3D Reconstruction in Micrometer Scale With Simple Inline Digital Holography

Kai Carmin and Amir Weil
Supervisor - Uri Israeli
The Hebrew University of Jerusalem, Lab B (77335)
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Digital Holography is about capturing object's interference patterns with coherent light and using the it the data encoded in it to reconstruct details in 3 dimensions. In this experiment we will build an Inline holography system, which we we will use to capture holograms. We apply a reconstruction algorithm to recover details on micrometer scale objects, about their shapes and position in 3 dimensions. eventually, we will show how it is possible to measure distances between objects in the depth axis with 7-10 micrometer precision.

INTRODUCTION

Digital holography involves the recording of holograms using CCD cameras. A hologram is a photograph of a light interference pattern, which contains information about the intensity and phase of the light field. We use a coherent light source to illuminate an object, thus creating an interference pattern between the wave-front of the coherent light source, and the scattered or diffracted light from the object. This method can be used to calculate numerically the wave pattern at different distances and therefore reconstruct objects from the hologram at different planes [1]. Our coherent light source is called the *reference wave* and is denoted by R(x,y), and the scattered wave from the object is called the *object wave* and is denoted by O(x,y). thus the distribution of both waves at the detector plane (X,Y) can be described by:

$$\Psi_{detector}(X,Y) = R(X,Y) + O(X,Y) \tag{1}$$

and the hologram will be the recorded intensity

$$\begin{aligned} H(X,Y) &= |\Psi_{detector}|^2 \\ &= |R(X,Y)|^2 + |O(X,Y)|^2 \\ &\quad + R^*(X,Y)O(X,Y) \\ &\quad + R(X,Y)O^*(X,Y) \end{aligned} \tag{2}$$

For our purposes we use a plane wave as reference beam, so we choose R(x,y)=1 since the intensity is approximately constant. therefore we recover O(X,Y) from the hologram:

$$H_0(X,Y) = O^* + O \tag{3}$$

The wave can be propagated in space using the Fresnel-Kirchoff equation:

$$U(x,y) =\approx \frac{i}{\lambda}\iint H_0(X,Y)\cdot\frac{e^{-ik|\vec{r}-\vec{R}|}}{|\vec{r}-\vec{R}|}dXdY \tag{4}$$

There are several ways to solve this integral, we will use the Angular Spectrum Method. Taking $\vec{k}$ to be:

$$\vec{k} = \frac{2\pi}{\lambda}\begin{pmatrix} cos\phi sin\theta \\ sin\phi sin\theta \\ cos\theta \end{pmatrix} \equiv \frac{2\pi}{\lambda}\begin{pmatrix} \lambda u \\ \lambda v \\ cos\theta \end{pmatrix} \tag{5}$$

when $(\lambda u)^2 + (\lambda v)^2 \leq 1$. obviously equation 4 is a convolution, which can be easily solved in Fourier space using the transform given by 5, giving us the solution:

$$U_z(x,y) = FT^{-1}\left[FT\left[H_0(X,Y)\cdot e^{\frac{-2\pi i z}{\lambda}\sqrt{1-(\lambda u)^2-(\lambda v)^2}}\right]\right] \tag{6}$$

When H_0 is the captured hologram and U_z is the solution for propagation to distance z from the hologram plane.

EXPERIMENTAL SETUP

There are two main setups for digital holography called Off-axis and Inline, in our experiment we used the inline method as described in figure 1

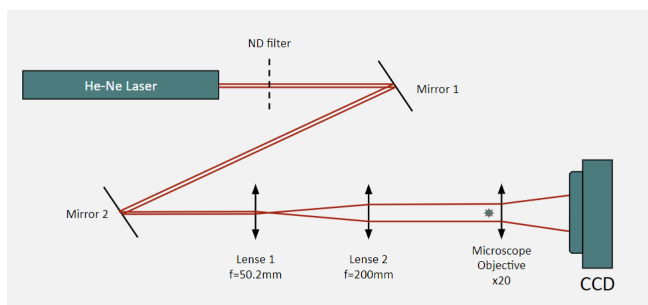

FIG. 1. Inline setup for digital holography. He-Ne laser beam directed by two mirrors. Lenses are used to expand the beam to the microscope objective entrance. A sample is placed near the objective focal plane and a CCD camera after it.

