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THREE-DIMENSIONAL PARTICLE IMAGE VELOCIMETRY MEASUREMENT TECHNIQUE

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ABSTRACT

The experimental flow visualization tool, Particle Image Velocimetry (PIV), is being used to determine the velocity field in two-dimensional fluid flows. In the past few years, the technique has been improved to allow the capture of flow fields in three dimensions. This paper describes changes which were made to two existing two-dimensional tracking algorithms to enable them to track three-dimensional PIV data. Results of the tests performed on these three-dimensional routines with synthetic data are presented. Experimental data was also used to test the tracking algorithms. The test setup which was used to acquire the three-dimensional experimental data is described, along with the results from both of the tracking routines which were used to analyze the experimental data.

INTRODUCTION

Recent measurement techniques in modern experimental fluid mechanics require the development of methods for the measurement of whole, instantaneous velocity fields. Particle Image Velocimetry (PIV) is a full-field, noninvasive flow visualization method. As originally developed, it could track two-dimensional flows. Figure 1 shows a typical two-dimensional PIV setup. In order to advance the study of single and two-phase flows, the ability to measure time-dependent, three-dimensional velocity fields needs to be developed.

Recently, progress has been made in extending two-dimensional tracking algorithms to three-dimensional flow fields.[1,2,3] The main feature of PIV is that a full-field flow visualization can be produced. This visualization is capable of providing both time varying and instantaneous maps of both qualitative and quantitative fluid flow parameters (such as velocity, shear stress, vorticity, and turbulence) over an extended region of interest without disturbing the flow field under investigation.

The techniques required in three-dimensional PIV are similar to those used in two-dimensional PIV. However, there are a few differences. Two-dimensional PIV data is obtained by shaping a pulsed or chopped laser beam into a thin sheet of light which is passed through the seeded fluid of interest at a timed interval. The reflected light from the particles in the two-dimensional plane of the sheet of light is captured by the digital camera or cameras which are set perpendicular to the sheet. With known time between pulses, imaging system hardware, and imaging tracking analysis software, the flow field can be tracked to produce a velocity field plot.

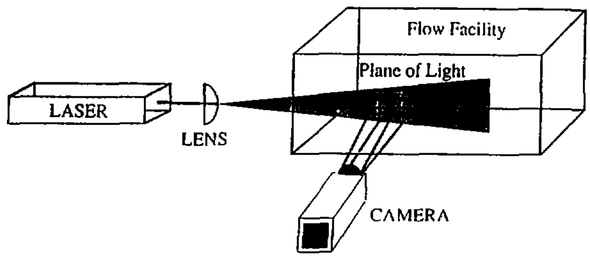

Figure 1: Two-Dimensional PIV Setup

Three-dimensional PIV requires that a volume of light be used (instead of the sheet of light used in two-dimensional PIV). This three-dimensional method also requires that several cameras acquire data simultaneously, instead of the single camera which can be used in two-dimensional PIV. Finally, a more intensive calibration of the camera images is required than that normally used in two-dimensional PIV (for tracking the data).

The interest in a three dimensional tracking method mainly stems from the flexibility it offers. Researchers have had success in tracking two-dimensional flows.[4,5] However, when two-dimensional data is acquired, the effect of the third dimension can cause particle tracking algorithms to produce incorrect vectors. Since turbulent flows are by their nature three-dimensional (especially flows containing bubbles), a two-dimensional method usually proves inadequate under these conditions.

Three-dimensional data can be obtained by recording and combining multiple two-dimensional images obtained from several cameras placed at different angles. This paper reports the modification of two existing two-dimensional tracking algorithms to produce two algorithms capable of tracking tracers seeds through consecutive image frames in a three-dimensional space frame with a common time lapse.

