

Calibration of Plenoptic 2.0 Cameras and use in 3DPTV Investigations

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ABSTRACT

Plenoptic 1.0 cameras have already been investigated as a means for performing 3DPIV. Plenoptic 2.0 cameras have an enhanced in-plane resolution, but are limited to less dense particle fields by their depth-detection method, and are thus less appropriate for 3DPIV. A technique more suited to less dense particle fields is 3DPTV. Time-resolved 3DPTV will be possible due to the high frame rate available with these cameras. Experiments to quantify the performance of the cameras for 3DPTV are being undertaken. These experiments involve the use of fixed 3D particle fields. Preliminary results indicate that plenoptic 2.0 cameras show some promise in 3DPTV applications. Reasonable agreement between applied displacements and camera-measured displacements was observed. Issues with the current depth detection method have been noted, and possible improvements have been identified. General distortions and their effects on imaging with plenoptic 2.0 cameras have been identified. To correct the issues with depth detection and distortions, a calibration method has been identified. Two-frame particle tracking has been used to obtain preliminary results. Implementing the calibration method and a time-resolved tracking approach are the next steps to improving the camera's performance in 3DPTV.

1. Introduction

The usefulness of plenoptic 1.0 cameras, where the micro-lens array focuses the aperture of the main lens onto the CCD (Adelson and Wang 1992; Ng et al. 2005), in performing PIV investigations has been evaluated in the literature (Thurow and Fahringer 2013; Thurow et al. 2014). However, concerns have been expressed that plenoptic 2.0 cameras, where the micro-lens array focuses an array of small coherent images onto the CCD (Lumsdaine and Georgiev 2009), are ambiguous in how the angular and spatial components of a light field are captured and used (Thurow et al. 2014). However, recent work (Heinze 2014) has resulted in a commercially available metric calibration method (Raytrix GmbH) for properly scaling plenoptic 2.0 imaging results into physical space.

Another concern with plenoptic 2.0 cameras is that the algorithms used for reconstructing these lightfield images require the assumption of a depth value for each micro-lens, reducing the viable seeding density and limiting usefulness in PIV experiments (Thurow et al. 2014).

However, algorithms exist that estimate depth values over small areas of each microlens (Perwaß et al. 2012) through the use of cross-correlation algorithms similar to those used in PIV, leading to increased depth resolution.

In a previous investigation (Nobes et al. 2014), a commercial plenoptic 2.0 camera was used with an in-house 3D particle tracking velocimetry (PTV) algorithm in an attempt to track 3D flow fields in both macro-scale and micro-scale experiments. This study had several limitations: a poorly matched $f/\#$ between the microlenses and main optic, the availability of only 100 refocusing planes due to software limitations and difficulty accurately determining the depth locations of the particles. The work also highlighted that the thick possible refocusing plane had significant change in magnification over the image depth along with the presence of the spherical focal plane. Both require a rigorous calibration of the lightfield to allow particle positions to be correctly regenerated.

This investigation will aim to locate particles in 3D using a plenoptic 2.0 camera and perform time-resolved particle tracking. Two methods for particle localization are investigated. The first is the use of 3D centroid detection on stacks of more than 100 refocused image planes. The commercial software's implementation of local depth detection will be investigated as an alternative depth detection method. Finally, time-resolved 3DPTV will be performed on the localized particle sets. To better quantify the overall performance of all the algorithms used, a target with a fixed 3D matrix of particles, moved in a known way, will be used for preliminary testing. The ultimate goal of this investigation is to be able to scale these measurements into physical space.

2. Overview of System Design

The primary goal of the present study is to be able to perform time-resolved 3D velocity tracking of a moving fluid. To this end, a relatively low-resolution, high-speed focused plenoptic camera (R5, Raytrix GmbH) is used. The low resolution, reduced further by the plenoptic refocusing algorithm, makes this approach less compatible with the high particle seeding densities associated with PIV. The plenoptic 2.0 refocusing algorithms are also generally poorly compatible with high seeding densities due to the effects of aliasing (Bishop and Favaro 2009). To obtain the maximum possible resolution of the fluid flow with low seed density, a 3DPTV (Particle Tracking Velocimetry) approach is proposed. This approach will make use of 3DPTV resources previously developed in-house (Homeniuk 2009).

