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Advanced Imaging Methods Using Coded Aperture Digital Holography

Joseph Rosen

School of Electrical and Computer Engineering, Ben-Gurion University of the Negev, P.O. Box 653, Beer-Sheva 8410501, Israel; rosenj@bgu.ac.il

Abstract: Optical imaging has been well known in nature and technology for decades. Recently, new methods of optical imaging assisted by computational imaging techniques have been proposed and demonstrated. We describe several new methods of three-dimensional optical imaging, from Fresnel Incoherent Correlation Holography (FINCH) to interferenceless Coded Aperture Correlation Holography (COACH). FINCH and COACH are methods for recording digital holograms of a three-dimensional scene. However, COACH can be used for other incoherent and coherent optical applications. Possible applications for these imaging methods, ranging from a new generation of fluorescence microscopes to noninvasive imaging methods through a scattering medium, are mentioned.

Keywords: Digital holography; Incoherent holography; Imaging systems; Coded aperture.

1. Introduction

Coded aperture correlation holography (COACH), the main topic of this article, was proposed as a new technique of incoherent digital holography [1]. Hence, we begin this article with a brief history of imaging using holography [2], digital holography [3], and incoherent holography [4]. Since many holograms in the past and today have been recorded as the result of interference between two light waves, wave interference is the natural starting point. The phenomenon of optical two-wave interference has been well known since the first decade of the nineteenth century when Thomas Young published his famous double-slit experiment [5]. Young's experiment produces an interference pattern between two light waves, but this pattern is not considered a hologram because neither of the two interfering waves contains any image information.

The revolutionary transition from Young's interference pattern to a hologram occurred in 1948 in Dennis Gabor's pioneering work presenting for the first time what is known today as the Gabor hologram [6]. This and similar holograms are recorded by two-wave interference between a wave carrying the object information and another wave called a reference wave, which does not contain any object information. However, the reference wave in the Gabor hologram passes through the observed object before the interference pattern between the beams is recorded on the photographic plate [6]. This type of hologram in which light from the object is used as a reference beam (although it does not contain any image information of the object but only the image background) is called a self-reference hologram [7]. Another distinct feature of the Gabor hologram, in

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contrast to the Young experiment, is the zero angle between the two interfering beams. A holographic recording system in which there is no angle between the reference and image beams is called an on-axis system. The Gabor hologram is also classified as a spatially coherent hologram because the light source illuminating the object is a point-like source. Holography, in general, is classified into coherent and incoherent holography depending on the light nature used for object illumination. Wave interference can be easily achieved with coherent light beams, but many imaging tasks are widely applicable only under incoherent illumination. In general, imaging systems under incoherent illumination have a frequency response called the modulation transfer function, with a larger spatial bandwidth than coherent systems with the same aperture dimensions [5]. Hence, the incoherent image usually has a higher image resolution than the coherent image. From now on, unless something else is explicitly said, "incoherent light" throughout this article refers to quasimonochromatic spatially incoherent light.

The next historical milestone in holography is the off-axis hologram proposed by Leith and Upatnieks in 1962 [8]. The recording configuration of this hologram is characterized by a nonzero angle between the image and reference beams, and consequently, the twin-image problem of the Gabor hologram has been solved. The twin-image problem is the inability to extract the desired component representing the required image out of four components recorded on the raw hologram [9]. Because the twin-image problem is no longer a problem, the image of the observed object can be reconstructed from the off-axis hologram by illuminating it with a reference beam, and this image can be viewed clearly without interruptions by other light waves. The off-axis hologram is not a self-reference one, and by that aspect, it also differs from the Gabor hologram. In the aspect of spatial coherence of the illumination, the off-axis hologram is similar to Gabor's – they are both considered spatially coherent holograms. The transition from the Gabor hologram to the off-axis hologram was easier with the invention of the laser with its relatively high temporal coherence since the optical path difference between the object and reference beams is not restricted as it is in the Gabor hologram.

Incoherent holograms have appeared since the mid-sixties [10,11], and all of them were based on different implementations of the self-interference principle [12]. The self-interference principle means that the light from each object point splits into two waves modulated differently before creating an interference pattern on the recording plane. According to this definition, a self-interference hologram is also a self-reference hologram because both interfering beams come from the same object. However, unlike self-interference, in a self-reference hologram, the reference beam does not contain image information. Under the self-interference principle, Bryngdahl and Lohmann suggested sorting interferometers for recording incoherent holograms into two types [13]. The first is radial shear, in which the observed image is replicated into two replications with two different scales. The other type is rotational shear, in which the observed image is also replicated into two versions, but in this case, one replication is rotated by some angle relative to the other replication. The entire holograms recorded using the self-interference principle are the stage in the evolutionary chain of holography in which both interfering waves carry the object's image. This new stage has practical meaning; under certain conditions, the self-interference principle leads to the violation of the Lagrange invariant [5], leading to better image resolution.

