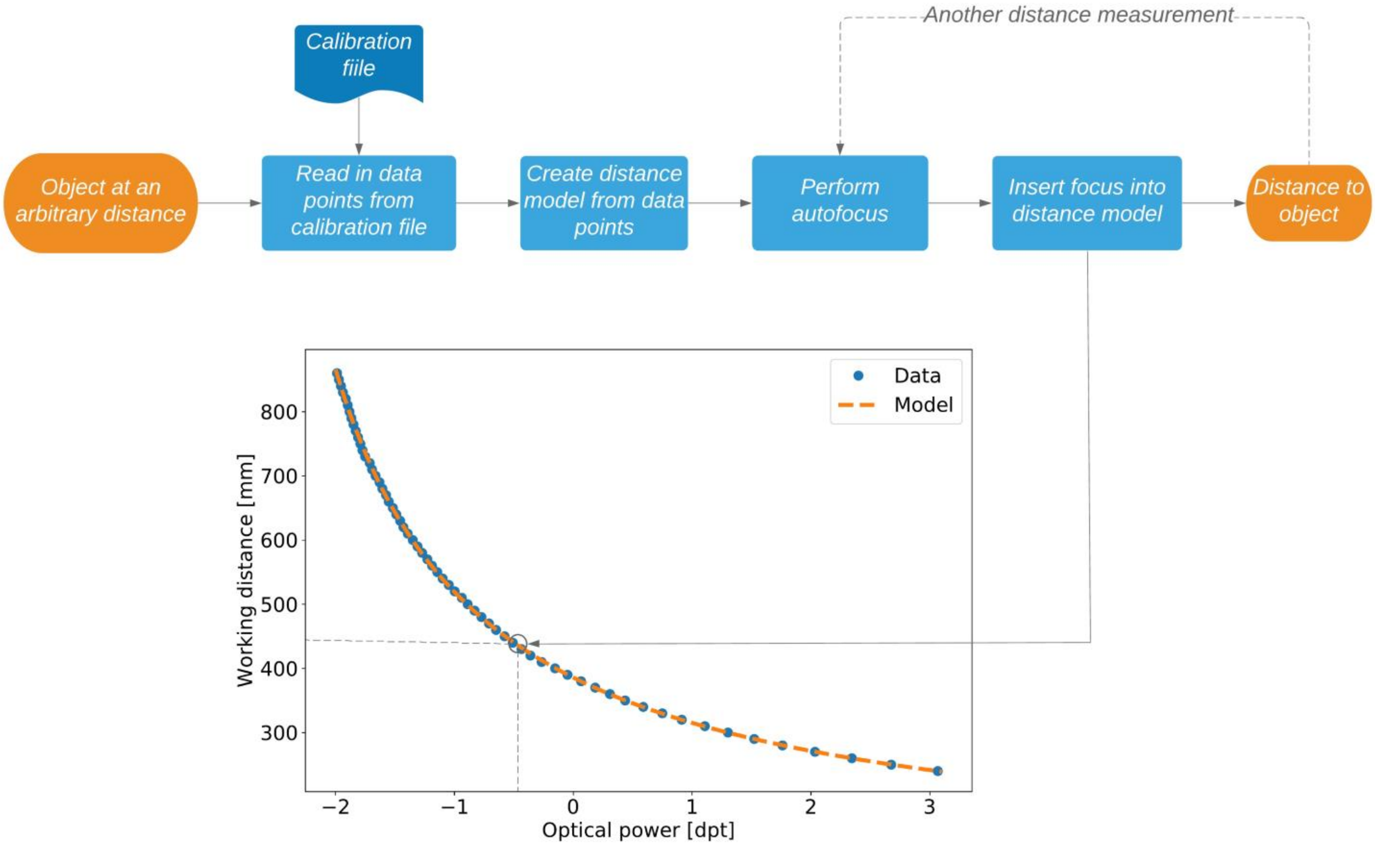

*Figure 3: Program flow of the distance sensor. The software first reads in the calibration file which contains the data to fit a model onto. In our setup the optical power scales inversely proportional with the working distance, therefore the model relates to* $\frac{1}{x}$*. Once the autofocus is performed the focus position obtained is inserted into the distance model to obtain the object distance.*

Every setup requires individual calibration of the distance measurement algorithm (see figure 4). To obtain a calibration curve, several distance/diopter combinations must be obtained by using the autofocus algorithm. After collection of a sufficient number of data points (60 in our example), a model is fit to the data. If the tunable lens is placed in front of a fixed focus lens (so called “front lens configuration”) the calibration curve has the shape of $\frac{1}{x}$ as theoretically expected from the lens equation (see plot in figure 3). If the tunable lens is placed between optics and sensor (so called “back lens configuration”) the curve is more linear. An increase of calibration points leads to a more accurate result of the distance measurement with the new sensor.