Fig. 1 shows the configuration used for acquiring images. The plenoptic 2.0 camera captures images of a particle ‘phantom’. This phantom is composed of particles suspended in a gelatin matrix. This ensures that the particles remain fixed relative to each other in 3D space, and is analogous to a field of particles in a fluid. Displacement tracking of the particles can then be performed by taking one image, moving the phantom, and then taking a second image. Illumination is provided by a high-intensity LED light source (ThorLabs).

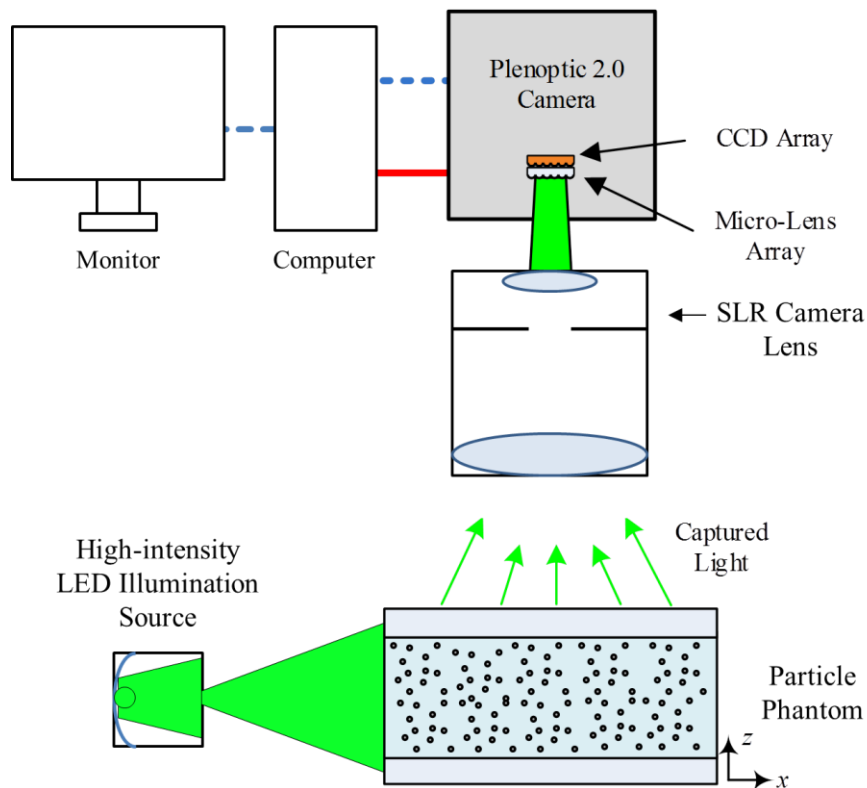


Fig. 1 A schematic of the experimental setup

3. Experimental Data and Processing

3.1 Depth Processing Approaches

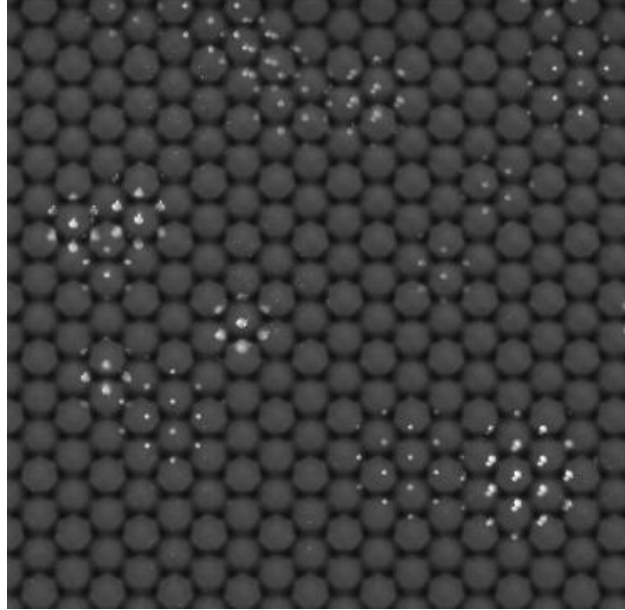


Fig. 2 A raw image of a particle field, cropped to show microlens images

Fig. 2 shows a sample raw image of a particle field captured with a plenoptic 2.0 camera, highlighting the images formed by individual microlenses. These images need to be further processed to be able to locate the particles. Two approaches have been investigated. The first is to refocus the entire field of view to a series of single depths, forming a 3D stack of 2D planar images. Two of these image planes, at different depths, are shown in Fig. 3. Different particles will be in focus depending on the depth of the plane selected. The 3D stack is then processed to determine the 3D centroid locations of individual particles. This approach was used in the previous investigation (Nobes et al. 2014), but with less depth resolution than is now available.

