Three-Dimensional Single-shot Ptychography

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Abstract: We introduce three-dimensional single-shot ptychography (3DSSP). 3DSSP implements a novel algorithm to reconstruct multiple 2D planes of a 3D object. We analyze the technique’s performance via numerical simulations, and we demonstrate it experimentally. © 2020 The Author(s)

1. Introduction

Studies of dynamic anisotropic processes like the evolution of plasmas, filamentation, material modifications, turbulent and laminar flows are critically limited by the lack of advanced imaging techniques. Here we introduce three-dimensional single-shot ptychography (3DSSP), a novel technique for time resolved simultaneous phase and amplitude contrast 3D imaging. This breakthrough technique will dramatically improve the amount and relevance of information extracted from experimental studies of dynamic, anisotropic phenomena. Ptychography is an exciting computational microscopy technique that uses a sophisticated algorithm to process a collection of far-field intensity measurements simultaneously returning both the phase and amplitude of the probing illumination (probe) and specimen (object). In conventional ptychography the object is scanned transverse to the probe and diffraction patterns from overlapping regions of illumination are collected. Transverse scanning an oversampled probe beam limits the minimum collection time but increases the technique’s robustness and removes the need for a-priori knowledge of the specimen [1]. Recently developed single-shot ptychography removes the need for scanning by introducing a novel experimental apparatus that provides the same set of diffraction patterns from overlapping illumination on the object in a single shot [2]. This dramatically reduces the acquisition time for ptychographic dataset and heralds the possibility of time-resolved, simultaneous phase and amplitude contrast imaging, as recently demonstrated experimentally [3]. 3DSSP uses the same experimental system as single-shot ptychography, shown in Figure 1, but implements a novel algorithm to reconstruct multiple 2D planes (slices) of a 3D object. The new algorithm leverages an additional powerful constraint that naturally emerges from the single-shot geometry to deconvolve the diffraction patterns from multiple axially separated slices. Numerical simulations show that 3DSSP can reconstruct multiple slices of an extended 3D object where similar imaging techniques would fail. We experimentally demonstrate 3DSSP by reconstructing orthogonally oriented strands of

2.3DSSP Experimental setup and algorithm

![Diagram of 3DSSP experiment](image)

*Figure 1* Schematic representation of the 3DSSP experiment and results from an exemplary simulation. The experimental system is shown above. The recorded diffraction patterns are fed into the 3DSSP algorithm and multiple 2D planes (3 in the example above) are reconstructed. The reconstructed planes match up well with the simulated continuous 3D object. Interestingly, the broken loop object simulated here is not recoverable by standard 2D projection-based imaging techniques.

In a time resolved 3DSSP experiment an incoming ultra-short plane-wave laser pulse is broken up into a number of beamlets by a diffractive optical element (DOE) like an array of pinholes. These beamlets are collimated and then cross at the Fourier plane of the 4F imaging system (crossover point). A 3D object is placed some distance from the crossover point and diffraction patterns from each beamlet are recorded individually by applying a centroidal Voronoi tessellation to break up the detector. In addition to dramatically reducing the acquisition time for a ptychographic
dataset, the geometry of the system allows for 3D imaging in a single shot. One critical piece of information for a psychograpic reconstruction is the position of the probe relative to the object for each recorded diffraction pattern. In the 3DSSP system the position of each beamlet on the object changes as a function of the distance from the crossover point. These beamlet shifts preclude application of conventional multi-slice psychograpic algorithms like 3PIE [4], but our new 3DSSP leverages the known beamlet shifts to deconvolve diffraction patterns from axially separated 2D slices of a 3D object. Algorithmically, this is achieved by defining a new inter-slice propagator that propagates and shifts each beamlet between slices. Interestingly, our newly developed 3DSSP algorithm executes successful reconstruction even without optimizing its performance. This suggests that we can further improve the technique through algorithmic optimization [5].

3. Results

We investigated the performance of the new 3DSSP system with numerical simulations and demonstrated the technique experimentally. Our proof of concept simulation is shown in the foreground of Figure 1. We simulated the diffraction patterns from the continuous 3D broken-loop structure, then we fed the diffraction patterns into the 3DSSP algorithm and successfully reconstructed 3 slices of the object as shown. In other numerical simulations not shown here we successfully reconstructed multiple slices of significantly more detailed 3D objects like an image of a human brain from MRI scans. Additionally, we examined the axial resolution of the system theoretically and with simulations and found that the achievable axial resolution for 3DSSP is consistent with the depth of field of a conventional microscope. We demonstrated 3DSSP experimentally by reconstructing the phase and amplitude of two orthogonally oriented strands of hair axially separated by 5mm using the system shown in Figure 2. The results of the reconstruction are shown on the right side of the figure, as expected the algorithm successfully deconvolves the two slices such that each hair only shows up in the correct slice. This preliminary experiment only scratches the surface of the potential applications of 3DSSP which will be a highly beneficial tool for studying anisotropic dynamic phenomena. As demonstrated here, the system is currently capable of simultaneous amplitude and phase imaging of multiple slices of a 3D object. To enable time resolved imaging we can replace the CW 532nm illumination in the current system with a pulse of light from a mode locked Ti:sapphire laser.

![3D SSP Experimental Results](image)

**Figure 2 left** Schematic of the experimental setup used to demonstrate 3DSSP. The system uses a femat spiral array of 40 pinholes illuminated by CW 532nm laser and 5cm focal length lenses. The grey lines represent orthogonally oriented strands of hair axially separated by 5mm. The first hair was placed 5mm from the crossover point. **Right** The results from the 3DSSP experiment, the reconstructed amplitude and phase of the vertically oriented hair in slice one are shown in a) and b) respectively, while the amplitude and phase of the horizontal hair in slice two are shown in c) and d) respectively. The algorithm successfully deconvolves the two slices such that the first slice only shows a verticle hair, while the second slice only shows the horizontal hair.

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