## P443-444 Final Lab Report

# Holography techniques and Digital Holography


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**Abstract**

Holography techniques are used in various different fields mainly in imaging microscopic images for biomedical applications. Holography is a way to preserve the phase information from a given light source which is in contrast to images from a CCD camera which are basically two dimensional intensity plots. The phase information is stored in the form of interference patterns. In this report, the reconstruction of the hologram is emphasised upon. We also review techniques used to reconstruct the object and explain how the reconstruction could be done digitally. A Brief introduction to computer generated graphics is given and finally we propose ways to optimize the reconstruction process using machine learning.



*Keywords:* Interference,Digital holography, Machine learning.


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# 1. Introduction

## 1.1 Depth Perception

When we see an object, we have an idea of how far away it is because we have stereo vision. We get two images of (nearly) the same objects - one from our right eye and one from our left. From any one image, we can "fix" a line, in which the object is located. We can perceive the objects to be closer by imagining their size to be smaller and we can imagine the objects to be farther away by imagining them to be bigger. We can do the same thing for the other eye. However, two lines will only meet at one point and hence, we can estimate how far the object really is. But we cannot estimate depth in a "usual" image. When we see a photograph, we are only seeing one view, and hence, it is impossible to estimate the depth. Regardless, we can estimate the depth with our experience and intuition.

## 1.2 Principles of Holography

A beam scattered from a particular object is made to interfere with a reference beam of known wavelength and phase. The recorded Interference pattern can be further used to reconstruct the original scattered object beam using diffraction. A hologram records the interference pattern between a reference light and light reflected from any object surface. Once the hologram is recording, if light is incident of the hologram from the same angle as the original reference light, the the entire scene is recreated when viewed from a particular direction. Hence, when we see a hologram, we can perceive it's depth since we get a stereo vision of the scene as described above. The technique was developed by Dennis Gabor for which he was awarded the Noble Prize in 1971.

# 2. Study of the experimental Setup

## 2.1 Formation of Interference patterns

A laser creates a coherent source of light. A shutter is used to protect the holoplate since it is very sensitive to light. A beam splitter divides the light into two beams - one to be used as reference and one to be used to reflect from the object. Note that in this case, the object becomes the entire scene. Since the contrast of an intereference pattern is highest when the two light beams have equal intensities, an ND filter is used to dim the reference beam which will have more intensity at the holoplate as it directly falls on the holoplate as compared to the reflected light from the object. Mirrors are used to direct the beams to the holoplate.

This generates an inteference pattern of the object (light reflected from the object) and the reference beam. Following this, the hologram is developed using chemicals in a dark room.

### 2.2 Reconstruction of the object beam

After the hologram is created, when light is incident on the holoplate with the same angle of incidence as the original reference beam, it gets transmitted into 4 beams. Two of these beams just pass through the holoplate as though it was never there. One of them converge to make a real object of the image and one of them diverge. The diverging beam is the one of most interest. When viewed from some particular angle, it converges to form a virtual image of the original object.

## 3. Apparatus

As described in the sections above, the following apparatus is required:

- *laser*: 25 mW He-Ne with wavelength 633 nm.
- *mirrors*: M1 and M2 were small plane mirrors and M3 was a large mirror.
- *object*: An object is needed whose hologram will be created.
- *beam splitter*: A 50-50 beam splitter, which split the incoming beam into two outgoing beams of equal intensity.
- *holoplate and chemicals*: used to record the intensity pattern and develop the hologram. The chemicals used are potassium dichromate and sulphuric acid.
- *dark room, optical bed, mirror holders.*
- *Microscope Objective*: A microscope objective increases the beam size. Since we want light to fall on the entire object, but the laser only creates a small beam, a microscope objective along with an aperture is used to thicken the beam and make it gaussian.

## 4. Theoretical Background

### 4.1 Construction of the Hologram

We will first analyse what exactly is stored in the holoplate, i.e., the intensity of the light falling on each point of the holoplate.

- Consider some point in the holoplate. The intensity of light at that point will be due to the light from the object and from the reference.
- The light from the object, O, will be of the form $O_0\exp[i\psi_{object}]$ and that from the reference, R, will be of the form $R_0\exp[i\psi_{reference}]$ where $\psi_{object}$ and $\psi_{reference}$ are the phases of the source and the reference at that point.

