My Report on Digital Hologram

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Dec. 31st, 2020

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Outline

Background[4]

- Originated in 1940s[1], the venerable field, holographic microscopy, described a way to record an interference pattern (the hologram) from an object in an electron microscope and reconstruct a three-dimensional (3D) image of the object optically.
- The invention of the laser made it much easier to record holograms optically, launching the fields of holographic photography and holographic microscopy.[2]
- The later development of the digital camera led to another revolution in holographic microscopy, one in which the reconstruction could be done digitally rather than optically.[3]

[1] **D. Gabor, Nature 161, 777–778 (1948).**

[2] **E. N. Leith and J. Upatnieks, J. Opt. Soc. Am. 55, 569–570 (1965).**

[3] **U. Schnars and W. Jüptner, Appl. Opt. 33, 179 (1994).**

[4] **R. Alexander, et al. Journal of Applied Physics 128, 060902 (2020).**

Basic Principle: Digital Recording

Interference Method

$$
\begin{aligned}
I(\xi,\eta) &= |R(\xi,\eta)+G(\xi,\eta)|^2 \\
&= R_0^2 + G_0^2 + R_0 G(\xi,\eta)\exp(-i2\pi b\xi) + R_0 G^*(\xi,\eta)\exp(i2\pi b\xi) \\
&= R_0^2 + G_0^2 + 2R_0 G_0 \cos(\Phi_G - \Phi_R)
\end{aligned}
$$

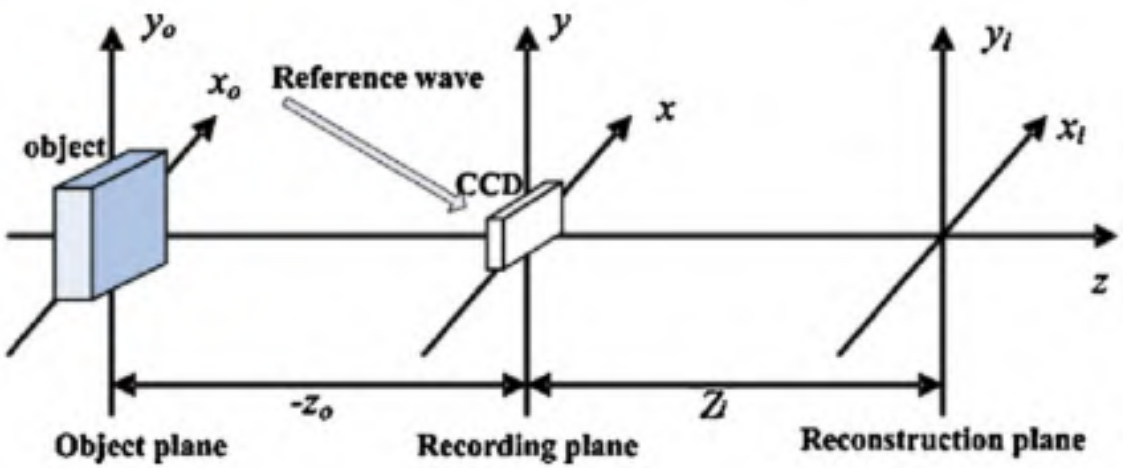


Figure: Simplified optical path[1]

[1] **P. Qiu, J. Gu, Optik 125(2014) 2652–2655.**

Basic Principle: Hologram Processing

Fourier Transform & Fresnel Diffraction

$$U_I(x_I, y_I) = \frac{e^{jkd}}{j\lambda d} \int\int I(u,v) C(u,v) \exp\left[\frac{jk}{2d}\left((x_I - u)^2 + (y_I - u)^2\right)\right] \mathrm{d}u\mathrm{d}v$$

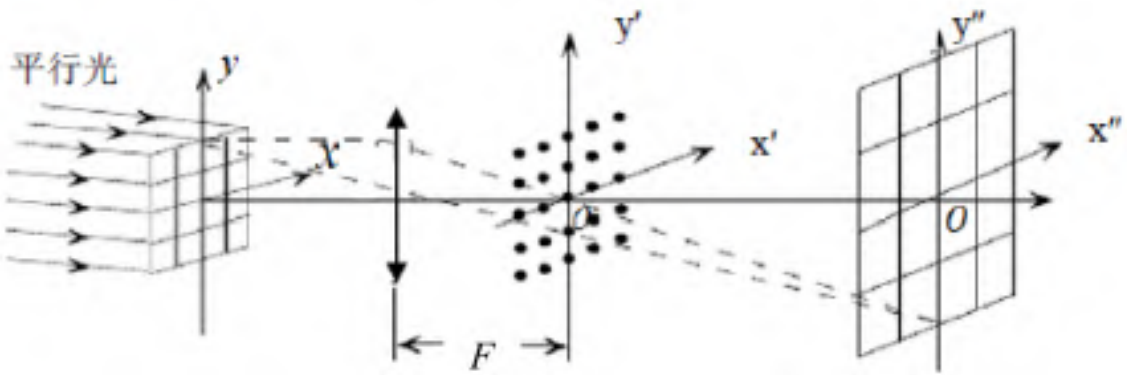


Figure: Abbe Imaging Principle[1]

[1] **Lectures on Modern Physics Experiments**.

