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A FAST DATA REDUCTION ALGORITHM FOR MULTI-FRAME PARTICLE-IMAGE VELOCIMETRY

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An efficient tracking algorithm for the reduction and analysis of particle image velocimetry data is described. Using Fast Fourier Transforms, it is shown that one hundred identical particles performing random motions superimposed on Poiseuille flow and recorded on two successive frames may be tracked in about one minute of time on a Cyber 175 computer.

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TABLE OF CONTENTS

LIST OF ILLUSTRATIONS v

INTRODUCTION 1

GIVEN TRACKING PROBLEM 1

PHYSICAL CONSIDERATIONS 3

IMPLEMENTATION OF PHYSICAL CONSTRAINTS:
THE TRACKING ALGORITHM 4

DEMONSTRATION 6

DISCUSSION 7

CONCLUSIONS 8

REFERENCES 9

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By	
Distribution/	
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LIST OF ILLUSTRATIONS

1. Flow Diagram of Tracking Algorithm 5

2. Simulated Tracking Problem 7

INTRODUCTION

The use and analysis of the signatures of light reflected by scattering sites in a moving medium has been actively pursued for the determination of flow velocities.[1-3] A good overview of the subject was given by Adrian.[3,4] Here we address the problem of the associated data reduction, in particular when the number of scatterers is relatively small (the order of 100), and the particles are relatively large, of the order of tens of microns; this is called particle image velocimetry (PIV).[4]

Particle image velocimetry is of considerable interest, especially for flows where there is only limited transverse motion, i.e., where particles in the flow field generally stay within well defined hyperplanes. In many situations of interest to ballisticians these conditions are met. Spatial particle distributions within flows are of some importance since they influence many processes of interest, including heat transfer and velocity distributions of the carrier gas near bounding surfaces. In addition, since excellent time resolution in the data acquisition is now possible with the use of pulsed lasers, the simultaneous determination of the position and subsequent inference of velocities of a large number of particles at the same time is a considerable advancement over Laser Doppler Anemometry (LDA),[5] where a large number of measurements at the *same* location need to be performed to establish the required flow statistics of a single point. Also, average measurements may not accurately reflect the true nature of the flow behavior.

Going beyond current practice of recording the data on photographic film followed by manual data reduction, we address the case when two frames of a scene, separated by a small temporal displacement, are available from charge coupled device (CCD) recordings. It is shown that, even in the case of hundreds of particles, identification, tracking, and determination of particle velocities can be obtained within minutes even on a slower mainframe computer. In the next section, a new algorithm for PIV data reduction is described. This is followed by an example of a simulated Poiseuille flow with one hundred embedded particles of identical shape. A random motion has been superimposed on each of the particles as they traverse the flow field. We conclude with an assessment of the developed technique.

GIVEN TRACKING PROBLEM

The particles under consideration can change in apparent shape and brightness during their motion, since they move in and out of focus and also might be abrading. Therefore, any potential tracking algorithm cannot cue on individual particle signatures such as edge segments, shape, size or optical brightness. The particles must be considered identical. The main guides to matching corresponding particles must therefore be their positions and local configurations. The problem is further exacerbated by the fact that only two images are to be given. Therefore, a detailed history of particle shape and/or trajectory changes cannot be kept. We summarize the problem as follows:

1. The particles undergo nonrigid motion with a strong random component.

2. Many particles are present, the order of 100 or more. Hence, the field is relatively densely populated.

3. The particles are identical, and placed in a uniform field. We equivalently model the particles as uniform circular disks against a (different) uniform background.

4. Only two images are given.

5. The time interval between images is large enough that particle travel of many diameters can occur.

6. The deterministic component of motion is Poiseuille.

7. The number of particles is conserved, over the two images.

8. The aim is to establish the particle correspondences from image 1 to image 2. Then the difference in corresponding particle positions gives the required velocities.

