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An In-depth Review of Volumetric Three Component Velocimetry (V3V)

Jeshwanth Kundem[1*]

Abstract

Volumetric Three-Component Velocimetry (V3V) is a technique developed by TSI to measure the velocity fields in a volumetric domain. It is a 12-mega-pixel CCD camera with three apertures for 3D recording of images. V3V can obtain readings from a volume up to 140 × 140 × 100 mm^3 at the 7.25 *Hz* capture rate used in the PIV technique. The particle images are processed using a pattern search algorithm, to find the positions of the tracer particles, then particle tracking is performed to obtain the 3D velocity vectors. V3V has the capability of capturing up to 50,000 particles in a single image. This paper is a general review on the basic theory of V3V and its applications.

Keywords:

V3V;
PIV;
LDV;
CCD Camera.

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Author correspondence:

Jeshwanth Kundem
Email:
jeshwanth.kundem@outlook.com

1. Introduction

As we all know most of the flows in nature are three-dimensional. To understand these complex flows one should have advanced experimental techniques which can extract the instantaneous field information in a volumetric domain. Unfortunately, the traditional PIV techniques can capture only on a 2D slice. While Stereoscopic PIV methods can get the third component of velocity but is still on the 2D slice not on a volume. It also fails to provide information about the velocity gradient concerning the third direction. Attempts to get the quasi-instantaneous measurements in the volumetric domain with stereoscopic PIV employed scanning the laser in the third direction with the help of a rotating mirror.

Holographic PIV on the other hand is capable of providing truly volumetric data, involving interrogating an interference pattern generated by interference of reference laser beam with light seeded by the particles. However, these use photographic films as the recording medium, which severely limits the number of realizations. Another method of obtaining volumetric data is Tomographic PIV which uses at least three cameras oriented at different angles to completely get the volumetric data. However, some of the obvious drawbacks of this technique are the time and complexity of using more than three cameras and very long processing for smoothing during the reconstruction of images.

[1*] Aerospace Engineering & Mechanics Department, University of Minnesota – Twincities, USA

So the purpose of this paper is to introduce a truly volumetric technique for three-dimensional flow measurement in a volume up to 100 *mm* in depth with cross cross-sectional size of 140*mm* × 140*mm*. The key idea of this technique is a single-body 3D camera that records tracer particle images from three different views simultaneously. It is based on the Defocusing Digital PIV (DDPIV) concept developed by Pereira and Gharib [3]. The three sensors in the camera are arranged in a triangular pattern, so once the images are obtained the 3D positions of the particles can be directly obtained with a pattern search algorithm. This approach is different from the triangulation methods used in stereo-vision photogrammetry since often there are large numbers of particles, and it is unreliable to use the triangulation method.

This paper describes in detail the V3V configuration, the calibration method and the Image processing technique. The results of some general flows captured using V3V will be discussed. These results are very promising and indicate the 3D nature of the flow field and the flow structure can be revealed using the V3V system.

2. V3V System Configuration

In general, the system consists of the 3D camera probe, a Nd: YAG double pulsed laser with optics to generate the volumetric illumination, a synchronizer, and a computer system with Insight V3V software (figure 1). Typically it can measure up to a distance of 670*mm* from the camera probe. The orientation of the camera probe concerning the cone is flexible. Focusing is generally not required since the camera is designed to have a large enough depth of field.

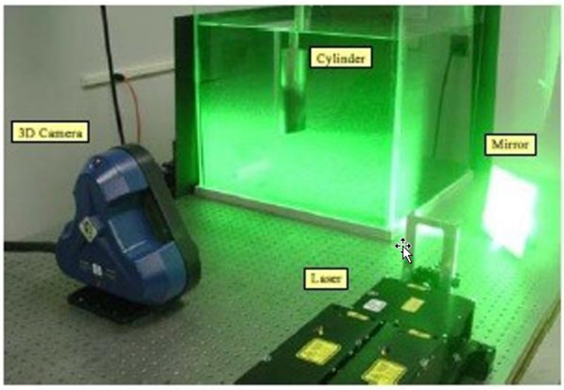

Figure 1. *V3V System in action*

The operation is similar to a typical PIV system. The camera is synchronized with a pulsed laser and images are captured during two successive laser pulses by predetermined time interval. Moreover over the V3V can continuously run for up to one hour using Direct Recording technology.

3. Imaging Principle (3D) and Calibration

V3V in principle uses a multi-view photogrammetry technique. Since the camera has three image sensors arranged in a coplanar triangular pattern (face plate) the fields of view of the three sensors intersect to form the viewing region. The three particle images look like a triangle in the image plane (triplet figure 2). The size of the triangle determines the depth position. The closer the particle is to the face plate the larger the size of the triangle and vice versa. On the other hand, the x and y positions of the particles can be determined by the centroid of the triangles.