Developments

- Nowadays, digital holographic microscopes are often used for fast 3D imaging of transparent specimens. 3D information is encoded in each 2D image (hologram), and these images can be acquired as quickly as the camera allows.[1]
- Ovryn and Izen[2] and Lee et al.[3] took advantage of digital recording and computational power to fit exact scattering solutions directly to the holograms. Today, that approach is being used to characterize particles and track their motion in a variety of applications.
- With the developments of machine learning, new technics such as automatic phase aberration compensation are becoming available.[4]

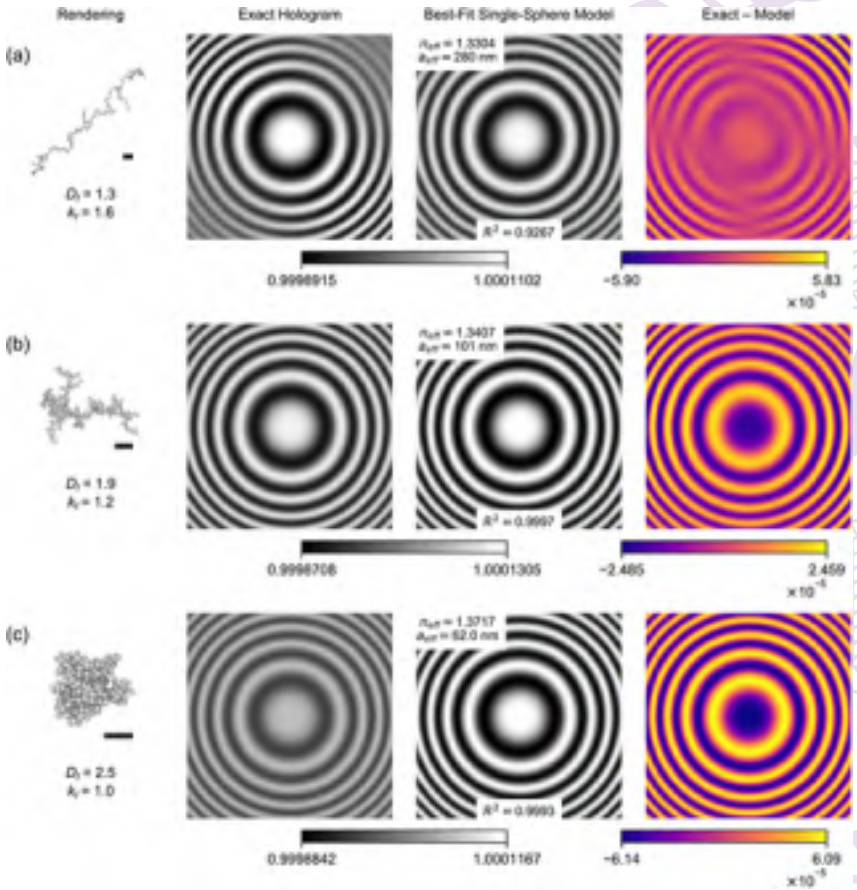
[1] **R. Alexander, et al. Journal of Applied Physics 128, 060902 (2020).**

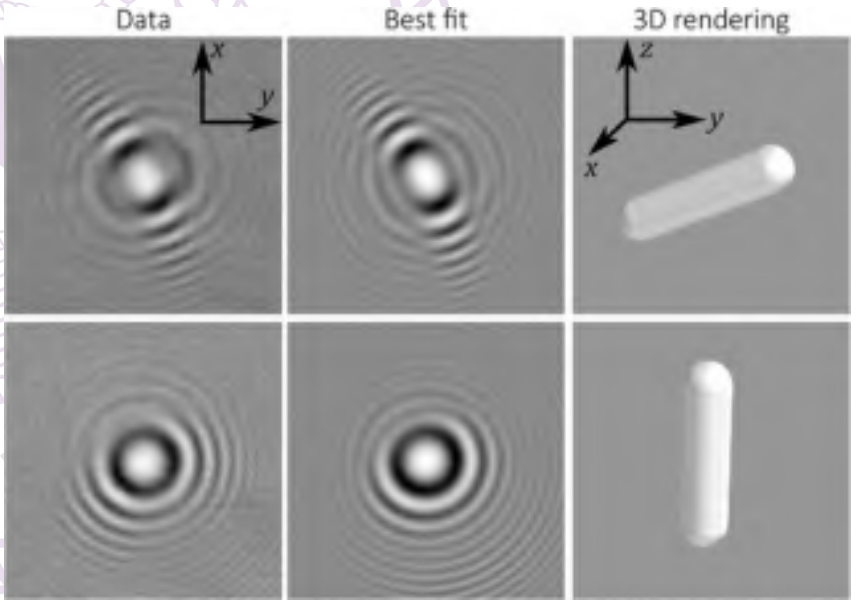
[2] **B. Ovryn and S. H. Izen, J. Opt. Soc. Am. A 17, 1202–1213 (2000).**