We used a He-Ne laser with wavelength of $\lambda = 632.8[nm]$ directed by two mirrors to make an optical axis. Two lenses are used to expand the beam in order to cover the entire sample (placed on a glass near the focal plane) and microscope objective with even intensity distribution. The objective used has 20X magnification with 0.4 [mm] focal length. finally a CCD camera with pixel size of $3.5[\mu m]$ is place behind the objective to capture the hologram. In order to capture the interference pattern we started each measurement by focusing the objective on the sample, and gradually increase its distance from it. by doing so we can control the hologram plane and test different states of the interference pattern.

RECONSTRUCTION PROCESS

Acquiring a hologram is the first step, but alone it won't do much. A reconstruction algorithm is used to propagate the wave backwards, thus obtaining a numerical reconstruction of objects in different depths. We use an algorithm designed for inline-plane wave holography [2] for reconstruction:

(1) normalize the hologram with the background
(2) transform the hologram to Fourier space using FFT
(3) calculate the propagation term and multiply with the hologram as shown in equation 6
(4) transform back to the spatial domain
(5) for the intensity take the absolute value

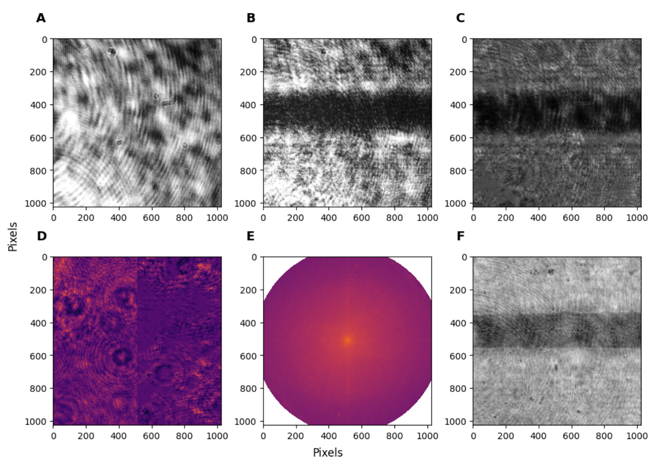

FIG. 2. The reconstruction process on a hologram of a hair. A) background image, B) hologram, C) normalized hologram, D) hologram in Fourier space, E) propagation of $z = 270[\mu m]$ in Fourier space to the object plane, F) inverse Fourier transform to the the hologram of object plane

This algorithm is visualized in Figure 2, which illustrates image manipulations on a hair hologram according to the algorithm steps. To find the exact depth of which the object is in "focus" (the interference pattern converges to the edges) we ran the algorithm on varying ranges and resolutions and examined the propagation on each frame. That is, we did a manual search on the depth axis once we have recovered the desired range from the algorithm. As seen in image (F), a reconstruction of $270[\mu m]$ from the hologram plane brings us to the hair plane successfully.

RESULTS

Using this method allows for reconstruction of complex shaped objects in the micro-meter scale. Our first example is of small soap grains on microscope slide, along with a small scratch on the glass. Figure 3 shows the reconstruction procedure for both. Our reference is a hologram took at the glass plane, which is approximately in focus with the samples, although our setup was not sensitive enough to get it spot on.

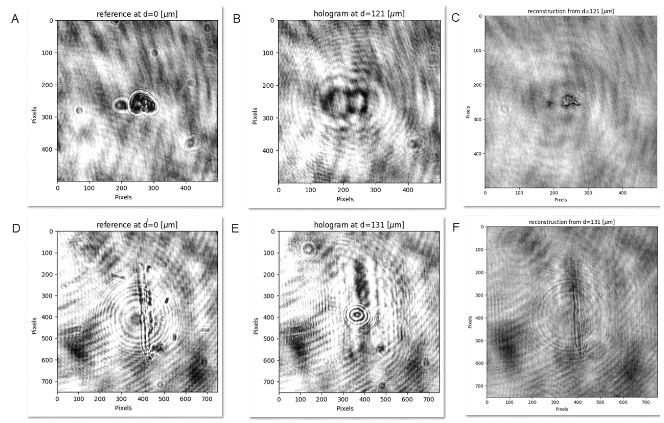

FIG. 3. Reconstructions of soap grain and scratches. A) Image of a soap grain almost in focus, B) Image of the grain's interference pattern at around 120 microns, C) reconstruction of the grain. D) Image of a scratch almost in focus, E) Image of the scratch interference pattern at around 130 microns, F) reconstruction of the scratch.

