Transmission Holograms

A Three-Dimensional Examination

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Though commonly perceived as three-dimensional photographs, holograms are in fact much more than enhanced pictures. In a hologram all information is retained so that when reconstructed it appears to be identical in shape, depth and texture to the original subject. Before a hologram is reconstructed into the three-dimensional objects we associate with the technique, the hologram merely appears as a high contrast pattern of interference. A useful analogy is to consider a hologram as information recorded into the plastic of a vinyl record. Just as no one can look at the series of notches and determine how a song will sound, no one can look at the interference patterns that make up a hologram and determine the object it represents. It is not until reconstruction that holograms take on pictorial qualities. Although after reconstruction holograms may appear to be almost magical, in fact it has been the specific technological advances in the field of optics that have allowed for the creation of these images; the practical applications of holography are just beginning to be conceived.

The first step leading to the discovery of holography was unearthing the property of light that allows it to act both as a wave and as a particle. In 1801, Thomas Young, a British physician, allowed rays of sunlight to pass through pinholes in a black screen and observed diffraction patterns on the opposing screen where one would expect to find two dots corresponding to the two holes. These patterns of interference and diffraction presented “the first clear proof that light added to light can produce darkness” (Gabor 1). If it were not for the experimental verification of this property, holography would never have been created. Each step of progress can ultimately be traced back to this first experiment by Young.

In 1947, nearly a century and a half later, Dennis Gabor was working to improve the process of electron microscopy at the Research Laboratory of the British Thomson-Houston Company in Rugby, England when he began experimenting with the idea of holography.

Electron microscopy uses electrons rather than photons to illuminate objects because their deBroglie wavelength is much shorter. Due to this shortened wavelength, the images from electron microscopes can be hundreds of times more magnified than those from normal microscopes (Zworykin 81).

Even with the advances he was making in this field, Gabor still was not satisfied. The restrictions of electron microscopes are due to the necessity of limiting the aperture lens to a width so small that the spherical aberration error is comparable to that of the diffraction error. In correlation with Heisenberg's uncertainty principle, in adjusting the aperture to correct the diffraction error, the spherical aberration error (or correction error) became so large that there was no way to clearly see the image. Figure 1 presents a diagram of an electron microscope. The process can be described as follows: the electrons pass through the series of electron lenses, electromagnetic coils, used to direct and focus the beam of electrons, and apertures to finally allow viewing on the screen (Zworykin 15). If one follows the path of the electrons, it can be seen that limiting the aperture width limits the span of electrons. In limiting the span of electrons, it becomes impossible to focus the image on the screen. Gabor could never make the image clear enough to complete the original goals of his experiment.

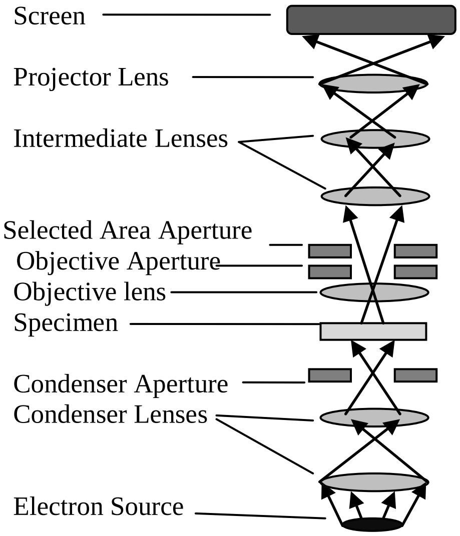


Figure 1: The process of electron microscopy. (Adapted from: http://www.indepthinfo.com/microscopes/electron.htm)

However, in attempting to perfect the images from his electron microscope, Gabor unknowingly overcame an obstacle that directly led to the development of holography. Gabor realized that by initially using electron science and focusing the image using classical optics the process of electron microscopy could be refined. He recorded the electron diffraction patterns rather than directly recording the image; later, he reconstructed the image using the diffraction pattern. When this same technique is applied to photons rather than electrons, a hologram is created. In conjunction with this insight, Gabor also discovered that while ordinary photographs only record the image of the standing wave maxima, electron photographs could store all the information about an object using its diffraction patterns and then revert back to an image through means of this mapping (Gabor 4). Figure 2 presents a hologram before and after it has been reconstructed. In fact the hologram presented is the first hologram ever to be created. Before it has been reconstructed, it appears to be merely an indiscernible pattern of black and white. This, in essence, is the basis of holography although there were many more hurdles to overcome before it became the refined process it is today.

