Flow Measurement and Instrumentation 49 (2016) 70–88

Contents lists available at ScienceDirect

Flow Measurement and Instrumentation

journal homepage: www.elsevier.com/locate/flowmeasinst

Parametric study on light field volumetric particle image velocimetry

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ARTICLE INFO

Article history:
Received 30 December 2015
Received in revised form
5 March 2016
Accepted 1 May 2016
Available online 3 May 2016

Keywords:
Volumetric particle image velocimetry (3D-PIV)
Light field imaging
Plenoptic camera
Multiplicative algebraic reconstruction technique (MART)

ABSTRACT

This paper presents a comprehensive investigation on how key design features can affect the performance of a plenoptic camera for single-camera volumetric velocity measurement technique. It firstly presents the prototyping of an in-house high resolution plenoptic camera; followed by an introduction to the framework of reconstructing 3D particle images from 2D light field images. Based on linear optics, a set of synthetic light field images were then generated by tracing light rays from a point light source to the plenoptic camera sensor. Detailed analysis were performed on these images to examine the effects of key parameters such as pixel microlens ratio (PMR), microlens geometry, reconstruction iteration number, relaxation factor and voxel to pixel ratio on the resolution of plenoptic camera and the final particle reconstruction quality. It is found that the microlens geometry is the vital parameter that affects the overall system performance. Hexagonal microlens generally outperforms square microlens in terms of resolution and reconstruction quality. Another important parameter is PMR, which affects resolution in *x*-, *y*- and *z*-directions, and high PMR does not necessarily lead to a better reconstruction quality.

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1. Introduction

As a non-intrusive planar velocity measurement technique, two-dimensional particle image velocimetry (2D-PIV) has progressed rapidly over the past thirty years, and is maturing into a standard fluid diagnostic method which is widely used in many areas such as fundamental fluid mechanics, micro-fluids, biofluids, aerodynamics, combustion and turbomachinery [1–4]. However, many fluid phenomena are highly complex and three-dimensional in nature, and two dimensional velocity measurements are therefore insufficient to elucidate their complicated fluid physics completely. In view of this limitation, principles and techniques of 2D-PIV have been extended by multiple studies to enable the measurements of two-dimensional three-component (2D-3C) and full volumetric velocity fields (3D-3C).

One of the first attempts was to introduce one additional camera to the traditional 2D-PIV system, and measure the third velocity component according to stereoscopic imaging principles (Stereo-PIV) [5,6]. As Stereo-PIV can only provide an additional third velocity component into a 2D velocity field, a natural extension was to simultaneously measure 2D-3C velocity slices for multiple planes by using a series of scanning laser sheets and a pair of high speed cameras [7,8]. The so-called Scanning PIV is fundamentally a 2D-3C method, and its measurable velocity cannot exceed 1 m/s due to limitations in camera frame rate, laser repetition rate or scanning mirror speed [9]. On the other hand, instead of measuring 3D velocity through multiple view geometry, Defocusing Digital PIV (DDPIV) recovers depth information from defocused images which are normally produced by a three-aperture mask. As DDPIV estimates particle 3D coordinate from its triple defocused images, a single camera DDPIV system is limited to flows with very low particle density, and normally a triple-camera arrangement is needed to resolve the flow field with satisfactory accuracy [10,11]. One of the truly volumetric velocity measurement techniques is Holographic PIV (HPIV), which records three dimensional particle displacement by in-line or off-axis holography and subsequently calculates velocity distribution by particle tracking or cross-correlation from reconstructed digital holograms. The application of this technique, however, is greatly limited by its cumbersome experimental setup and small measurement volume when holograms are recorded by CCD/CMOS sensors [12–14]. A significant step forward in the development of three dimensional velocity measurement techniques is Tomographic PIV (Tomo-PIV), which typically uses four cameras to capture particle images from different viewing angles and reconstructs 3D particle image via multiplicative reconstruction technique (MART) [9,15]. Tomo-PIV has advantages in high spatial resolution as well as relative large measurable volume (measurable range along optical axis is smaller than lateral directions though),

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http://dx.doi.org/10.1016/j.flowmeasinst.2016.05.006
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Table 1
Summary of current volumetric PIV techniques.

Type	Number of cameras	Measurement volume (mm^3)	Seeding density (ppp)
DDPIV [10,11]	1–3	150 × 150 × 150	0.034
HPIV [12–14]	1	10 × 10 × 10	0.0015–0.014
Tomo-PIV [9,15]	2–8	80 × 100 × 20	0.02–0.08
SAPIV [16]	8–15	65 × 40 × 32	0.015–0.125

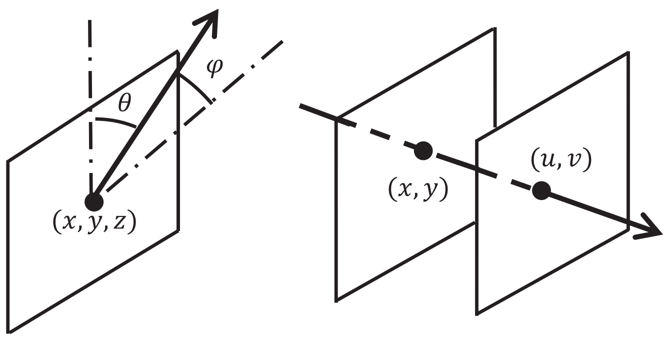

Fig. 1. Light field parameterisation methods [22].