MULTI-FRAME TRACKING ALGORITHM

The particle track velocimetry technique (PTV), one of the image processing techniques, is generally applied to flow visualization pictures in which the displacements are examined to determine the velocity field. Recently, two methods have been developed to obtain the displacement of the seed from one time step to the next. The first is the multi-frame particle algorithm and the second is the cross-correlation tracking algorithm. The purpose of the multi-frame particle tracking code was to track images through multiple time steps.[5] In this technique, a minimum of four sequential images are required. A direct point-by-point matching of images from one frame to the next is performed. These images can be data obtained with a PIV system, or from synthetic data.

A set of 13 files created as the output of the image analysis (particle determination) contain the information necessary for three-dimensional tracking schemes. The tracking scheme tracks particles through four frames directly and through 13 frames sets indirectly. A track was based on the minimum variance (called a sigma value in this paper) of length, angle, average size, and average gray level of all possible tracks from some starting particle centroid. The tracking was accomplished by the prediction of the displacement and the direction of the particle through four consecutive time steps. Figure 2 pictorializes the tracking procedure. The search volume in the second frame for a particle starting in the first frame was determined by a rough estimate of the maximum flow-field velocity. The search volumes in the third and fourth frames were based on a fraction of the second frame's search volume. The center of the search volume in frame 3 was found by straight-line projection of a possible track for a spot found in frame 2. For each spot then found in frame 3, the center of a search volume in frame 4 was determined using the length of the track from frames 2 to 3 and the deviation of the track's angles between frames 1 and 2 and frames 2 and 3. A statistical method was used to determine and dispose incorrect tracks if more than one track shared the same spot. Note that the perfect track would have a σ_{total} value of 0.0. The following relations are used to calculate σ_{total}:

$$\sigma_l^2 = \frac{[l_{1-2} - \bar{l}]^2 + [l_{2-3} - \bar{l}]^2 + [l_{3-4} - \bar{l}]^2}{3} \quad (1)$$

$$\sigma_\theta^2 = \frac{[\theta_{1-3} - \bar{\theta}]^2 + [\theta_{2-4} - \bar{\theta}]^2}{2} \quad (2)$$

$$\sigma_\Phi^2 = \frac{[\Phi_{1-3} - \bar{\Phi}]^2 + [\Phi_{2-4} - \bar{\Phi}]^2}{2} \quad (3)$$

$$\sigma_*^2 = \sigma_l^2 + \sigma_\theta^2\, \bar{l}^2 \cos^2\bar{\Phi} + \sigma_\Phi^2\, \bar{l}^2 \sin^2\bar{\Phi} \quad (4)$$

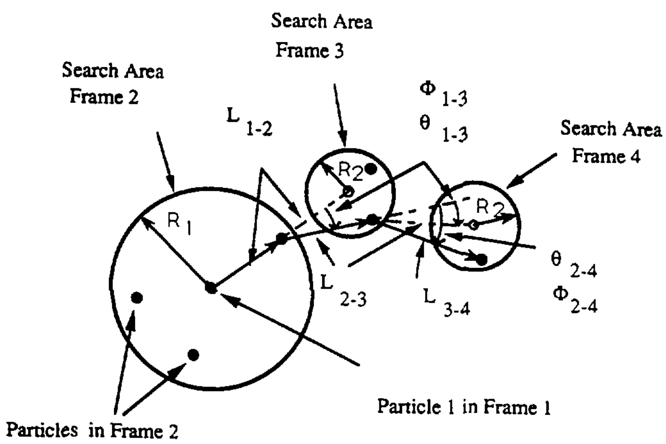

Figure 2: Description of the Multiframe Tracking Technique

Where:

σ_l = The standard deviation from the mean for the lengths of the vectors

σ_θ = The standard deviation from the mean for the angles in the x-y plane

σ_Φ = The standard deviation from the mean for the angles with respect to the z-axis

