https://doi.org/10.1051/epjconf/202226610005

Holographic single-image depth reconstruction

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Abstract. In this article a camera-based single-image sensor is presented, that is able to measure the distance of multiple object points. The experimental results show an accuracy of 8,51 µm within a depth range of 20 mm. The sensor consists of a camera, whose lens is upgraded with a diffractive optical element (DOE). It fulfils two tasks: adding a vortex point spread function (PSF) and replication of the vortex PSFs to a predefined pattern of *K* spots. Both, shape and rotation of the vortex PSF is sensitive to defocus. By applying the depth reconstruction to each of the *K* replications and averaging the results, we experimentally show, that the reconstruction of the depth signal can be improved by a factor of up to 3.

1 Introduction

When an object point is imaged to a detector, its lateral position (x,y) can be detected rather easy by calculating the Center of Gravity (CoG) of the PSF, whereas the axial dimension (z), thus the distance of the object point, is lost. It can be reconstructed by evaluating the increasing diameter of the defocused PSF, but the achievable accuracy is bad. The accuracy of this reconstruction can be improved by increasing object-space numerical aperture (NA) of the imaging system. However, a large NA limits the depth of field and, therefore, the measurement range. Another possibility to improve the depth reconstruction of object points is to modify the PSF of the imaging system. A classic way of PSF modification is, for example, a superimposed astigmatism by the use of two orthogonal cylindrical lenses. In the last two decades mainly for the application in optical microscopy other ways of PSF manipulation based on diffractive optical elements (DOE) were developed. The purpose is, to modulate the phase of the light in a way, that the shape of the PSF corresponds to the changing distance z. Popular examples are the corkscrew PSF (CS-PSF) [1], self-bending PSF (SB-PSF) [2], tetrapod PSF (TP-PSF) [3] and double-helix PSF (DH-PSF) [4]. The ratio between measurement range and accuracy reached by those techniques ranges between 280 and 560.

This contribution addresses the question, to which extent it is possible to create a single-image depth reconstruction with both, good accuracy and large measurement range to use it as a single-camera 3D position sensor. Therefore, we combine a PSF modification method known from microscopy with a holographic replication technique called multipoint method (MPM) [5] and apply it to a low NA objective lens. The low NA lens ensures a large measurement range and the combination of the multipoint method and the PSF modification is used to increase the accuracy of depth detection.

2 Principle and results

For the PSF modification technique we use the DH-PSF introduced by Baránek et al. in [4]. The discrete spiral phase modulation (SPM) modifies the incoming light in a way, that the transversal component of the resulting intensity profile consists of two helixes rotating around each other. In the image plane, this forms two spots that rotate around a common axis. The angle of rotation is dependent on the defocus of the object point. The MPM is used to replicate this DH-PSF to a predefined pattern. Each copy consists of two rotating spots. So if the object point is moved in z, all DH-PSF replications show the same angle of rotation. By averaging all measured angles, errors caused by photon noise and discretisation are reduced and, therefore, the accuracy of the measured rotation angle can be improved theoretically by a factor equal to the square root of the number of replications. In Fig. 1 the principle of the multipoint double-helix PSF is shown for four replications.

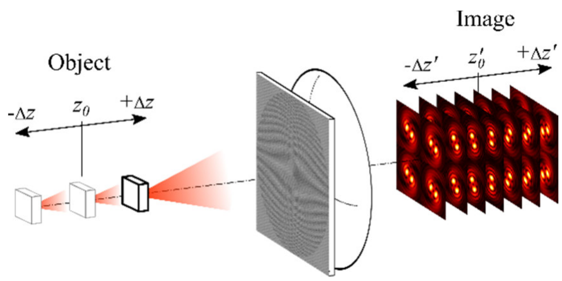

Fig. 1. Combination of the MPM and the DH-PSF. The two rotating spots created by the SPM are replicated to four copies [6].

The experimental setup consists of a linear stage (Walter Uhl GT6-BO01) that is used to move a point light source (fibre coupled laser, $\lambda = 633$ nm) in z. The camera system

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has a low NA objective lens (f' = 50 mm, NA = 0,0595) with a DOE mounted in front, to perform the replication to $N = 25$ copies and induce the vortex phase modulation. The distance between light source and objective lens is 234 mm and the depth measurement range is 20 mm.