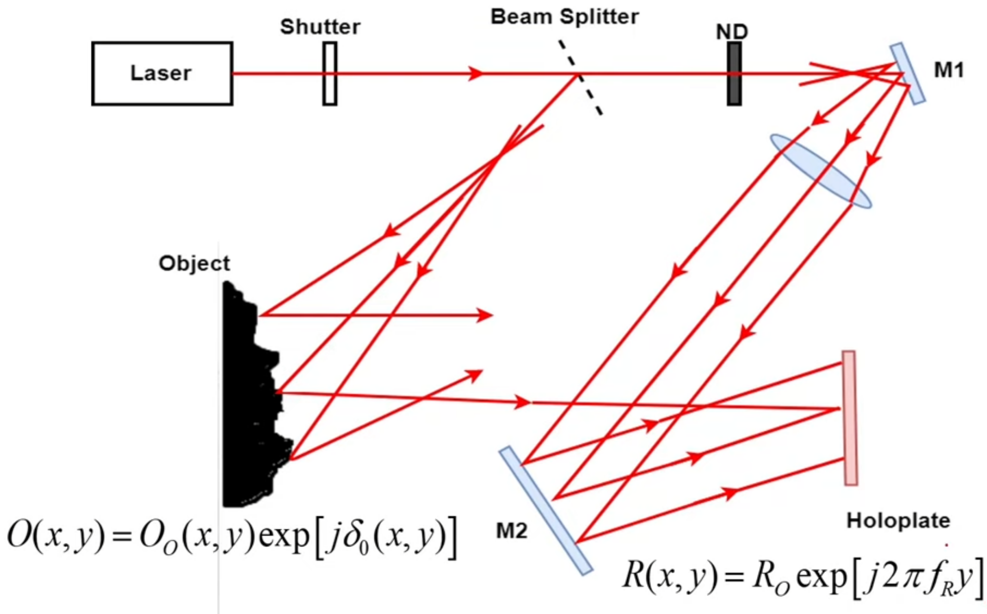



**Figure 1.** Construction of holograms

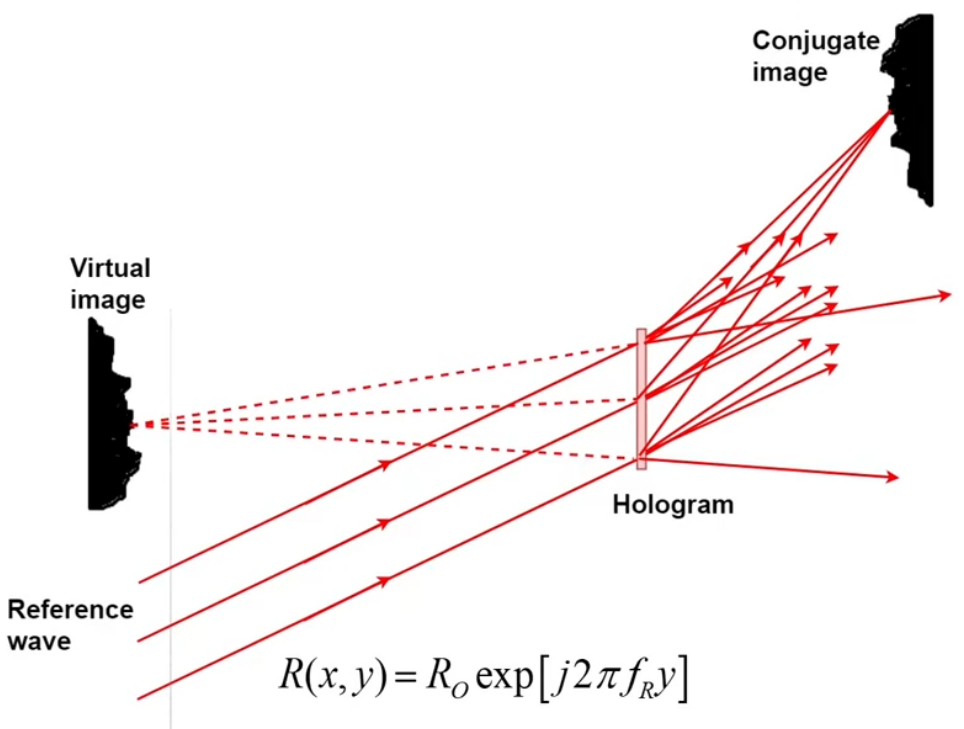



**Figure 2.** Reconstruction of a hologram

- Note that $\psi_{reference}$ is known (can be calculated).
- The intensity of light at that point is | O + A |$^2$.
- Expanding this, we get

$$I = O_0^2 + R_0^2 + OR^* + RO^*$$

- The hologram stores this intensity which captures the phase information. Since,

$$OR^* + RO^* = 2O_0R_0cos(\psi_{object} - \psi_{reference})$$

Hence, even though the hologram is capturing intensities at each point, since it's capturing an interference pattern, the phase information is being captured. We will also define exposure E of a point as the intensity I at that point multiplied by the time T for which the laser was on (holoplate was illuminated)

## 4.2 Coherence

Coherence is a measure of similarity in frequency and waveform of two waves. A laser creates waveforms that have high spatial and temporal coherence.