One obvious method of establishing the correspondences, matched filtering,[6] does not apply because of premise 3 above. The method of optical flow,[6-8] must also be considered. It applies when the image scene is continuously changing both temporally and spatially. For example, a camera is slowly panning across an image field. However this requirement violates premises 3 and 5 above, according to which the image field is binary, and discontinuous spatially, and the particle motion is large, hence discontinuous temporally.

The open literature does not extensively treat this kind of tracking problem. Published work on *dynamic scene analysis*,[9-12] generally limit attention to either rigid or quasi-rigid motion of a single, or at most a few, objects. This violates premises 1 and 2 above. Other authors, e.g., as in Ref. 13, allow for multiple particles but consider cases where the field is rather sparsely populated, violating premise 2, and where small particle travel occurs between frames, violating premise 5. Under these conditions, there is no correspondence problem. Estimation of the particle positions, and outputing a dot at each such position on an image screen, directly gives the particle orbits.[13] An ingenious method of tracking multiple particles,[14] is based on the idea of predicting each particle's motion based on its past history. However, this violates premise 4, according to which there is no extensive past history.

An analog method of multiple particle tracking was proposed,[15] which uses a far-field, double exposed hologram as the recording medium for the two images. However, this approach is limited in scope to two special scenarios: When the particles are close to uniformly distributed over the images, or the particle movements do not correlate with position. These are overly restrictive conditions for the given problem.

Much previous work in tracking has been motivated by the needs of the home television industry, or by the problem of inferring 3-D shape from 2-D projections. These have very little in common with the premises 1 - 8 at hand. By contrast, medical blood cell tracking has much in common with our problem. The first publication of this kind appears to be Ref. 16, where a system for tracking single white blood cells is described. Then, in Ref. 17, an advance on this work was reported, whereby the automatic tracking of many cells was carried out. The aim, however, was not to establish the particle correspondences, but rather to estimate the mean or aggregate motion of the blood cells. Hence, when multiple candidates for a correspondence occur, one is *arbitrarily* selected: these events occur so infrequently that the overall estimate of aggregate motion is not seriously affected. By contrast, because of premise 2 above, such events will frequently happen in our problem.

Also, each wrong decision on a correspondence gives directly a wrong velocity estimate. Hence, we pay careful attention to the problem of multiple candidates.

Another medical tracking problem analogous to ours arises in 2-D gel electrophoresis imagery. There, the aim is to match corresponding protein spots from one gel image to another. The state-of-the-art matching procedure appears to be that of Ip and Potter;[18] see also Refs. 19 and 20. Their algorithm consists of a global linear transformation applied to one image, followed by final, local matching with the second by use of a "chamfering" technique. The linear transformation takes advantage of the powerful prior knowledge that to good extent the two images are simply translated and rotated versions of one another. Unfortunately, this is not true of particles undergoing Poiseuille flow. Also, this linear step requires, for its execution, the *manual* matching of many reference spots, e.g., 15 to 20 pairs in experiments cited. This conflicts with our aim of a completely automated tracking procedure.

Skolnick[21] has proposed an automatic matching approach in gel electrophoresis imagery. Correspondences are established by a matching of graphs generated by connecting each gel spot center (a "node") with lines ("edges") to its nearest neighbors. If the graphs for corresponding spots in successive frames are similar enough, and if they are not too separated spatially, then the spots are accepted as matched. This was a proposed technique, without demonstration. Evidently, it depends for its utility on a situation where most particles preserve their relative positions during motion. This violates our premises 1 and 6, according to which the particle motion is nonuniform.

Finally, Greaves[22] uses a simple nearest-neighbor rule, of Euclidean measure, to select corresponding microorganisms in two microscopic slides viewed by a video system. Unfortunately, this simple selection rule will not work in our problem, as will become evident from demonstrations given later. The field is so crowded that the correspondences so established will be strongly dependent upon the order with which the pairings are made, and too often the nearest neighbor to a particle is the *wrong* pairing for that particle.

