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Compressive holographic imaging based on single in-line hologram and superconducting nanowire single-photon detector

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ABSTRACT

A novel compressive holographic 3D imaging method based on single in-line hologram and superconducting nanowire single-photon detector (SNSPD) is proposed. It utilizes the Mach–Zehnder interferometer to form just one-only in-line 3D hologram on CCD plane, and then apply compressive sensing (CS) approach to perform the 3D hologram acquisition process with a digital micro-mirror device array (DMD) placed in the CCD plane and a SNSPD. Once the 3D object measurements sensed by a SNSPD is got via compressive sampling with DMD in the pure optical domain, original 3D object can be reconstructed numerically via certain signal recovery algorithms of CS and digital holography. Computer simulations demonstrated the feasibility and the efficiency of the method. This method is supposed to break through the limitation of array imaging based on the superconductor diode and large measurements in compressive holographic imaging based on the multi-step phase-shifting digital holography.

1. Introduction

Compared with traditional optical holography, digital holography provides an easy and highly sensitive way to record the holograms using a CCD or CMOS detector and numerically reconstruct the object on a computer [1]. It is used in many areas including digital holographic microscopy [2], 3D imaging [3], biofluid [4] and so on. But over the past several years, the huge storage and bandwidth requirements for storing or transmitting the holographic data has been a main limiting factor for application of digital hologram technology [5–8]. Fortunately, the newly developed theory known as compressive sensing (CS) [9–11] provides a new direction on imaging system designs. Based on compressive sensing, many new applications have already sprung up in the realm of holography. The group of the Duke Imaging and Spectroscopy Program (DISP) first formulated hologram data compression as a compressive sensing problem [12]. Then we may mention in-line compressive holography [13–16], off-axis compressive holography [17–18], compressive incoherent holography [19–20], compressive Fresnel holography [21–22]. Our team has demonstrated the feasibility of the compressive phase-shifting holography of four-step and two-step based on compressive sensing [23–25]. A proof-of-concept experiment evaluating the phase distribution of an ophthalmic lens with the three-step compressive phase-shifting holography is also provided [26]. In optical domain, few applications of this single-pixel imaging setup in digital holography extending to coherent regime have been reported though many successful applications of compressive sensing for holography have been demonstrated [13–22].

On the other hand, acquiring large amounts of image data can be expensive at wavelengths where traditional CMOS or CCD sensing technology is limited. Based on compressive sensing, it is ability to obtain an image with a single detection element with lower storage requirement of image data and cost of holographic imaging devices [27–28]. Due to the unique measurement approach, we can adapt not only low-cost photoelectric detector but also high-quality photoelectric detector according to the system requirement. The SNSPD is a new type of single-photon detector, based on non-equilibrium hot electro effect in superconducting super thin films, providing with the advantages of low dark count and high detection rate. Nowadays, the SNSPD is currently a research focus because of many potential applications in high resolution imaging such as biological imaging [29–31]. However,

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because of the limitation of the fabrication and performance for superconducting single-photon detector, it exists some difficulties for array imaging. Fortunately, combined with compressive sensing, we can provide a new angle to tackle this challenge.

We develop a new 3D compressive holographic imaging scheme combining the CS-based single-pixel-camera with single in-line hologram in fully optical domain. In our method, we use the Mach-Zehnder interferometer to generate one-only in-line hologram of 3D object, and then on the base of CS theory, address the acquisition step by measuring the inner products between the hologram and the pseudo-random binary patterns generated by a DMD plane. With this method, we can directly acquire the compressed hologram of the 3D object to perform compressive sampling in analog domain with a superconducting diode. Then the acquired data is processed to produce a reconstruction of the 3D object using reconstruction algorithms of CS and digital holography. Because just one-only in-line hologram is recorded to reconstruct the original object, so this method can greatly reduce the number of measurements and the reconstruction errors, simultaneously, improve the data compression rate in the compressive holographic imaging system, compared with the proposed compressive holographic imaging based on the multi-step phase-shifting digital holography [23–26]. We can apply compressive holographic imaging to biochip for improving the noise suppression ability of the system and the sensitivity of signal detection. Moreover, through applying SNSPD to our method, we can breakthrough the limitation of array imaging which is based on the superconductor diode and we wish to realize highly sensitive 3D biomedical imaging in the future.