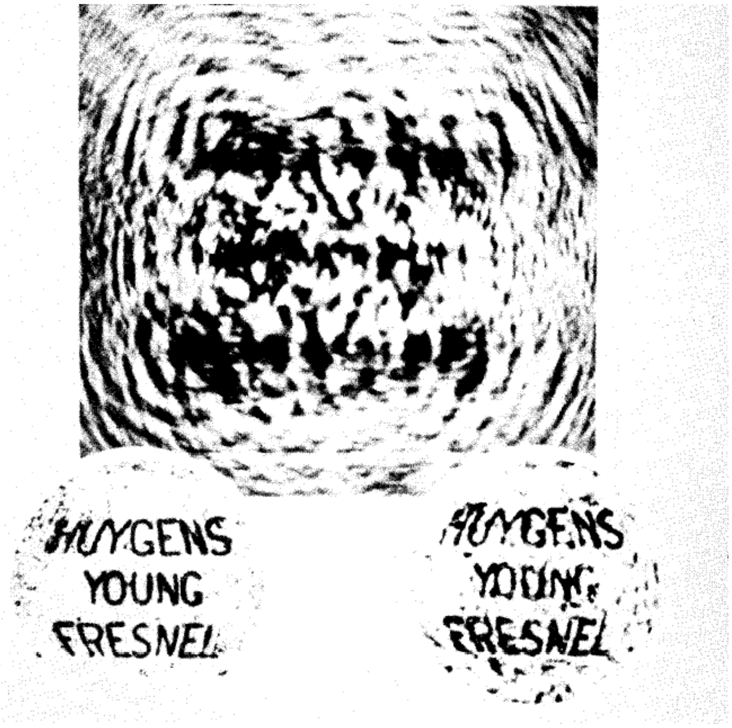
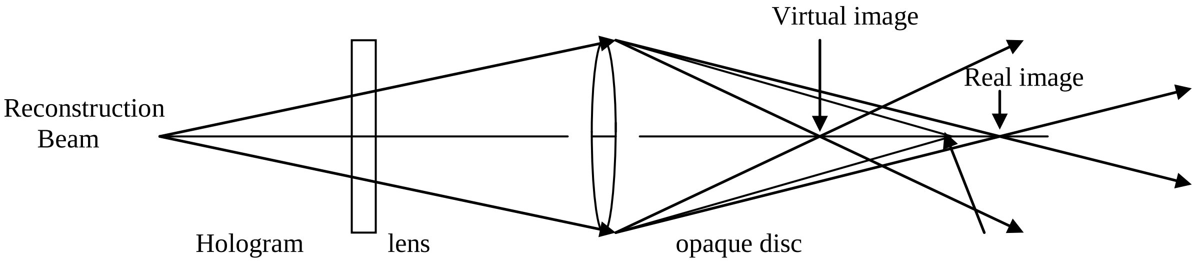


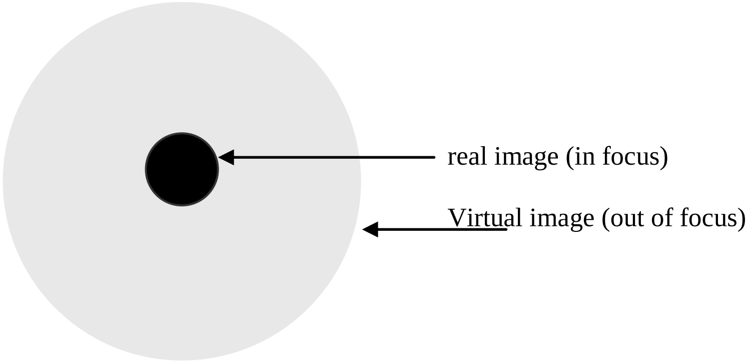
Figure 2: Gabor's first successful hologram (Gabor 3)

Today, there are two distinct techniques used to create holograms both using the same basic process. Coherent light is diffracted as it hits an object, and the diffraction creates an interference pattern. This pattern is recorded on a recording medium, either photo emulsion paper, special crystals or films. Later the image is illuminated with another beam of coherent light, known as a reconstructing beam, and the three-dimensional object appears. The first technique of transmission holograms we will discuss is the one Gabor developed sixty years ago, known as single beam holography. The other technique was not made possible until 1960 when Theodore Maiman at Hughes Research Laboratories presented the first laser. This technique has come to be known as split-beam holography and will be discussed in further detail later on in the text.