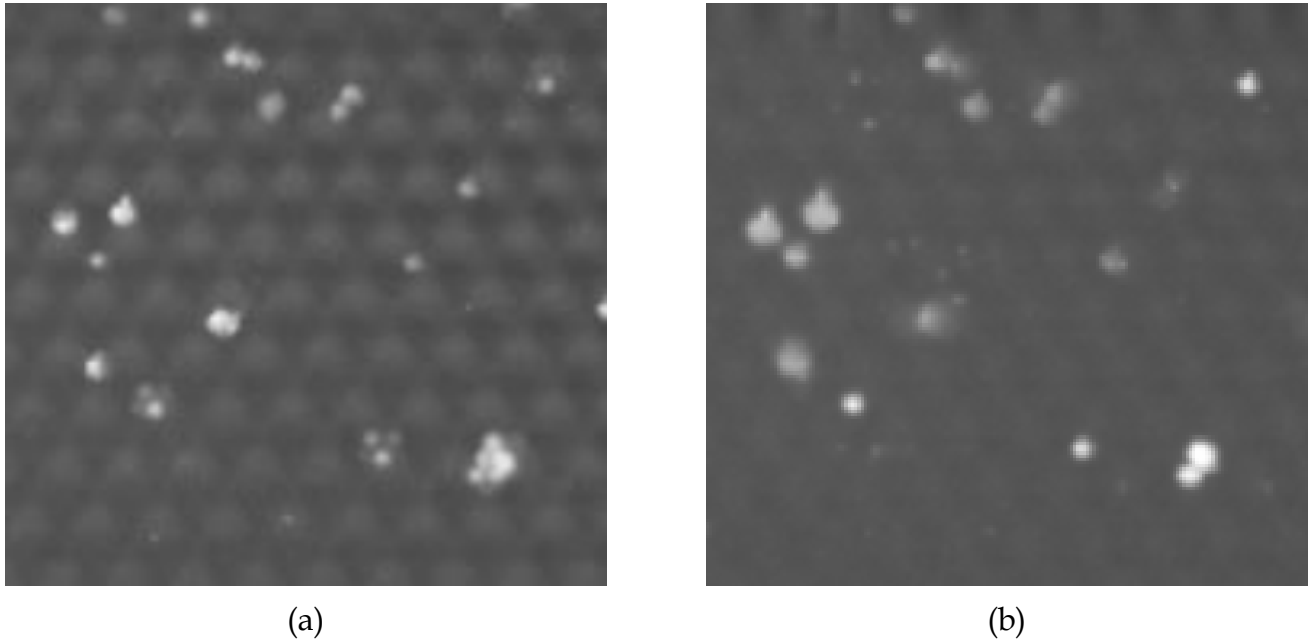


Fig. 3 Near-field (a) and far-field (b) refocused images

The second approach is to determine the virtual depth locations of individual particles directly from the raw image by cross-correlating small regions of neighboring microlenses. This approach is designed for solid objects (Perwaß et al. 2012), but can be re-purposed for particle fields. Individual particle images can then be assembled into a single image based on their calculated depths; this is called a ‘full focus’ image. A second image then contains information about the depth of each particle. A sample full focus image with its associated depth map is shown in Fig. 4. Note how the in-focus particles from the images in Fig. 3a (upper left) and the particles from Fig. 3b (lower right) are all in focus in the total-focus image. Further, the depth information from the slicing technique is now incorporated in the depth map in Fig. 4b; near-field particles are labeled orange while far-field particles are labeled green. The values of the depth map correspond to the *virtual depth* of the detected feature. Virtual depth is defined as the distance in front of or behind the microlens array to which the main lens projects the image of the feature, relative to the distance between the microlens array and the CCD.