[3] **S.-H. Lee, et al. Opt. Express 15, 18275–18282 (2007).**

[4] **T. Nguyen, et al. Opt. Express 25, 15043-15057 (2017).**

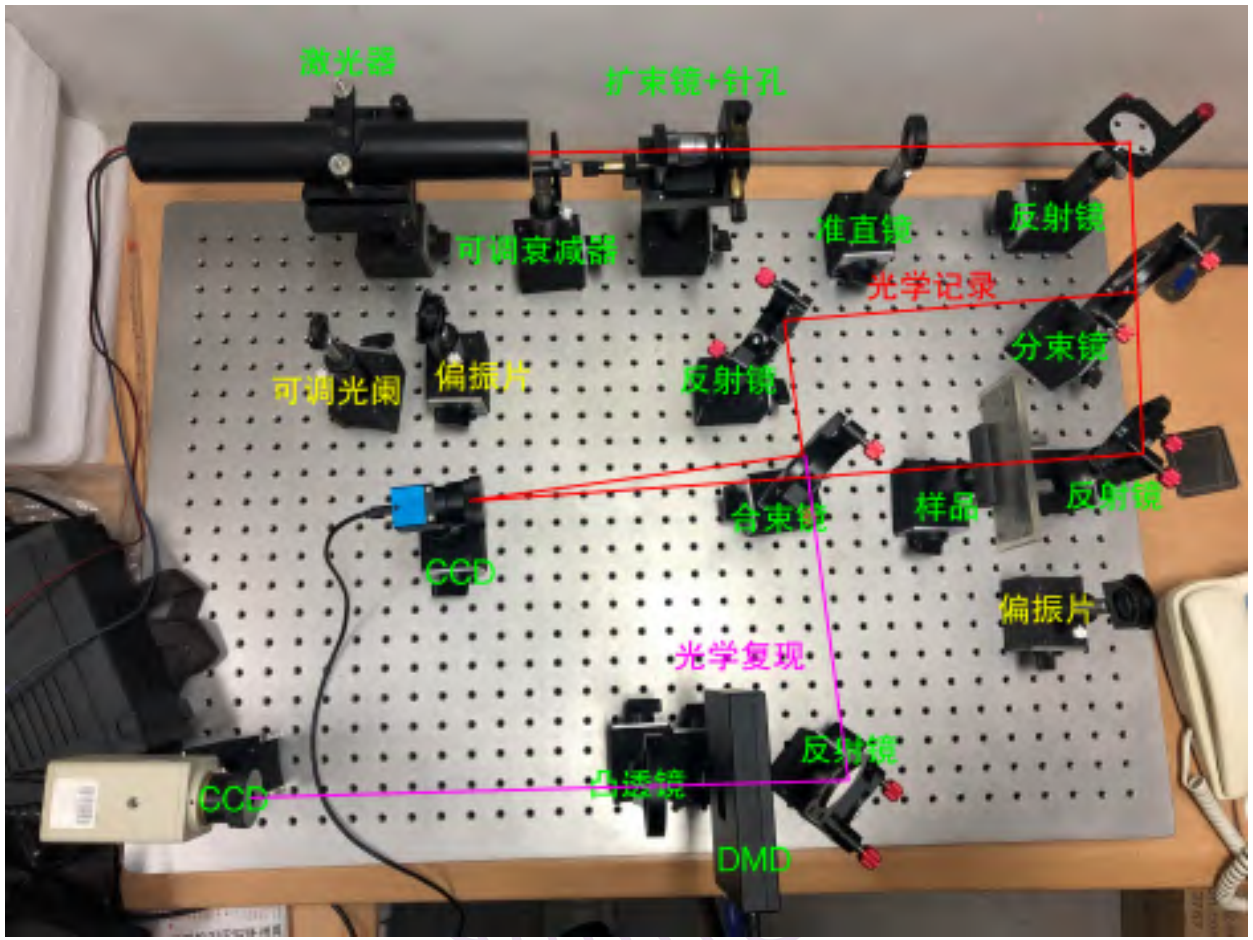
Applications





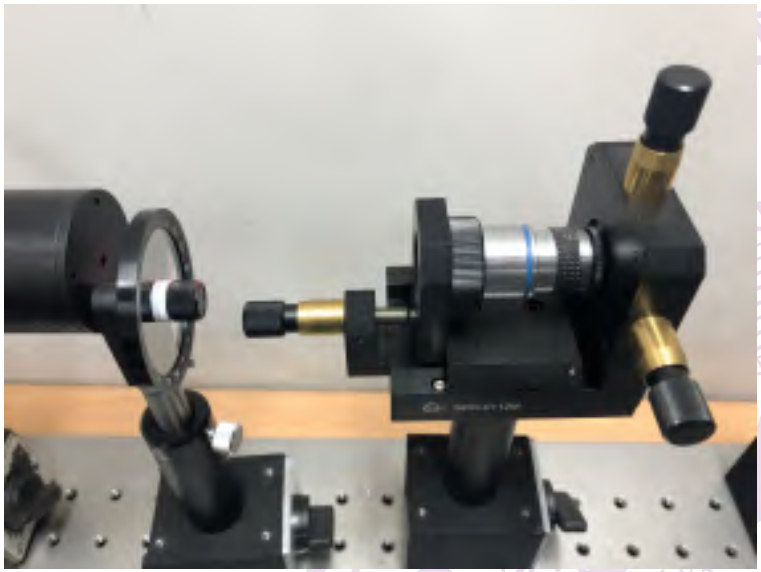
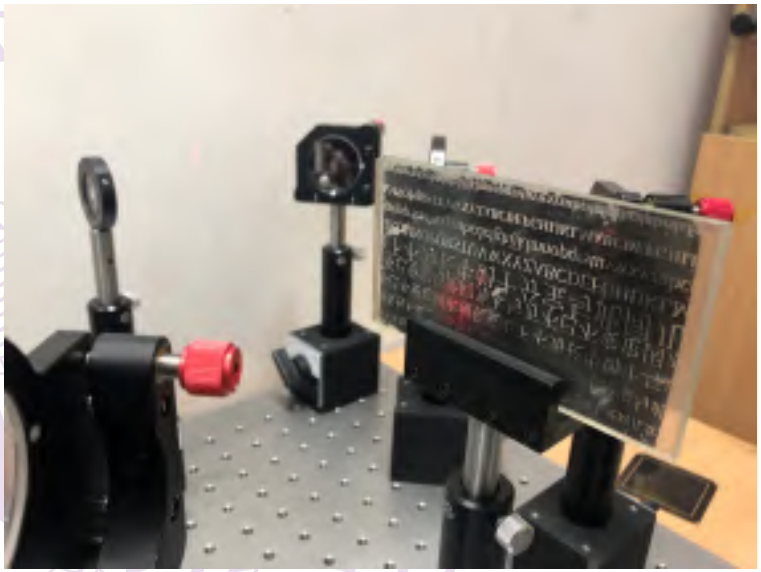
(a) J. Fung and S. Hoang, Transfer 236, 106591 (2019) (b) Wang et al., Opt. Express 24, 23719–23725 (2016)

Construction of the experimental platform



I found a complete set of instruments from various places in the laboratory, built an experimental platform, and contacted the manufacturer to supplement, repair, and debug the experimental equipment.

Apparatus

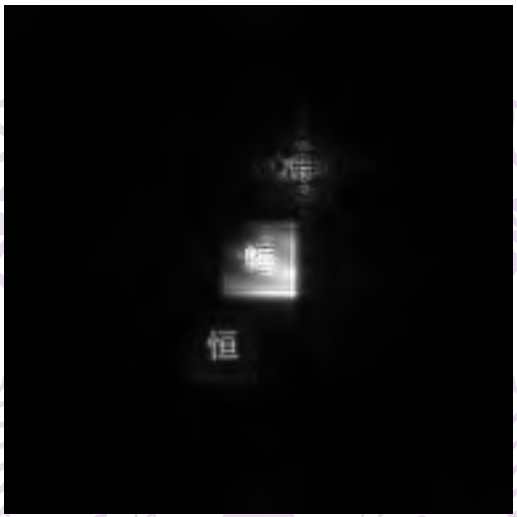
Review Basic Recurrent Experiments

I successfully reproduced all pre-required experimental content, which can be combined freely.

- Optical recording holograms
- Digital generating holograms
- Optical reproducing objects
- Digital reproducing objects
- Real-time display for optical holograms

Basic Holograms

(a) Optical Recording



(b) Digital Reproducing

(c) Digital Calculating

(d) Optical + Digital

(e) Optical + Optical

(f) DMD for Reproduction

Difficulties

- Incomplete experimental equipment

Complete the experimental equipment

- Tiny & Damping experiment platform (**Redesign optical path**)
- Data line of CCD (**Buy**)
- Power cable of DMD (**Buy**)
- Optical instruments scattered (**Find or Buy**)

