# PERFORMANCE EVALUATION OF AN OPTICAL FLOW TECHNIQUE FOR PARTICLE IMAGE VELOCIMETRY

Georges M. QUÉNOT

CLIPS-IMAG, 385, rue de la Bibliothèque, B.P. 53, 38041 Grenoble Cedex 9, France

*Summary* This paper presents a quantitative performance evaluation of an Optical Flow technique on the test data of the PIV-STD group of the Visualization Society of Japan. Near the optimal conditions for the method, the accuracy (average velocity error divided by the average velocity module) is below 2 % and it is below 4 % in all other cases except for very high and very low in-plane velocities.

## INTRODUCTION

The experimental fluid mechanics technique of Particle Image Velocimetry (PIV) has proven to be a valuable method for quantitative, two-dimensional flow structure evaluation[1]. It enables the measurement of the instantaneous in-plane velocity vector field within a planar section of the flow field. Nowadays, almost all PIV is done by computer image processing on digital images[2] and most methods are based on image intercorrelation. Optical Flow techniques[3–4], conventionally developed for detecting motion of large objects in a real world scene, were also recently successfully applied to the PIV problem[5]. The objective of the present study is to better characterize the performance of the optical flow technique for PIV and how it is influenced by experimental parameters (particle density and size, in-plane and out-of-plane velocities). For convenience and easy comparison of results, a standard PIV test set was used[6].

## OPTICAL FLOW FOR PIV

Many techniques have been developed for the computation of optical flow. Not all of these are well suited for the DPIV problem. Many require long image sequences that are not easily obtainable experimentally and/or do not perform very well on the particle image texture (especially multi-resolution methods). The technique that was chosen for the PIV application was introduced as the Orthogonal Dynamic Programming (ODP) algorithm for optical flow detection from a pair of images[3]. It has been extended to be able to operate on longer sequences of images and to search for subpixel displacements[4]. The ODP based PIV will be referred to as ODP-PIV. The technique cannot be detailed here but it is fully explained in [5]; it can be related to classical intercorrelation techniques but with the following differences:

- Basic matching is searched on elastic image strips (either horizontal or vertical) instead of being searched on rigid blocks, and strip matching is performed using Dynamic Programming which enforces continuity and regularity constraints.
- A global, dense, continuous and coherent image matching is iteratively updated and refined using alternatively horizontal and vertical strip matchings and by reducing the strips' width and spacing along with the iterations.

## THE VSJ PIV-STD PROJECT

A research group (PIV-STD) organized by the Visualization Society of Japan (VSJ) has developped standard image test sets for quantitative performance evaluation and comparison of PIV systems[6]. They are distributed via internet (`http://www.vsj.or.jp/piv/`) and publicly available. The site offers "standard" image sequences for 2D and 3D flows and a program able to generate custom image sequences with several independently tunable parameters (particle size, particle density, average in-plane velocity and average out-of-plane velocity). Results are presented here using standard and custom sequences.

## RESULTS ON STANDARD IMAGES

The first standard image sequence (s01) is a "typical" case defined by the following parameters : $N = 4000$ (number of particles), $T = 33$ ms (time interval, defining the scale of the in-plane velocity), $v = 7.39$ pixel/interval (in-plane velocity), $L = 20.0$ mm (light sheet thickness, defining the scale of the out-of-plane velocity), $w = 0.017$ -/interval (out-of-plane velocity, fraction of the particles leaving and entering the light sheet per interval), $P_a = 5.0$ pixel (average particle diameter) and $P_d = 1.4$ pixel (standard deviation of particle diameter). The seven following standard image sequence (s02 to s08) differ from the typical case by only one parameter. The images are 256 $\times$ 256 pixels representing an actual 100 mm $\times$ 100 mm area. The ratio between the in-plane and out-of-plane average velocities is of about 0.12 (defining a 2D flow). Figure 1 shows one image of the first sequence and the used velocity field.