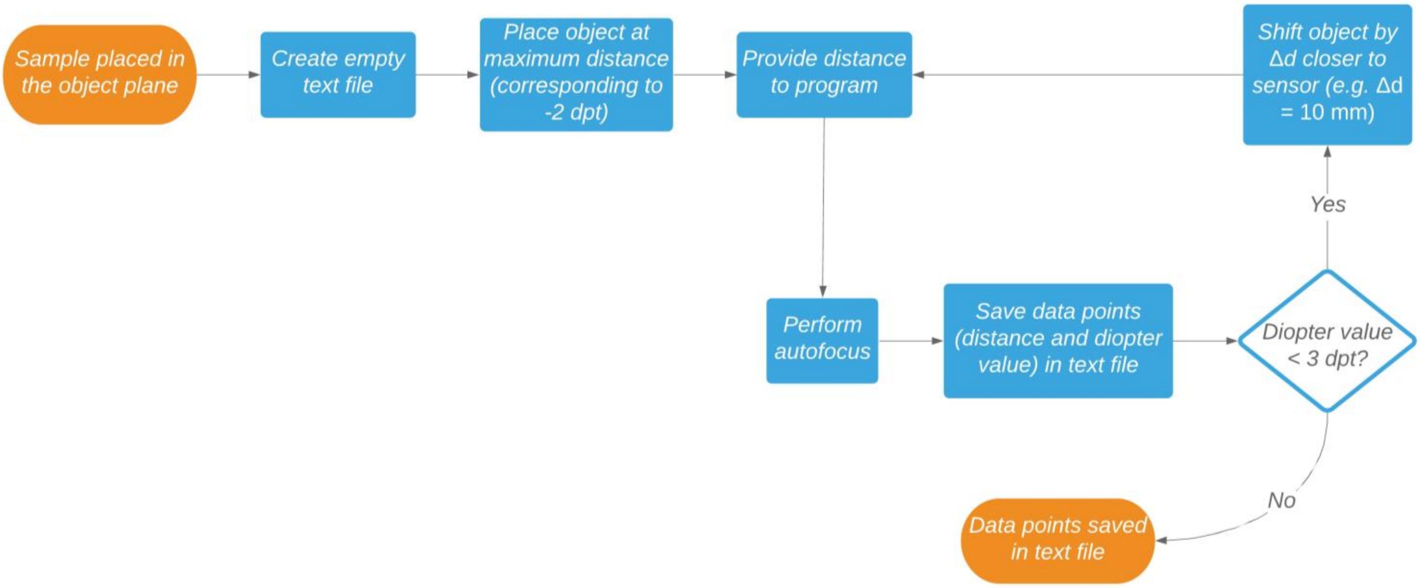

*Figure 4: Program flow of the distance calibration. The software collects the information about the distances from the camera to the object and the respective diopter settings and saves them in a text file. The data serves for the calibration of the distance sensor. An increase of calibration points leads to a more accurate result of the distance measurement, therefore the displacement of the object Δd should be small.*

## Hardware for applications with large working distance

The accuracy of the distance sensor depends on the configuration of the hardware. An example hardware configuration optimized for working distances of several 100mm is illustrated in figure 5. It consists of a high-resolution sensor (IMX253 1.1" 4104x3004), connected to a C-mount lens (Kowa LM50FC, WD=300mm, F/1.8) and the Optotune focus tunable lens EL-16-40, which has a focus range of 5 diopters and a clear aperture of 16mm (resulting in an effective f-number of F/3.1). The components are set up in a front lens configuration where the tunable lens is placed in front of the fixed focal length lens.

The working principle of the EL-16-40 is based on Optotune's well-established technology of shape-changing polymer liquid lenses. The optical fluid in the core is sealed off with an elastic polymer membrane as shown in figure 6. An electromagnetic actuator exerts pressure on the container with the fluid and therefore changes the curvature of the lens ranging from concave to convex. By changing the electrical current flowing through the coil of the actuator, the optical power of the lens is controlled.