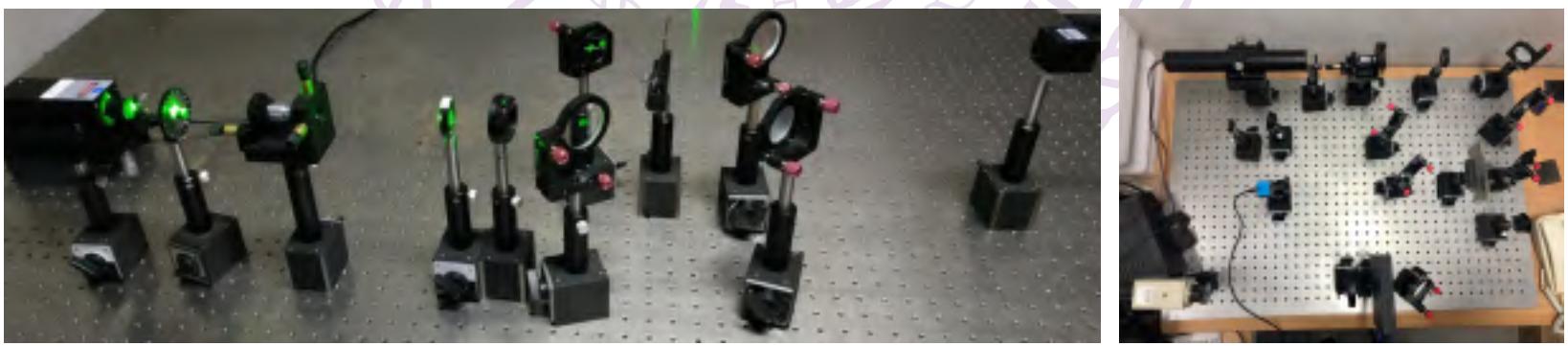


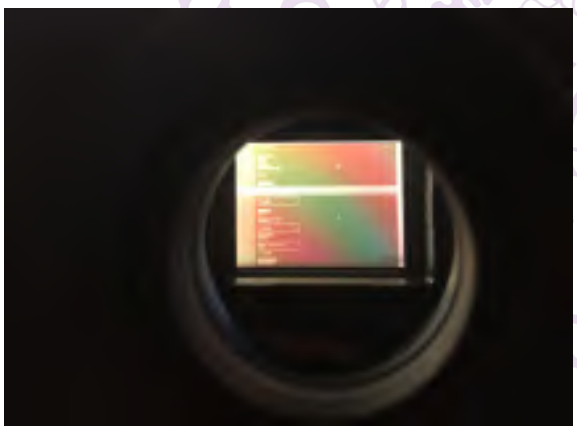
Figure: Not enough test bench size. Left: Designed; Right: Actually.

Difficulties

- Incomplete experimental equipment
- DMD malfunctions when using the VGA adapter in Windows 10

Solution

- I changed another computer in lab 6B805 in the beginning but failed.
- Then, I used command "xrandr" in Archlinux instead to manually adjust display settings.



(a) DMD Mulfunction, you can see 2 mouse icons at the same time

(b) DMD Function, clearly show the hologram

Difficulties

- Incomplete experimental equipment
- DMD malfunctions when using the VGA adapter in Windows 10
- Hologram field of view is small

Solution

Add an extra lens in the optical path to minify the object first.

Difficulties

- Incomplete experimental equipment
- DMD malfunctions when using the VGA adapter in Windows 10
- Hologram field of view is small
- The holographic reproduction result is not clear

Solution

- Optimize the quality when optical recording
- Optimize the hologram

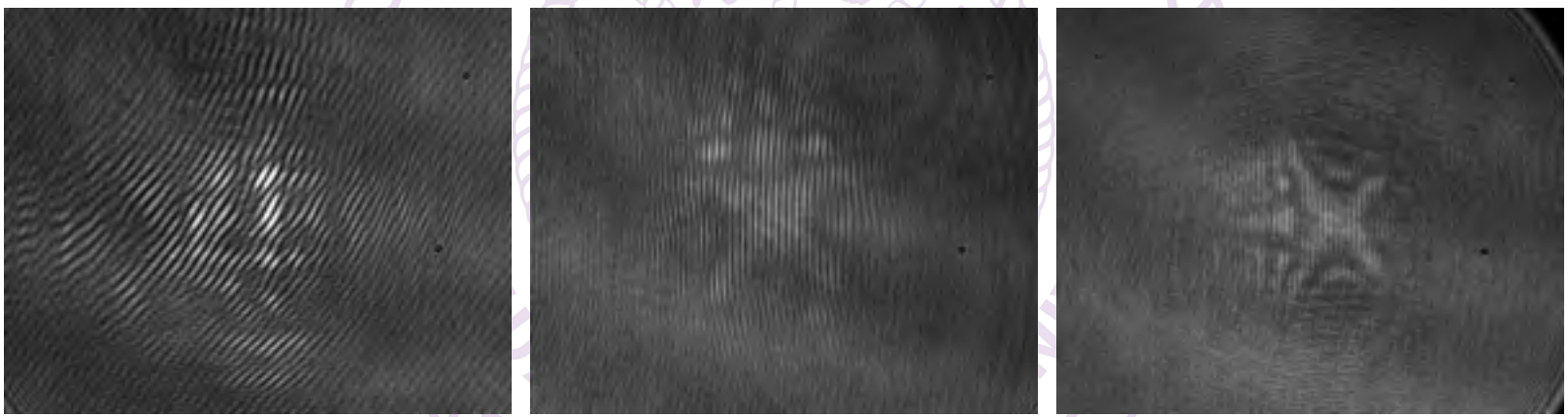
The solution below will be introduced in next section.

(a) Blurred image

(b) Defective Hologram

Improvement of Optical Recording Quality

- Use interference method to strictly adjust parallelism and collimation.
- Make the stripes denser to increase the resolution.
- Let fringes along the vertical direction to keep the diffraction direction consistent.



Improvement of Digital Reproducing Quality

Motivation

- Zero-order Noise
- Sensor-dust
- Conjugate image
- Blurred image

- In order to enhance the quality of digital reproduction, researchers have tried numerous methods, such as filters[1][2], differential algorithms[3][4], phaseshift average[5][6], etc. Or using many combination methods.
- Following will show 3 operators I have used.

[1] P. Qiu, et al. Optik 125 (2014) 2652–2655.

[2] W. Zhang, et al. Optics Communications 356 (2015) 589–594.

[3] Choongsang Cho, et al. IEEE PHOTONICS TECHNOLOGY LETTERS, VOL. 25, NO. 12, JUNE 15, 2013.

[4] K. Nenadic, et al. Int. Arab J. Inf. Technol. 15.2 (2018): 186-193.