This 3D imaging concept is based on pinhole optics and assumes there is no physical error. A real-world camera behaves in a slightly different way. Therefore a calibration procedure is needed to remove these distortions. The main errors are due to Mechanical misalignment - which is the misalignment of CCD sensors when the camera is assembled, Optical distortion - introduced by the lens and flow facility, Pinhole optics - the aperture locations of the lens placed in front of the CCD sensors are not known apriori. All these problems are taken care of in multi-plane calibration.

In the calibration images of a calibration plate are captured in planes across the depth of the measurement volume. Once the 2D calibration images are captured, a 2D Gaussian fit is used to find the dot locations on the plate, and are then related to known geometries to determine the 3D locations. Figures 3 & 4 show the calibration signature graph formed by the centers of the calibration target in each plane. Unlike the calibration in stereo PIV, the calibration that is employed to quantify the deviation is essentially a 2D to 2D mapping between the image plane and the object planes at different z.

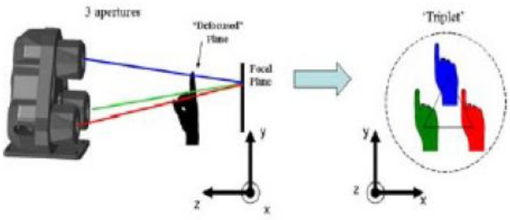

Figure 2. *Triplet Concept*

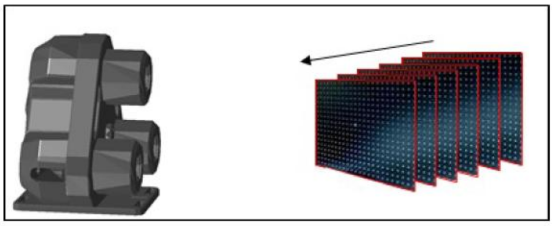

Figure 3. *Calibration Procedure*

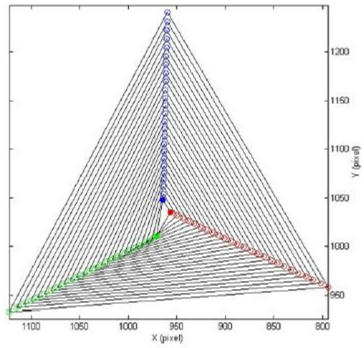

Figure 4. *Calibration signature graph*

4. Image Processing

The images look identical to standard PIV images, although these images record particles in a large volume instead of the planar sheet (figure 5). The idea behind the processing is to get the 3D positions from the raw images. One V3V capture consists of 6 separate images, one from each aperture at two different instances (A and B). The displacement of the particles is obtained in four stages.

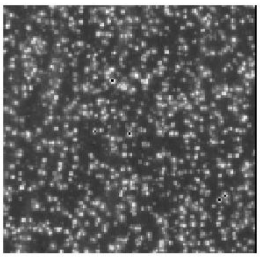

Figure 5. *Raw particle image (128 X 128 pixels)*

4.1 2D Particle Identification

In this step, we identify the x and y locations of the particles in individual images from all the apertures. At first, a baseline intensity threshold is set, this quickly reduces the search area and eliminates the background. The second parameter is a local ratio, in which the center of the particle must have high intensity compared to the surroundings. Finally, a Gaussian intensity profile is fitted to the particle image the peak of which gives the center of the particles. The 2D Gaussian fit is chosen because of its unique ability to separate overlapped particles [3] equation (1), where a_i is the amplitude of particle image i and (x_{ci}, y_{ci}) are subpixel coordinates of the particle image centroid. r_i is the particle image radius and is taken as the standard deviation term of the Gaussian function.

$$g_i\left(x,y\right)=a_i exp\left[\frac{\left(x-x_{c_i}\right)^2+\left(y-y_{c_i}\right)^2}{2r_i^2}\right]$$

(1)

4.2 3D Particle Identification (triplet search)

Images from each of the apertures are effectively combined to obtain the 3D location. Each 'triplet' represents a single particle in the flow field. As mentioned before the centroid represents the x and y location and the size of the triplet gives the z location, the correspondence of a 2D image from one aperture to the other aperture is obtained through volumetric spatial calibration 3. Figure 6 displays the 2D representations of the view from each aperture. Green represents the ray extending from the left aperture, while the red is from the right aperture. Similarly in the other day's images, the blue ray is from the top aperture. In all the images the ray from the corresponding aperture appears as a dot. Then the particles are tracked to match a given pattern, in this case triangle ([2]) The search is done in two steps, a coarse search and a fine search which is depicted in Figure 7. The coarse search requires the particle position to match within 1 pixel for all three images and the fine search requires it to match within 0.5 pixels. If a triplet is not found that falls within 0.5-pixel criteria, the 2D particles are not used. This process is repeated for all the particles.