The basic concept behind single-beam holography is that an object creates a hole in the beam of light as it passes through the pattern of interference of the hologram. The focal length can easily be calculated using basic techniques of optics. If a small opaque disc is placed at exactly this focal point, then a real and a virtual image will appear. One will be in focus and the other blurred. As long as the blurred virtual image remains present, the real image can never be fully focused (Caulfield 25). This problem was the first technological hurdle to be overcome after the initial invention of holography (Gabor 5). The diagram below illustrates the process of reconstructing a hologram:



(a)



(b)

Figure 3: (a) A typical Gabor hologram reconstruction set-up and (b) the resulting image. (adapted from Caulfield 24)

As shown, the technique of single-beam holography results in the real and virtual images existing along the same axis. The undiffracted portion of the reconstructing beam blurred the image of the hologram and thus Gabor was never able to develop a method of creating a clear hologram. It was not a lack of understanding that caused this halt in progress but merely the fact that the necessary technology had not yet been developed. Once laser beams were invented the necessary tools were available to eliminate the problematic virtual image. Though today split-beam holography is virtually universally used in the professional setting, an understanding of single-beam holography remains crucial to an understanding of holography in general as it is the most practical starting place for amateur holographers. In fact single beam holography has some distinct advantages. The fact that the object and reference beams are superimposed allows for ease in path matching and thus holograms can be produced for objects at arbitrary distances (Caulfield 23).

Before delving into the science and mathematics of split-beam holography, we will examine the set-up needed to create a hologram as shown in figure 4.

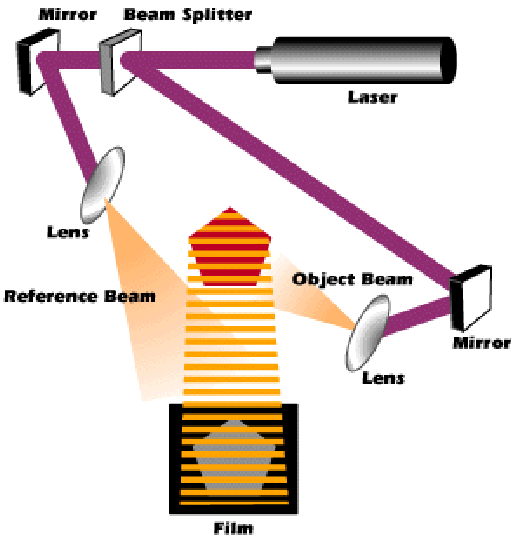


Figure 4: A diagram depicting the set up to create a hologram. (http://www.sgmt.at/ReferE/holomake.gif)

Initially, a laser beam is split into two separate beams, a reference beam and an object beam. Both individual beams are then directed by way of mirrors through individual lenses. The object beam reflects off the object to the recording media while the reference beam is reflected directly to the recording media. The object beam carries with it all the information of the original object. The object beam and the reference beam merge to create an interference pattern. It is this interference pattern that is recorded in the recording media and can be reconstructed to create a hologram.

The fundamental difference between split-beam holography and single-beam holography is that split-beam holography uses a device to split a highly concentrated beam of light before it reaches the object. As long as a recording medium is placed within this overlapped portion, a hologram will be recorded. In the reconstruction process of the hologram, the reconstruction beam is split into three separate beams: the secondary image, the undiffracted beam and the primary image, as shown in figure 5.

