All-in-Focus Image Reconstruction from In-Line Holograms of Snowflakes

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Abstract—In-line holography enables particle measurements in large imaging volumes with an extended depth of field compared with conventional imaging systems. Accurate measurements of the structural details of the particles are practically possible only if the measured details are brought in focus. In order to extract in-focus images of objects recorded into a digital hologram from a large set of holograms in a feasible manner, automated focusing and segmentation are needed. The twin image present inherently in the in-line holography data leads to extra noise that makes this a challenging problem. We propose a new depth estimation method for in-line holography, where the stack of reconstructed intensity images is analyzed. First rough object locations are estimated where the object depths are estimated with a wavelet based focus measure. Clusters of depth estimates are used with plane fitting to approximate the object orientation in the 3D volume to obtain the final all-in-focus images. We show that the proposed method can be used to obtain sharp images of planar objects, such as snowflakes.

I. INTRODUCTION

Particle size and shape measurements are important in many fields, such as in process monitoring in plants and in meteorology. The measured properties of airborne water and ice particles, known as hydrometeors, can be used to improve the predictions on weather changes, radar calibrations or estimating critical conditions like road surface freezing. The properties of hydrometeors are interesting not only in meteorology but also in winter sports planning, where the quality of the snow affects the preparation of the equipment like skis [1].

It has been demonstrated that the shape and size of hydrometeors can be measured using in-line holography [2], [3]. Compared with conventional imaging techniques the depth of focus is greatly extended using holographic imaging, which is pronounced with macroscopic and microscopic imaging applications [4]. The large imaging volume resulting from the extended depth of focus of the single view point in-line holography provide unbeatable advantage over any other imaging system in applications where imaged particle densities are low, but good measurement statistics are needed within the shortest possible response times. Precipitation of snow is one of such applications. Others include e.g. the detection of microorganisms like Escherichia coli (E. coli) from drinking water using direct imaging method.

In-line holography is based on capturing a diffraction pattern image of the particles inside the measurement volume using a coherent light source, typically a laser or a narrow-band light emitting diode. In a constant magnification in-line setup, the divergent light waves emitted from the source are first collimated using a lens, resulting in nearly planar light waves, referred here as reference wavefront. As the reference wavefront propagates forward and interacts with objects, part of the wavefront scatters, and an altered wavefront results from the interference of these two wave components. The diffraction patterns created from the result of mutual interference can then be recorded using a digital camera detector to record a digitized hologram, as illustrated in Fig. 1. An example of a background subtracted hologram containing snowflakes is shown in Fig. 2. The diffraction patterns can be numerically backpropagated to object space for example by the Huygens convolution, the Fresnel transform and the Angular spectrum method [5].

In in-line holography the reference beam and the objects
which scatter the light are located on the same optical axis, as opposed to off-axis holography where there is an angular difference between these two components. This property makes it easier and cheaper to realize an in-line holographic imaging system. The downside of the simpler in-line method is that the two images of the object generated after the reconstruction, the real image and the virtual image, are located on the same optical axis, i.e. one on the other. The virtual image, also called as the twin image, is an out-of-focus image of the real image in the reconstructed image plane located at a distance twice the reconstruction distance. In off-axis holography the virtual image is separated spatially and therefore has typically only a negligible visibility in the reconstructed image. The twin image causes background noise in the reconstructed images making the focusing task more difficult. The amount of noise depends on the imaging geometry and on the size and location of the object.[6]

As a single view point method, in-line holography does not provide a full 3D image but merely a stack of 2D images. Therefore the dimensional measurements of flat-shaped particles, for example such as snowflakes, are possible only if their orientation is known. Getting the information about particle orientation is essential since the other means, either holographic or conventional, to get the same information about particle dimensions would require an imaging system with multiple viewpoints. This would significantly reduce the greatest advantage of the single viewpoint in-line system; the substantially larger imaging volume compared to conventional imaging, and especially to any imaging system utilizing multiple viewpoints.

However, the segmentation of the particles in holographic images or the estimation of object depth is not trivial. While there exist auto focusing methods for in-line holography, these typically find a single main focus plane or are usable only with a very small number of objects. In this work, we describe a new approach to construct all-in-focus images with in-line holographic data containing planar objects. We show that the method works for multiple objects with both synthetic and real hologram data and it produces sharper images than using direct depth estimates.