- *spatial coherence*: If a particular wavefront is inspected, a high spatial coherence implies that the phase of the wavefront is same for a large distance in space. Ideally, the phase should be same in a wavefront for all of space but that is not practical
- *temporal coherence*: If a single point in space is fixed, and it's nature is analysed as time passes, high temporal coherence implies that the nature does not change for a large amount of time.

Coherence is quantified by coherence length and coherence time. The later is the inverse of the uncertainty in the frequency of the laser and the former is speed of the wave times the coherence time.

## 4.3 Reconstruction of the hologram

After the hologram is recorded, light is shone in the same direction as the reference beam and all of the rest of the apparatus is removed. We will now analyse the behaviour of this phenomenon. The when light is incident on a surface, some of it's parts will be reflected and the rest will be transmitted. The ratio of the the transmitted beam to the incident beam is known as the transmittance. The form of transmittance taken here is non-trivial. However, assuming that the form is as shown in eq (), the following analysis follows.

- To reconstruct the hologram, we shine the same reference beam in the hologram. The transmitted wave will be of the form t(x,y)xR(x,y) where R is the reference beam and t is the transmittance at that point.

- In our case, the transmittance is of the form

$$t(x,y) = t_0 - \beta E(x,y) \tag{1}$$

- Hence, we have

$$t(x,y)R(x,y) = (t_0 - \beta E(x,y))R(x,y)$$

- Putting E = I.T, and expanding I, we get 4 terms, which correspond to the 4 different beams. They are:

  1. $t_0 R(x,y)$ which is just the reference wave scaled by $t_0$
  2. $-\beta T O_0^2(x,y)R(x,y)$ which is again a wave is the direction of the reference wave
  3. $-\beta T R_0^2(x,y)O(x,y)$ which is similar to the object wave
  4. $-\beta T R_O^2(x,y)O^*(x,y)$ which is the conjugate object wave

Each of these four expressions represents one of the four beams in section 2.2. The first two beams are similar to the original beam and pass unaffected through the hologram but scaled by some factors. The 3rd beam is similar to the beam that was reflected from the object. Hence this creates a virtual image of the object when viewed from some particular angle. This is our main beam of interest and this creates the 3D image. The fourth beam creates a conjugate real object.

# 5. Digital Holography

The main idea is to replace the photo-chemical procedures of conventional holography with electronic imaging. Instead of a holo-plate, The interference pattern is now captured on a CCD camera. This setup is more stable and less time consuming. However, the resolution of the object beam obtained is limited by the resolution of the camera. This is not the case for the photochemical holo-plate. Historically, generating a complex-valued holographic fringe pattern presents two difficult problems: first, simulating and computing the pattern with enough spatial resolution to produce the intended image, and second, writing the pattern to some material or device capable of recording its detail.

## 5.1 Physical intuition

We could use numerical techniques to compute The collective interference of a simulated object wave, with a reference wave at a set of discretized locations throughout the combined field to generate a hologram of that scene. From this interference pattern (assuming good enough spatial resolution), the object can be reconstructed by simulating diffraction using numerical techniques. The type of diffraction it is supposed to undergo entirely depends on how far we want the object to be so that the paraxial approximation can be applied. Computed holograms traditionally fall into one of two classes: Fourier holograms, appropriate for far-field Fraunhofer diffraction, and Fresnel holograms, which produce images in the near field. The fundamental difference between these two diffraction models is the range of length scales in which they "operate". Throughout the end of this discussion, we will only be considering regimes where paraxial approximation is valid i.e. we will only consider fourier holograms. The reconstruction of Fresnel holograms can also be done using the same numerical techniques.

## 5.2 Simulating the interference patterns

The physics of the formation of the interference patterns is as explained in the above sections. Thus if we can somehow simulate the wave front of the scattered beam from the object, we can simulate interference between the scattered beam and a reference beam by superposing the two and taking the square. Lensless Fourier holography is possible by placing a point source reference at the object plane. The point source can be simulated by the following equation

$$\begin{aligned} R(r) &= \frac{exp(ikr)}{r} \\ R(r) &= \frac{exp(ik\sqrt{x^2+y^2+L^2})}{\sqrt{x^2+y^2+L^2}} \end{aligned}$$

where,

- $R(r)$ is the reference beam
- r is the distance from the point source origin to locations on the imager surface.
- L is distance distance of the centre of the imager to the point source origin.

