Plenoptic Particle Streak Velocimetry (pPSV):
3D3C fluid flow measurement from light fields with a single plenoptic camera

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Keywords: Light Field, Plenoptic Camera, Particle Streak Velocimetry, Particle Streak Tracking, 3D3C flow measurement

For a number of complex fluid flows, the three dimensional measurement of the three component velocity field are paramount for performing subsequent analyses. This need for this type of 3D3C measurement technique has been identified since the beginning of fluid flow analyses by Prandtl, but has been mainly hampered due to hardware limitation. In recent times, with the advent of decreasing prices of cameras and lasers with significant performance improvements of the same, a number of approaches for 3D3C measurements have been proposed and are frequently employed.

Standard approaches have contributed to major breakthroughs in contemporary fluid flow analysis; most of them have some disadvantages for certain applications. For example, in scanning PIV approaches, the scan rate of the laser sheet needs to be high enough to "freeze" the fluid flow, which is not always possible in high Reynolds number flows. Particularly for synthetic aperture and tomographic PIV and also to a lesser extend in stereo approaches, a large optical access needs to be available and the associated hardware can be quite expensive. These limitations will be addressed in the approach presented in this contribution. A single plenoptic camera (Adelson and Bergen, 1991) makes it feasible to record the light field of a particle distribution, which can then be reconstructed from approaches of computational photography. Our approach is based on the concept introduced by Lumsdaine and Georgiev (2009) and Georgiev and Lumsdaine (2010), which is also termed "Plenoptic 2.0".

The camera used in this measurement has micro lens images with a diameter of approx. 23 pixels. In a first calibration step, the centers and radii of the micro-lenses have to be measured on the camera’s sensor. Such a calibration image is shown in Figure 1. By imaging a white plane, the detection of the micro lenses is easy to accomplish.

![Fig. 1 The calibration image for detecting the micro lenses on the sensor. The upper right corner shows a magnification to pixel level.](image)

Our technique is based on particle streak velocimetry. Therefore, we choose a long integration time to obtain streak images along the trajectory of particles. Particle streaks in the focal plane of the main lens are images as one streak on the sensor. Streaks at another depth are visualized multiple times in different micro-lenses. This can be seen in the raw image shown in Figure 2. Detecting these streaks and performing a triangulation is then used for reconstructing the depth of the particles, as shown in Figure 2. In addition, all-in-focus images can be computed from the raw images from algorithms of computational photography. From these all-in-focus images, the horizontal streak position and trajectory can be extracted very accurately. The velocity along streaks is encoded by varying the illumination, similarly to our approach proposed previously (Voss and Garbe, 2010).

![Fig. 2 left: raw light-field image; right: depth map; In the evaluation the all-in-focus images are used to extract the horizontal trajectory information \((x, y, v(x))\) and the computed depth maps are used to add depth information \((z)\).](image)

Our measurements indicate an accuracy of better than 1% relative error.