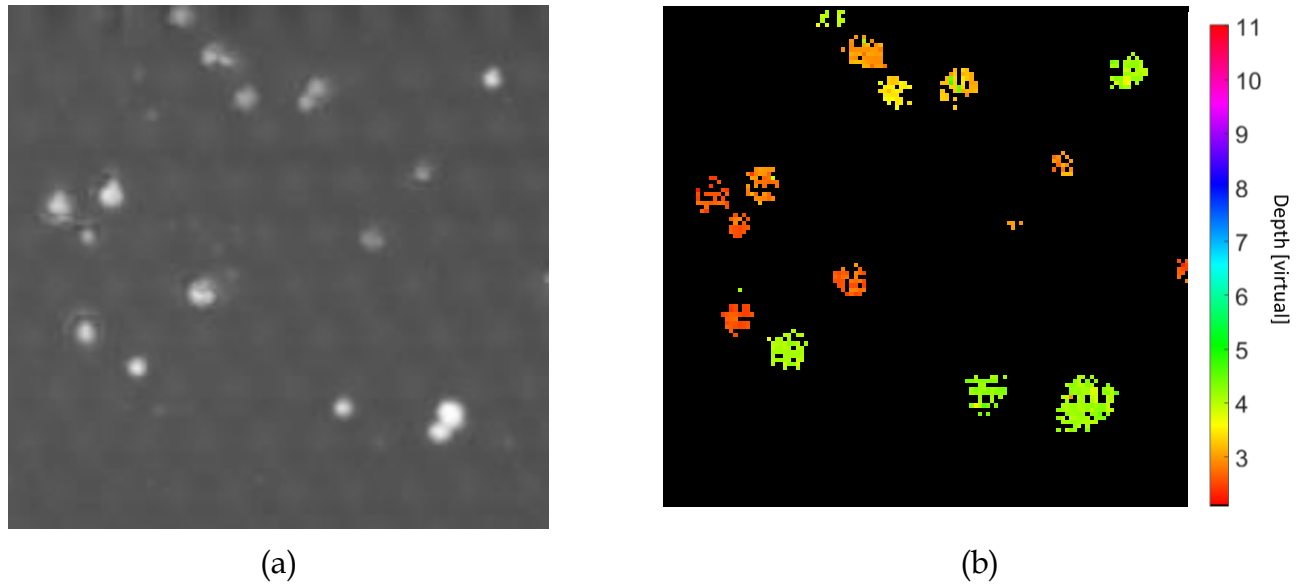


Fig. 4 Full-focus image of particle field (a) with calculated virtual depth map (b).

3.2 Particle Location Approaches

In the refocusing approach, 3D centroid detection is performed on stacks of 2D images to determine the locations of individual particles, outputting a list containing the (x,y,z) locations and approximate volumes of each detected particle. In the depth triangulation approach, 2D centroid detection is performed on the full focus image, generating a list of (x,y) locations with associated areas. These (x,y) locations are then searched in the depth map, averaging the calculated depths across the particle area to determine a (z) depth location. The depths found by both methods are virtual depths, which is to say that they represent locations behind the microlens array to which the main lens would project an image of the object. These are expressed in terms of a ratio relative to the distance between the microlens array and the CCD (Perwaß et al. 2012). These depth calculation methods are performed for each image in the acquired time series. The particle lists are then compared using the particle tracking algorithm.

3.3 3D Particle Tracking

Implementing the 3D particle tracking algorithm is the same for both approaches. This method is outlined in Fig. 5. For each particle in the first (x,y,z) set of particle coordinates, vector distances to all particles within a given search radius T_s in the next image are calculated. These are then compared to the vectors produced by particles in a neighborhood T_n . The vector taken to be correct for each particle is the vector that is the most similar to the neighboring particles' vectors.