σ_* = The total standard deviation

l_{1-2} = The length between the particles in the 1st and 2nd frames

l_{2-3} = The length between the particles in the 2nd and 3rd frames

l_{3-4} = The length between the particles in the 3rd and 4th frames

θ_{1-3} = The angle in the x-y plane between l_{1-2} and l_{2-3}

θ_{2-4} = The angle in the x-y plane between l_{2-3} and l_{3-4}

Φ_{1-3} = The angle with respect to the z-axis between l_{1-2} and l_{2-3}

Φ_{2-4} = The angle with respect to the z-axis between l_{2-3} and l_{3-4}

$\bar{l}$ = The average movement of particles between frames $= (l_{1-2} + l_{2-3} + l_{3-4})/3$

$\bar{\theta}$ = The average θ angle of the vectors $= (\theta_{1-3} + \theta_{2-4})/2$

$\bar{\Phi}$ = The average Φ angle of the vectors $= (\Phi_{1-3} + \Phi_{2-4})/2$.

The total standard deviation can be cast as a dimensionless value as follows:

$$\sigma_{total}^2 = \frac{\sigma_*^2}{\bar{l}^2} \quad (5)$$

or,

$$\sigma_{total}^2 = \frac{\sigma_l^2}{\bar{l}^2} + \sigma_\theta^2 \cos^2\bar{\Phi} + \sigma_\Phi^2 \sin^2\bar{\Phi} \quad (6)$$

Tracks originate in frames 1 through 10 and conclude in frames 4 through 13. After these ten sets of four-frame tracks are calculated, any tracks which start in different frames, but use the same spot in their common frames, are added together to form long tracks up to 13 frames in length. For example, consider two four-frame tracks, originating in frames 1, 2, 3, 4 and frames 2, 3, 4, 5, respectively. If both tracks share a common spot in frames 2, 3, 4, then these two sets of four-frame tracks are combined into one five-frame track. A new sigma value is computed by linear averaging of the original four-track sigma values. These tracks are then cross referenced against each other to assure that all tracks are unique, i.e., no two or more tracks contain the same spot within the same frame. This occurrence is called track crossing and occurs infrequently, but often enough that it must be treated.

CROSS-CORRELATION ALGORITHM

The second tracking method which can be used is the cross-correlation technique. It is a dynamic particle tracking method which can be quickly performed between two sequential, high resolution (640 x 480 x 8 byte) images. The particle velocity is found by determining the correspondence between particles in two sequential video frames. Every particle belongs to a characteristic group which has a specific local distribution pattern in the first binary image and a possible candidate pattern in the second binary image, where the latter is shifted so that the centroids of the possible particle pair coincide.[6] One particle in the first image will correspond to the particle in the second image which keeps the most similar pattern, providing the local pattern of the distributed particles change little within the sequential frame acquisition time. This method is especially useful when only two sequential images are available, and the multiple time frame particle tracking method (requiring at least four sequential video images) cannot be performed.

The cross-correlation algorithm correlates between two frames of data. A candidate volume is formed in the second frame, centered on the location of a spot in the first frame. The radius of this volume is determined by estimating the maximum possible movement for particles between frames. Each frame 2 spot in this volume is a candidate for matching with the frame 1 spot. A match would indicate the position of the frame 1 spot in frame 2. A dynamic volume is then produced around each candidate, encompassing at least five other spots in frame 2. The radius of this volume is used to produce a dynamic volume in frame 1 around the frame 1 spot. The two volumes are compared. This comparison produces a correlation coefficient, C_{ij}, which measures the overlap of spots in the two volumes. Figure 3 demonstrates how this overlap is measured. A correlation coefficient of 1 indicates a perfect correspondence between the two volumes, and the closer this value is to 1 the more likely it is an accurate particle match. A correlation coefficient of 1 is only possible if each spot is the same size in both frames, and each spot in

