A HIGH PERFORMANCE SYSTEM FOR 3-DIMENSIONAL PARTICLE TRACKING VELOCIMETRY IN TURBULENT FLOW RESEARCH USING IMAGE SEQUENCES

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ABSTRACT:

The standard method in turbulent flow measurement is Laser Doppler Anemometry, which gains only 2-dimensional information about the velocity with good accuracy, but only for stationary points. 3D-PTV is able to cover all three components of a spatial flow field using stereoscopic image sequences. The determination of the 3rd component of the velocity vector requires the solving of the stereo correspondence problem.

In contrast to other methods which solve first the stereo correspondence for single images and do the particle tracking as a second step, this paper describes a high-performance algorithm working on image sequences, where the first step is the particle tracking and then in a second step the stereo correspondence problem is resolved for particle trajectories not for single particles. The advantage of this approach are the ability to track the particles for long time intervalls (7-10 s and more) while the stereo correspondence has a matching rate between 90% and 100% at particle densities up to750 particles and still a matching rate of 65% at 2000 particles. The typical computation times on a Silicon Graphics Indy (MIPS R4000, 100MHz) are 0.25 seconds/image for the particle tracking and 10 seconds for the stereo correspondence with sequences of 150 images and 350 particels. These are considerable short times.

The system has been developed using real image sequences. In a second step simulated data has been evaluated and it can be shown, that the limitations of the system come from the particle tracking. Thus further study will focus on improvement of the particle tracking.

1 INTRODUCTION

Three dimensional flow measurements have a wide area of interest. They are used in industrial applications as well as in basic research. Of special interest is the study of turbulence and transport processes [Jä-85], where image processing methods are able to gain the needed information. While Particle Imaging Velocimetry allows the determination of 2-dimensional flow fields. 3-dimensional PTV is able to cover all three components of a spatial flow field using stereoscopic image sequences. Also PIV is not able to observe trajectories, which can be measured with 3-D PTV for longer sequences with an evident smaller amount of calcaulating operations.

To obtain spatial information, the stereo correspondence problem has to be solved. Working on single images (Adamczyk 1988 and Maas1992) gives ambiguities, getting more severe with increasing particle density.

Thus the stereo correspondence problem is solved comparing image sequences, whereby the stereo correspondence is achvied for particle traces in image sequences instead of single particles in single images. This new approach has the advantage of reducing the ambiguities and thus allows to work with high particle densities(>2000 Particles) while at the same time the amount of calculations is minimized and therefore the algorithm is considerable fast.

The system has been developed using real image sequences. Simulated data has been computed for optimization and to find out the limitations of the system

2 PRINCIPLE OF THE SYSTEM

The flow is visualized using polystyrol particles ranging from 50 to 150 µm in diameter. After illuminating an observation volume image sequences are recorded using two cameras. The image analysis includes:

- calibration of the camera system
- 2D-particle tracking
- solving the stereo correspondence problem for particle traces
- determination of spatial velocity data

This paper focuses on the stereo correspondence algorithm and the simulation. The calibration technique and the particle tracking are described in (Netzsch 1992, Posch 1990, Tsai 1986, Hering 1995, Wierzimok 1992).

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3 EXPERIMENTAL SETUP

Measurements have been performed at the large circular wind-water tunnel at Heidelberg University.

Tracer particles (Wierzimok 1990) have been spherical polystyrol particles with diameters ranging from 50 to 150 µm. Image sequences of an observation volume have been taken with two CCD-cameras (NTSC, 30Hz, interlaced). Both camera signals (camera 1: red, camera 2: green) have been superimposed and recorded simultanously using an analog Sony Laserdisc Component Videorecorder (YUV-Signal), which allows access on single images.

The red and green signal have been splitted during digitization. The digitized images have been stored on WORM disk.

Measurements have been made in four camera positions:

- cameras positioned horizontal and vertical
- in each position with parallel and rotated optical axes

4 2-D PARTICLE TRACKING

Essentially the 2-D particle tracking consists of two steps: particle segmentation and particle tracking. The first step is to separate the particles from the background and to determine the water surface. The particle tracking automatically traces a particle's path from image to image througout the complete sequence. For this purpose two algorithms have been implemented. The first one (Netzsch 1992) uses global thresholds reducing the computational time while the second one (Hering 1992, Wierzimok 1992) is based on a region growing algorithm and is suitable for high particle densities.

Figure 1 shows the result of the 2-D particle tracking for a sequence of 70 images (2.3 sec) processed with algorithm 1. The cameras have been positioned horizontally with parallel optical axes. Only trajectories of particles that have been tracked more than 5 images are presented. As in all following figures, the upper half represents the right camera, while the lower half represents the left camera.