[5] Hsieh, Wang-Ta, et al. 3D Research 2.2 (2011): 1..

[6] Sha, Bei, et al. Optics express 22.19 (2014): 23066-23072..

Hologram Operator

There are many commonly used operators: Roberts, Cross, Prewitt, Sobel, Canny, Marr-Hildreth, Laplace, etc.

Laplace Operator

An isotropic second-order differential operator, which has rotation invariance.

$$\nabla^2 = \partial_x^2 + \partial_y^2$$

For programming convenience, it can be discretized into the following four templates:

0	1	0
1	-4	1
0	1	0

1	1	1
1	-8	1
1	1	1

0	-1	0
-1	4	-1
0	-1	0

-1	-1	-1
-1	8	-1
-1	-1	-1

In actual use, a convolution operation is performed around each point in the image to extract the edge of the image.

Hologram Operator

Sobel Operator

A first-order differential opeartor, which is also used for extracting the edge of the image.

$$G_x = \begin{pmatrix} -1 & 0 & 1 \\ -2 & 0 & 2 \\ -1 & 0 & 1 \end{pmatrix}, \qquad G_y = \begin{pmatrix} 1 & 2 & 1 \\ 0 & 0 & 0 \\ -1 & -2 & -1 \end{pmatrix}$$

$$G = \sqrt{G_x^2 + G_y^2}$$

It has some rotation variants

Substarct Mean Intensity

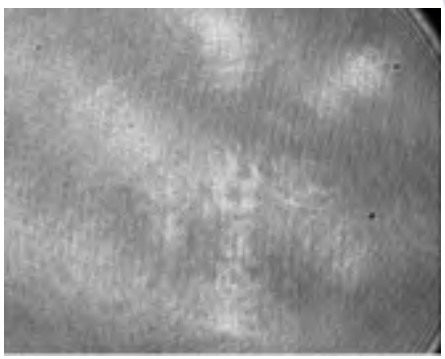
An operator to deduce DC-noice.

$$I = I_0 - \mathrm{mean}(I_0)$$

Filters

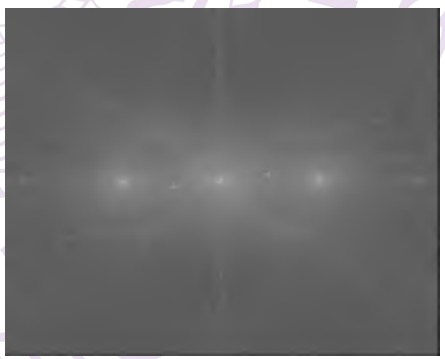
High Pass Filter

Low frequencies in spectrum space represent the intensity of the image, while high frequencies represent contour features. High pass filters can be used to suppress the average noise, especially the zero-order and the average background intensity.

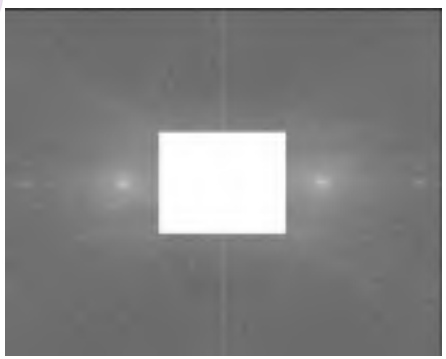


(a) Hologram

(b) Hologram After Filter



(c) Fourier Transform



(d) High Pass Filter

Self-design Operator

New Design Operator I

- Mean substract (Reduce DC noise of Hologram)
- High Pass Filter (Reduce zero-order noise after Fresnel diffraction)
- Sobel Operator (Reduce zero-order noise after Fresnel diffraction and conjugate image)
- Intensity Filter (Remove the "fog" around)

