3D particle reconstruction using light field imaging

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Abstract The measurement of three‐dimensional (3D) velocity field of fluid flows can be carried out with different imaging techniques: scanning PIV, defocusing PIV, tomographic PIV, holographic PIV, synthetic aperture PIV, stereoscopic PTV. Most of these techniques involve the simultaneous use of multiple cameras and/or complex optical configurations. The use of plenoptic camera permits to overcome some limitations of the proposed techniques allowing to obtain with a single camera multiple images on different focus plane simultaneously. This can be done by reconstructing the so called light-field. In fact, the plenoptic camera allows to describe the intensity of the rays that pass through every point of a plane by means of a micro-lenses matrix in front of the sensor. In this way, the recorded data is elaborated with the plenoptic function and it is thus possible to refocus a single volumetric image of a fluid flow seeded with tracer particles. Taking into account that the minimum size of the image of a particle occurs when the particle itself is located in the focus plane, it is possible to identify at each instant its position in the image plane and also in the direction of the optical axis of the camera system. Once the position of the particle is determined, it is also possible to calculate the size of it by using Gaussian optics or by calibrating the camera system with objects of known size. The obtained particles centers coordinates in the three-dimensional space can then be linked in time by using an appropriate Lagrangian particle tracking technique. With a single camera it is thus possible to reconstruct the three-dimensional particle trajectories of fluid flows and calculate simultaneously the particle dimensions.

In this work some preliminary results, concerning the size of the particle, the area of its image, and the position of the plane of focus, from the arbitrary origin of the z axis, are presented.

1. Introduction

A complete description of the flow field of a fluid requires a simultaneous measure of the three velocity components in a volume (3C-3D). Techniques such as Laser Doppler Anemometry 3C or 3C Stereo-PIV does not give all the necessary information, as they provide measures of the three component velocity, respectively, at one point and in a plane.

Recently, different imaging techniques have been proposed, which allow to obtain velocity fields 3C-3D. Among these, the most important are:

- 3D-Particle tracking velocimetry (3D-PTV);
- defocusing digital PIV (DDPIV);
- holographic PIV (HPIV);
- PIV tomography;
- synthetic aperture PIV (SAPIV).

3D-PTV is a technique that allows to determine the position in space of each tracer particle, through
a stereoscopic reconstruction based on the acquisition of the same scene by multiple cameras (Maas et al., 1993, Ouellette et al., 2006). The technique permits to work with large volumes, but with low seeding density. In order to reconstruct the 3D flow field, an accurate calibration of both the internal and external parameters of the cameras is required. Recently, several improvements have been introduced (Willneff & Gruen, 2002, Shindler et al., 2010), that help to make the 3D reconstruction and the calibration of the cameras more robust.

The digital defocusing technique is based on the defocus of the seeding particles through the positioning of a mask, with three apertures shifted away from the optical axis (three circular holes whose centers are placed at the vertices of an equilateral triangle), in front of the lens (Pereira & Gharib, 2002). In this way, a single particle will appear on the image plane as a multiple object (three areas related to a blurred image of the particle) whose mutual distance is closely related to the distance of the plane of focus of the camera. The measurement system currently used consists of a single camera with three optical off-axis. Suitable algorithms allow to recognize the pattern of the equilateral triangle and consequently to reconstruct the position of the particles in the 3D interrogation volume. The principal limitation of the technique is related to the low density of the tracer. In fact, a large number of tracer particles would result in an overlapping pattern, making them more difficult to identify.

Holographic techniques such as holography PIV allow the reconstruction of the position of the particles in the three-dimensional space, via the interference pattern that is formed by the reflected light from the particles and a beam of coherent light incident on the volume of investigation (Hinsch, 2002). The nature of the interference pattern is used to trace the phase of the light wave diffracted by the particle, which is closely related to the distance of the particle from the sensor. The interrogation volume is related to the size of the recording device. The use of analog devices guarantees high resolutions, due to the greater dimensions than digital sensors, but presents different technical disadvantages which have limited the use (Zhang et al., 1997). The digital holography PIV, however, is easily usable, but is often limited to small volumes of measurement and to delicate optical setups.

Tomographic PIV makes use of several simultaneous views, typically four, of the illuminated particles, and their three-dimensional reconstruction as a light intensity distribution by means of optical tomography (Elsinga et al., 2006). The reconstruction is performed with appropriate algorithms yielding a 3D distribution of light intensity discretized over an array of voxels. Actually, tomo-PIV allows to operate with higher seeding density than other techniques, reaching values of about 0.05 particles per pixel (Elsinga et al., 2006). On the other side, the measurement volumes are still small.