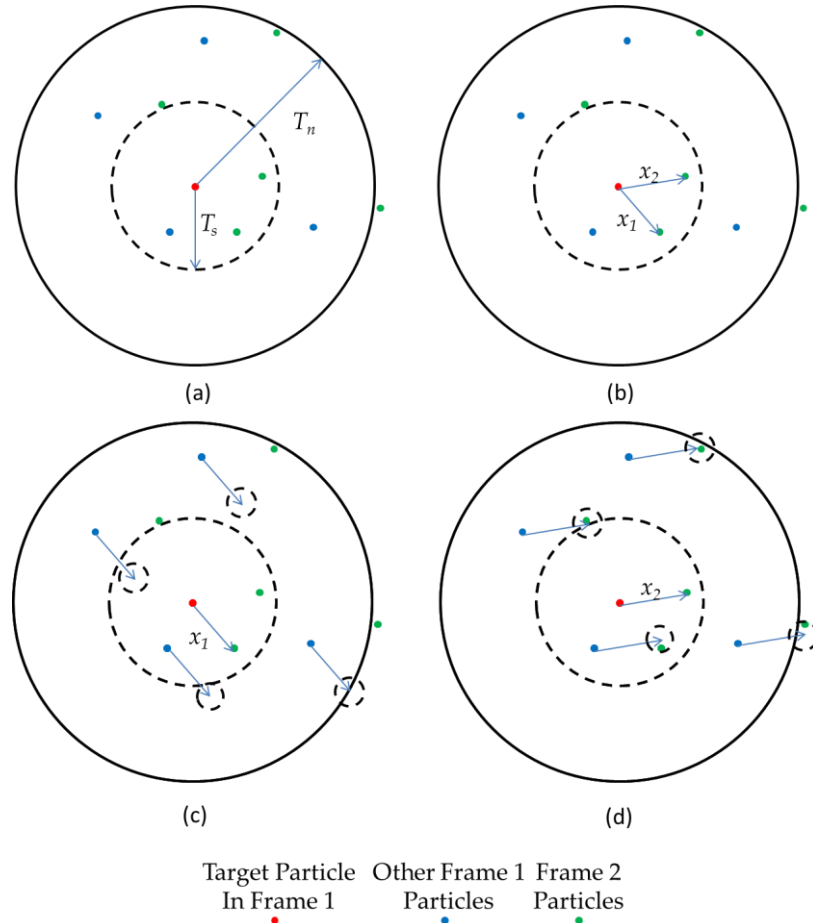


Fig. 5 Particle tracking approach (after Homeniuk 2009). (a) Frame 1 particles within T_n and frame 2 particles within T_s are identified. (b) Vectors are generated for target particle, for each frame 2 particle within T_n . (c,d) Vectors are checked against particle motion within T_n . In this case, vector x_2 is selected (d).

4. Results

In order to test the plenoptic 2.0 camera's tracking ability, two images of the phantom were taken. The applied z -displacement between positions was 3mm. The depth triangulation approach and a 2D centroid location method were applied to find the (x,y,z) positions of individual particles. Amplified unfiltered vector displacements of the detected particles in the phantom are presented in Fig. 6a (x - z plane, 5x amplification) and b (x - y plane, 50x amplification). Circles in these figures give the origin points of each particle, and the associated lines show the detected vectors. A general trend of motion towards the camera ($+z$) can be observed in the particle motion from Fig. 6a. Fig. 6b shows that, ignoring outliers, there is a general trend of particle motion away from the centre of the image. The inconsistent vectors observable are present due to the lack of post-process filtering.