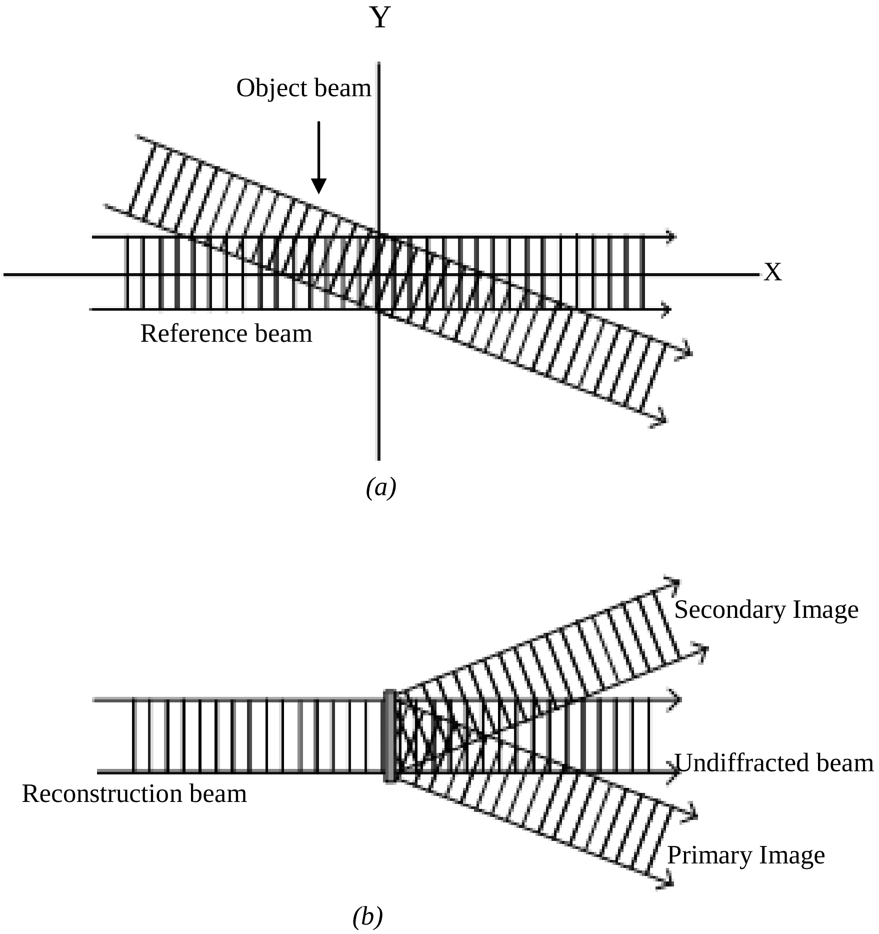


Figure 5: (a) is the construction of the hologram while (b) uses the hologram from (a) to reconstruct the object wave. (adapted from Caufield 18)

To understand a hologram is to understand the interference pattern made by the reference beam and the object beam. In the technique of split-beam holography it is easiest to consider first the object as a single point an infinite distance away. If this assumption is made, then the object wave can be considered to be a plane wave. If the reference wave is also a plane wave, then the interference pattern will be equivalent to that in Young's experiments over two centuries ago. His work can be considered to be a diffraction grating. In this way any hologram can be approximated as a diffraction grating where the diffractions will be sinusoidal in transmittance. When a hologram is lit up by way of a plane wave it is diffracted into a zeroth order wave and two first-order waves. When using the method of split-beam holography, each of the waves is separated, eliminating the problems of interference that originally were problematic to Gabor. As shown in figure 5, the two first-order waves are observed, and of these two the one traveling in the same direction as the original object wave is the one to be reconstructed (Smith 13).

Now we will consider a more complex object. Let us call *O* the monochromatic wave coming from the object, *H* the recording medium and *R* the wave coherent with *O*. Any object can be uniquely described by its amplitude and phase; *O* contains all of this information and thus can accurately reconstruct the image. The reference beam *R* aids in recording the amplitude and the phase of *O*. Therefore, the total field on *H* is *O+R*, while the recording medium responds to $|O+R|^2$.

It is assumed that the hologram has a unique amplitude transmittance t(x) that can be expressed as a function of exposure E(x) such that t(x)=f[E(x)]. In the Taylor series expansion of this function, the first two terms are the only ones that need to be considered. Thus, t(x) becomes $f(E_o)+\beta E(x)$. For the scope of this text it is sufficient to ignore the constant term $f(E_o)$ thus t(x) is simply given by:

$$t(x) = \beta \cdot E(x) = \beta \cdot |O+R|^2 = \beta \cdot (|O|^2 + |R|^2 + OR^* + O^*R)$$

where the * denotes complex conjugates. We will now assume that the hologram given by this amplitude transmittance is illuminated only by one reference wave, namely R. Therefore the transmitted field at the hologram is:

$$\Psi(x) = R(x) \cdot t(x) = \beta \cdot \left[R|O|^2 + R|R|^2 + |R|^2 O + R^2 O^* \right]$$

We will assume R to be a uniform wave so that $|R|^2$is a constant. Thus, the third term of $\Psi(x)$ is:

$$\beta |R|^2 O = const \times O$$

This term represents a wave with identical information to that of the original object wave (Smith 15).