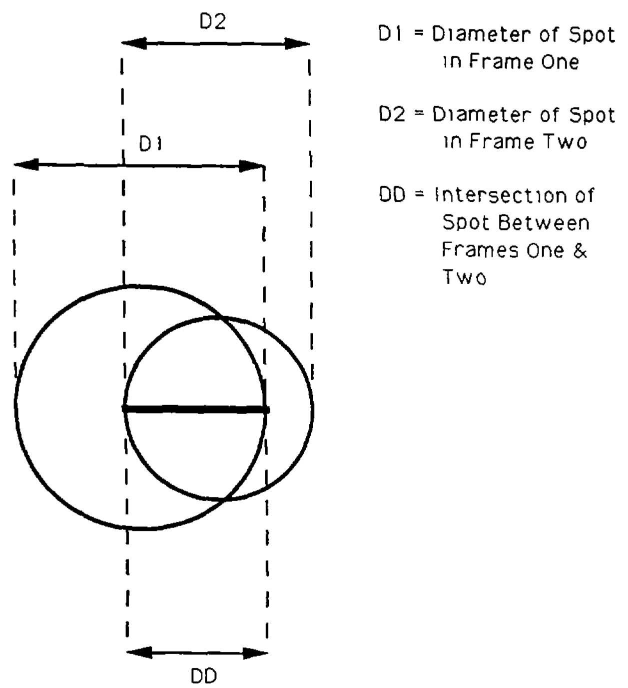

Figure 3: Intersection of Spot i Between Frames 1 and 2

frame one overlaps itself in frame two when shifted by the velocity vector predicted.

Equation (7) is used to calculate a correlation coefficient on binary images, Cij, between dynamic region in frames 1 and 2:

$$C_{ij}=\frac{\sum_{i=1}^{P_1}\sum_{j=1}^{P_2} D_{i,1}\cap D_{j,2}}{\sqrt{\sum_{i=1}^{P_1} D_{i,1}\times\sum_{j=1}^{P_2} D_{j,2}}} \quad (7)$$

The velocity for a particle is determined by the particle movement divided by the image acquisition time. The tracer particle pair with the largest Cij value is then identified as a particle pair match. Given an irrotational flow, large values of Cij (close to 1.0) are obtained for the correct particle correspondence. In regions of high vorticity, the Cij values can be much smaller, and the identified matches are not always correct. Another means of checking is required to remove erroneous vectors. Two checks are performed. The first check calculates the sum of the distances between all corresponding centroid pairs.

The second check determines a reliability index for a possible candidate pair based on the number of particles which overlap, Nij, and the amount the radii of those particles overlap, Rij, which occur when checking a correspondence for possible pair i-j. This overlap was used in part for calculating the Cij value and was displayed earlier in Figure 3. When all correspondences are completed, the pair reliability index Pij is calculated with Equation (8),

$$Pij = Nij \times Rij \quad (8)$$

The possible pair with the largest Cij value, the largest Pij value, and the smallest sum of the distances between centroids is generally found to be the correct match.

TESTING

To verify the ability of these two tracking algorithms to track particle movement in three dimensions, two types of tests were conducted. The first test was with synthetic data and the second with experimental data. To produce the three-dimensional synthetic data, a standard flow was required to create sets of particles with known positions to be moved through several frames. Simulated flow around an inviscid sphere and simulated flow to a drain was used for this purpose. The tracking method was then performed using these frames of data to produce particle tracks. Comparisons were made between the tracks produced in the method and the known particle tracks.

Figures 4 and 5 show output produced by the multiframe tracking code using synthetic flow around a sphere as input. Since the multiframe code produces tracks across all the frames, the tracks can be seen to curve around the sphere. Figures 6 and 7 show output produced by the cross correlation code using the same flows as in figures 4 and 5. Since the cross correlation code uses only two frames, the tracks are straight vectors. Figures 8 and 9 show output from the multiframe code using synthetic drain flow from the top and side.