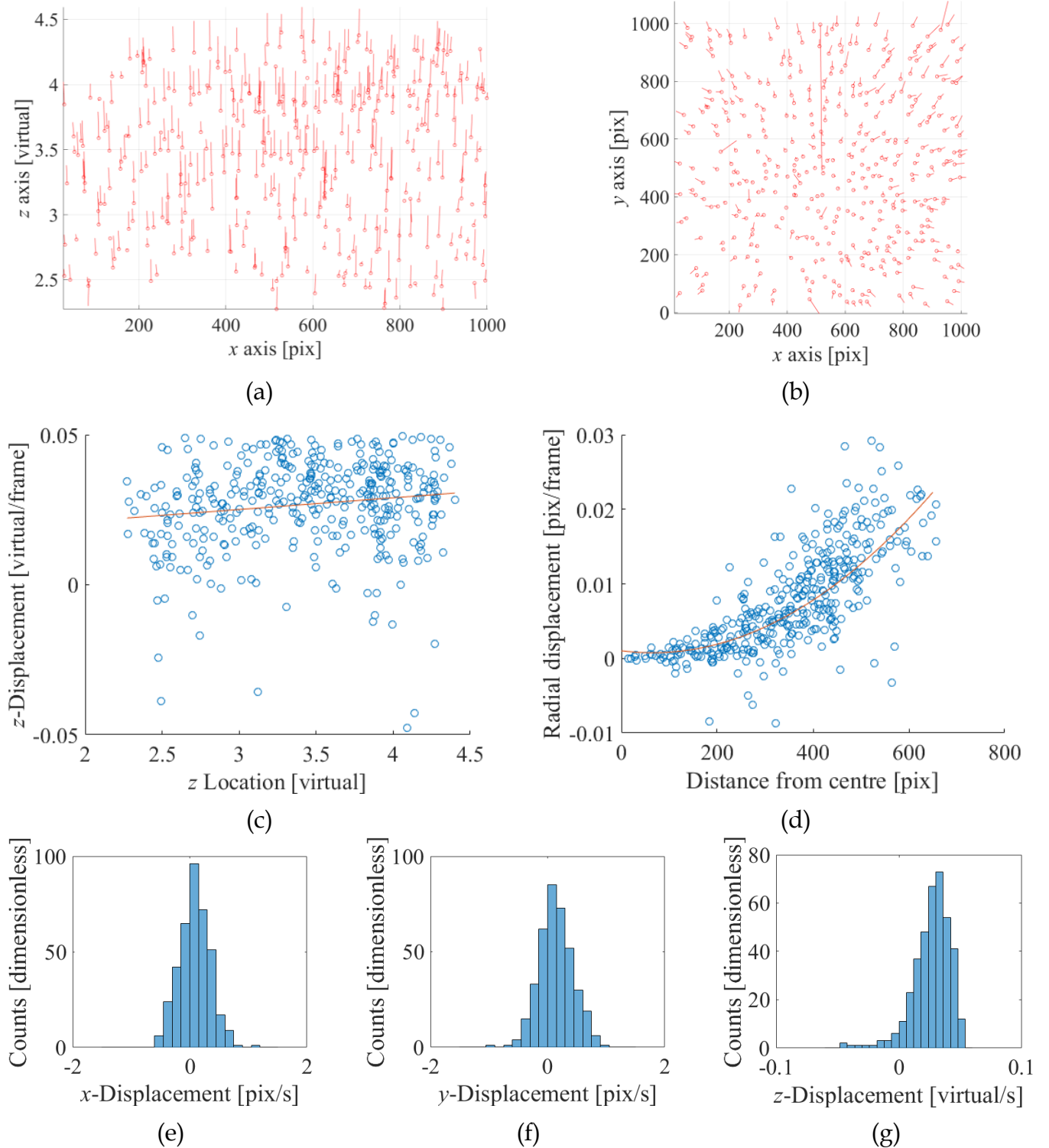


Fig. 6 Vector data results. (a) Vector map of displacement in x - z plane (b) Vector map of displacement in x - y plane (c) z -displacement as a function of z -location, with trend line (d) Radial displacement as a function of radial distance from image centre, with trend line. (e-g) PDFs of x , y , and z displacement

A PDF of z -displacement is given in Fig. 6g. This PDF confirms the general upward trend and gives some idea of the consistency of the approach. Ideally, since the displacements of all particles were the same, a delta function with a single peak should have been observed. Instead, the PDF takes the shape of a skewed normal distribution. The deviation from the expected result is produced by random errors associated with the particle tracking algorithm and systematic errors in the depth calculation process. The systematic errors arise from the lack of a proper calibration. Without proper calibration, the correspondence of virtual depth to physical depth is not exact. This is due to various distortions, and other factors such as misalignment of the microlens array (Heinze 2014). These distortions also produce the normally distributed in-plane (x,y) displacements observable in Fig. 6e and f.

One of the main issues noticed with plenoptic imaging is that the magnification of the camera varies with depth. This effect is produced by the conical angle of view of the optics. This adds an additional challenge for particle tracking, as far-field particles appear to move shorter in-plane (x,y) distances than near-field particles. This can be observed from sample calibration target images shown in Fig. 7. When moving a planar target out-of-plane (shown by the red lines), the camera's field of view changes (shown by the blue lines). Effectively, near-field objects end up with higher magnification than far-field objects. This effect is observed in the phantom data as a dependence of radial displacement on radial position, measured outwards from the (x,y) centre of the image as observed in Fig. 6b. This is confirmed by the generally increasing trend observed in Fig. 6d, where radial displacements are plotted against radial positions. **Error! Reference source not found.**