Our reconstruction process allows for fine tuning the amount of propagation, and recovers the delicate shape of the grain and the scratch.

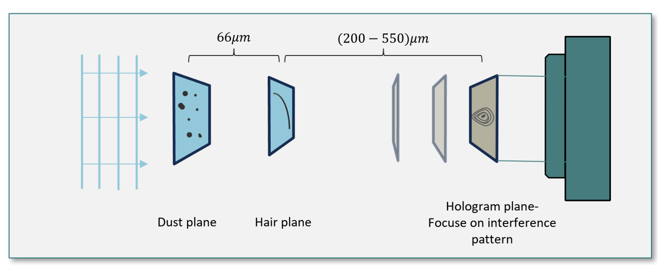

FIG. 4. Sketch of the different optic planes in the system; showing the 'dust plane' on the sample glass and the 'hair plane' which is closer to the CCD. The hologram plane, which is the plane captured in focus by the CCD. on the left a coherent and extended light beam, on the further right the CCD.

After we've managed to propagate and reconstruct numerically a sample from it's interference pattern (hologram plane) to the original object plane, we can reconstruct two objects in different planes of the same sample using the same hologram. As shown in Figure 4, from now on we will define the center of the hair as the 'hair plane', the plane of the sample in which the dust particles are 'dust plane' and the hologram plane as before. The reconstruction of these two planes are shown in Figure 5.

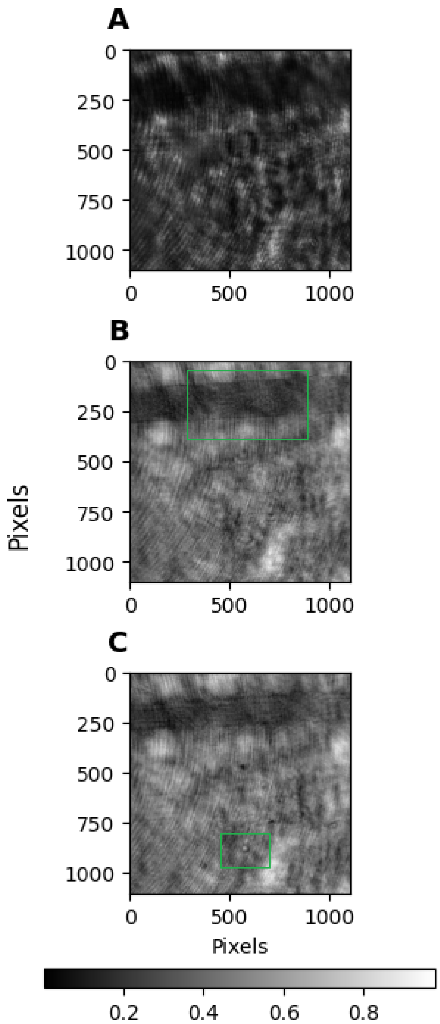

FIG. 5. top: the interference pattern of a hair and dirt sitting in different planes taken about $250[\mu m]$ from the center of hair; middle: reconstruction of the hair to a distance of $248[\mu m]$ (numerically); bottom: reconstruction of dirt to a distance of $308[\mu m]$ (numerically)

We can see on the top, the hologram of the interference pattern of dust and a hair, positioned in different planes captured in a distance of about $250[\mu m]$ from the center of the hair. Obviously it's very difficult to say using this image if the two objects are in the same plane, different ones, which is closer to us or even the shape of them. Using only this hologram we've reconstructed two planes: The 'hair plane'(middle image) in a numerically measured distance of $248[\mu m]$ from the hologram plane, and the 'dust plane' (bottom image) numerically measured distance of $308[\mu m]$ from hologram plane. Using this reconstructing method we can look at the hair and the dust separately, find objects we couldn't find from a single microscopic image (notice that the dust isn't visible on the reconstructed hair plane) and even tell where every particle is found in the depth of the system.

