Application of Plenoptic Imaging in Multiphase Flows

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ABSTRACT

The acquisition of the third, or “depth”, coordinate in space during the imaging of a phenomenon, such as liquid atomisation, can contribute a great deal to the understanding of the physics behind it. Plenoptic imaging allows us to instantaneously acquire “3D images”, permitting, with suitable image processing software, the 3D reconstruction of the object space. This paper presents a computational code which optimizes the design of the optical arrangement of a plenoptic camera according to the demands of an experiment. The attributes of the plenoptic camera (depth of field, field of view, angular and spatial resolution etc.) were derived as a function of the of intrinsic geometry of the plenoptic camera, allowing its optimization for specific purposes. Using this design code, a prototype plenoptic camera was manufactured, which is suitable for both sparsely (PIV images) and densely (droplet images) filled object spaces. A calibration image of individual 0.2mm diameter dots and a levitated droplet with diameter of 0.98mm were placed initially at the focal plane of the plenoptic camera and then at increasing distance from it, to test the amount of angular information captured on the sensor of the camera, form which the information about the third coordinate in the image is derived. This paper presents the results of an iterative reconstruction, based on the MLOS-MART algorithm, for the 3D reconstruction of the object space. The reconstruction performed by the algorithm was evaluated against a test phantom of four particles located in object space. The reconstructed particle coordinates were in complete agreement regarding the initial x, y coordinates, although additional ghost particles arose in the direction of the optical axis. Finally, this paper demonstrates the feasibility of the application of a plenoptic camera and 3D reconstruction of the object space in multiphase flow context.

1. Introduction

A traditional camera records an object, or scene, as an image which is an intensity distribution on a generally planar photosensitive surface or sensor, formed at the image plane of the camera’s lens. As a result, the intensity of the light only is captured on the sensor, while the angular information associated with the direction of the rays striking the sensor is not acquired: as a consequence, the depth of field is finite which depends on, among other parameters, the aperture of the lens. A plenoptic camera (also called a light-field camera) similarly captures an image on a single camera sensor but, in contrast, includes information about the the direction of the rays also. All this information is recorded on a conventional (planar) digital sensor once,
simultaneously, focused at a nominal objective plane and, through the application of an appropriate algorithm, allows the generation of an in-focus image over finite range of objective plane distances from the lens, distances which are much longer than the depth of focus of a conventional camera. This leads to the ability to re-construct a three-dimensional representation of the object using the so-called “four dimensional” information captured by the plenoptic camera’s planar sensor (i.e. the conventional intensity distributed over the x, y coordinates of the plane, \(I(x, y)\), as well as the \(\theta(x, y), \phi(x, y)\) angles relating to the angles of incidence of the rays relative to the normal to the plane of the sensor). With suitable algorithms the intensity distribution on the sensor \(I(x, y)\) combined with the direction of the light rays \(\theta(x, y), \phi(x, y)\) give information about the object in the z-direction (i.e. parallel to the optical axis), thus the plenoptic image could be refocused in virtually any plane within the depth of field of the light-field camera. The depth of field (or focus range) is considered as the distance between two planes along the optical axis (z-axis) in which the scene remains “acceptably sharp” (i.e a threshold in ERR explained in following section). Within that depth of field, the plenoptic camera is able to achieve a three dimensional re-construction of the object or scene.

The angles relating to the angles of incidence of the rays relative to the normal to the plane of the sensor are recorded by incorporating a Micro-Lens Array (MLA) which is placed in front of the image sensor (the distance depends of the particular type of plenoptic camera) and constitutes the main intrinsic geometrical difference between a traditional and a light-field camera. The micro-lens array consists of a planar array of many microscopic lenses with tiny focal lengths: their purpose is to provide a known divergence of the individual incident light rays before reaching the sensor; which is how the angular information is captured and recorded on the camera sensor. As a result, instead of acquiring the traditional two dimensional image, the equally two dimensional plenoptic image is composed of as many tiny non-overlapping images (micro-images) as the number of the micro-lenses on the micro-lens array. Every micro-image differs from its neighbours, because the light-rays were diverted by the micro-lens differently, depending on the corresponding micro-lens position in the array.