By comparing the tracks created by the tracking algorithms to the original synthetic tracks, the tracking algorithms can be evaluated. Figure 10 shows the analysis of the tracking codes at various velocities based on synthetic flow around a sphere. Each algorithm was evaluated with two

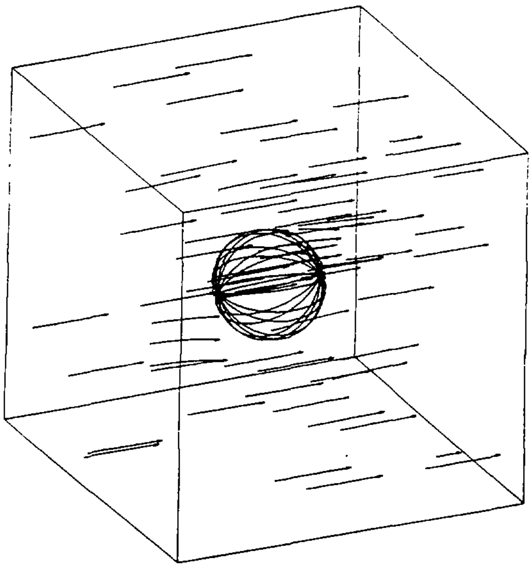

Figure 4: Output from Multiframe Tracking Code
(synthetic flow around sphere,10 frames, 50 particles, 15 pixels/frame)

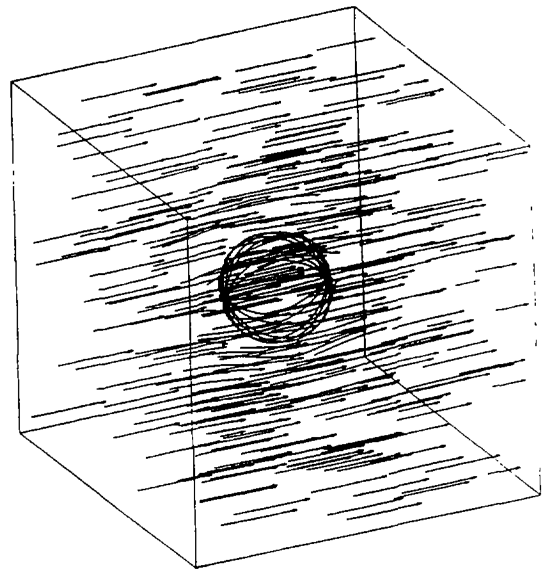

Figure 5: Output from Multiframe Tracking Code
(synthetic flow around sphere,10 frames, 500 particles, 15 pixels/frame)

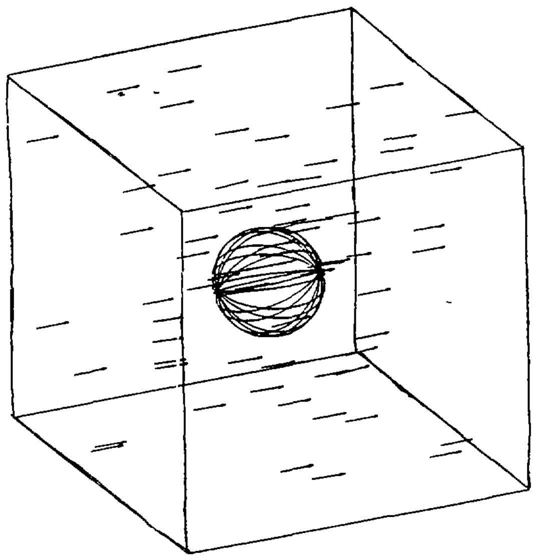

Figure 6: Output from Cross Correlation Code
(synthetic flow around sphere, 50 particles, 15 pixels/frame)

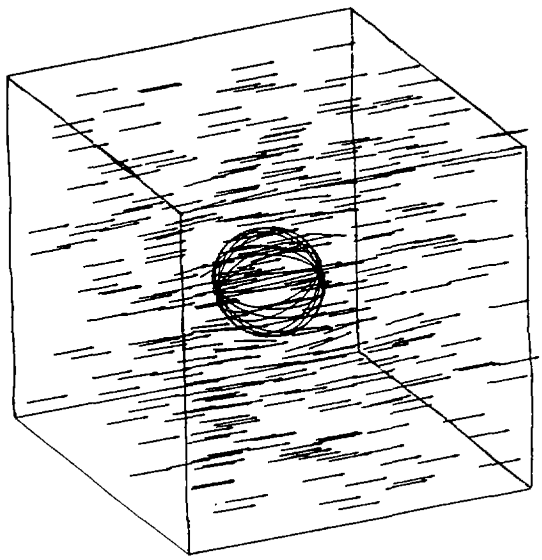

Figure 7: Output from Cross Correlation Code
(synthetic flow around sphere, 500 particles, 15 pixels/frame)

