1 Introduction

Holography has a long historical context, first introduced by Gabor.[1] In the introductory article, Gabor[1] introduced holography as a means of improving the resolution of electron microscopes via the recording of interference patterns between sample and reference fields. The phase of the sample field would be embedded within the interference pattern and could then be coaxed out from the recorded hologram in order to produce the whole information of the sample field—namely, the phase and intensity functions. Gabor termed this methodology “holography,” based on the Greek root word “holos,” which means “the whole.”

The details of Gabor holography will be given in greater depth in Section 2.1.1. In summary, although the method was proposed as a means of improving the resolution of electron microscopes, this holographic process was tested optically. Monochromatic light was focused in front of a transparent, partially occluded sample, such that the sample was illuminated by a divergent beam. The part of the beam that passed through the sample served as the sample field, while that which passed around the sample served as the reference field. The two components of the field then super-imposed downstream to create interference patterns that were recorded by a holographic film. A holographic image could then be recreated by sending a new reconstruction reference beam back through the film, where the encoded phase of the sample field would be imparted upon the reconstruction beam, and a holographic image would result.

Although the principle of holography had an early conception, it stagnated by 1955 or so. The lack of inertia was the result of “twin images” that were formed during the reconstruction process. Much as a lens can be used to create real and virtual images, holography also results in two images. From the observer’s perspective, one of the twin images forms downstream from the holographic film as a real image, where the light rays constructively converge. However, changing the perspective means that a second virtual image can be traced back behind the film to a point of apparent origination of the object. These two twin images lie along the same principal axis of the Gabor holographic system due to the inline configuration. As a result, even when resolving one of the images, its twin image will lie out of focus in the plane, causing distortion and a poorly resolved image.

Holography gained new life with the advent of the laser. Leith and Upatnieks[2] addressed the twin-image problem. A stronger, coherent source allowed them to split the incident beam into two paths—separate sample and reference arms, which could then be recombined at the holographic film for recording. However, the ability to separate the two beams meant that the reference beam could be imparted at an angle off-axis with respect to the sample field. This “skew reference wave” configuration resulted in the twin images being angled away from the principal axis of the holography system, therefore, being angularly separated as well as by the depth of their respective reconstruction planes. This way, when reimaging a single holographic image, the twin image would no longer overlap and or cause distortions, thereby improving the resolution of the reconstructed hologram.[2]

Holography saw other advances in the coming decades, including the use of pulsed lasers in order to eliminate motion artifacts within the hologram and holographic interferometry. A particular application of the latter was non-destructive testing of materials in an industrial setting.[3] The use of computers enabled computer-generated holography for the recording or reconstruction of holograms. A natural progression beyond computer-generated holography was the development of numerical reconstruction of holograms. Finally, with the widespread use of digital recording devices, such as CCD cameras, digital holography was born.[4–6] Of particular importance here is that in reconstructing their digital hologram, Schnars and Juptner[4,6] recognized the reconstructed field, which takes the form of a discrete Fourier transform. By that time, there was a well established understanding of the fast Fourier transform (FFT), which could be employed computationally in place of the discrete Fourier transform. The holographic reconstruction process was thereby simplified and could be carried out computationally in short order. Holographic films processed with chemicals were officially replaced with digital media (the CCD) and computer processing.

One limitation to holography—digital or otherwise—is that the object that is captured via the hologram has to either be small in size or far enough away from the holographic medium such that the entire object can be holographically recorded. Holography, and digital holography in particular, lends itself very well to microscopy—the realm of imaging minute objects. The Fresnel diffraction pattern from a minute object can be captured directly by a small, nearby CCD sensor for holographic reconstruction. Moreover, the introduction of optical elements within a holographic device can be used to increase the magnification of the sample, opening the door to biological, metalurgical, and industrial applications, etc. The use of holographic films in order to create 3-D images has evolved into the application of holographic principles in combination with optical systems, digital imaging devices, and computational reconstruction. Over the last decade or so, large advances have been made in such applications, and the body of work in digital holographic microscopy (DHM) continues to grow and advance.

The focus of this text is the design and holographic reconstruction via DHM. The following section will give a brief overview of DHM configurations, along with their respective advantages and disadvantages. We will then move on to a more in-depth look at the particular design and numerical reconstruction of two DHM configurations. The particular applications of DHM are numerous and growing, including 3-D object reconstruction and particle tracking, quantitative phase imaging (QPI), particle sizing, and the detection of object deformations and vibration. In a medical context, DHM can aid in understanding the physiological characteristics of diseases, such as cancer, at the cellular and intracellular levels, along with their detection, diagnosis, and therapeutic response.