Advances in digital holography for real-time imaging in fluid environments

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Digital holography is a robust and powerful tool for observing three-dimensional flows or objects in fluid environments. Challenges in processing data efficiently or understanding fundamental limits as applied to fluidic environments have limited its use. We present a straight-forward in-line digital holographic imaging system which has a high resolution, a low cost, and a compact size. Fast processing is done by using combining a graphics processing unit (GPU) with advanced algorithms. Advances in characterizing the fundamental optics and improving algorithms lead to improved performance and new applications.

1. Fundamental Characterization

New approaches to characterizing fundamental limits are presented and verified for in-line holography. The first approach models diffraction image formation by collections of point particles, such as the tracers used for digital holographic PIV, from an information theory viewpoint.

The intensity, I, at a detector plane can be written as \( I = H\bar{a} + \bar{w} \), where \( H \) is the system Hopkins matrix and describes the transfer of information from the imaged volume to the detector, \( \bar{a} \) is a random binary vector denoting which voxels contain tracer particles, and \( \bar{w} \) is the cross-talk noise. A stability metric, \( \delta \), calculated from the eigenvectors of \( H \) and the variance of \( \bar{w} \), predicts the maximal information content as a function of parameters. A peak in \( \delta \) as a function of particle density is shown for simulations. Experiments with micro-beads support the optimal density predictions.

A second characterization approach uses space-frequency analyses in the Wigner domain to simplify estimates of resolution and field of view for both planar and spherical reference waves. Relations for the imaged object and the detector to achieve un-aliased recording without losing information are presented using these methods. The volume observable with digital holography under these conditions is shown to be a function of the number of detector pixels only.

2. Algorithms and Applications

To handle large data sets and respond to an interest for real-time results, parallel processing is done on GPUs. Reconstructions for 1024x1024 pixel regions are computed significantly faster than video rates, making the inversion process interactive and results available in milliseconds to seconds. This opens up application areas in monitoring or controls; an interactive display has already been created for the MIT Museum showcasing real-time holography.

Examples of how the processing and algorithms are used in realistic settings are presented. Samples from an in situ imager for ocean microbiology studies are shown, where the use of a high resolution and large field of view imaging system is critical. In the second example, the bubble and droplet size algorithm is used to image oil droplets suspended in water. A series of holograms is able to track the changes in the droplet statistics over time as the droplets coalesce and settle.