The emission cone of the pinhole in an actual experiment will modify this ideal point source.

## 5.3 Wavefront reconstruction

Once the hologram has been recorded and we have recovered the original object wavefront in the plane of the imager by multiplying by a numerical reference beam, the next step is to back-propagate the wavefront to the object plane, thereby reconstructing the object.

### 5.3.1 Different ways to reconstruct the hologram

The holograms can be reconstructed digitally in various ways

- Angular Spectrum Propagation
- Fresnel Method
- Huygen's Convolution Method

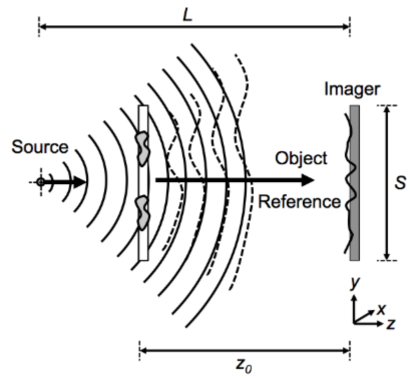



**Figure 3.** Set-up for in-line holography

- Using several Phase shifted holograms (for on-axis holography)

[1] Since the data is digitally stored, we can manually subtract the dc terms from the interference expression to get

$$I'(x,y) = O(x,y)R^*(x,y) + O^*(x,y)R(x,y)$$

Now we can multiply this equation by the reference wave whcih is approximated by the point source to get

$$I''(x,y) = O(x,y)R^*(x,y)R(x,y) + O^*(x,y)R(x,y)R(x,y)$$

$$I''(x,y) = O(x,y)|R(x,y)|^2 + O^*(x,y)R(x,y)R(x,y)$$

If we divide this expression by $|R(x,y)|^2$ we get the twin images along with a certain factor multiplied to the conjugate image.

$$I'''(x,y) = O(x,y) + O^*(x,y)\frac{R(x,y)R(x,y)}{|R(x,y)|^2}$$

Our further analysis assumes negligible interference.

The Angular Spectrum method has several advantages over other traditional methods such as so-called direct Fresnel method or a Huygen's Convolution method. In particular, the Fresnel method only provides valid reconstructions at relatively large distances under the paraxial approximation. When the entire path from the source to the object to the imager is only on the order of a few mm, the paraxial approximation may not be valid. Its advantage, however, is that numerical reconstruction can be very fast, requiring only a single Fourier transform to propagate the field from the detector plane to the object plane. While the short distance behavior of the Huygen's Convolution technique is significantly better, it requires three Fourier transforms. The angular spectrum technique does not use

[1] the following analysis is for In-line(on axis) holography. This type of holography is mainly used in biomedical image analysis

any approximations and is therefore valid over short distance, even to zero.

Furthermore, it requires only two Fourier transforms and maintains a constant pixel size with distance. While the constant pixel size at any reconstruction distance gives a constant field-of-view that may limit imaging microscopic samples, consideration of the geometric magnification provided with a point-source reference wave alleviates this concern.

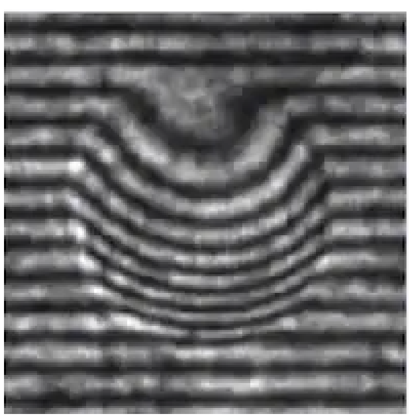
## 5.4 How Fourier transforms come into the picture

- In order to separate the object from the reference beam, we use a fourier transform.

$$I = OO^* + RR^* + OR^* + RO^*$$

$$\mathscr{F}[I] = O \otimes O + R \otimes R + R \otimes O + O \otimes R$$

- Broadly speaking, our main task is to get information about the object wave. we need to seperate the third term in the above equation. The first two terms are the auto-correlation terms and the next two are the cross-correlation terms. We need to extract out one of the cross correlation terms in the fourier space and take the inverse fourier transform back into the plane of the camera.
- A fourier transform is a way of expressing a function in sinusoidal basis. Hence if a function is a superposition of sinusoids, then we only get points(1D) or lines(2D) etc. as the fourier transform.