Now that we have given a basic overview of the workings of holograms, let us consider the application of the hologram. The scope of possibility for the applications of transmission holograms is endless and much of the promise is yet to be discovered. Holograms have been used for such practical purposes as data storage, security purposes and medical imaging. In addition they are used on the notes of many currencies as a measure to dissuade counterfeiters; holograms are used is a vast array of product marketing and are commonly used for personal entertainment and decoration. Although these are all applications of transmission holograms, there are other methods of creating holograms, and each unique technique has its own possibilities of advancing science. However, with each application of holography a unique obstacle may need to overcome.

For the purpose of this text let us look more carefully at one of the more fascinating applications, namely pattern recognition. Holographic pattern recognition involves two patterns interacting with each other without any particular care to alignment and without the necessity of a lens. To set up such a phenomena, one works with two line drawings. The English alphabet, or any set of characters for that matter is merely a collection of line drawings. These two line drawings are placed in front of a recording medium as shown in figure 6:

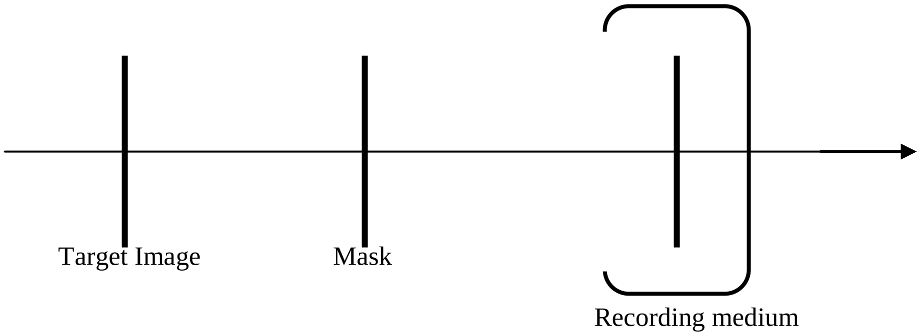


Figure 6: Basic set-up of character recognition. (Meyer-Arendt 329)

We will call the image on the left the target image and the image on the right the mask. The target image is generally an opaque line drawing on a transparency, while the mask is created using a series of pinholes. For each pinhole in the mask, a separate image is created. The interference pattern of the object waves from the target image moving through the pinholes will distort the original image to create a new image.

We will let M(x,y) be the transmittance function of the target image and I_o be the light intensity. Therefore the light passing through and around the target image is given by: $I(x,y)=I_0M(x,y)$. As we turn our attention to the mask, we see that that if N(x,y) represents the transmittance function of the mask, the light intensity after passing though both the target and the mask is given by: $I(x,y)=I_0M(x,y)N(x,y)$. However if a hologram is used in place of a mask, it can be easily used to determine which character is being examined. For example, if a hologram has been made to represent a specific line drawing or character then the resulting image can be focused to result in a single bright dot. Hence any other letter that is illuminated will merely result in a blurred circle. Therefore, if a body of text were to be illuminated, every instance where the particular letter occurred one would see a bright dot (Meyer-Arendt 330).

As with much new technology character recognition is not perfect yet. There are still some technological challenges to overcome. One such obstacle is that there are many letters that appear within others. For instance the letter F is contained within the letter E, and the word “lie” is contained by the word “believe,” not to mention all the different ways of writing different letters. Every handwriting style and every font constructs letters using a unique line drawing (Meyer-Arendt 331). Even with these obstacles, even computers using fuzzy logic – a computing system based on approximate reasoning rather than precise – do not have the potential to recognize or convert characters with such ease (Ranawana 1).

The field of holography has been developing for the past sixty years and continues to evolve. Little did Dennis Gabor know when he first began formulating holograms that the applications of holography would span far beyond the scope of electron microscopy. Although holography was used first as a focusing mechanism, it has additionally become a means of recording three-dimensional images of the subjects. While the full potential of holography can only be imagined, it is certain that people will continue to conceive of countless new uses for holograms. It is equally certain that scientists will continue to expand the technology needed to make future applications of holography reality.

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