After managing to separate different depth planes and numerically calculate their distances from the hologram, which is common for all the reconstructed objects, we can use this method to calculate depth distances between objects in different planes. This of curse is done by taking the difference between the object's numerically measured distances from the hologram plane. We used this distance measuring system to estimate the accuracy of the system and see how capturing holograms in different planes effect the quality of the reconstruction, as shown in Figure 6.

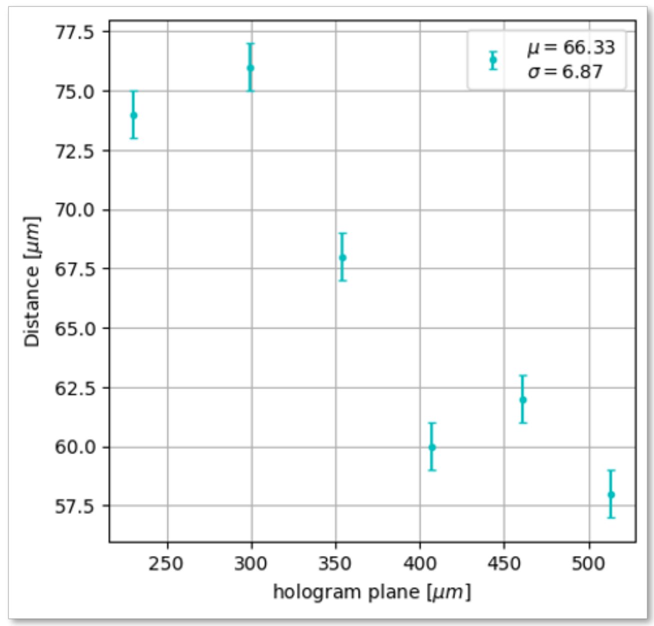

FIG. 6. The graph shows Numerically measured distances between 'hair plane' and 'dust plane' in relation to the hologram plane's distance from sample (hair plane). deviation in the distance (y axis) are entered artificially

Figure 6 shows the relation between the numerically measured distance between the 'dust plane' and 'hair plane' to the distance of the hologram plane from the sample. This was done by taking 6 holograms in different distances from the same sample. deviation in the distance (y axis) are entered artificially since during the reconstruction process it's hard to say in the scale of one numerical micrometer which is more focused. The mean distance measured numerically between the hair plane and the dust plane was $66[\mu m]$ with a big deviation of about $7[\mu m]$. which is in the scale we would expect it to be (average human hair is $60 - 120[\mu m]$). The standard deviation of our measurement indicates we can get around $5 - 10[\mu m]$ resolution in depth with the setup we used, though it is noticeable that the measured distance has a decreasing relationship with the hologram's distance from the sample. This might happen either because when the interference pattern is far from the object it fades and gets noisy with our not so optimal system, or either can be explained by optical distortions caused by the objective lens which is more significant in these distances.

DISCUSSION AND CONCLUSION

We have manged to capture interference patterns on a micro-metric scale and reconstruct object's complex shapes using their interference patterns. We've also managed to separate and reconstruct objects in different depths using one interference pattern. On top of that we've roughly measured depths of the system and got an estimation for the accuracy of the system. Most of our experiment dealt with just managing to capture, reconstruct and identify object's shapes and locations in a three dimensional space. the next step would have been to characterize the system's limits, ideal sizes, distances and other work conditions, characterizing it's errors and resolution properly. we believe there is a chance to improve both the system's and reconstructing algorithm's accuracy and abilities.

REFERENCES

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[2] Tatiana Latychevskaia and Hans-Werner Fink, "Practical algorithms for simulation and reconstruction of digital in-line holograms," Appl. Opt. 54, 2424-2434 (2015)