Self-design Operator

New Design Operator II

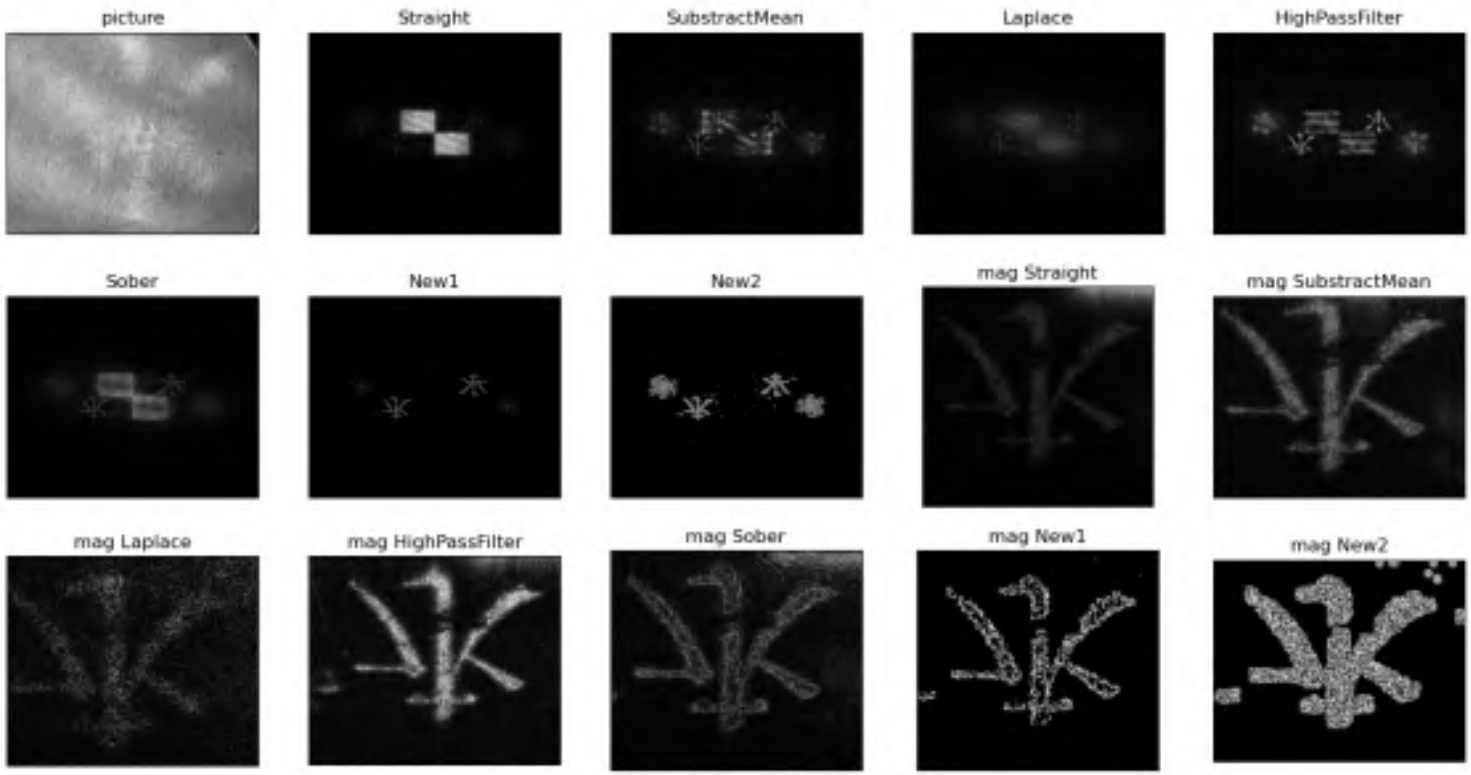
- Operator I
- 3x3 pooling (Repair the "defects")
- 5x5 convolution (Differential method while keeping the inner continuity)