Simulations and experiments show, that the two rotating spots, created by the double-helix, form a tail, whose length is growing with the angle of rotation. More information regarding the simulations can be found in [6]. The tail formation is shown in Fig. 3 (d). There one DH-PSF replication is shown for a defocus of 8.9 mm. With growing defocus, the tail becomes a double spiral, as shown in Fig. 3 (e). This tail makes it difficult to evaluate the rotation angle using the CoGs of both spots. Therefore, we use the method of cross correlation with a reference image stack. The reference images are acquired at $K = 2000$ equidistant points in the measurement range of 20 mm. A measurement is performed by positioning the light source inside the measurement range, acquire an image and cross correlate it with the reference image stack. The peak of the resulting correlation energy curve marks the measurement result.

In Fig. 2 the measurement result is shown for a measurement consisting of 520 equidistant points acquired in the measurement range of 20 mm. The plot shows the error between measured distance change and the actual distance change of the linear stage, which is taken as reference. The standard deviation of the error signal is σ_{520} = 7.86 µm. In total three measurements with different number of equidistant measurement points are carried out. The mean standard deviation of all three measurements is $\bar{\sigma}$ = 8,51 µm and the signals show good reproducibility [6].

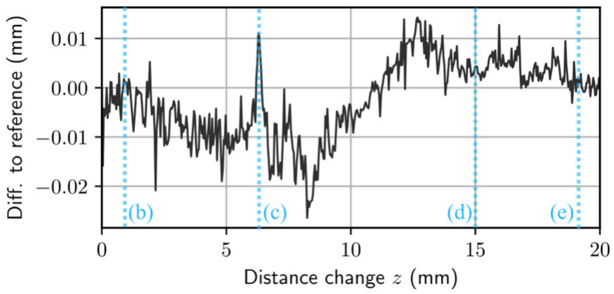

Fig. 2. Measurement result plotted as error over distance change. The error is calculated as the difference between measured distance and the linear stage position (reference). The blue dotted lines (b) to (e) refer to the images of Fig. 3 (b) to (e).

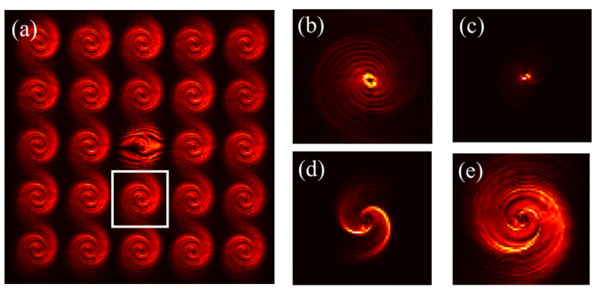

Fig. 3. (a) Cluster of $N = 25$ replicated DH-PSF at distance change $z = 20$ mm. The DH-PSF marked with a white square is shown for different distances and, therefore, defocus states in images (b) to (e) ; (b) $z = 1$ mm ; (c) $z = 6.1$ mm . Here the light source is in focus; (d) $z = 15$ mm ; (e) $z = 19$ mm .

This leads to the assumption, that the remaining error is of systematic nature and calibration could even improve the accuracy.
In Fig. 3 (a) the whole cluster of $K = 25$ replicated DH-PSF is shown. The spot marked with a white square is shown in the images (b) to (e) for different distances and defocus states. In (c) the light source is in focus and all information is stored in a few bright pixels, which makes it difficult to reach high accuracy with the method of image correlation. Therefore, the error signal in Fig. 2 shows a small peak at this position.
To evaluate the improvement achieved by the multipoint method, each of the 25 replicated DH-PSF is evaluated individually. This is done by cutting both, the measurement images and the reference image stack into 25 image sections containing only one DH-PSF each. The results show, that depending on which spot is evaluated, the reconstruction accuracy can be improved by a factor of up to 3.
The measurement range to accuracy ratio of the proposed position measurement system is 20 mm / 8.51 µm = 2350, which is very high compared to other single-image measurement systems. Nevertheless, there are still some points, such as 3D calibration, lateral shifted light source or lateral position measurement, that need to be addressed in future work to be able to use this method in a 3D position measurement sensor.

3 Summary

The presented single-image depth measurement system is based on the combination of a DH-PSF and a spatial replication method, which is both created by a phase modulating DOE placed in front of the imaging lens. The system is able to detect the distance of one or multiple point light sources with an accuracy of 8,51 µm within a measurement range of 20 mm. This offers the possibility to create a cost effective single-camera 3D position measurement sensor that can detect the 3D positions of multiple point light sources.

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