This idea was conceived by Lippmann [1] in 1908, but due to technological limitations it had not been widely realized until 1992 when Adelson and Wang [2] made one of the first attempts to construct a plenoptic camera. However, due to the limited sensor resolution of the camera’s sensor at that time, the image resolution of the output images of their light-filed camera was low and impractical for application to flows in fluid mechanics research. Since then, advances in plenoptic imaging have been rapid due to algorithm developments [3], [4], [5], [6], as also
technological growth, both of which have led to the commercial production of light-field cameras.

Moreover, the technological improvements on the micro manufacturing of optical equipment has recently permitted the utilization of a plenoptic camera in the context of applications to fluid mechanics. Specifically, Thurow et al. [7] compared experimental results from stereo PIV and plenoptic measurements visualizing the wing tip vortex of a flat plate. The results were found to be in reasonable agreement showing that plenoptic PIV is a viable option. Cenedese et al. [8] used the Lytro commercial plenoptic camera and acquired plenoptic images of spherical particles. They measured the area which the particles were covering as a function of the distance in the optical axis direction, but due to the low frame rate of the plenoptic camera were unable to measure the velocity of the flow field. Nonn et al. [9] measured the velocity inside a water analogue of a combustion engine using a commercial (Raytrix) plenoptic camera. The results were compared with a scanning light-sheet technique and found to be within reasonable agreement. Lillo et al. [10] acquired measurements of fuel sprays (three different spray angles 70, 80 and 90°) simultaneously using a plenoptic camera Raytrix R29 and a high-speed CMOS camera with the purpose of 3D re-construction and depth estimation; both were based on an in-house code which cross-correlates the images formed by the individual micro-lenses (micro-images). The results produced by the plenoptic camera were found to be in good agreement with the ones of the high-speed camera but, for a more robust analysis, further development in reconstruction techniques is needed to treat translucent objects mainly because of the low intensity contrast in the micro-images.

Plenoptic imaging is an emerging technology and literature, especially in multiphase flows, is limited. Most research has been done using commercial plenoptic cameras, the usage of which may not be optimised for experiments in fluid dynamics. So, the aim of this paper is to manufacture a plenoptic camera for the acquisition of images with sufficient resolution to identify droplets (with characteristic size from 0.5mm to 5mm) at a distance of 0.2m from the camera which permit the 3D re-construction of the droplets’ shape. This will be realised with an algorithm that determines how, and to what extent, the intrinsic geometry of a plenoptic camera and the pixel size of its sensor contribute to the attributes of the image (depth of field, spatial and angular resolution), thus allowing its optimization for a particular experimental set-up. In particular, a plenoptic system depends on several variables:

- Size of the pixels
- Ratio of the micro-lens diameter to the pixel size
- F-numbers of the micro-lens and the main lens, which should be equal so as to avoid micro-image overlapping on the sensor plane
- Ratio of the micro-lens focal length to the distance between the sensor plane and the micro-lens array

This work presents a parametric analysis, with the inputs being the previous variables, to quantify the reconstruction quality of the object space.

2. Theoretical model

There are two types of plenoptic cameras: the conventional plenoptic camera or Plenoptic 1.0 [4] and the focused plenoptic or Plenoptic 2.0 [5]. In the conventional plenoptic imaging concept, a micro-lens array is positioned at the image plane of the main lens and the sensor is positioned at the focal length of the micro lens. Spatio-angular sampling is fixed. In other words, the amount of spatial information captured on the sensor is equal to the number of the micro-images (in this case the number of micro-lenses) and the angular information captured is the number of different views of the object space (in this case the number of the pixels under each micro-lens).

In the focused camera (Plenoptic 2.0) concept, the micro-lens array is also focused on the image plane of the main lens but the image sensor is placed at a distance greater, or smaller, than the focal length of the micro-lenses. As shown in Fig.1, the image plane of the main lens is formed at a distance \(a\) in front of the micro-lens array, \(b\) is the distance between the micro-lens array and the sensor of the camera and \(S_0\) & \(S_i\) are the distances between the object and image planes from the main lens respectively. The spatio-angular sampling is now not fixed but, as will be discussed later, depends on the ratio \(a/b\).

