Holographic reconstruction of the displacement vector on arbitrary objects

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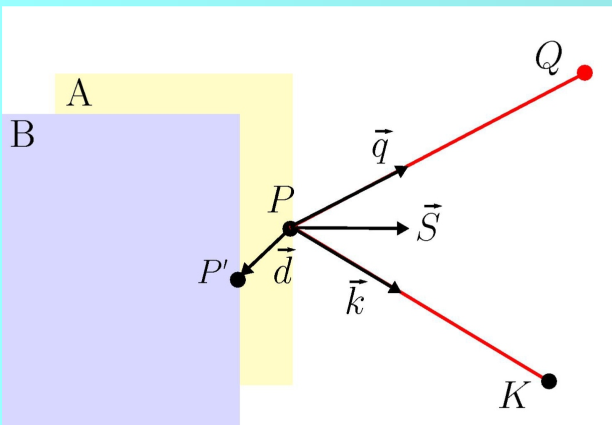
With the help of digital holography it is possible to get amplitude as well as phase information of an optical wave field at the position of the detector. Numerical reconstruction enables the user to reconstruct an image of the object via back projection in space. In earlier works, our group was able to demonstrate 3D surface reconstruction of an object by combining digital holography and stereophotogrammetry [1, 2]. Therefore, two cameras have been used. In this work, we will demonstrate an additional technique [3]. We are going to reconstruct the three dimensional phase distribution on the objects surface by recording holograms at four different positions in space and stereophotogrammetric matching of the resulting images.

Measuring procedure



It is possible to calculate the deformation vectors $\vec{d}$ of the deformation of an object by evaluating phase differences $\Delta\varphi$ measured, if the sensitivity vector $\vec{S}$ is known.

$$\Delta\varphi = \vec{S}\cdot\vec{d}$$

Additionally, the phase measured has to be unwrapped.

To get access to the full deformation vectors of arbitrary objects, four cameras are needed. They also have to be located in different planes to gain observation directions that are linear independant to each other. Due to the change of the sensitivity vector in every object point, the shape of the object must be known as well. The objects shape was calculated by applying the 8-point algorithm to a stereophotogrammetric measurement to three pairs of cameras, with one camera being in all three pairs. Since the relative positions and orientations are given by the 8-point algorithm, the camera matrix **K** can be calculated automatically.

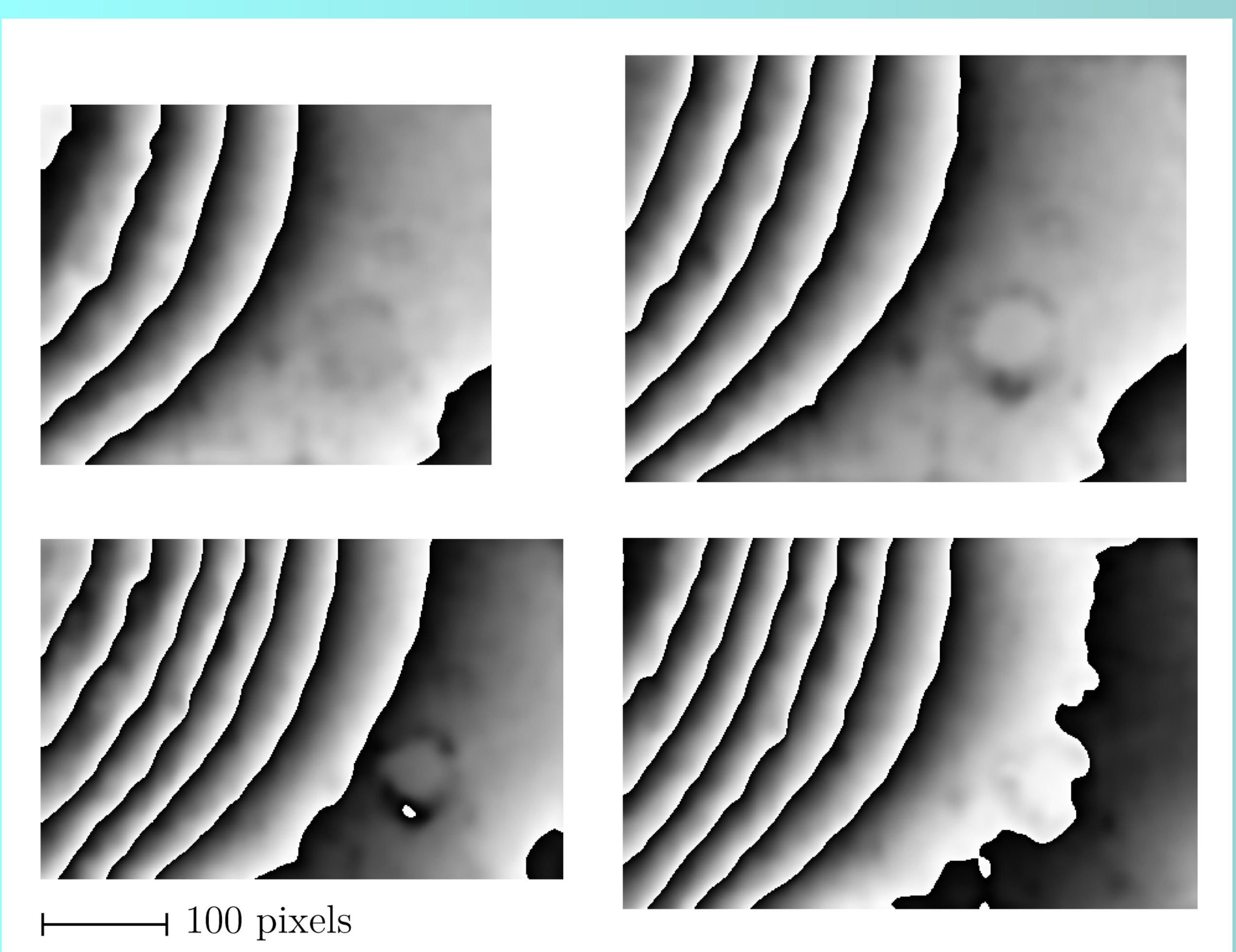
$$K = \begin{pmatrix} k_0^x - k_1^x & k_0^x - k_2^x & k_0^x - k_3^x \\ k_0^y - k_1^y & k_0^y - k_2^y & k_0^y - k_3^y \\ k_0^z - k_1^z & k_0^z - k_2^z & k_0^z - k_3^z \end{pmatrix}$$