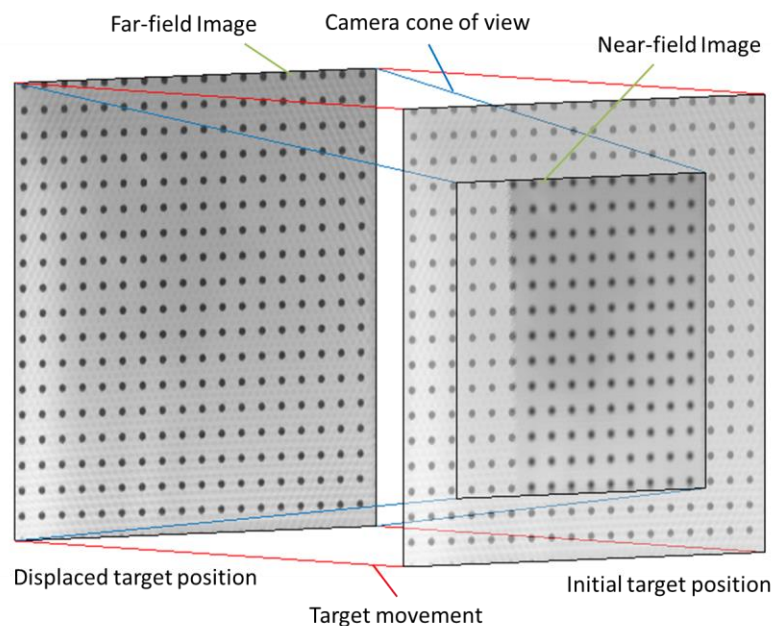


Fig. 7 Change in magnification when moving a target out-of-plane

Another issue is that the particle depths (z) and locations (x, y) are calculated in virtual and pixel space, respectively. Because of the camera's conical angle of view (Fig. 7) and the inability to convert virtual depths directly to physical depths accurately, it is difficult to say anything about how distances in image space correspond to those in physical space. This limits the camera's application as a measurement tool if a calibration method is not implemented.

An issue with the current setup not directly associated with the plenoptic camera is that the particle tracking code implemented thus far is designed for two-frame tracking. This increases the chance that bad vectors may be accidentally kept, leading to false velocity measurements. Shifting to a multi-frame tracking approach has the potential to make the particle tracking algorithm more robust.

5. Future Work

As was apparent from the particle tracking results, there are some inconsistencies in how the current algorithms detect and track the depths of individual particles. The method used to approximate the depths of particles is based on detecting the median of depth values near the 2D centroid of the particle. For fairly dense particle fields such as the one imaged, the particles end up overlapping, producing clusters of different depths. Currently, the depth-detection algorithm does not do anything to deal with these clusters, which will have led to some of the inconsistencies in the particle tracking results. Updating this algorithm is likely to lead to improved depth detection.

In order to correct for the issues discussed in section 4, it is necessary to implement a calibration method that can scale from image space to physical space. A method for doing so has been developed (Heinze 2014), and is available for commercial use (RxLive 3.1, Raytrix GmbH). However, to better understand and customize the calibration to meet the demands of particle localization, this calibration method will be investigated and further developed. The calibration method will incorporate results derived from the thin lens model, Brown's distortion model (Brown 1966) and corrections for Petzval field curvature (Reidl 2001; Johannsen et al. 2013). Implementation will involve acquiring plenoptic images of a 2D target, at multiple positions and angles. Target models will be generated. The imaged locations of key points on the target, re-projected to physical space using the calibration algorithm, will be compared to the model. This method will be implemented within an iterative solver to determine the values of the calibration

parameters. Ultimately, this will allow measurements made by the plenoptic 2.0 imaging system to be scaled into 3D object space.

The other issue discussed was that the 3DPTV algorithm currently implemented only tracks particles across two frames. Improving this algorithm will involve tracking individual particles across multiple frames. This will increase the robustness of the algorithm, preventing false-positive vector generation by comparing each particle's vectors across multiple frames.

6. Conclusion

Overall, the use of a plenoptic 2.0 camera for tracking particles in 3D appears promising. The camera has already demonstrated a reasonable capability to track out-of-plane particle motion. However, there are still some issues with depth detection that have led to inconsistencies in the tracking algorithm. Furthermore, a calibration method still needs to be implemented to be able to scale the results from image space into object space. With these limitations addressed, the use of a plenoptic 2.0 camera in time-resolved 3DPTV will allow macro-scale and micro-scale fluid-tracking experiments to be performed.

7. Acknowledgements

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8. References

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