Supplementary Material: Phase shifting digital holography with random phase steps: A novel robust algorithm

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Supplementary Material

In this supplementary information we provide the reader with some extra detail about the numerical simulations and experimental systems that were presented in this publication.

Numerical simulations

We begin with the numerical simulations. To generate our object wavefield we have chosen the following function:

$$o(x,y) = \exp\left[-(x^2+y^2\right]\exp\left(-j2\pi 1000y\right)\exp\left(j\pi 10^6 y^2\right) \tag{1}$$

and

$$r = \exp\left[-\frac{j4\pi}{\lambda}a\sin(2\pi\gamma t)\right] \tag{2}$$

We note that we assume there is no spatial variation in the reference field. This has been discussed further in the manuscript. We have chosen the following parameters for the simulation: We record the intensity at a set of different spatial locations separated by a pixel size of 3.45 microns. Note that we ignore the effect of spatial averaging that occurs over the finite extent of a pixel, and rather express the intensity at exactly that spatial location. We have chosen the following values: $\lambda = 520$ nm, NX = 20, Ny = 1440.

We generate a set of holograms using these parameters in the following manner:

$$H(x,y) \quad = \quad |O(x,y)+R|^2 + noise \tag{3}$$

where noise is a uniformly distributed random number ranging from [-Max[H]/10 to Max[H]/10]. This matrix was then converted into integer matrix and saved on the computer. A series of these holograms were generated and used as a test input for analyzing the proposed algorithm.

We will now provide some extra detail pertaining to Fig. 4(f). To generate the standard deviation results here – we used 25 frames to estimate the I_{AC} and I_{DC} parameters. We then attempt to recover $\alpha^R(x)$ using 5, 15, 25, and then 35 frames. For each recovered $\alpha^R(x)$ we compare the result to the actual phase distribution, $\arctan[o(x,y)]$ and calculate the standard deviation.

First experimental example

In the first experimental result we present a series of holograms captured when two coherent beams are overlapped and the resulting intensity is captured on a CMOS detector. We use a 520 nm Cobolt 06-MLD laser with a 1 nm bandwidth and a coherence length of approximately 280 microns. The CMOS array used to capture the hologram intensity is an IDS board level camera model number: U3-3042SE-M, with 1456 x 1088 pixels of pixel pitch 3.45 microns. We capture 12 bit frames at a frame rate of 9 FPS, and with a minimal exposure time of approximately 30 microseconds.

Below we present an image of the setup taken from our lab where the different optical components are labeled. We use a single mode fiber at the input to the system which is then collimated using a doublet lens (30 mm) available from Thorlabs. After collimation the beam is passed through a half wave plate. Then a polarizing beam splitter is used to divide the beam into an object and reference path. By rotating the half wave plate we can control the power levels in the object and reference arms. In the reference arm, the beam is incident upon a mirror which is mounted on a piezo actuated motion stage, acquired from Piezo system Jena GmbH PZ-38 and the actuator is driven by a Piezo system Jena amplifier 12V40 series. The piezo motion stage is driven by either a linear ramp waveform or by a sinusoidal waveform.

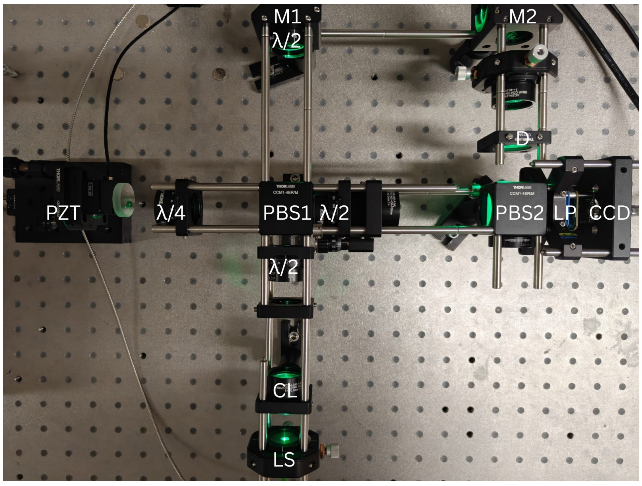

Figure 1: Schematic depicting a holographic system used in experiment 1.

The frequency is set at 1 Hz, and the the peak to peak voltage is set at 182 mV resulting in a full stroke motion of approximately 1 micron. This will cause an estimated maximum phase shift in reflection of 4 π.
The reference beam which is initially reflected by the polarizing beam splitter passes through a quarter wave plate twice and hence on its second pass through the same polarizing beam splitter is now transmitted. A second polarizing beam splitter combines the reference and object fields again before they pass through another linear polarizer and are detected by the CMOS array. The object arm was adjusted to produce a set of spatial frequency fringes in the recorded hologram.

Second experimental example

In this second experimental result we demonstrate imaging of some biological cell samples. Again we use a 520 nm Cobolt 06-MLD laser with a 1 nm bandwidth and a coherence length of approximately 280 microns. The CMOS array used to capture the hologram intensity is an IDS CMOS array: U3-31R0CP-MGL with 5326 x 4608 pixels of pitch 2.74 micron. We capture 12 bit frames at a frame rate of 6 FPS, and with a minimal exposure time, rated at 60 microseconds. A single mode fiber delivers the laser light into a 50/50 beam splitting fiber to form a reference and object beam – the optical system is designed to be symmetric with both reference and object arms having the same optical elements. We use two Zeiss objectives [Epiplan] 40x NA 0.6 and 165 mm Zeiss tube lens acquired from Thorlabs. A pellicle beam splitter, placed before the tube lens, combines the reference and object arms and directs the light through the tube lens and onto the CMOS array.

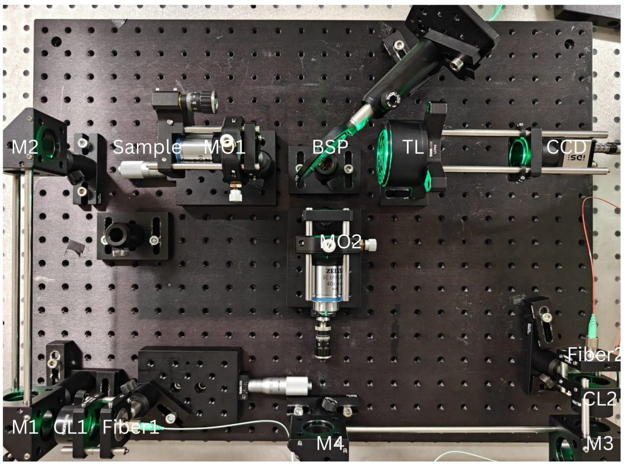

Figure 2: Schematic depicting the second digital holographic microscope imaging system.