![Fig.1 Sketch of a Plenoptic 2.0 optical system](image-url)
Let $r(q, p)$ be the radiance distribution at a given plane perpendicular to the optical axis, where $q=q(x, y)$ and $p=p(\theta, \phi)$ denote the position and the direction respectively with respect to the optical axis. The direction of the rays can be described as being transformed by multiplication with an optical transform matrix. The transformation matrix $T$, (Eq.1), used for the translation of a light ray in space, is:

$$T = \begin{pmatrix} 1 & t \\ 0 & 1 \end{pmatrix}$$  \hspace{1cm} \text{Eq. 1}$$

where $t$ is the translation distance and the transformation matrix $L$, (Eq.2), is used for the refraction of a light ray by a lens:

$$L = \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix}$$  \hspace{1cm} \text{Eq. 2}$$

where $f$ is the focal length of the lens. For example, let $r, r'$ be the radiance distribution before and after a lens and $f$ the focal length of the lens: then the refraction is modelled according to: $r'=L r$. Moreover, both the micro-lens array and the main lens are considered to be thin lenses so (Eq.3) can be used. In particular, in the case of the main lens:

$$\frac{1}{f_{\text{main}}} = \frac{1}{S_o} + \frac{1}{S_i}$$  \hspace{1cm} \text{Eq. 3}$$

where $f_{\text{main}}$ is the focal length of the main lens and $S_o$ & $S_i$ are the distances of the main lens from the object plane and the image plane respectively (Fig.1). Diffraction effects are taken into consideration due to their importance in PIV measurements, where the image of seeding particles on the sensor is of order of the size of a pixel; however for general purpose applications, such as liquid atomization, the characteristics length scale in the object space is far bigger than the diffraction limit of the pixel, so this consideration is of minor importance.

3. Results

Parametric Analysis

As shown in Fig.1, the image plane of the main lens is formed in front of the micro-lens array. As explained by Perwass and Wietzke [6], the number of micro-lenses from which a point in the image plane is viewed depends on the distance of the image plane from the micro-lens plane. If
the “fill factor” of the micro-lens array (the ratio of the active area to the total array of the micro-lens array) is unity, the plane which has all of its points viewed by at least one micro-lens is called the theoretical covering plane. In reality, due to the space between the micro-lenses on the array, the theoretical covering plane is further away from the micro-lens array plane and therefore is called the total covering plane. In order to achieve a stereoscopic view of a scene which enables the reconstruction of the object space, a point needs to be viewed by at least two micro-lenses. The plane which has all of its points viewed by at least two micro-lenses is called the double covering plane. As a result, from only the double covering plane and onwards is a point viewed by at least two individual micro-lenses; this enables the triangulation of the image points and thus the reconstruction of the object space. The theoretical, total and double covering planes are shown in Fig.2. When a point is viewed by two or more individual micro-lenses, then two or more pixels will be illuminated by that single point. The concomitant number of useful pixels on the sensor (effective resolution) decreases as the image plane moves further away from the micro-lens array. Another term that will be used later is the effective resolution ratio (abbreviated to ERR) which is the ratio of the effective resolution to the resolution of the sensor. Moreover, for the same reason, the effective resolution of the main lens is unity on the image plane and falls with increasing distance for planes further away from it (Fig.2).

For a square pixel size of \( d_p = 5.5\mu m \), micro-lens diameter \( d_m = 0.125mm \) and focal length \( f_m = 0.25mm \), Fig.2 shows the characteristics of a plenoptic camera as a function of the main lens and micro-lens distance. The micro-lens array is placed at 0mm and the sensor is at -0.34mm on the optical axis (\( i.e. \) parallel to the \( z \)-axis), which is slightly longer than the focal length of the micro-lens (\( i.e. \) this is “Plenoptic 2.0” design). The theoretical, total and double covering planes of the micro-lens array, as discussed in previous section, are also illustrated. The thinner vertical lines are the focal planes of the micro-lenses. In addition, Fig.2 shows the ERR of the micro-lens array and that of the main lens. Finally, for an arbitrary, constant ERR, the image-side depth of field of the plenoptic camera is deduced. In particular, as can be seen from Fig.2, for an ERR of 0.15 the depth of field of the camera is almost 2mm.