The next significant event in hologram history occurred in 1967 with the invention of the digital hologram by Goodman and Lawrence [14]. Digital holography is an indirect imaging technique where holograms are first acquired using a digital camera, and then the image is reconstructed digitally by a computational algorithm [1,3]. Thus, digital holography is a two-step process that has some advantages over regular digital imaging. For example, a hologram can contain depth information of three-dimensional (3D) objects utilizing phase information encoded in the interference patterns between an object and the reference beams [1,3]. Other useful information recorded on a hologram might be the wavefront shape of the wave passing through the object, enabling quantitative phase imaging (QPI) [15]. The first digital hologram was coherent and recorded on a digital camera by an off-axis setup [14]. Another notable difference between this new digital hologram and those mentioned above is the transformation between the complex amplitudes on the object and the hologram planes. The two-dimensional (2D) Fourier transform was the transformation from the object to the hologram planes in the case of the Goodman-Lawrence hologram, thus indicating the type of hologram as a Fourier hologram. An optical (nondigital) Fourier hologram was proposed a few years before by Vander Lugt [16]. In 1997, Yamaguchi and Zhang recorded on-axis digital holograms in which the twin-image problem was solved by recording four different holograms of the coherently illuminated object and processing them in the computer in a procedure called phase shifting [17]. The transformation between the object and camera planes in the Yamaguchi-Zhang system follows Fresnel free-space propagation, and hence, this digital hologram is considered a Fresnel hologram [6,8,18].

In the field of incoherent digital holography, technology evolved to unexpected solutions. The minimal number of camera shots, one in the Goodman-Lawrence hologram [14] and four in the Yamaguchi-Zhang technique [17], was replaced by scanning techniques that do not make use of the self-interference principle. Under scanning techniques, there are two main methods of recording incoherent digital holograms of a general 3D scene. The more well-known method has been optical scanning holography [19,20], in which the 3D object is scanned by an interference pattern between two spherical waves, and the reflected light is summed into a point detector. In optical scanning holography, the wave interference is between two spherical waves, neither of which carries any image. Moreover, the interference pattern is not recorded but is used as a detector of the object points' depth. The other scanning technique was implemented without wave interference and has been a more computer-aided method in which the hologram is generated from multiple view projections of the 3D scene [21,22]. Both methods are based on different processes of time-consuming scanning of the observed scene to yield a 2D correlation between an object and a 2D quadratic phase function.