*Figure 5: Machine vision setup with a C-mount camera, a 50mm lens and the Optotune focus tunable lens in a front lens configuration.*

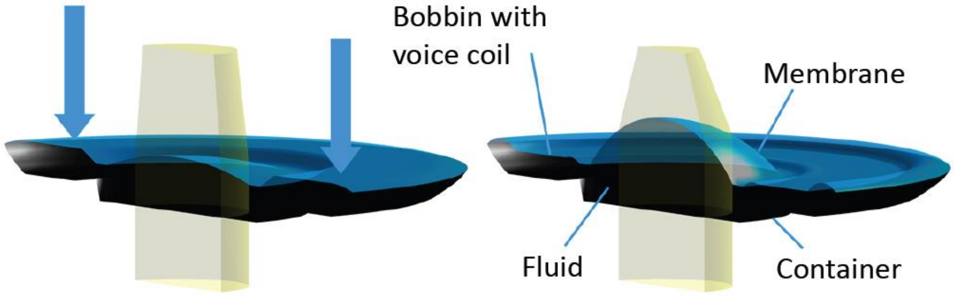

*Figure 6: Working principle of Optotune's electrically focus tunable lens EL-16-40.*

## Resulting focus time and precision

Using a liquid lens as an autofocus solution has several advantages: it is compact, covers a large focusing range and most importantly it is very fast and reliable compared to mechanical focusing methods (>1B cycles). Upon a change in control current it takes only about 15ms for the liquid lens to settle (in the case of the EL-16-40). It is thus possible to change focus over 60 times per second. There is a tradeoff between speed and precision. Our algorithm was optimized for precision and takes between 0.5 and 0.9 seconds to complete, depending on the on the distance of the object. Factors that influence the speed of the autofocus are the focus range, diopter step sizes, exposure time of the camera and if high resolution sensors are use the frame rate of the camera. With high a high speed camera, it would be possible to simply let the tunable lens oscillate over the entire range at e.g. 20 Hz, which would allow for achieving distance measurements within 25-50ms.

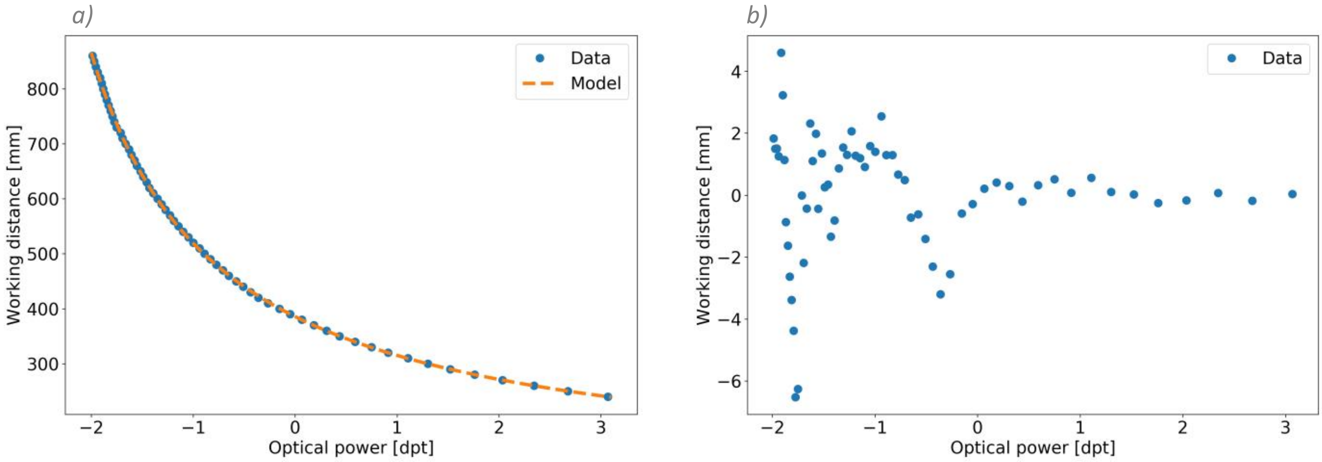

*Figure 7: a) Calibration curve of the distance sensor provides the corresponding distance for a known optical power corresponding to the configuration shown in figure 5. b) Residuals (data point at $x_i$ – model at $x_i$) of the calibration curve. The residuals are more spread for negative diopter values or large distances, proving that the distance sensor is more accurate in the positive diopter range of the lens.*