factors, yield and reliability. Yield is the number of tracks found divided by the number of tracks produced, while reliability is the number of correct tracks divided by the number of tracks found. By multiplying the two together, the number of correct tracks divided by the number of tracks generated is obtained. From figure 10, it can be seen that the cross correlation code has a higher yield, but a lower reliability at high velocities than the multiframe code. Figure 11 shows the analysis of the tracking codes, again at various velocities, but based on synthetic drain flow. Again, the cross correlation generally has a higher yield, but at the cost of reliability. Analysis was also done based on the number of tracks, but did not show a change in the performance of the codes until more than 5000 tracks were analyzed.

EXPERIMENTAL DATA ACQUISITION

The setup to acquire experimental data for the tests of the tracking algorithms included three Charge Coupled Device (CCD) cameras (640 x 480 resolution), a high-energy Nd-YAG pulsed laser, two PC/AT computers and three frame grabber boards. Each camera was connected to its own frame grabber board. Two of the boards were located in one computer and the third board was located in a second computer. All three cameras were focused on the same volume of space in a channel of seeded water. This test volume is determined by the placement of a calibration object. The setup for this experiment is shown in figure 12.

The light source is a pulsed Nd-YAG laser. It has a peak throughput energy of over 1.0 Joules per pulse for the primary wavelength of 1064 nm (infrared). The pulse width is approximately 8 ns, with a 7 mm circular, Gaussian distributed shape. The light can be placed into position with a

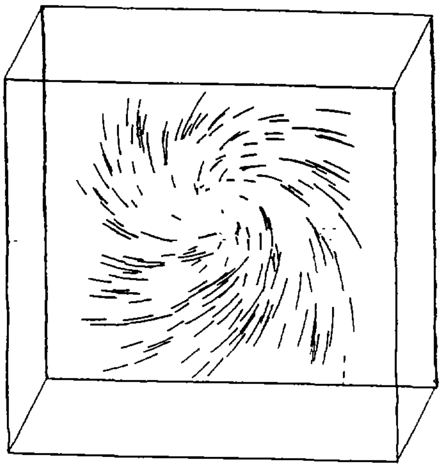

Figure 8: Output from Multiframe Tracking Code Top View (into drain)
(synthetic drain flow, 4 frames, 200 particles, 30 pixels/frame)

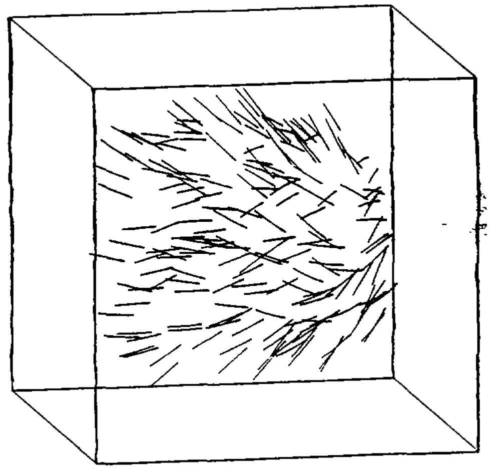

Figure 9: Output from Multiframe Tracking Code Side View
(synthetic drain flow, 4 frames, 200 particles, 30 pixels/frame)