Applying the camera matrix to the first equation results in

$$K\cdot\vec{d} = \frac{\lambda}{2\pi}\Delta\vec{\varphi},$$

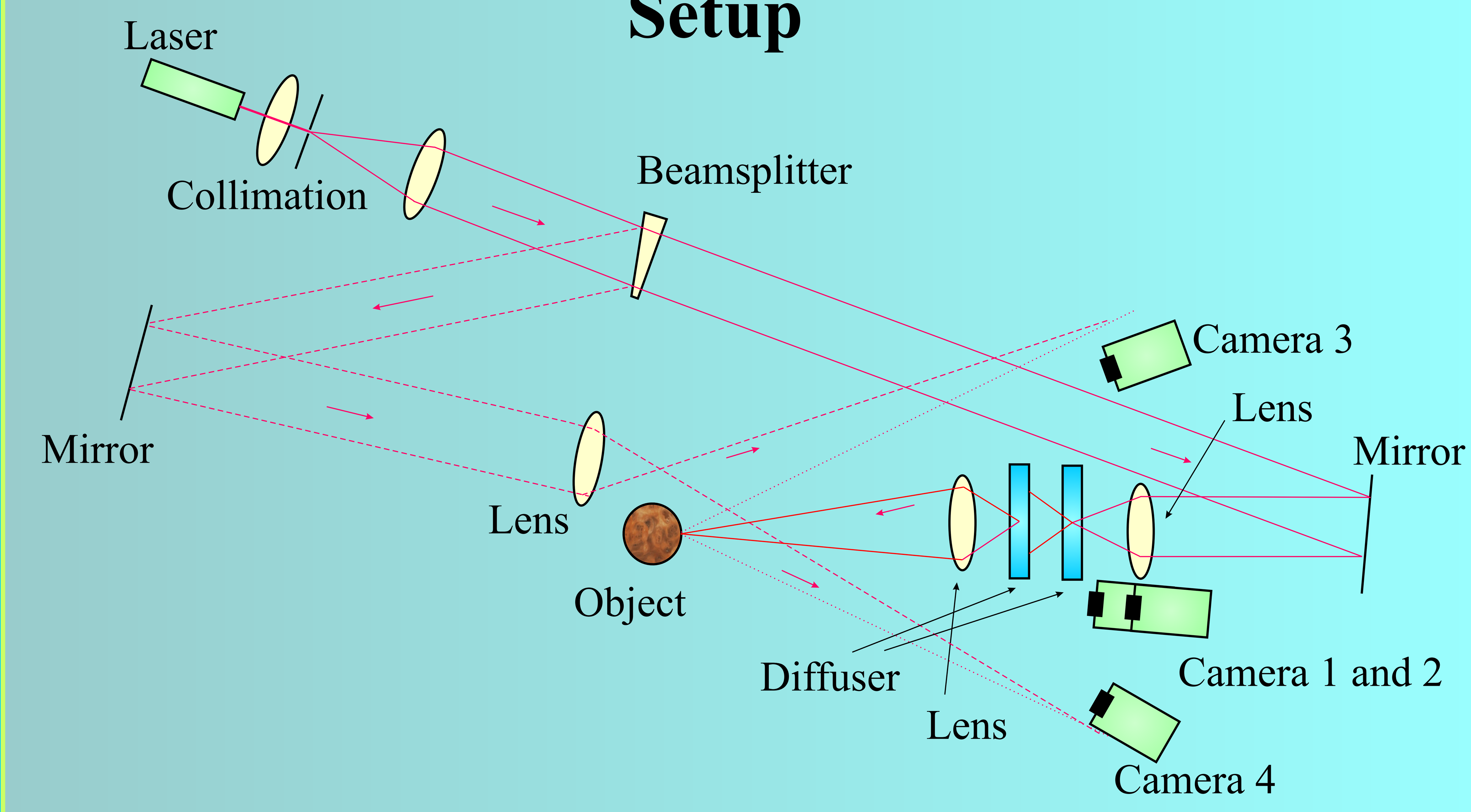
which can be solved for the deformation vectors, as long as the difference vectors of the camera matrix are linear independant.
The three components of $\Delta\vec{\varphi}$ are the differences of $\Delta\varphi$ of the first camera with each other camera, respectively.