PHYSICAL CONSIDERATIONS

A correspondence algorithm must be sought which does not rely on individual object shape and/or brightness cues (see premise 3). The only other cueing information left is possible knowledge of particle dynamics, i.e., flow characteristics. In fact, we have such knowledge. In our problem, the particles overall follow Poiseuille-like flow, which is laminar and deterministic, with a superimposed random component of motion exemplified by local eddies. Hence, in the net there should be strong correlation of motion, but only over finite correlation distances. Effectively, many neighboring particles move together, or "clump." Hence, preference should be given to identifications that define commonly moving particles, or clumps. Furthermore, the deterministic component of Poiseuille flow is assumed to take precedent: given no further information, if a particle is observed to belong to more than one clump, we presume that it should be identified with the larger clump, provided this does not imply too large a correlation distance.

A second piece of prior information at hand is knowledge of a maximum possible motion displacement r_{max} over the field. This can be deduced from knowledge of the time interval τ between exposures and an estimate of the maximum possible velocity of a particle. With this information, potential correspondences that would require motions greater than r_{max} can be ruled out. Furthermore, if $r_{max} \leq N/2$, where N is the image width (and height), a computational time and core storage advantage results (see below).

IMPLEMENTATION OF PHYSICAL CONSTRAINTS: THE TRACKING ALGORITHM

A mathematical operation that permits the incorporation of clumping and maximum distance considerations is that of cross correlation. See the flow diagram in Figure 1, step (c). If image 1 is cross correlated with image 2, the global maximum in the output will occur at a lag, or spatial vector displacement between the images, where the largest number of particles overlap. This defines the largest clump. The second-largest maximum will occur at a lag for which the second-largest number of particles overlap; etc, for all significant maxima within the largest possible displacement radius r_{max}. Let there be M in all. The maxima were found by simply centering a 3×3 cross shaped window upon each output point. A maximum is defined to occur when the center point is higher than its four neighbors within the cross. The M lag maxima describe the vector displacements of M clumps of particles from image 1 to image 2. In a general scenario, there will be many clumps of commonly moving particles, each moving by a generally different amount and in a different direction. Although the cross-correlation outputs do not identify *which* particles moved together to form each maximum, they at least identify the lags in question. With these known, a different computer operation identifies the particles *within* each clump. This is described in the third paragraph following.

The cross correlation operation was also chosen because it is convenient to implement digitally. Let image 1 be denoted as f, image 2 denoted as g. The Fast Fourier Transform (FFT) algorithm permits the cross correlation f ⊛ g to be computed for two images f and g, as[23]

$$f \circledast g = FFT^{-1} \{FFT(f)\ FFT(g)^*\} . \qquad (1)$$

The asterisk denotes a complex conjugate, and the -1 indicates an inverse FFT. The FFT algorithm is notably fast. Also, by Eq. (1), only three FFT operations need be done to produce the required output that locates the lag maxima. Finally, size considerations should be mentioned. If the images f and g are N×N pixels, then ordinarily the output f ⊛ g will be 2N×2N pixels, i.e., four times the area of each input. However, if it is known that no particle has been translated from f to g by greater than N/2 pixels, i.e., $r_{max} \leq N/2$, then all output maxima must instead lie within an N×N central field of the output. This permits a reduction in required computer core storage by a factor of 8 (factors of 2 in each direction, plus a factor of 2 for the complex arithmetic used).

A further size reduction was enforced. By extensive use of disk intermediary storage files, it is possible to require but one core storage array of dimension (2, N, N). Without the use of such disk files, three such arrays would have been needed, plus seven of dimension (N, N). For an image of size N = 128 or larger, this amounts to a considerable reduction in core storage requirement.

Assume that, in a pre-processing step, every particle in the two images is replaced by an identical disk of known (x, y) position. See steps (a), (b) in Figure 1. The particles within each clump were then identified in the following way. (See step (e) of Figure 1.) Displace image 2 from image 1 by one of the M lags defined above. Then for each particle position in image 1, every particle position in image 2 is sampled to see if the two particle disks overlap. Of all such overlapped disks, the pair with the smallest mutual displacement is chosen as defining a particle-pair correspondence. With the given scenario of little a priori knowledge governing particle motion, it is logical to prefer nearest-neighbor pair identifications over all candidates that are otherwise equally valid.