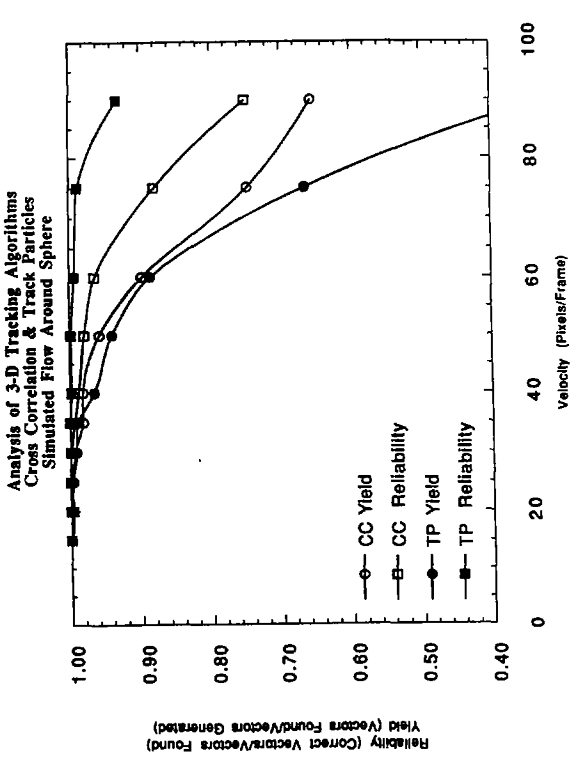

Figure 10: Analysis of 3D Tracking Algorithms Cross Correlation and Track Particles for Simulated Flow Around a Sphere

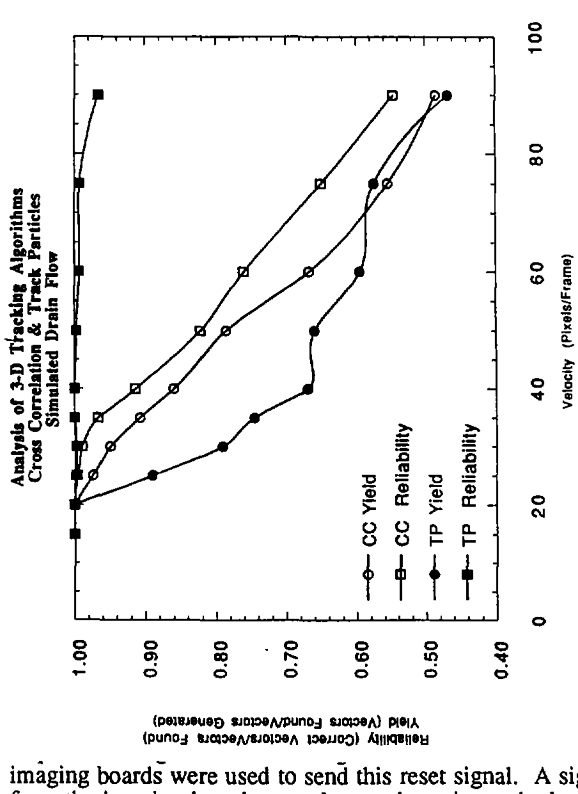

Figure 11: Analysis of 3D Tracking Algorithms Cross Correlation and Track Particles for Simulated Drain Flow

set of high energy mirrors. The light is expanded from the 7 mm circle into a conical volume of light approximately 4 cm in diameter with a set of two spherical lenses.

The near infrared laser light produced by the laser has an extremely high absorption cross section in water. So a frequency doubling crystal is used to convert the 1064 nm (infrared) light into 532 nm (green) light. This results in a drop in the maximum energy output to 400 mJ. However, the extremely low absorption cross section at this wavelength more than makes up for the loss in energy.

The imaging boards were used to control the timing between the video cameras and the laser. The video cameras were operated in an asynchronous reset mode (the cameras acquire an image when a reset signal is received). The imaging boards were used to send this reset signal. A signal from the imaging boards was also used to trigger the laser. Because of the limited capabilities of the cameras and lasers, the time between each laser pulse was approximately 54 ms. The frame grabber boards were also used to acquire the images.