II. RELATED WORK

Huang and Jing have studied performance of several conventional focus measures [7] and Langehanenberg et al. review auto focusing methods for holographic microscopy using off-axis techniques [8]. Commonly used approaches contain the spectral analysis, variance of gray value distribution, edge detection using gradients and Laplacian filtering. Algorithms based on thresholding the focus measures were reported as being applicable to autofocus in digital holographic microscopy.

Li et al.[9] have used intensity image stacks for particle depth estimation in in-line holograms. Each image in a reconstruction stack was median filtered to remove noise prior to 2D estimation of particle centroids. A depth estimate for each centroid location was formed by finding the maximum gradient in a window defined by the particle size.

Panday et al. [10] detected the particle depths by detecting the median, mean or the minimum of the light intensity within a rectangular sampling window at different depths. A problem stated with this work is the manual sample window size selection. Edge strength, or the gradient, of object intensity or complex amplitude has been also used as a measure for the focus of objects reconstructed from in-line holograms [11]. With astronomical images a weighted ratio between the Euclidean norms of high and low frequency wavelet coefficients has been used as a focus measure [12].

Xie et al. [13] have created 3D surface reconstructions from conventional microscope images captured at different focus depths. The depth estimation was based on the wavelet decomposition of the intensity image and measuring the relation of high frequency energy and low frequency energy in a local window. The images from different depth were joined together by fusing the wavelet coefficients from maximal response depth and computing the inverse wavelet transform. Direct application of above method fails with in-line holographic images as the twin images and the noise at different depths is captured with the wavelet reconstruction (see Fig. 9). However, this approach appeared to be more promising than the other tested focus measures, like the maximum gradient or the variance of a Laplacian filtered image [14], and thus is used as a starting point for this work concentrating on in-line holograms.

III. THE LOCAL AUTO FOCUS ALGORITHM

The approach can be divided into five steps: 1) creation of an image stack, 2) extraction of the expected object locations, 3) depth estimation, 4) plane fitting and 5) compilation all in focus image based on depth estimates. The first stage is to create a volume of intensity images at different depths. The rendering methods used in this work were Fresnelet transform [15] for the synthetic images and the angular spectrum method [5] for the real in-line data.
The expected object locations can be estimated in the recorded intensity volume by summing up the intensity image depthwise. This intensity map is thresholded for a mask that contains the regions of interest (ROI) in 2D (Fig. 3). Here the standard deviation of four from the mean value in the map was used for thresholding.

A. Depth Estimation

The intensity image volume is converted first to a depth estimate volume, where the depth is estimated for each of the pixels in 2D. Here the modified measure from [13] was used only to estimate the local focus depth. The measure $M_l^Ω$ compares the average low frequency energy in the whole image $Ω$ used only to estimate the local focus depth. The measure $M_l^Ω$ was assessed by voting so that each point within a given threshold contributed equally:

$$Q_{C_i}^{ROI} = \sum P_{C_i}(x, y, z)$$

$$P_{C_i}(x, y, z) = \begin{cases} 1, & \text{if } (a_1 x + b_1 y + c_i - z)^2 < \theta \\ 0, & \text{otherwise} \end{cases}$$

For each of the clusters $C_i$ in a ROI, a plane $a \cdot x + b \cdot y + c = z$ was fit to the points by solving the corresponding set of linear equations for the coefficients $a, b,$ and $c$. The quality of each fitted plane was further inspected by calculating the residual differences respectively. Fig. 5 shows the synthetic hologram. The synthetic image was formed by applying Fresnel transform on five separate images containing two crosses, two diamonds and a disk to different depths having unity depth differences respectively. Fig. 5 shows the synthesized hologram (top left) and Fresnelet reconstructed images at different depths, where the disc is in focus (top right).

B. Plane Fitting

The depth estimate $Z(x, y)$ is noisy, especially in the areas that do not contain real objects but artifacts from out of focus fringes (Fig. 6). The data may contain large objects inside surfaces due to the background extraction done for the hologram data. The medium and small sized snowflakes can be estimated to be planar and this can be used to improve the depth estimates. While the depth estimate may be globally very noisy, locally the planarity is prominent. The plane fitting is carried out for each ROI by applying clustering with voting for the best fit from the clusters.