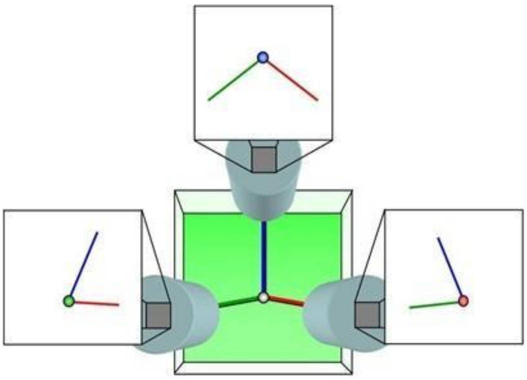

Figure 6. *Representation from each aperture*

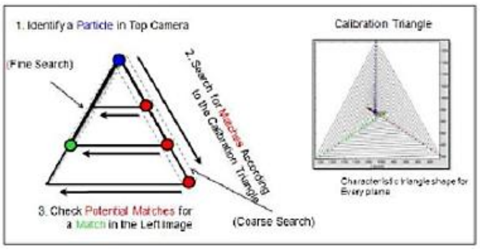

Figure7. *Triplet search based on calibration graph*

4.3 3D Particle Tracking

Once you identify the particles, the next step is to match the particles in both frames. The particle tracking method is a natural choice because the positions of the particles are available. There are three algorithms for particle tracking - the nearest neighbor method, the relaxation method, and the particle matching method. In this paper, we talk about the more general idea of a relaxation method. However, differently from the cross-correlation method, in which the positive estimate is increased only if the neighboring particles find their partners exactly at the same location, the positive estimate in the relaxation method is increased when the neighboring particles find their partners within a finite distance from the parallel displacement point. This approach is the main reason why the algorithm is more effective in rotating and shearing motions in the flow.
The detailed process of the relaxation method is as follows [1]. In the first step, each particle from the first frame preselects its candidate from the second frame using equation (2).

$$|x_i - y_j| < R_s$$

(2)

where x_i and y_j are the coordinate vectors from the first frame and second frame particles and R_s is the maximum possible displacement of the particles. Similarly, every first particle selects its neighbors in the first frame (equation (3)).

$$|x_i - x_k| < R_n \tag{3}$$

where x_i and x_k are the coordinate vectors of the reference and neighboring particles and R_n is the radius of the vicinity in which similarity motion is preserved.

Next, the probability of matching between the first frame and the second frame is introduced. P_{ij} denotes the matching probability for particle i in the first frame to particle j in the second frame and the no-match probability P_i defined for the same particle. Both should satisfy equation (4) and equation (5) shows the initial probability, where M denotes the number of preselected particles from the second frame.

$$\sum_j P_{ij} + P_i^* = 1 \tag{4}$$

$$P_{ij}^{(0)} + P_i^{(0)} = \frac{1}{M+1} \tag{5}$$

In the next step the particle probability is updated according to equation (6) where A and B are weighting constants (usually $A = 0.3$ and $B = 3.0$) and P_{kl} is for the neighboring particle k concerning its candidate l.

$$\tilde{P}_{ij}^{(n)} = \tilde{P}_{ij}^{(n-1)} \left(A + B \sum_k \sum_l \tilde{P}_{kl}^{(n-1)} \right) \tag{6}$$

The contribution from the neighbor's probability is limited to satisfying the condition from equation (7), where R_c is the radius of the relaxation area in which deviation from parallel motion is allowed.

$$|d_{ij} - d_{kl}| < R_c \tag{7}$$

In the last step, the updated probabilities are normalized equations (8) and (4), and are ready to use for the next iteration. The no-match probability is normalized by itself since it cannot be updated using equation (6). Usually, it takes 10 to 20 iterations to complete the process.

$$P_{ij}^{(n)} = \frac{\tilde{P}_{ij}^{(n)}}{\sum_j \tilde{P}_{ij}^{(n)} + P_i^{*(n-1)}} R_c \tag{8}$$

4.4 Grid Interpolation

From the relaxation method, we obtain the displacement of the particles at random positions for each sample according to particle locations. It is best to have a rectangular grid to analyze other characteristics of velocity like vorticity etc.,. This can be done by Gaussian-weighted interpolation. Velocity at each node is calculated by proportionality based on the distance to the nearest randomly spaced vectors.

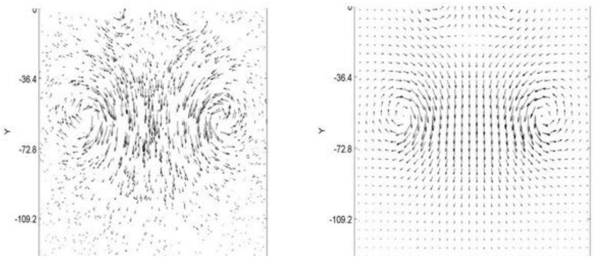

Figure 8. *Grid interpolation of a vortex ring*

5. Conclusion

The paper covered various aspects of V3V and how it can be implemented in an industrial lab. Even though the core concept is based on PIV, V3V provides a portable way of getting 3D profiles of velocities, with a minimal amount of calibration compared to at TSI 4 camera image-based system.

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