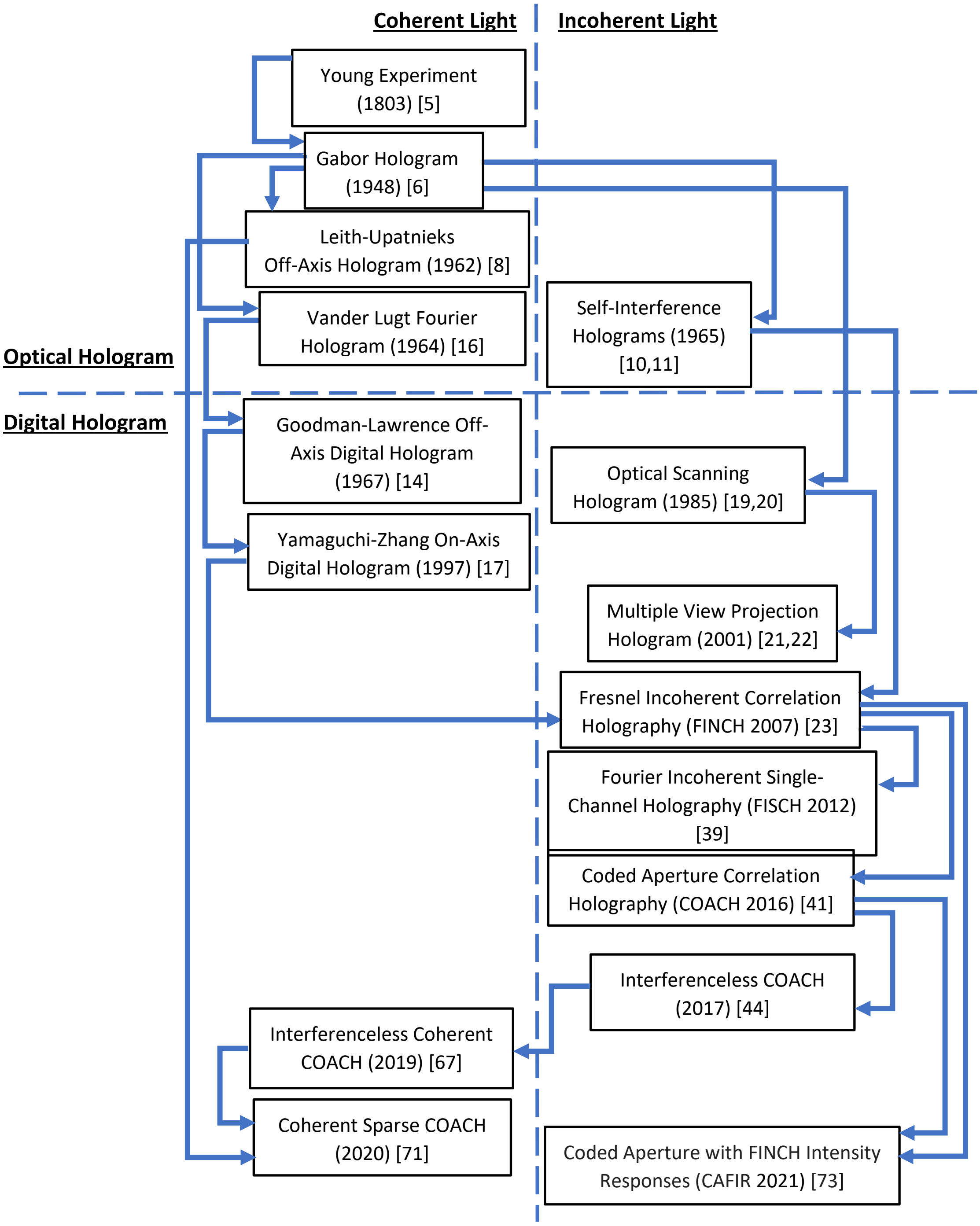

Figure 1. Scheme of holography history as described in the text. The blue arrows indicate the flow and influence of the various ideas.

The next landmark is that the required 2D correlation in Refs. [19-22] can be performed without scanning. Fresnel incoherent correlation holography (FINCH), published in 2007 [23], was a return to the principle of self-interference and was proposed as an alternative to the scanning-based holography methods mentioned above. Following the first FINCH, many other incoherent digital holograms have been proposed, and most of them are based on the self-interference principle [24-38]. Fourier incoherent single-channel holography (FISCH) [39] is a typical example of using the self-interference principle, but the obtained hologram, in this case, is a 2D cosine Fourier transform of the object. As mentioned above, in the entire holograms recorded using the self-interference principle, both interfering waves carry the object's image. However, the image information is never the same in both interferometer channels. In FINCH, the images are in-focus at different distances from the aperture, while an infinite distance is also legitimate. In FISCH, one image is rotated by 180° around the origin of the image plane relative to the other image. In terms of the Bryngdahl-Lohmann analysis, FINCH is radial shear, and FISCH is rotational shear. An exceptional example of an incoherent digital hologram based on the self-reference rather than the self-interference principle was proposed by Pedrini *et al.* [40], but the energetic inefficiency of this hologram recorder has probably prevented further developments in this direction.