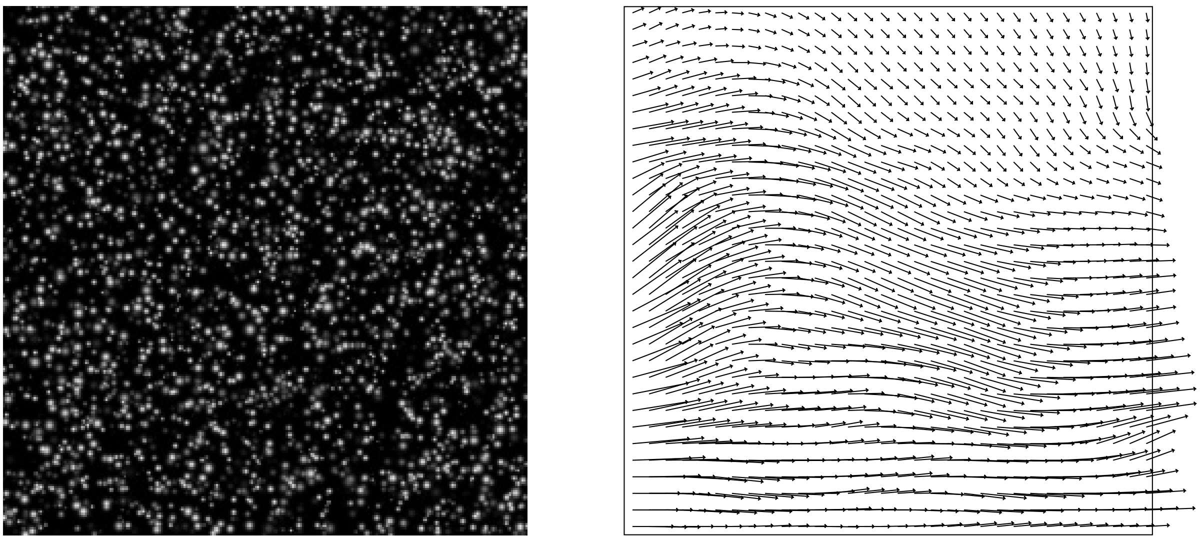

Figure 1: One particle image and the correct velocity field

Table 1 displays the parameter set used for the eight standard sequences as well as the accuracy results for the ODP-PIV method using repsectively two, three and four images. ODP-PIV control parameters are tuned differently for low and high out of plane velocity (s08 sequence). Accuracy results are displayed in percentage as mean error $\pm$ standard deviation of error, the error being the relative error (absolute error in pixel/interval divided by the average in-plane velocity also in pixel/interval).

As it will be seen in the next section, the typical case parameters are not optimal for the ODP-PIV method (they are probably tuned for Particle Tracking methods) for the particle density (at least 2.5 times too small) and size (twice too big). However, the default in-plane velocity

| No. | $N$ | $T$ | $v$ | $L$ | $w$ | $P_a$ | $P_d$ | 2 images | 3 images | 4 images |
|---|---|---|---|---|---|---|---|---|---|---|
| s01 | 4000 | 33 | 7.39 | 20.0 | 0.017 | 5.0 | 1.4 | 3.52±2.91 | 3.29±2.74 | 3.21±2.66 |
| s02 | 4000 | **100** | 22.4 | 20.0 | 0.053 | 5.0 | 1.4 | 10.8±11.7 | 10.2±10.2 | 10.2±10.5 |
| s03 | 4000 | **10** | 2.24 | 20.0 | 0.005 | 5.0 | 1.4 | 9.82±5.14 | 9.74±5.00 | 9.75±4.96 |
| s04 | **10000** | 33 | 7.39 | 20.0 | 0.017 | 5.0 | 1.4 | 1.97±2.67 | 1.45±1.82 | 1.33±1.53 |
| s05 | **1000** | 33 | 7.39 | 20.0 | 0.017 | 5.0 | 1.4 | 3.53±3.42 | 2.68±3.14 | 2.33±2.98 |
| s06 | 4000 | 33 | 7.39 | 20.0 | 0.017 | 5.0 | **0.0** | 2.30±4.13 | 1.50±1.57 | 1.33±1.41 |
| s07 | 4000 | 33 | 7.39 | 20.0 | 0.017 | **10.** | 4.0 | 2.93±4.51 | 2.23±2.95 | 2.08±2.89 |
| s08 | 4000 | 33 | 7.39 | **2.0** | 0.176 | 5.0 | 1.4 | 7.79±13.0 | 5.05±4.57 | 3.90±3.82 |

Table 1: Results on standard images

scale is near the optimum and the out-of-plane velocity has negligeable effect (except for the s08 sequence).

The accuracy for the typical case (s01) is below 4 % for the three variants. Severe accuracy degradation occurs when the average in-plane velocity is far (3 times smaller or larger, s02 and s03) from the optimum one. Increasing the particle density (s04) highly improves the accuracy while decreasing again the particle density (s05) does not further degrade the accuracy. Reducing the particle diameter standard deviation improves the accuracy (s06) as well as incresing the particle diameter (s07, however this is linked to the insufficient particle density). Finally, high out-of-plane velocity (s08, 17 % of particle appearance and disappearance per interval) significantly degrades the accuracy. However, even in this case, using the four images, we still get an accuracy of about 4 %. Near the optimal particle density (s04), the accuracy is as good as 2 % using only two images and below 1.5 % using the four images.

## RESULTS ON CUSTOM-MADE IMAGES

Custom image sequences were generated using the version 2 of the custom made standard image program in order to evaluate the effect of the various tunable parametrs. These image sequences are also publicly available from the VSJ server from: `http://www.vsj.or.jp/piv/java/tmp2/-<No.>/index.html`. The `<No.>` field is to be replaced by the corresponding test set number indicated below.