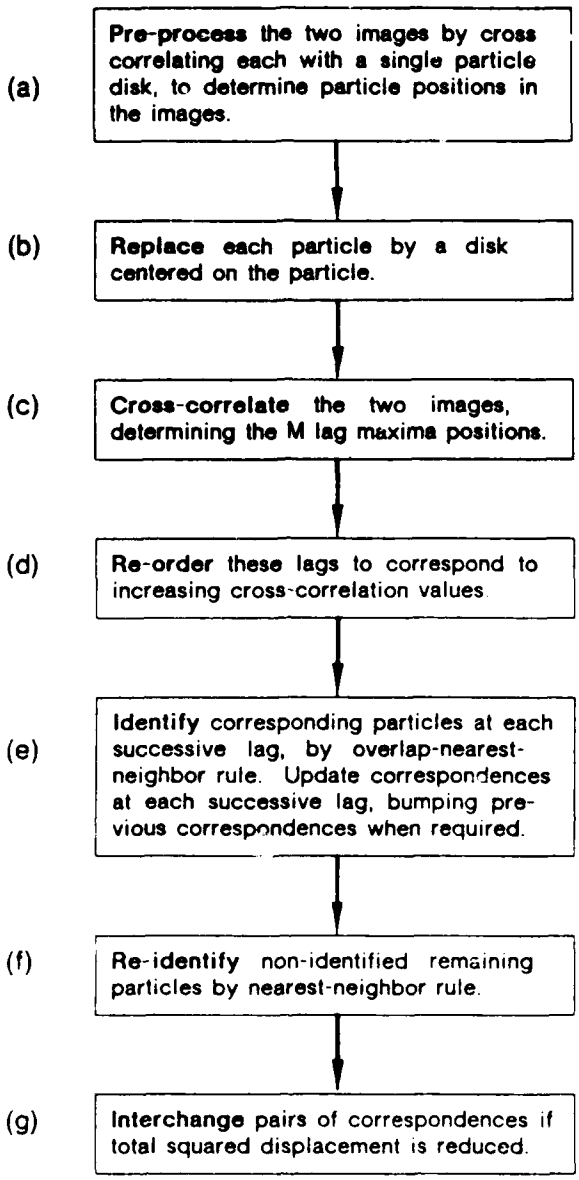

Figure 1. Flow diagram of tracking algorithm.

The M lags are ordered such that their corresponding cross correlation maxima increase in size, before the foregoing identifications are made. See step (d) in Figure 1. Then at each lag, a new set of particle correspondences is established as above, with each such set *replacing* any conflicting correspondences established at previous lags. For example, if at lag 1 particle 10 of image 1 is identified with particle 8 of image 2, i.e., identification (10, 8) is made; while at lag 2 identification (10, 5) is made; then identification (10, 5) takes precedence, until possibly at some subsequent lag particle 10 is assigned to yet a different particle of image 2. In this way, the larger clumps associated with the later lags are given preference in defining particle identifications.

As with the nearest-neighbor rule described above, this is intuitively a correct choice. If the particle flow was perfectly smooth and laminar, all particles would travel together in one grand clump. However, the extent to which random eddies and other sources of randomness actually creep in is not known. Hence, it makes sense to give preference to large scale, or laminar, flow.