In the presented example the uncertainty of the autofocus is 0.01 diopters. The uncertainty of the distance sensor is determined by the calibration curve scaling with 1/x, see figure 7a. Due to this shape the curve is steeper for smaller diopter values. This means that the same diopter interval taken in the negative diopter range corresponds to a larger distance interval than if it was taken in the positive diopter range. Therefore, in this case the uncertainty of the distance value increases with the working distance. This is shown in figure 8 representing the standard deviation for four different distances together with the maximal and minimal change to the mean value. In the positive diopter range the standard deviation is up to one order of magnitude smaller than in the negative diopter range. This fits well with the relation of depth of field vs. object distance, which is quadratic:

$$\mathrm{DOF} \approx \frac{2u^2 Nc}{f^2}$$ whereas u = distance, N = f-number, f = focal length, c = circle of confusion

The repeatability shown in figure 8 is well withing the depth of field of the imaging system. For example, the DOF at 323mm calculates to 1.4mm, but the largest delta in the repeatability test is only 0.25mm.

Another method to visualize this effect is the calculation of the residuals (data point at $x_i$ – model at $x_i$), see figure 7b. Since the residuals are more spread for negative diopter values or large distances, the distance sensor is more accurate in the positive diopter range of the lens.

The three parameters: Repeatability of the measured distance, value of the uncertainty due to the model and complete distance range are defined by the individual optical setup used. For the setup presented here with front lens configuration on a 50mm lens, the lowest uncertainty of the distance measurement is 0.3 mm for a complete distance range of 620 mm (240 mm - 860 mm). Based on the requirements, the measurement precision and uncertainty can be varied using a different configuration, for instance a lens system with a different focal length or a back lens configuration. For laser processing applications with f-theta lens, the combination of the presented front lens configuration with an f-theta lens can be expected to provide a repeatability well within the Rayleigh length of the processing laser.

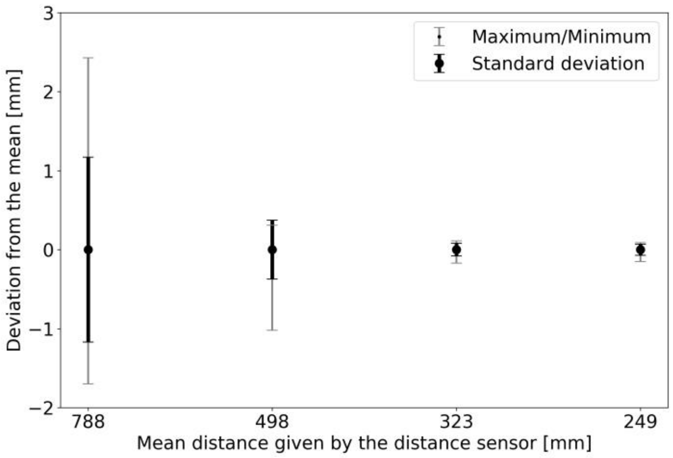

*Figure 8: Repeatability of the presented configuration showing standard deviation and maximal and minimal deviation from the mean value over 10 measurements at four different distances. All values are well within the depth of field, which is smaller for shorter working distances leading to a higher precision.*

We would like to add that the algorithm was very stable and worked for nearly all materials incl. paper, cardboard, PCBs, several types of metal but had issues with white ceramic.

## Conclusion

The presented liquid lens system allows for fast autofocus and distance measurement within a single vision system. Thanks to the method of deriving the best focus from the maximum position of a fitted distribution, it is not required to actually capture the best focused image during the AF sweep, which results in high speed and robustness of the algorithm. The optics can be tailored to reach the desired precision and focus range, whereas there is generally a trade-off between the two. The precision reached is well within the depth of field of the optics, which is in the setup presented for example 0.25mm at a distance of 323mm.

For more information, please contact sales@optotune.com.

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An example of an Optotune lens used to retrieve the shape of 3D objects can be found in this publication: https://www.osapublishing.org/oe/abstract.cfm?uri=oe-27-21-29697