The synthetic aperture PIV is based on the use of an array of synchronized CCD cameras distributed such that the fields of view overlap (Belden et al., 2010). The images are then recombined using appropriate algorithms based on the concept of the light field imaging, to obtain different planes of focus. These are then recombined in order to reconstruct the 3D light field intensity, by refocusing the images throughout the entire volume. Typical 3D-PIV techniques then be applied to the intensity fields to extract the 3D velocity fields. Although the technique enables large volumes to be resolved with greater seeding density, the simultaneous use of several cameras (up to eight cameras) currently limits the practical use.

The limitations of the described techniques may be overcome by using a plenoptic camera. This is also based on the light field theory, but using only one single camera. It allows to measure 3C-3D velocity fields with a single acquisition and refocusing the single image through the interrogation volume. The suggested system is particularly efficient and easy to use even though the actual performance of the commercially available plenoptic camera are very limited in terms of frame rate and resolution. The limitations of the implementation of these early devices will be quickly resolved.
2. Plenoptic camera

Actually, the images are acquired through sensors (analog: photographic film; digital: pixel of CCD or CMOS cameras) sensitive only to the energy of the incident radiation. In this way the information on the polarization and the phase which would allow evaluating the distance between the sensor and the source emitting the wave are lost. It is likely that the future sensors will capture, in analogy to what happens for radar, all the parameters that characterize an electromagnetic wave: amplitude, phase and polarization. These sensors will have dimensions of a fraction of the wavelength, therefore, to acquire in the visible range of the electromagnetic spectrum, a few tens of nanometers. Pending these developments, to resolve some of the limitations of current imaging systems, the use of a plenoptic camera may be useful. Its operation principle has been proposed in the early years of the last century (Ives 1903, Lippman 1908) but only the most recent technological developments allowed its concrete realization.

The plenoptic camera allows to describe the intensity of the rays passing through every point of a plane by employing the plenoptic function \( r(x,y,\vartheta,\phi) \), being \( x \) and \( y \) the coordinates of the point where the ray intersects the plane, and \( \vartheta \) and \( \phi \) the angles the ray forms with the same coordinate axes. This function allows to detect the direction of the incident rays on the sensor and then to reconstruct 3D images solving the problems associated with computer vision (Georgiev and Intwala 2003, Ahrenberg and Magnor 2006, Lumsdaine and Georgiev 2009, Lynch 2011).

Figure 1 shows a classical system for the acquisition of images generated by sources located on the plane of focus \( \pi \) and outside that plan obtaining the same out of focus images both if the source is located upstream and downstream the plane \( \pi \). If an array of pinhole an array of pinhole is placed an array of pinhole (Figure 2), the images recorded by the elementary sensors for the sources located outside the focal plane are substantially different and it is then possible to determine the distance between sensor and source. The use of pinhole produces unclear images, to increase the sharpness it is necessary to reduce the diameter and the thickness of the opening and this entails the need to increase the exposure times. In addition, a hole of dimensions comparable with the wavelength produces undesired problems associated with diffraction. For these reasons, the array of pinhole is replaced by an array of small lenses (microlenses).

![Figure 1. Images of a source placed in the plane of focus and out of that plane, which was acquired with a standard camera.](image-url)
Figure 2. Images of a source placed in the plane of focus and out of that plan, which was acquired with a camera equipped with a pinhole matrix placed in front of the sensor.

Figure 3. Scheme of a plenoptic camera.

Figure 3 shows a scheme of the plenoptic camera where different characteristic planes are identified and the transformations that define the plenoptic function going from one plane to another:

- **Plane of focus,** \( r(x,y,\vartheta,\phi) \)

\[
\begin{bmatrix}
x' \\
y' \\
\vartheta' \\
\phi'
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & t & 0 \\
0 & 1 & 0 & t \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
x \\
y \\
\vartheta \\
\phi
\end{bmatrix}
\]

- **Plane where the thin principal lens is located,** \( r(x',y',\vartheta',\phi') \)

\[
\begin{bmatrix}
x'' \\
y'' \\
\vartheta'' \\
\phi''
\end{bmatrix} =
\begin{bmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
-1/f_m & 0 & 0 & 0 \\
0 & -1/f_m & 0 & 0
\end{bmatrix}
\begin{bmatrix}
x' \\
y' \\
\vartheta' \\
\phi'
\end{bmatrix}
\]