Here agglomerative hierarchical clustering using Ward linkage was applied to the depth estimates [16]. The clusters were obtained by cutting the linkage at the 15% of the maximum distance in the clustering tree resulting typically between five to fifteen clusters. The number of points used for initial clustering was limited to 2000 and the possible remaining points were assigned to the clusters based on the distance to the cluster centers.

The $M_l^{(x,y) \in I}$ for each image at depth $z$ forms a new volume of data where the local maximum depthwise gives an estimate for the local focus:

$$Z(x, y) = \max_z M_l(x, y, z)$$

IV. Results

Method was tested with both real data and a synthetic hologram. The synthetic image was formed by applying Fresnel transform on five separate images containing two crosses, two diamonds and a disk to different depths having unity depth differences respectively. Fig. 5 shows the synthetic hologram (top left) and freselet reconstructed images at different depths, where the disc is in focus (top right).

Fig. 6 shows the initial depth map estimate from Eq. (4), the plane fitted estimate, and the reconstructed all-in-focus...
A point cloud, containing a planar object, is first segmented to groups. For each group, a plane is fitted and fitting score calculated according to Eq. (5). The best fit found in this case is presented on the right. The fit can be further improved by refitting the plane only to points that are close to the best-voted plane. Also in this example there are points that are close to the best cluster fitted plane and are on the object but not in the initial cluster.

Fig. 5. Synthetic hologram image (top left) and reconstructions at different depths: (top right) disc in focus, (bottom left) diamonds in focus, and (bottom right) crosses in focus.

image for the synthetic data. The mean normalized depth estimates for the disk is 1.00, for the diamonds 2.01 and 2.04 and for the crosses 3.98 and 4.03 with the respective standard deviation of 0.0224, 0.041, 0.079, 0.064, and 0.024. The constructed all-in-focus image shows a good focus of the constructed objects and the observed deviation from the plane fitting is negligible. This indicates that the plane fitting is not affected too much by the out of focus fringe noise.

The depth map estimate and the constructed image for real data containing snowflakes is shown in Fig. 7. The depth is here in millimeters. The snowflakes were imaged in free fall and images were captured using one microsecond light pulses [3]. With this data, good depth estimates can be visually observed in the sharp all-in-focus image Fig. 7. A comparison of reconstruction for one of the snowflakes with direct WAVR measure, with median value and the suggested approach is shown in the Fig. 9.

The estimated depth map for the selected snowflake suggests that the flake is tilted in the depth plane about 0.7 millimeters. Without the ground truth this can be verified only by the visual inspection of the result image, which shows sharper edges compared with the median image and less noisy result image than the direct application of the depth estimate.

An example of plane fitting to the noisy data is presented in the Fig. 10. The green dots mark the points used in the final plane fitting. The scattering interference (blue markers) is handled correctly with the clustering approach used in plane fitting.

Fig. 6. Top: the raw depth estimate for the synthetic data and corresponding result image without the suggested approach. Bottom: the plane fit approach for the depth estimates for each object and the all-in-focus result.
V. DISCUSSION

The visual inspection of the results show that the depth estimates were successfully extracted from the intensity image stacks reconstructed from the holograms. All-in-focus images were constructed not only for synthetic data but also for real in-line holograms containing snowflakes with an apparent tilt in the depth direction. The planes estimating the planar object orientations in the imaging space clearly improves the result image sharpness.

While here simple bounding boxes were used to collate the objects at different depths, the extracted image in each box could be used to create more accurate masks of the objects enabling the extraction of more closely spaced objects at the different depths. One clear disadvantage here is that the use of a prior estimate of the object locations may threshold very small objects away from the image. However, the thresholding could be done in adaptive manner so that local variation in the intensity image volume is taken into account. Also other heuristics could be specified for the approach, like using for the clustering some volume near the median based initial guess.
For the further work it is planned to create a known planar objects that are rotated with known angles to obtain a ground truth image captured using in-line holography. Also, as the depth resolution in in-line holography is inferior compared to the lateral resolution practically in all imaging setups, holograms of known objects should be taken using different magnifications and numerical apertures. The data can be then be used to estimate the robustness and limitations of the proposed approach.

It must be also noted that very large snowflakes may be formed by the aggregation of several smaller snowflakes. These large objects do not agree with the assumption on the planarity. Therefore it is also necessary to study if the large objects can be analyzed using a similar approach, but with multiple levels of clustering where the object is broken down to smaller planar subsections.

REFERENCES