As a result a time sorted linked list of particle trajectories is obtained. The time sorting occurs automatically, because of the sequential processing of the image sequences. The trajectories itself consist of another linked list containg the center of mass of the particle in camera coordinates and the image number as a time stamp. The time resolution is given by the NTSC standard.

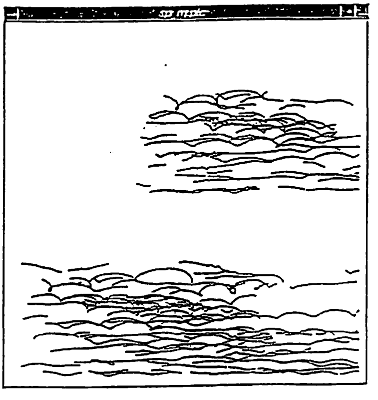


Figure 1 Result of the 2D-particle tracking. The upper half shows the left camera, the lower half the right camera.

5 STEREO CORRESPONDENCE

The stereo correspondence problem is to find for a given trajectory in the right (left) camera coordinate system the corresponding trajectory in the left (right) camera coordinate system. With respect to the constraints it is possible to find correspondence criteria to match the trajectories fast and reliable.

5.1 Constraints

The following constraints can be found: .

- uniqueness (5.1)
- epipolar constraint (5.2)
- correspondence has to match for the whole trajectory (5.3)

Because each particle exists physically exactly one time the corrsepondence must be solved unique. Ambiguties not being resolved indicate an error in the particle tracking respectively to high particle densities.

A point in the right image corresponding to a point in the left image must lie somewhere on a particular line. This line is the epipolar line. The length of the epipolar line can be resctricted with the knowledge of the size of the illuminated light sheet. The position of the epipolar line is estimated using a 3D grid positioned in the light sheet.

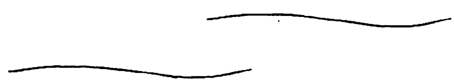
A single trajectory can only be created by a single particle. Thus the correspondence has to be carried out for all points of a trajectory. not for some part(s) of the trajectory.

5.2. Correspondence criteria

Single particles don´t distinguish in size, shape or light intensity. Thus features resulting of the epipolar constraint are used to match corresponding trajectories. Considering the multimedia geometry (Maas 1992), the epipolar line is a curve, which can be approximated by a polygon. Adding a tolerance to this polygone given by the accuracy of the camera coordinates, we get a two dimensional search area. to find the point of a possible corresponding trajectory. This criterion has to be satisfied for every single point of the corresponding trajectory. To save computation time a rectangle is used as the search area instead of the polygon.

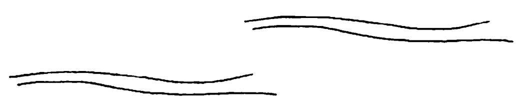
Applicating this criterion creates a linked list of correspondence candidates. containing null. one or multiple candidates. The following cases can be found:

- 1:1 Both. the left and right trajectory have just a single candidate. the trajectories correspond



- 1:m (m:1) the left (right) trajectory has multiple right (left) candidates. These again have exactly this left (right) trajectory as a candidate.
  Example: the lower trajectory got parted by a disturbance in the particle tracking

- m:m the left trajectory has multiple right candidates and these by themselves have multiple left trajectories as candidates



The correspondence is uniquly solved in the first case (1:1). In case (1:m) the trajectories match if there is no time overlap between the m candidates und thus represent a single particle. In all other cases additional criteria have to be used to eliminate ambiguities.

With respect to constraint (5.3) candidates corresponding only for one or multiple short parts can be excluded.

Constraint 5.1 (uniqueness) leads to another criterion: matching ambiguities have to be resolved, that the number of correspondences is maximal. Example (Figure 2):

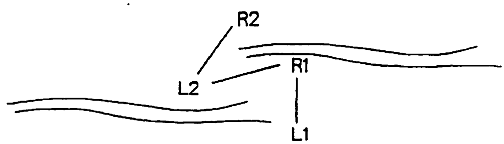


Figure 2 uniqueness criterion

Trajectory R1 has the possible candidates L1 and L2, trajectory R2 has the candidate L2. Two possible solutions exist:

- R1 matches L1, than R2 matches L2
- R1 matches L2, no match for R2 and L1

Other matches can be excluded because of the uniqeness criteria. The first solution is the one with the largest reliability, because it matches all four trajectories (provided that there are no errors in the particle tracking).

5.3 Results

Real image sequences have been evaluated with the presented algorithm. The average matching rate was between 90% and 100% at particle densities from 100 to 600 particles. For a character recognition system this would be an inacceptable rate, but in this application 5% ambiguities are an excellent result, because the particles by themselves are a statistical preselection of positions to measure the flow field. Thus even a matching rate of 80% would be a satisfying result. For more importance is a fast processing, since this technique is only useful if large quantities of images can be evaluated.