Tables 2, 3 and 4 respectively the effect of the variation of the particle density, the particle size and the average in-plane velocity on the accuracy. In all image sequences the light sheet thickness has been set so that the same rate of particle appearance and disappearance (5 %, about three times the one of the standard images) is used for all image sequences. The image parameters and the accuracy results are displayed exactly in the same way as for standard images.

| No. | $N$ | $T$ | $v$ | $L$ | $w$ | $P_a$ | $P_d$ | 2 images | 3 images | 4 images |
|---|---|---|---|---|---|---|---|---|---|---|
| 100 | 6000 | 30 | 6.66 | 6.42 | 0.050 | 2.0 | 1.0 | 2.85±2.44 | 2.25±2.17 | 1.97±1.76 |
| 101 | 8000 | 30 | 6.66 | 6.42 | 0.050 | 3.0 | 1.0 | 2.51±2.68 | 1.93±2.54 | 1.67±1.79 |
| 102 | 10000 | 30 | 6.66 | 6.42 | 0.050 | 3.0 | 1.0 | 2.36±2.27 | 1.80±1.78 | 1.63±1.75 |

Table 2: Results on custom images, variation with particle density

The optimal number of particles is 10000 (one particle by 6.4 square pixels density), which is the maximum allowed by the sequence generation program. However, it is estimated from the data that the optimal density without that limitation would be about the same. The optimal

| No. | $N$ | $T$ | $v$ | $L$ | $w$ | $P_a$ | $P_d$ | 2 images | 3 images | 4 images |
|---|---|---|---|---|---|---|---|---|---|---|
| 106 | 10000 | 30 | 6.66 | 6.42 | 0.050 | 1.0 | 0.6 | 3.32±3.40 | 2.43±1.89 | 2.15±1.51 |
| 105 | 10000 | 30 | 6.66 | 6.42 | 0.050 | 2.0 | 1.0 | 2.46±2.57 | 1.96±2.01 | 1.77±1.71 |
| 107 | 10000 | 30 | 6.66 | 6.42 | 0.050 | 2.5 | 1.0 | 2.34±2.00 | 1.74±1.42 | 1.54±1.29 |
| 102 | 10000 | 30 | 6.66 | 6.42 | 0.050 | 3.0 | 1.0 | 2.36±2.27 | 1.80±1.78 | 1.63±1.75 |
| 103 | 10000 | 30 | 6.66 | 6.42 | 0.050 | 4.0 | 1.5 | 2.48±2.34 | 1.88±1.59 | 1.68±1.47 |
| 104 | 10000 | 30 | 6.66 | 6.42 | 0.050 | 5.0 | 2.0 | 2.88±3.93 | 2.14±2.18 | 1.87±1.80 |

Table 3: Results on custom images, variation with particle size

| No. | $N$ | $T$ | $v$ | $L$ | $w$ | $P_a$ | $P_d$ | 2 images | 3 images | 4 images |
|---|---|---|---|---|---|---|---|---|---|---|
| 111 | 10000 | 25 | 5.55 | 5.35 | 0.050 | 2.5 | 1.0 | 2.51±1.97 | 2.07±1.75 | 1.89±1.64 |
| 107 | 10000 | 30 | 6.66 | 6.42 | 0.050 | 2.5 | 1.0 | 2.34±2.00 | 1.74±1.42 | 1.54±1.29 |
| 112 | 10000 | 35 | 7.77 | 7.49 | 0.050 | 2.5 | 1.0 | 2.29±2.36 | 1.71±1.61 | 1.57±1.62 |
| 108 | 10000 | 40 | 8.88 | 8.56 | 0.050 | 2.5 | 1.0 | 2.16±3.50 | 1.76±2.79 | 1.53±2.49 |
| 113 | 10000 | 45 | 9.99 | 9.63 | 0.050 | 2.5 | 1.0 | 2.20±4.29 | 1.79±3.97 | 1.61±3.05 |
| 114 | 10000 | 50 | 11.1 | 10.7 | 0.050 | 2.5 | 1.0 | 2.63±7.45 | 1.89±4.90 | 1.68±4.58 |

Table 4: Results on custom images, variation with average in-plane velocity

particle diameter is around 2.5-3.0 pixel. The optimal average in-plane velocity is of about 8-9 pixel/interval. This last value may change for higher relative out-of-plane velocities ($w$, a value of 0.05 is used here).

In the neighborhood of the optimal parameters, the accuracy is always better than 3 % using only 2 images and better than 2 % using four images. These results might degrade if noise is added (no noise model is implemented in the standard image generator) but it has been shown using another test set that the method is rather robust to noise[5].

## CONCLUSION

This study has confirmed that Optical Flow based on the use of Dynamic Programming is a very efficient technique for PIV. Under controlled and optimal conditions (particle density, size and in-plane velocity) the average relative accuracy of the velocity for the whole image can be as good as 2 % and still below 4 % for a wide range of conditions around the optimal ones.

Further investigations will be conducted in order to also quantify the effects of noise, higher out-of-plane components and three-dimensional flow structures.

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