and is being widely used in experimental fluid mechanics studies. Another multi-camera 3D velocity measurement technique is synthetic aperture PIV (SAPIV) [16]. It uses a large camera array (normally 8–15 cameras) to capture the light field image for seeding particles and reconstructs 3D particle image through synthetic aperture refocusing method. SAPIV can tolerate much higher particle density than Tomo-PIV and its measurable range along optical axis can be on the same order as lateral directions. Characteristics of different volumetric PIV techniques discussed about in terms of number of cameras, typical measurement volume and spatial resolution (particles per pixel, ppp), are summarised in the table below. Note that key parameters like measurement volume and seeding density of these volumetric PIV techniques may change in the future with the advancement of CCD/CMOS sensor technology and 3D reconstruction algorithms. For more details on the respective volumetric velocity measurement techniques, readers are referred to the above-mentioned papers (Table 1).

The above-mentioned 3D-PIV techniques employ either highly complex optical systems or multi-camera arrangements, which not just complicates experimental procedures and increases hardware cost, most importantly, it prevents these techniques from being applied in many flow scenarios where

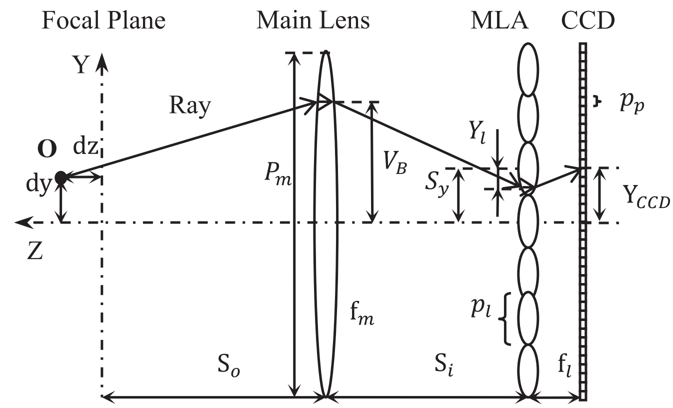

Fig. 3. Light ray path of plenoptic camera.

optical access is limited. As such, measuring volumetric velocity fields via a single camera is highly desirable for the experimental community. One recently developed single camera 3D velocity measurement technique employs a three-vision prism to realize triple-view particle image recording with one CCD sensor [17]. Following similar data processing procedures as Tomo-PIV, this technique can provide accurate 3D velocity measurement for a relatively small volume. Another single camera volumetric velocity measurement technique is the light field photography based PIV (shorted as LFPIV hereafter). Unlike the camera array system used by SAPIV, the LFPIV records particle 4D light field images through the combination of a high resolution micro-lens array (MLA) and a high resolution CCD sensor (the so-called plenoptic camera). Studies have demonstrated that LFPIV can resolve 3D velocity fields through ray tracing based reconstruction and 3D cross-correlation [18,20]. Although LFPIV is still in its early development stage, attempts have been made on measuring IC-engine flow by LFPIV, showing its great potentials in resolving complex 3D flows [20,21]. In particular, the authors are motivated to employ the present light field based volumetric particle image velocimetry technique in the areas of complex jet flows [22–26] and flapping membranes [27–29] in the future. Preceding studies have demonstrated that while 2D-PIV techniques may be able to shed light on certain aspects of the flow scenarios, full appreciation and quantification of the 3D flow fields remain elusive. Good understanding of the 3D flow fields is essential towards optimizing complex jet flows and flapping membrane dynamics for mixing enhancements and renewable energy generation respectively.

The current work presents a systematic analysis on the effects of key optical and experimental parameters on particle image reconstruction accuracy as well as measurement resolution of

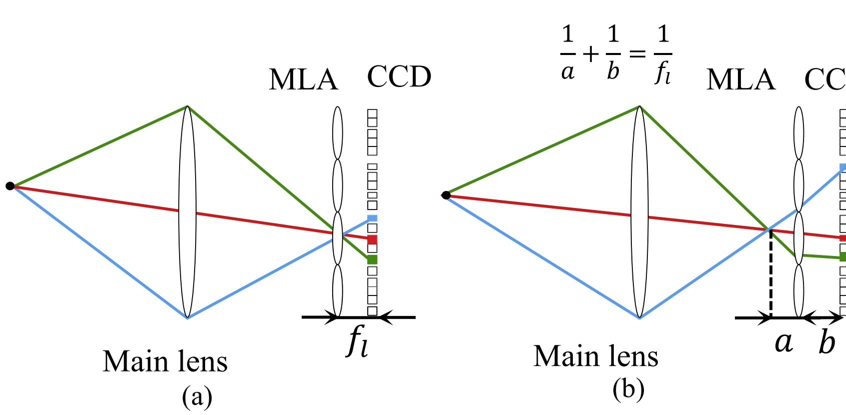

Fig. 2. Schematic of (a) plenoptic camera and (b) focused plenoptic camera.

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