Interferometric holographic recording of the objects deformation by 4 cameras

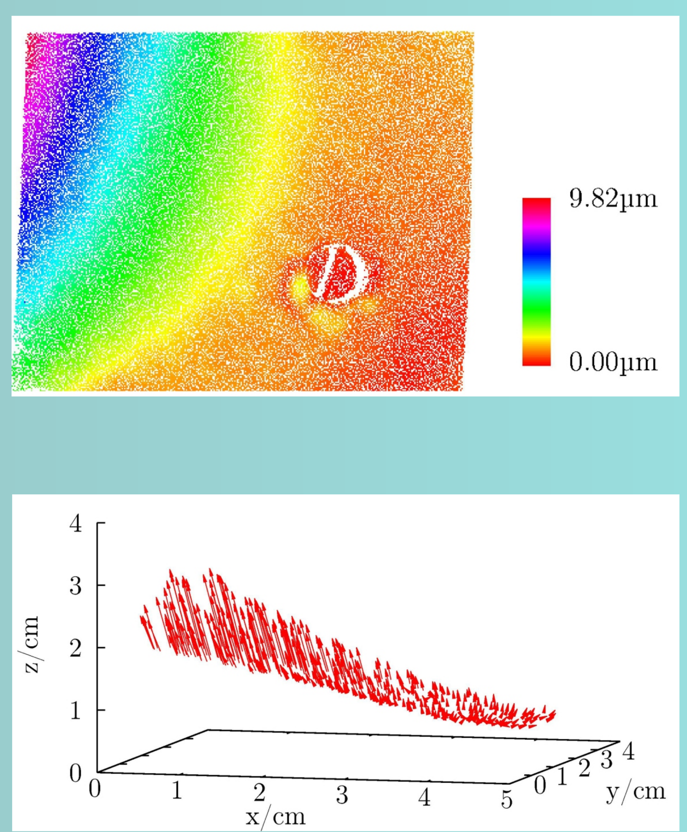


Two states of a plain object were recorded as holograms by all four cameras. After reconstructing and subtracting both states from each other, the phase-differences were calculated and unwrapped to gain values higher than 2π. The results can be found in the figure above for each camera. The sizes of the images differ from each other due to the different positions of the CCD-chips.