1	1	1
1	2	1
1	1	1

1	1	2	1	1
1	-4	-8	-4	1
2	-8	4	-8	2
1	-4	-8	-4	1
1	1	2	1	1

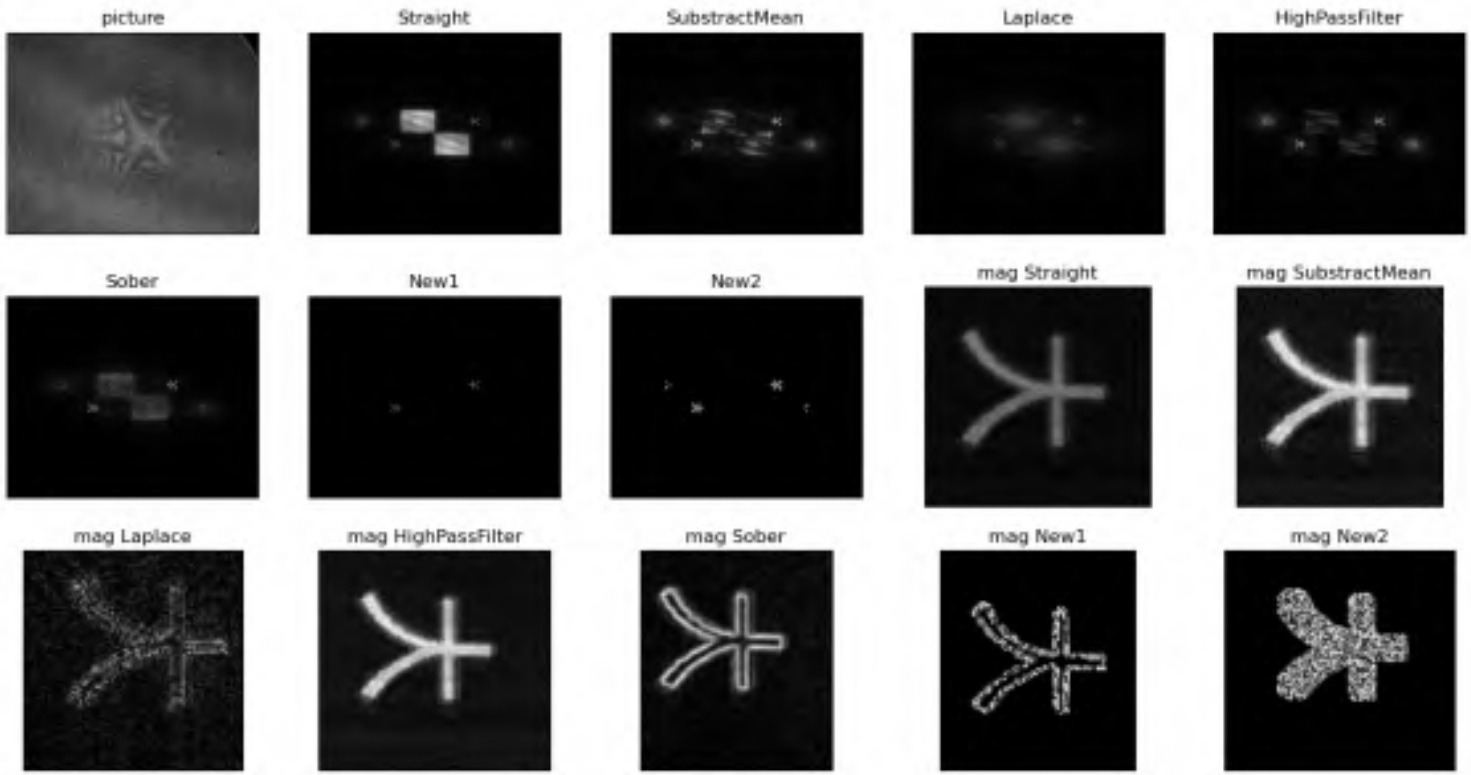
Results

Recording Distance: 40cm



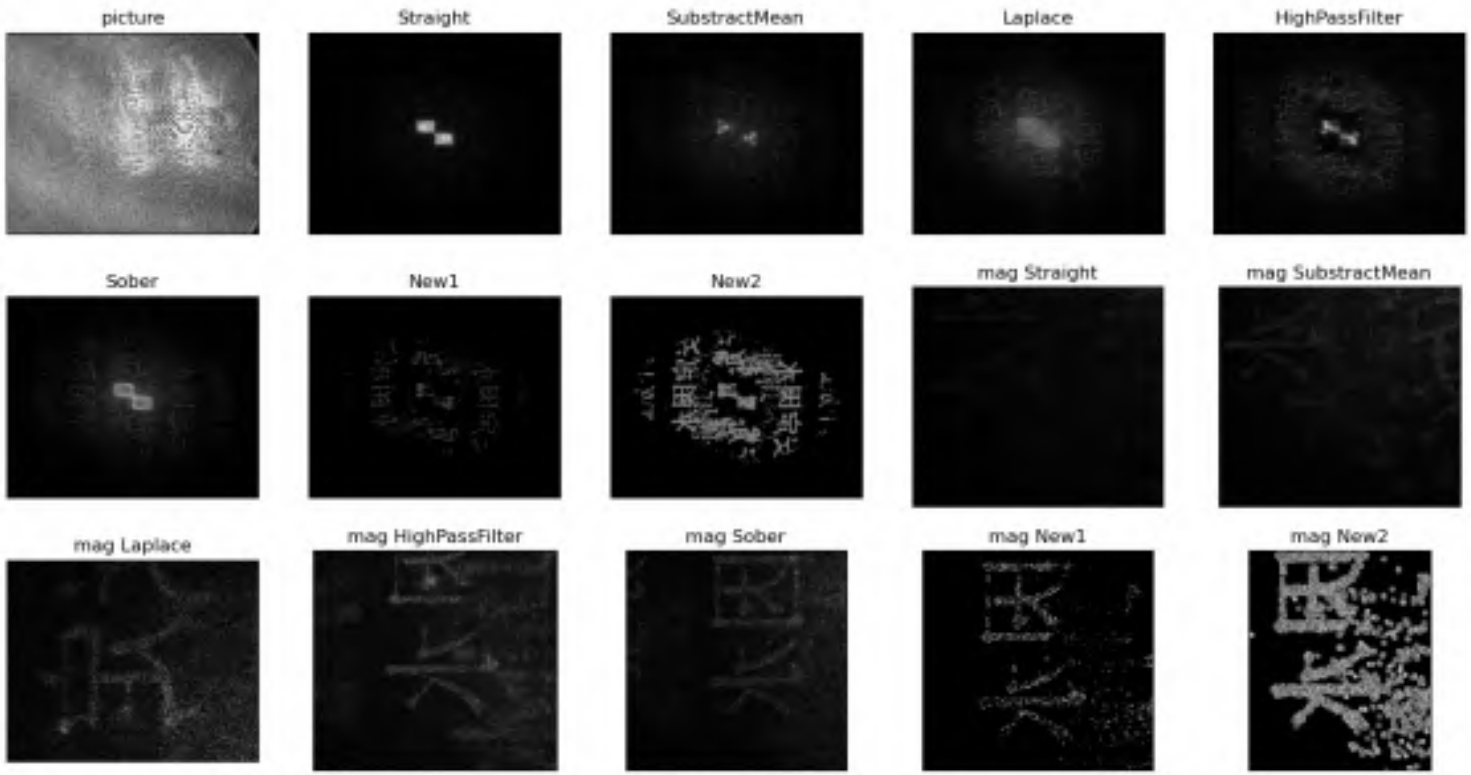
Results

Recording Distance: 40cm



Results

Recording Distance: -73.2cm



Difficulties Not Solved

- How to distinguish Image, Conjugate Image, and Zero-order? (For an automatic program)
- How to optimize the optical reproduction?
- How to increase the density of information while keeping the imaging quality?
- Any easy application in lab we can design?