2. **Coded aperture correlation holography (COACH)**

COACH [41-43] is a new evolutionary stage in which one of the two replicated objects' images passes through a coded scattering mask, resulting in the camera plane being a convolution of the image with some chaotic function. The other image is in focus at an infinite distance from the aperture. According to the classifications mentioned above, COACH is radial shear and belongs to incoherent self-interference on-axis digital holography. A significant difference between COACH and Fresnel holograms is in the image reconstruction process. In the Fresnel case, the image at a distance of z is reconstructed by a correlation between the hologram and a quadratic phase function parameterized with z. On the other hand, in COACH, the 3D image is reconstructed by a correlation between the hologram and a library of point responses acquired in the system calibration. From the COACH stage, the technology surprisingly evolved to a system without two-wave interference following the discovery that 3D holographic imaging could be achieved with a single beam configuration. The interferenceless COACH (I-COACH) [44] has been found to be simpler and more efficient than the COACH with two-wave interference. I-COACH is considered a digital hologram because the digital matrix obtained from the observed scene contains the scene's 3D information, and the 3D image is reconstructed from the digital matrix in a similar way as done with interference-based digital holograms. Although there is no two-wave interference in I-COACH, it is classified as on-axis digital holography because the recording setup contains components that are all arranged along a single longitudinal axis. Using the interferenceless version of COACH has enabled adapting concepts from coded aperture imaging by X-ray [45], in which the observed image is replicated over a finite number of randomly distributed points. In other words, the point response of the system has been modified from the continuous chaotic light distribution [41-44] to a chaotic ensemble of light dots [46]. Moreover, by integrating concepts from optical pattern recognition [47,48], the process of correlation-based image reconstruction has been modified to what is known as nonlinear image reconstruction [49]. Because of the two modifications, the modified impulse response and the change in the reconstruction process, I-COACH's signal-to-noise ratio (SNR) has been improved significantly [50]. Other imaging properties, in addition to SNR, have also been treated in the framework of COACH research. The image resolutions of I-COACH have been improved by several different techniques [50-52]. Field-of-view (FOV) extension in I-COACH systems has been addressed in [53] by a special calibration procedure. Ideas adapted from axial beam shaping have enabled engineering the depth-of-field (DOF) of an I-COACH system [54]. Sectioning the imaging space, or in other words, removing the out-of-focus background from the resulting picture, was demonstrated by point spread functions of tilted pseudo-nondiffracting beams in I-COACH [55]. Color imaging using various I-COACH systems has been treaded in I-COACH [56] and in a setup with a quasirandom lens [57].

COACH can implement several applications in addition to the initial and widely used application of 3D holographic imaging. For example, noninvasive imaging through scattering layers can be more efficient if the light emitted from the scattering layer is modulated by a phase aperture, as demonstrated in [58]. Another application is imaging by telescopes with an annular aperture, which is a way to reduce the weight of space-based telescopes [59]. The images produced by such telescopes might be clearer and sharper using COACH [60]. Imaging with a synthetic aperture system is another example that enables better image resolution without changing the physical size of the optical aperture [61]. COACH can image targets with an incoherent synthetic aperture with the advantage that the relatively small apertures move only along the perimeter of the relatively large synthetic aperture [62]. Although interferenceless imaging systems are simpler and more power efficient than systems with wave interference, the latter systems still have an important role in the technology, and the annular synthetic aperture [62,63] is an example of using two-wave interference between beams reflected from a pair of sub-apertures located along the aperture perimeter. More details about these advances and others of COACH and I-COACH can be found in two review articles [64-66]. The scheme of Figure 1 summarizes the holography history as described above, where the blue arrows indicate the flow and influence of the various ideas. The next natural step was to explore the new COACH concept in the area of coherent holography. In addition to 3D imaging, QPI is another main application for coherent holography. 3D imaging under coherent light using I-COACH was demonstrated in [67] but without phase imaging capability. QPI could not be performed by I-COACH, but various ways to implement QPI using phase apertures with [68] and without [69] two-wave interference and with [70] and without [71] using self-reference holography were found. Specifically, COACH's concepts have been integrated into a Mach–Zehnder interferometer [71] with the benefit of a broader FOV than a conventional QPI interferometer. A closely related technique of QPI is wavefront sensing, where a COACH-based Shack–Hartmann wavefront sensor was proposed recently [72] with the advantage of higher accuracy over the conventional Shack–Hartmann wavefront sensor.

2. Summary

The main benefit of sparse COACH is the ability to control the SNR and the visibility of the reconstructed image through the sparsity and complexity of the PSHs. However, in Ref. [73], we employ the sparse response of COACH to merge the imaging merits of FINCH and COACH into a single holographic system. In the apparatus of [73], the combination is done by granting the sparse COACH a response of a FINCH-type self-interference mechanism so that neither of the resolution types is compromised. In other words, the recently proposed imaging method integrates advantages from both FINCH and COACH techniques, such that this hybrid system has the improved lateral resolution of FINCH with the same axial resolution of COACH.

The development of holography has not ended, and from time to time, a new improvement is being published, so this article is only an interim summary of the field. However, the rapid development of COACH and other methods of phase aperture digital holography in incoherent and coherent optics might make this review a useful source for the holography community.

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