**(a)** Interference pattern of a sphere and a cosine wavefront


**(b)** Fourier transform of the interference pattern

## 5.5 Angular Spectrum technique

Diffraction of a wave-field can be understood as the propagation of a series of plane waves that make up that wavefield. An object field $O(x, y; z)$ has an angular spectrum $A(k_x, k_y; z)$

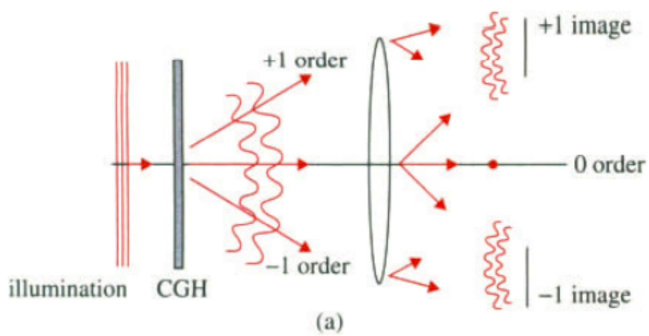



**Figure 5.** Reconstruction of a fourier hologram

directly related to its Fourier transform.The angular spectrum propagates from $z = 0$ to $z = z_o$ through the following expression

$$A(k_x, k_y; z_0) = A(k_x, k_y; 0) exp(ik_z z_o)$$

where $A(k_x, k_y; z_0)$represents the angular spectrum at a given $z_o$ location. Since the original wavefront was the inverse Fourier transform of its original angular spectrum, the new wavefront — propagated to a new z position — is simply the inverse Fourier transform of the new angular spectrum. The final equation obtained is

$$O(x, y; z_o) = \mathscr{F}^{-1}\left[\mathscr{F}[O(x, y; 0)] exp(iz_o\sqrt{k^2 - k_x^2 - k_y^2})\right]$$

# 6. References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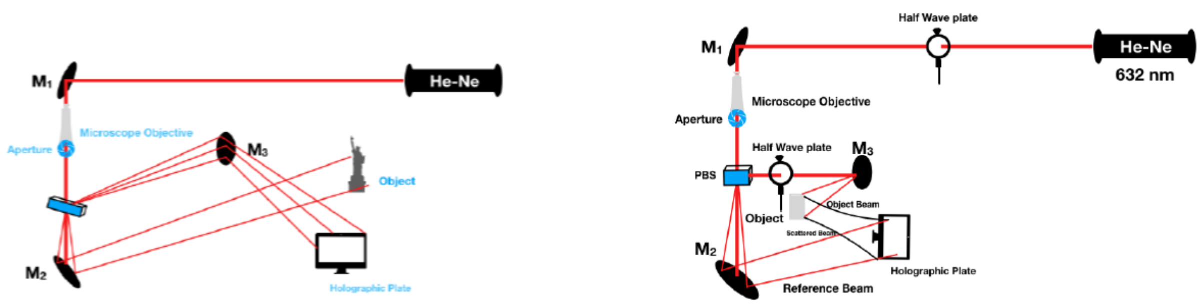
## 6.1 Holography with Polarising Beam Splitter

With a polarising beam splitter and a couple of half-wave plates, we could have control over the ratio at which the beams are split into two. We need the half wave plates since interference only occurs with beams of same polarisation. With this setup, we could get the maximum possible contrast and clarity in the hologram. To reduce the noise, the intensity of the reference beam should be high. However, the contrast of an interference pattern is the highest when the intensities of both the waves are equal. Hence, the ideal ratio for splitting is non-trivial and with this setup, we can tweak the ratios to get the most clear interference pattern.




**(a)** baseline setup

**(b)** Improved setup with intensity control

**Figure 6.** Figures represent the two different setups

# 7. Steps taken to improve the basic setup

In this section, we will first describe the source of error and why it is of relevance to the corresponding setup and then we will go through, in detail, the steps taken to reduce this source of error.

## 7.1 Possible sources of error

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## 7.2 Changes in the setup to reduce the error

# 8. Development Process

# 9. Attempts to improve results

## 9.1 Using a Neutral density filter

## 9.2 Using a polarising Beam Splitter

# 10. Possible reasons for obtaining poor quality holograms

## 10.1 Neutral density filter

## 10.2 Polarising Beam Splitter

# 11. Attempts at reconstructing the hologram digitally