Notice that in the previous step particle 8 in image 2 was "bumped" as a possible candidate for an identification. After looping over all lags in the previous step, there will be a list of such bumped particles from image 2. Likewise, there will be a list of still-unassigned particles from image 1 (those that did not have an overlapped disk, for *any* lag, with a particle in image 2). These two lists must somehow be matched up 1:1. At this point, all clumping tendencies have been established. The only rule left for match up is the nearest-neighbor rule. Hence, we loop over all such image 1 particles, finding the closest image 2 particle, and then eliminating each from its list. (See step (f) of Figure 1). This is admittedly an imperfect procedure, since the identifications will depend somewhat upon the order in which the particles are processed. For example, the particle pair (3, 8) may define the smallest particle distance to particle 3 of image 1, but 8 may have already been assigned to particle 2 of image 1 on the basis of closeness to 2. In practice, this kind of error does not happen very often. However, to minimize its occurrence a subsequent processing step is taken, (g) of Figure 1.

In this step, each identification (m_i, n_i), $i = 1, \ldots, P$, where P is the total number of particles in each image, is compared with every other identification (m_j, n_j), $j \neq i$, to see if an interchange of identifications, to (m_i, n_j), (m_j, n_i) will produce a smaller total displacement distance over both pairings. If it does, then the interchange is made. Again, this rule gives preference to small displacements. In practice, the rule eliminates all or nearly all errors described in the previous paragraph.

DEMONSTRATION

Figure 2 shows a simulated case study of particle identification. To aid visualization, image 1 consists of a regular 10×10 grid of particles, shown as white diamonds (discrete versions of circles). Field size is 128×128 pixels. The 100 particles are simulated to obey randomized Poiseuille flow, generally to the right. The center row of particles move maximally and the top and bottom rows minimally, according to a parabolic dependence on row. (The top and bottom rows are taken to be near the walls of a pipe containing the flow. Because of frictional interactions with the walls, particles close to them tend to move less than those in the main flow in the middle.) The center row has the maximum parabolic displacement, value r_{max}. Parameter r_{max} was given the value 6.0 pixels.

Each particle's direction of flow is made to depart randomly from the horizontal, with maximum randomness again at the walls since this is where eddy currents tend to maximally occur. The result is the black particle positions in Figure 2. As examples of extreme directional randomness, notice the lower-left most black particle positions. The black particles comprise image 2.

These two images were then processed, according to tracking algorithm (a) through (g) of Figure 1. At step (c), M = 5 lag maxima were found within the feasible region defined by r_{max}. The result is the correspondences shown by black connecting lines in Figure 2. (Where a black pixel and a white one overlap, as in the upper-left most pair, the black one dominates.) These results are encouraging, since every particle was correctly tracked.

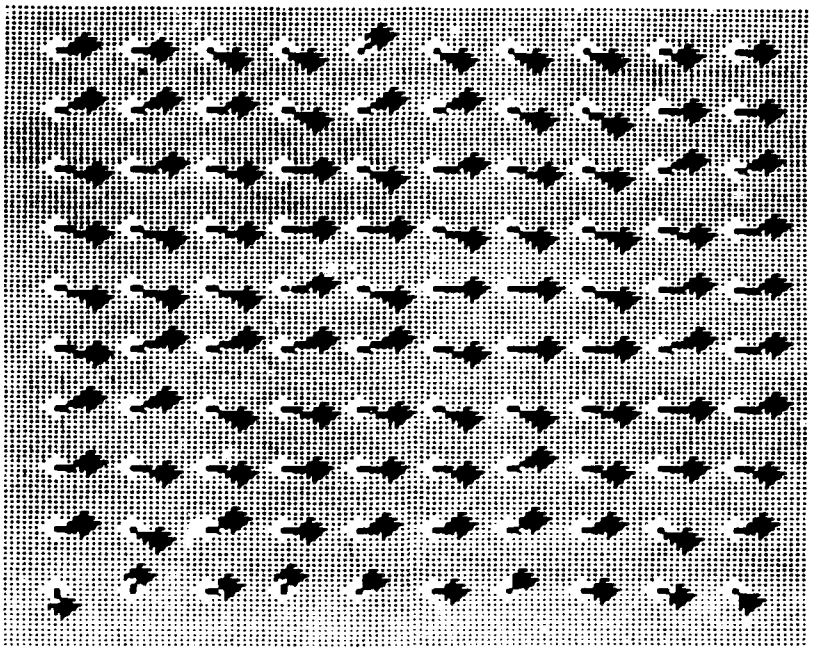

Figure 2. Simulated tracking problem. White particles are in image 1, black particles in image 2. Correspondences established by the tracking algorithm are designated by black connecting lines.