- **Plane where microlenses are located,** \( r(x''',y''',\vartheta''',\phi''') \)
\[
\begin{bmatrix}
    x' \\
    y' \\
    \theta' \\
    \phi'
\end{bmatrix}
= \begin{bmatrix}
    1 & 0 & 0 & 0 \\
    0 & 1 & 0 & 0 \\
    -1/f & 0 & 1 & 0 \\
    0 & -1/f & 0 & 1 \\
\end{bmatrix}
\begin{bmatrix}
    x'' \\
    y'' \\
    \theta'' \\
    \phi''
\end{bmatrix}
+ \begin{bmatrix}
    0 \\
    0 \\
    s_x/f \\
    s_y/f
\end{bmatrix}
\]

- Plane of elementary sensors, \( r(x''', y''', \theta''', \phi''') \)

where \( t \) is the parameter that identifies the translational of the rays passing though the plane of focus of the principal lens, \( f_m \) and \( f_l \) are the focal lengths of the principal lens and microlenses. The final equation accounts for the fact that the optical axis of the microlenses does not coincide with the optical axis of the principal lens while being parallel and shifted by \( s_x \) and \( s_y \) along the x and y directions in the plane perpendicular to the optical axis (Georgiev and Intwala 2003).

Figure 4 presents a xz section of images acquired with a plenoptic camera when:

- the source located on the optical axis in the plane of focus (Figure 4a);
- the source located on the optical axis upstream the plane of focus (Figure 4b);
- the source located on the optical axis downstream the plane of focus (Figure 4c);
- the source located outer the optical axis in the plane of focus (Figure 4d).

The position of the light source can be assessed by considering the different responses both in the xy plane and in the direction of the optical axis of the z system.

![Figure 4](image_url)

**Figure 4.** Images of a light source placed in different positions acquired with a plenoptic camera.

3. Test cases

This paper presents the analysis of images acquired with the camera Lytro\textsuperscript{TM} managed with a dedicated software for data collection. This system allows to obtain images with different planes of focus from a single acquisition. Figure 5 shows two images of the same scene with different focus. Images of equal size static particles focused on different planes are shown in figure 6. Figure 7 presents the image area relative to each particle for different focus evaluated in terms of number of
pixels that exceed a given threshold gray level. The position of the particle in the z direction is associated to the image with minimum area. The particle sizes are evaluated taking into account classic linear optics relations, or by calibrating the system, i.e., by exploring how the diameter of a well focused particle varies varying its distance from the plane of focus. The latter procedure does not require the knowledge of parameters that characterize the acquisition apparatus, not always easy to determine. Denoting with:
d the particle diameter;
$z_p$, the distance of the plane of focus from the origin of the z axis;
$z_o$, the distance of the z axis origin from the optical center;
a, the distance from the optical center of the plane where the image is formed.
It is:
\[
\frac{d}{z + z_o} = \frac{\sqrt{4\Lambda\pi}}{a}
\]
The previous relation connects the size of the particle, $d$, the area of its image, $A$, and the distance of the plane of focus from the arbitrary origin of the $z$ axis, $z_p$. The two parameters $z_p$ and $a$ may be determined through the calibration of the system.

Figure 8 presents a vertical and a horizontal section of the test section containing a fluid seeded with particles of different diameter; the sizes of the particle images may be estimated by focusing on different planes (Figure 9), the distance of the particles from the acquisition system and their diameter may be derived accordingly.
4. Conclusions

The use of a single plenoptic camera allows to obtain simultaneously a series of images of a scene with different plane of focus. It is thus possible to extract the position of objects in the image plane but also in the direction of the optical axis. Using two consecutive acquisitions of a plenoptic camera it is possible to link particle coordinates in the interrogation volume and reconstruct the 3D velocity field. Furthermore, since the area of the image particles is minimum when these are located in the plane of focus, it is also possible to evaluate their size through an appropriate segmentation algorithm.

Although the theory of light field is consolidated, the first plenoptic cameras characterized by high resolution were developed in the last twenty years. Nevertheless, the main limitations of these first cameras are related to the low frame rate (1 frame per second) which limits their use to the measurement of flow fields characterized by very low speeds. Moreover, the available dedicated software is designed for simple image processing, and is not oriented to the identification of objects in a 3D space. However, these limits will be soon overcome with the technology development.

References

• Lynch K (2011) Development of a 3-D Fluid Velocimetry Technique based on Light Field Imagining, Auburn University Phd Thesis