2. Methods

Our compressive holographic imaging system with a single-pixel detector is shown in Fig. 1. A linearly polarized laser beam is attenuated by several neutral density filters into the single photon level. The laser beam is then expanded, collimated, and divided into an object beam and a reference beam. Then the two waves overlap to form a 3D interferogram on DMD plane. The compressive sampling is obtained by computing random linear measurements of the interferogram I_H and the measurement matrix Φ in DMD plane and then collected by a highly sensitive superconducting photon counting system. This system simulates a 3D object imaging under ultra-weak illumination condition. Finally we can acquire the compressed hologram image by a traditional communication channel and then reconstruct it via the specific algorithm.

2.1. Compressive 3D holographic image acquisition

Suppose the 3D object in Fig. 1 setup is expressed as $O(x, y, z)$, where x, y and z indicate the lateral position, the axial position. The Fresnel diffraction field u_H of the 3D object on DMD plane is written as follows:

$$u_H(x_H, y_H) = \iiint o(x, y, z) h(x_H - x, y_H - y, z_H - z) dx\, dy\, dz, \tag{1}$$

where x_H and y_H are the lateral position on the DMD plane, and h is the point spread function (PSF) for the Fresnel diffraction. The depth map corresponding to z is acquired by the depth-variant PSF [32–34].

The observation process in Eq. (1) can be rewritten with linear algebra as follows:

$$u_H = Ho, \tag{2}$$

where the number of elements of the object data along the x axis is defined as N_x and y axis is defined as N_y which are assumed to be the same as that of the captured data for simplicity and N_z is the number of the elements of the z axis, respectively. $u_H \in C^{(N_x \times N_y)\times 1}$ is the vector captured data, $o \in C^{(N_x \times N_y \times N_z)\times 1}$ is the vector object data and $H \in C^{(N_x \times N_y)\times(N_x \times N_y \times N_z)}$ is a matrix indicating the Fresnel kernel. $C^{(a\times b)}$ shows an $a \times b$ matrix with complex numbers. Where H in Eq. (2) is written as follows:

$$H = \begin{bmatrix} H' & 0 & \cdots & 0 \\ 0 & H' & \cdots & 0 \\ \vdots & \vdots & \ddots & 0 \\ 0 & \cdots & 0 & H' \end{bmatrix}, \tag{3}$$

$$H' = \left[H'_1 \;\; H'_2 \;\; \cdots \;\; H'_{N_Z}, \right] \tag{4}$$

where $H'_z \in C^{N_x \times N_y}$ is a Toeplitz matrix indicating the Fresnel diffraction kernel for the Zth depth.

We utilize the Mach–Zehnder interferometer for the recording of just one-only in-line Fresnel hologram, and then the resulted I_H is projected on the DMD plane and expressed as

$$I_H(x_H y_H) = |u_r + u_H|^2 = |u_r|^2 + |u_H|^2 + u_r^* u_H + u_r u_H^*, \tag{5}$$

where u_r and u_H are the reference wave field and the object wave field on the DMD plane; the superscript "*" denotes a complex conjugate. In Fresnel holography, the term $|u_r|^2$ is simply a constant; hence the effect of $|u_r|^2$ can be removed by eliminating the constant term at the origin in the Fourier transform of the interference irradiance measurements $I_H(x_H y_H)$. The squared-field term $|u_H|^2$ can be regarded as the error e of digital hologram processing model. So we can proceed with

$$\begin{aligned} I_H(x_H y_H) &= |u_H|^2 + u_r^* u_H + u_r u_H^* \\ &= 2Re(u_H) + |u_H|^2 \\ &= 2Re(u_H) + e. \end{aligned} \tag{6}$$

When we ignore the error e of the system model, according to Eq. (2), we can get

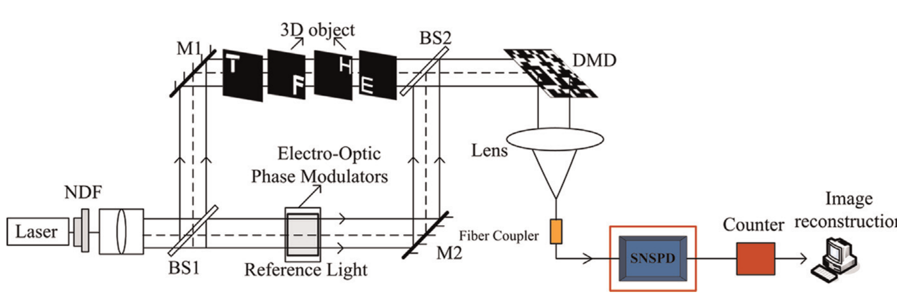

Fig. 1. Compressive holographic imaging based on single in-line hologram and SNSPD. NDF, neutral density filter; BS1 and BS2, beam expander; M1 and M2, mirror.