It is interesting to compare these results with what a simple nearest-neighbor rule might have given. On the basis of nearest neighbors, some erroneous identifications would be made, and some would be ambiguous. For example, consider the white particle in row 6, column 9. Its nearest black neighbor is to its left, 6 pixels away. However, the tracking algorithm correctly paired it instead with the particle to its right, distance $(6^2 + 3^2)^{1/2} = 6.3$ pixels away. Although this distance is larger, it was identified by the program with a large clump of commonly moving particles, and hence was given preference at step (e) of the algorithm. Also, for many particles nearest-neighbors would have led to an impasse, since two white particles exist which are *the same* distance from a given black one. For example, consider the white particle located at row 3, column 3. The black particles to its immediate left and right are each distance $(6^2 + 1^2)^{1/2}$ from it. A supplementary rule would have had to be invented in order to resolve the ambiguity.

DISCUSSION

Although the results in Figure 2 are typical, the algorithm does not of course always work this well. The central consideration is the amount of particle motion compared with the interparticle distances. If a black particle has moved so much that it overtakes the white particle immediately to its right, it might be erroneously identified with the latter white particle. Hence, particle movement should be less than the interparticle distances in image 1.

Another factor of importance is the designated size of the disks. Notice that disk size, as employed in the algorithm, does not have to be the actual or physical disk size. In practice, disk size only enters into the algorithm in step (e), where it is used as a kind of interaction distance. Specifically, it defines candidate correspondences for an image 1 particle. To be a candidate, an image 2 particle must overlap the disk of the image 1 particle. (The closest such image 2 particle is then selected.) Obviously, then, the size taken for the disk governs the chosen set of candidates. With too small a disk size, such a small set of candidates might be generated that the correct candidate is missed. Or, too large a disk will too strongly favor the last lags used in step (e), i.e. will tend to make correspondences that all correspond to maximum clump size. Hence, disk size is a useful tuning parameter. A good disk size is identified by reasonable looking correspondences, in the judgment of the user. For the results shown in Figure 2, the chosen disk radius was 2 pixels, as shown. This was the second run of the problem. In the first, a disk radius of 1 pixel was used instead. This resulted in all correspondences but eight in row 9 being correct, a success rate of 92/100. Hence, the algorithm is fairly tolerant of disk size. A range of disk sizes will give good results.

The simulation shown in Figure 2 was carried out by a Cyber 175 mainframe computer. CPU time was 51 sec, and central memory required 60,200 octal words in total (including all program statements and all execution arrays.) A major part of the CPU time was taken by the seven FFT operations performed--three to locate particle positions in image 1, three similarly for image 2, and one more to cross correlate image 1 with image 2. For 128×128 pixel images, it was empirically found that CPU time t varies with particle number P according to a linear relation

$$t = P/3 + 20 \text{ sec}, \quad 1 \leq P \leq 100. \tag{2}$$

Since the FFT operations are, of course, independent of P, the 20 sec contribution to Eq. (2) must be due to them. All other operations in the tracking algorithm require P/3 sec, over the indicated range of P. This bodes well for applications to larger problems, where P might be the order of 1000 particles, providing that approximate linearity holds for these P values as well.

CONCLUSIONS

A tracking algorithm has been developed that satisfactorily tracks 100 or more identical particles. Time and storage requirements are modest, with CPU time approximately linear in the number of particles. For proper use, particle movements should not exceed interparticle distances in image 1. Program operation is adjustable by an input effective particle size parameter, which is varied until satisfactory correspondences are made. Application of the algorithm to 1000 or more particles seems a reasonable future prospect.

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