25 Years of Particle Image Velocimetry in Aerodynamics
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# Accelerated Tomographic Particle Image Velocimetry for 3C-3D Velocity Measurements

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## ABSTRACT

Particle image velocimetry (PIV) has evolved rapidly with the adoption of digital processing and the principles of stereopsis and more recently tomography. By combining efficient digital imaging and evaluation with multiple views of a measurement region, the data yield of PIV has been extended from standard two-component two-dimentional (2C-2D) measurements to three-component two-dimensional (3C-2D) Stereo-PIV and three-component three-dimensional (3C-3D) Tomo-PIV. Stereo-PIV is now considered a relatively mature method for obtaining 3D flow measurement, but being a planar technique, is unable to deliver information about the 3D volumetric structure of the flow or the full velocity gradient tensor. Information contained in the velocity gradient tensor not only forms an important part of the Navier-Stokes equations, but is also required by the most popular vortex identification schemes. Acquiring this information requires instantaneous measurements in two planes, as in dual plane PIV, or even better through three or more planes using Tomo-PIV.

Tomo-PIV uses three or more cameras with angular-offsets and calibration procedures similar to those of Stereo-PIV, Tomographic reconstruction techniques are used to determine the 3D particle intensity field in a measurement volume such that the images recorded by each camera are instantaneously satisfied. Reconstructed volumes are then 3D cross-correlated to determine the 3D flow velocity in multiple planes within the reconstructed volume, enabling calculation of the velocity gradient tensor via finite differences or least square fitting. Unfortunately the extension to 3D does not come without its share of difficulties. Principle among these is the reconstruction and cross-correlation times. Reconstruction of a $1200 \times 1200 \times 180$ point discretized volume with the commonly used MART algorithm requiring over 2 hrs per volume, with a precalculated calibration based weighting matrix of 34 GB per camera, and Fast Fourier Transform (FFT) based 3D cross-correlation of $64^3$ point interrogation regions with a 75% overlap requiring approximately 3 hrs per volume pair. Each 16-bit volume also requires 495 MB of storage, resulting in processing requirements well beyond those of planar or Stereo-PIV. Recent studies of a turbulent boundary layers have required the use of computer clusters and months of processing time, representing significant obstacles to the widespread industrial use of Tomo-PIV.

Reconstruction time can be significantly reduced by using a multiplied line-of-sight estimation of the particle locations combined with an instantaneous SMART intensity correction, without loss of accuracy. Reconstruction of the previously mentioned $1200 \times 1200 \times 180$ point volume with an image seeding density of 0.04 particles per pixel (ppp) can now be performed in 10 minutes on a single CPU without any pre-calculated weight matrices. This method corrects the intensity in the volume one point at a time, making it possible to reconstruct sub volumes in a matter of seconds for rapid feedback on the reconstructed seeding density and velocity magnitudes as needed to optimising an experimental setup.

Accelerated Tomo-PIV is currently being applied to measure the 3D structure of a zero pressure gradient turbulent boundary layer at $Re_\theta = 7800$ and 13000 with measurement volumes corresponding to $440^+ \times 66^+ \times 440^+$ and $857^+ \times 128^+ \times 857^+$, respectively. Tomo-PIV can provide information about the flow at conditions well beyond what can currently be achieved by direct numerical simulation (DNS), making it a valuable addition to the study of turbulence.