3-D least squares matching for volumetric velocimetry data processing

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The paper presents a three-dimensional least squares matching (3-D LSM) approach applied to time-resolved volumetric particle image velocimetry (PIV) data to determine 3-D velocity fields.

1. Motivation

Volumetric PIV generates a tomographic reconstruction of a particle constellation from a limited number of synchronized camera views by applying a feasible reconstruction algorithm like MART or MinART. The advantage of PIV is the insensitivity to high seeding densities. This kind of tomographic reconstruction facilitates the implementation of a volume-based particle tracking technique rather than a discrete PTV (particle tracking velocimetry) approach, which may be prone to ambiguities at high seeding densities.

Volume-based tracking techniques deliver dense flow velocity field information by dividing time-resolved volumetric velocimetry data into cuboids of a predefined size and tracking these cuboids through the reconstructed sequence of voxel spaces. Herein, 3-D cross correlation (3-D CC) is a rather straightforward technique to determine 3-D displacement vectors between cuboids of two consecutive epochs with sub-voxel precision by calculating a 3-D CC coefficient field and fitting a Gaussian function into it to obtain sub-voxel accuracy. An implementation of this approach is quite simple but limited to the determination of the shifts in each direction only. Thus, cuboids with significant deformations will not be tracked reliably. Here, 3-D LSM offers the advantage of being adaptive to cuboid deformation, rotation and shear, which makes it a rather interesting alternative to 3-D CC.

2. Principle

3-D LSM is a volumetric matching technique. In analogy to 2-D LSM, 3-D LSM utilizes an iterative geometric and radiometric transformation between two (or more) consecutive cuboids in a way that the sum of the squares of the gray value differences between the voxels of the cuboids reaches a minimum. The geometric transformation is a 3-D affine transformation with 12 parameters, the optional radiometric adjustment may use a 2-parameters linear correction term. Like all non-linear least squares approaches, the estimation of the unknowns takes place in an iterative way and converges in a few iterations. The unknowns are updated after each iteration until a preset iteration criterion has been reached. In general, the residual amounts are non-integer values and the gray values in the search cuboid will need to be determined by interpolation. As a least squares adjustment method, 3-D LSM delivers information on the precision, determinability and reliability of the resulting transformation parameters for each cuboid. This includes the standard deviation of each of the parameters as well as the correlation between parameters. Furthermore, the level of significance can be calculated for each parameter in each cuboid. To decide whether a transformation parameter is significant or not, the multi-dimensional student test function is calculated. Non-significant parameters may be excluded from the estimation process in order to improve the strength of the solution and the convergence behavior. If parameters are detected to be non-significant, the least squares adjustment is repeated until only significant parameters remain. The essential advantage of these additional non-translational cuboid transformation parameters is the adaptivity to changes in scale, rotation or shear. If not considered, they may hamper the determination of velocity vectors or systematically deteriorate the quality or results. For the special case of tracking particles in liquids, a cuboid, while changing its shape due to deformations, will have a constant volume. Consequently, a volume constraint has to be implemented to consider the incompressibility of the liquid. It results in one additional linearized equation for the LSM equation system.

3. Some Results

The implementation of 3-D LSM has been validated with both simulated and real data. Further, experiments in real test environments were performed, like a vortex ring in a water tank. The accuracy potential (overall accuracy, standard deviation of the parameters etc.) as well as the reliability will be documented comparatively for all data sets. The parameterization for different flows and the percentage of significant parameters in accepted trajectories will be analyzed. Furthermore, a comparison between 3-D CC and 3-D LSM is given.