The instrument used for the calibration consisted of a grid with 16 points with known x,y coordinates mounted on an XYZ micropositioner. After an image is taken of the grid, it is moved a measured distance in the z direction. Thus, producing a total of 80 points with known x,y,z coordinates. Calibration images are taken for each of the cameras at each position. After the calibration data is acquired, the calibration grid was removed and the flow of water down the channel was started to induce movement. At this point, 13 time sequential images are taken with each camera.

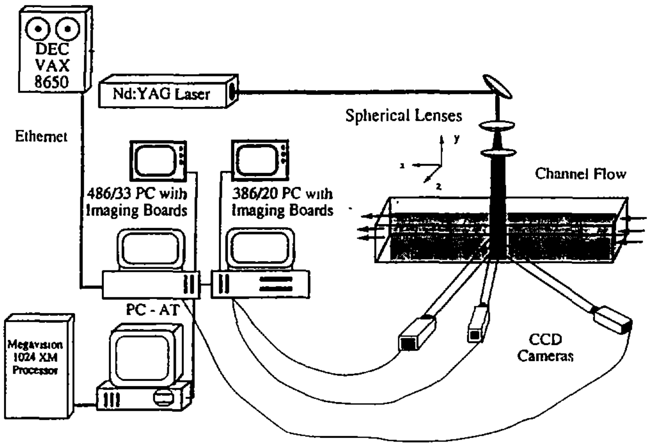

Figure 12: Three-Dimensional PIV Experimental Setup

The calibration data shows quantitatively the affect the z-dimension has on each camera (the shift in pixels in the camera image caused by the change in z-dimension). If the z-dimension is small compared to the distance from the camera to the lighted volume (in this experiment the z depth of the field was approximately 30 mm and the cameras were approximately 65 cm away), then the shift (dx/dz) can be considered independent of the z. Due to the large number of calibration points, dx/dz can be calculated not only for each camera, but for different regions in the camera image.

This data is used to determine the x,y,z coordinates of the tracer particles. This is accomplished by comparing the location of the spots from one camera image to the spots in the other camera images. Only one combination of spots will satisfy the dx/dz conditions for all three cameras.

RESULTS OF EXPERIMENTAL DATA TEST

Figure 13 shows the results from frames 1 and 2. For scale, the vectors in the x-y plane are roughly 3.5 mm long. Note that there is not much movement in the z-y plane. This is to be expected, since the flow was generally in the x direction (down the channel). The seed position can be determined to an accuracy of less than 0.5mm. Analysis is continuing to improve this accuracy.

CONCLUSION

Two three-dimensional tracking methods have been described which can be used to perform the tracking of seed particles in a flow field which has been imaged with a three-dimensional PIV method. The tests of these algorithms with synthetic and experimental data were described. The results of the tests showed that the algorithms can be used to effectively track three-dimensional flow fields. A method was also described which can be used to acquire experimental three-dimensional data for testing the algorithms.

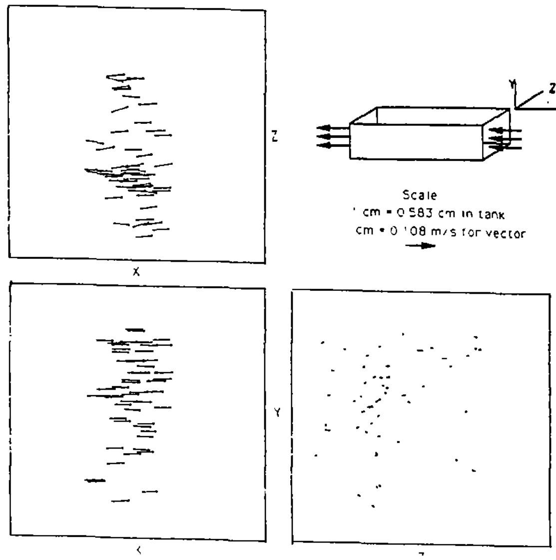

Figure 13: Velocity Field for Channel Flow (X-Z Plane, X-Y Plane, Z-Y Plane)

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