This novel algorithm gives the ability to determine and optimize the specifications of the camera (pixel size, micro-lens diameter, focal length, intrinsic geometry) based on the requirements of a specific experiment.
**Fig.2** Effective resolution ratio diagram of a plenoptic camera as a function of the distance between the main and micro-lens array. The thinner vertical lines are the focal planes of the micro-lenses. The micro-lens array is placed at 0mm and the sensor is at -0.34mm on the optical axis. The pixel size $d_p$ is 5.5μm square, the micro-lens diameter $d_m$ is 0.125mm and the focal length $f_m$ is 0.25mm.

**Object Space Acquisition and Re-construction**

The plenoptic camera having been designed, and knowing its intrinsic geometry (mainly the pixel size, focal lengths and distances), a computational code was created for the calculation of an image of the phantom (i.e. test case) in object space which is based on Gaussian optics. It is suitable for both sparsely (PIV images) and densely (droplet images) filled object spaces. To generate the object from an arbitrary, known, phantom, the transformation matrices, given in Eq.1 and Eq.2, enabled calculation of the trajectory of the light ray as it travelled from the object plane to the sensor plane of the camera where the plenoptic image was generated on the (computational) sensor.

For the evaluation of the re-construction technique, we used a phantom consisting of individual particles (point sources of light) which were randomly placed in the object space. Each particle emitted light rays of the equal intensity but over a limited range of solid angles, thereby permitting the application of geometric optics. As a first step towards the reconstruction of the object space, a Multiplicative Line-Of-Sight (MLOS) method was employed, whereby a single ray (with intensity equal to the pixel’s intensity) was emitted from each and every illuminated pixel.
on the sensor and, by using geometric optics, its trajectory from the object plane was ‘back calculated’. The light rays intersected inside the boundaries of the depth of focus of the plenoptic camera and these intersection points corresponded not only to the particles constituting the phantom but also to some so-called ghost (i.e. non-existent in the phantom) particles as well, without there being enough information \textit{a posteriori} to be able to identify these latter particles. For that reason, to reduce the radiance of the ghost particles and to be able to identify them, a Multiplicative Algebraic Reconstruction Technique (MART) [11] was employed as a second step towards the reconstruction of the object space. MART is an iterative, and computationally expensive, technique widely used in 3D PIV and in computer tomography. In order to make the reconstruction more computationally efficient, the object space as derived from the MLOS approach was used as an initial first guess to the iterative MART process. More details about the MLOS-MART reconstruction algorithm are to be found in [12].

For the plenoptic camera presented in the previous section (Fig.2), some preliminary results of the above reconstruction technique are presented. Fig.3 shows arbitrarily distributed particles in the object space, with each particle emitting $10^4$ light rays which were captured by the camera sensor using the ray-tracing technique discussed earlier. For the reconstruction of the particle locations from the plenoptic image, a 3D volume (10mm x 6mm x 2mm) consisting of 100x60x20 voxels was assumed. Voxels were considered to be spherical with diameter of the order of the micro-lens diameter (a higher spatial discretization would have been possible if smaller voxels were specified, however the computational cost would increase). Fig.4 shows the voxels with the highest radiance, after the reconstruction, using the MLOS algorithm and four MART iterations. From the figure can be seen that the $x, y$ coordinates of the phantom, and of the reconstructed, particles are in complete agreement but some ghost particles remain; this illustrates the inherent limitation of the iterative (ART) reconstruction techniques, however algorithm development may permit improved reconstruction quality.
Fig.3 Initial particle location (•) in object space coordinates

Fig.4 Initial particle location (•) in object space coordinates and reconstructed particles (○) with depth shown in the colour bar [mm]