The typical computation times on a Silicon Graphics Indy (MIPS R4000, 100MHz) are 0.25 seconds/image for the particle tracking and 10 seconds for the stereo correspondence with sequences of 150 images and 350 particles. These are considerable short times.

6 SIMULATION

6.1 Purpose

The algorithms have been developed with real image sequences. To test the quality and reliability of the algorithms a system to create computer simulated image sequences has been provided. The purpose of this simulation system is not to reproduce exactly the physical conditions, but to produce a set of known data making it possible to test the algorithms. The simulated data allows the examination of the influence of parameters, which can not easily varied during experiments, for example the particle density. The main goals are, to find out how the computational effort depends on the density of trajectories and where the limitations of the system are: in the particle tracking or in the stereo correspondence.

6.2 Realisation

The following parameters are used:

- length of the trajectories
- number of breaks in the trajectories
- number of particles resp. trajectories
- particle velocity (linear and radial)
- geometry: camera positions and size and position of the observation volume
- size of the epipolar search rectancle
- noise intensity

Positions and velocities are computed in three dimensions according to the setting of the parameters. The velocities are the superimposition of linear and radial components, to reproduce the typical orbital motion of real particles.

After computing the image seqences in world coordinates, a central projection is exectued to get the positions in the camera coordinate systems. The results are two synchronous sequences of particle positions, one for each camera.

An error in the particle tracking typicaly results in a break in the trajectory. Thus the number of breaks are used to examine the influence of the pariticle tracking on the stereo correspondence.

Sequences with densities up to 3000 particles have been used to test the reliability of the stereo correspondence algorithm.

Figure 3 shows a sequence with 1500 particles and a length of 40 images. The upper half represents the right camera and shows all trajectories, while the lower half shows only the corresponing trajectories in the left camera.

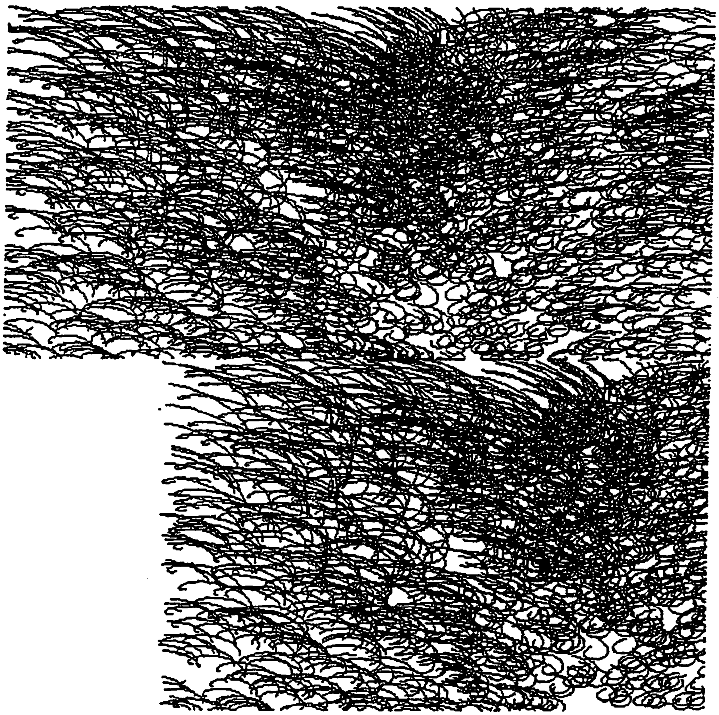


Figure 3 Simulated sequence with 1500 particles

6.3 Results

The simulations showed, that the quality of the stereo correspondence at high particle densities (> 1000) depends mainly on two parameters: the quality of the particle tracking and the exact knowledge of the epipolar line.

Simulating an error free particle tracking (0% breaks) the correspondene could be solved for 1300 particles at a matching rate of about 65%. Simulating a worse particle tracking (36% breaks) up to 850 correspondences could be found.

The above results have been evaluated using an epipolar search rectangle of the same size as in an experimental setup. Using a polygon as the search area results in a more accurate estimation of the epipolar line. This can be simulated reducing the size of the search rectangle. The results are then 1900 correspondences at a matching rate of 88% (0%breaks) and 1700 correspondences at matching rate of 77% (36%breaks).

7 SUMMARY AND CONCLUSIONS

A high performance PTV algorithm for the measurement of turbulent flow fields has been developed. Using trajectories to solve the stereo correspondence is the key to a high performance algorithm. which works fast and with high particel densities (> 2000 corresponding Particles). Tests on simulated sequences certified the reliability of the stereo correspondence algorithms. The simulations showed that the limitations are in the particle tracking. Further study will focus on this point.

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