Setup



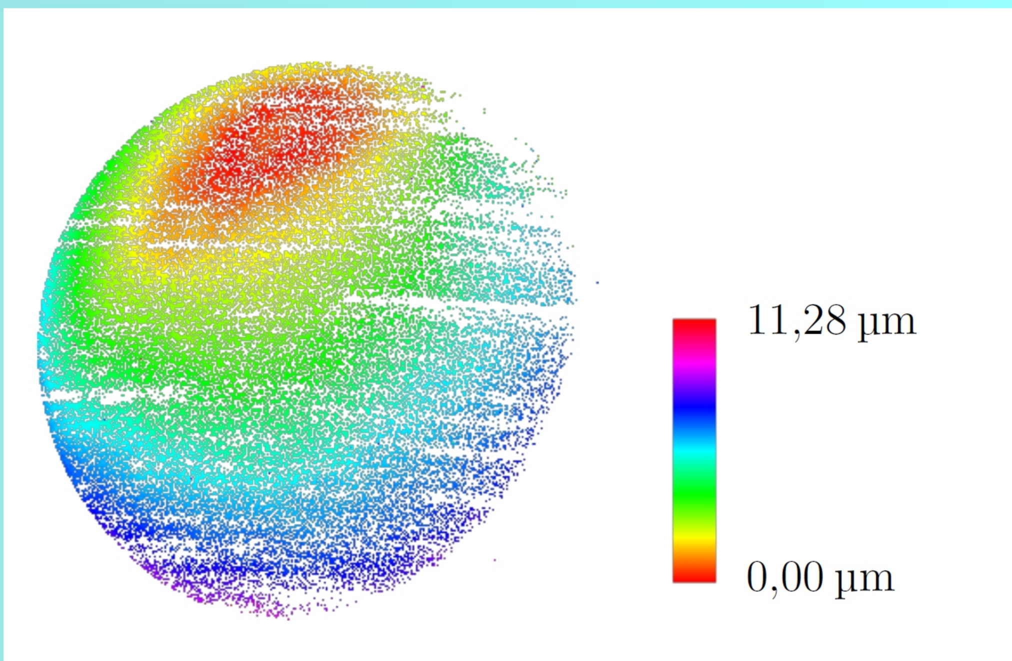
Calculated deformation vectors of a plain object



To gain the 3D shape of the object, the object (a plain metal plate of 40 x 50 mm^2 covered with paper) was illuminated with a structured illumination. Additionally, a speckle noise reduction was applied. As result, three 3D point-clouds of the object could be calculated, enabling a correlation of the deformation recorded by the four cameras. The deformation was realized by giving some pressure onto the object with the help of a micrometer screw.
The resulting vectors can be found in the images on the left. The first figure shows the absolute value of the deformation vectors for all 98.000 reconstructed points. The image below shows the full vectors of 0.4 % of all points found. They are magnified by a factor of 1000.

Deformation of a sphere

The shape of a table-tennis ball was recorded to demonstrate the possibility to measure deformation vectors on objects that are not plain. To gain a deformation, a small pressure was applied on top of the ball. The two states without and with pressure then were compared with holographic interferometry and the deformation-vectors were recorded as before. The results can be observed in the figure on the right. Compared to the plain object, the point-cloud of the ball is less dense due to a high speckle noise. In contrast, the calculation of the deformation vectors was not disturbed by the curvature of the ball.



Conclusion

We demonstrated a possibility to calculate the complete deformation-vectors of a macroscopic object with deformations in a small micrometer range. Therefore, a combination of stereophotogrammetry and digital holography was used. To gain sufficient information, the measurement had to be done with four cameras. Speckle reduction techniques have been applied with the stereophotogrammetric measurement to reduce the speckle in the reconstructed holograms. The result was a dense 3D point cloud of deformation vectors.
As objects a plain metal plate and a table-tennis ball have been used. No differences could be observed in the accuracy of the deformation vectors for both objects, but the 3D point-cloud was more dense in the case of the metal plate due to the combination of curvature and high signal-to-noise ratio.

1 - M. Grosse, J. Buehl, H. Babovsky, A. Kiessling, R. Kowarschik: *3D shape measurement of macroscopic objects in digital off-axis holography using structured illumination*, Optics Letters, Vol. 35 Issue 8, pp.1233-1235 (2010)
2 - H. Babovsky, M. Grosse, J. Buehl, A. Kiessling, R. Kowarschik: *Stereophotogrammetric 3D shape measurement by holographic methods using structured speckle illumination combined with interferometry*, Optics Letters Vol. 36, No. 23 (2011) 4512-4514
3 - R. Schwede, H. Babovsky, A. Kiessling, R. Kowarschik: *Measurement of 3D deformation vectors with digital holography and stereophotogrammetry*, Optics Letters accepted

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