3. Experimental results

Using the software described in previous section, a prototype plenoptic camera was constructed, with the characteristics shown in Fig.2, comprising a commercial 2MP CMOS Basler Ace camera with the addition of a micro-lens array (4264 individual micro-lenses) in front of the sensor. The micro-lens array was introduced in front of the camera’s sensor and had the ability to translate in the perpendicular to the sensor direction; permitting the increase-decrease of their separation distance. The translation distance was approximately 3mm, enabling the camera to be used either as a “plenoptic 1.0” design, if the distance of the micro-lens array from the sensor equalled the focal length of the micro-lens, or as a “plenoptic 2.0” design if the the image plane of the main lens was formed at distance $a$ in front of the micro-lens array (Fig.1).

As can be seen in Fig.1, the depth of field of the micro-lens array for an effective resolution ratio of ERR=0.1 was approximately 1.5 mm. How this is being transformed in the object plane depends on the main lens of the plenoptic camera. In other words, the depth of field of the plenoptic camera could be smaller, larger or equal to the depth of field of the micro-lens array depending on the main lens. In the case of the prototype plenoptic camera, the use of a commercial micro-Nikkor lens with 105mm focal length led to a depth of field equal to approximately 30mm.
Fig 4 illustrates the type of calibration image that was used to check the functionality of the plenoptic camera. The image consisted of white dots with diameter of 0.2mm with a pitch of 2mm on a black background. The image was back illuminated and placed at first at the focal plane of the plenoptic camera and then at increasing distances from the focal plane in order to test whether the angular information was captured by the plenoptic camera.

Figs. 5(a-g) show the raw plenoptic images as these was acquired by the plenoptic camera at increasing distances between the main lens and the object plane along the z optical axis. The field of view of the camera could be calculated from Fig. 5a and was found to be 18mmx10mm, which is close to an image magnification of 0.6.
**Fig. 5** Plenoptic images of the calibration image acquired at increasing distances from the focal plane of the plenoptic camera

It can be seen that while the calibration image is in the focal plane of the plenoptic camera, Fig.5a, each dot was seen by relatively few micro-lenses and that not all of the dots are in focus, which may be attributed to the fact that the normal to the target image was not perfectly parallel to the optical axis. As the working distance (distance between the main lens and the object plane) increases, Fig.5b-g show that the white dots are viewed by a greater number of micro-lenses, providing larger amounts of the angular information.

Finally, a plenoptic image of a droplet was acquired at an image magnification of 1.2. The droplet was spherical with volume 0.52μL and diameter approximately 0.98mm. It was placed inside the chamber of an ultrasonic levitator [13] where it was suspended. The droplet was initially placed at the focal plane of the plenoptic camera and subsequently the levitator was translated further away from the focal plane and the main lens of the plenoptic camera. A part of the plenoptic image is shown in Fig. 6 which shows that when the droplet was at the focal plane of the plenoptic camera (Fig. 6a), the image was focus while, as the distance increases, the separate views behind the micro-lenses became more distinct.
Fig. 6 Plenoptic images acquired of a levitated 0.98 mm diameter droplet for increasing distances of the droplet from the focal plane of the plenoptic camera at an image magnification of 1.2.

4. Conclusions

A novel code has been developed which permits the design, and hence optimization, of the characteristics of plenoptic camera for a given experimental requirement. This code led to the design of a plenoptic camera which is suitable for both sparsely (PIV images) and densely (droplet images) filled object spaces. This paper presents a simulation based on a phantom object
and its reconstruction; the reconstructed $x$, $y$ coordinates (i.e. in the plane parallel to the field of view of the camera) of the particles were in complete agreement with the initial $x$, $y$ coordinates, although additional ghost particles arose in the direction of the optical axis. A prototype plenoptic camera was constructed and used to view individually a calibration plate and a levitated droplet in increasing distances of these objects from the focal plane of the plenoptic camera. Overall, there is a strong indication that plenoptic cameras could contribute in great extend to the better understanding of liquid atomisation by providing additional information along the optical axis of the camera, which is lost during the imaging with conventional camera. However, additional development in 3D reconstruction algorithms are needed, especially for the modelling of translucent objects, such as droplets.

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References

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