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Optical diagnostics for fluid mechanics research from planar (2D3C PIV) to volumetric (Tomo-PIV) measurements

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Abstract. The three-dimensional aspects of Fluid Mechanics phenomena have for long been experimentally accessible by point-wise or planar measurement techniques only. A summary of the limiting factors and the key enabling developments for truly three-dimensional measurements is given. Two techniques (Tomo-PIV and Shake-the-Box) with the potential of becoming the main tools for such work are compared and the results from two recent measurements in automotive wind tunnels are presented.

1. Introduction

The interest in experimental approaches for volumetric flow field studies has been present since the early days of flow visualisation and due to the lack of suitable hardware and refined algorithms and processing power unsteady flow fields were predominantly characterised by planar PIV in the first decade of this century. Although holographic PIV and 3D-PTV and defocusing digital PIV (DDPIV) were successfully applied these techniques did have drawbacks and limitations which rendered them unfit to become popular or economically feasible. When holographic PIV began to mature and move from analogue film - requiring time-consuming wet-processing - and started to utilise digital cameras it suffered from the limited spatial resolution of those and still required high power lasers with good coherence and involved a challenging experimental workflow. For engineering or industrial purposes the need for highly specialised operators was undesirable. Conventional PTV in 2D and 3D did for many applications not meet the requirements of spatial resolution although the accuracy and the process of operation were well suited to be used by a wide range of labs. Since DDPIV utilises a tracking algorithm it has similar limitations in coping with higher seeding densities as standard PTV. Furthermore the need to have an additional aperture placed on each camera's lens the reduction of the effective F-number leads to high demands on particle signal which means either larger seeding particles' diameters (only easily accessible in water applications) or more laser power or both.

The Tomographic PIV technique [1] freed researchers from virtually all above mentioned restrictions and it performs the measurement of the particle motion field within a three-dimensional measurement volume without the need to track individual particles. It is based on the simultaneous view of the illuminated particles by any of the suitable digital camera models and any of the available lenses very similar to the well-established stereoscopic PIV configuration including the possibility to use stereo microscopes or high framerate cameras (time-resolved). Together with the flexibility to position the cameras in any desired geometric arrangement according to available optical access in the experiment this made Tomo-PIV a highly flexible and universal research tool with a workflow that is not too different from stereo PIV.

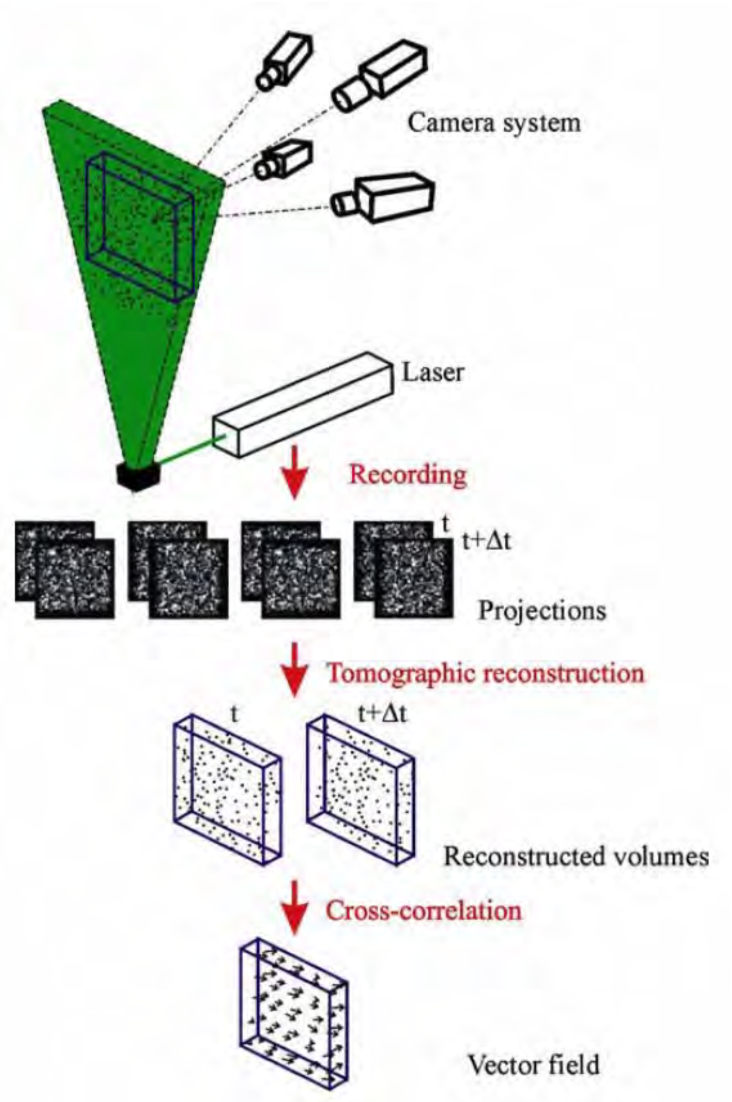


Figure 1. Tomo-PIV workflow reproduced from Elsinga [1]

The three innovative elements that paved the path to Tomo-PIV [2] in terms of algorithms are:
1) a tomographic algorithm to reconstruct the 3D particle field from the individual images
2) a 3D calibration procedure based directly on the particle images
3) three-dimensional cross-correlation with the volume deformation iterative multi-grid technique

In terms of hardware the enabling factors are clearly the increase in camera sensitivity and on the computer side the processing speed and storage capacity.

After Tomo-PIV was qualified in 2006 by several European laboratories (TU Delft, LaVision, DLR Göttingen, TU Braunschweig, Poitiers University) it quickly spread worldwide to academic labs and industrial sites for applications in liquids and gases and looking at the number of publications it can nowadays be called a de-facto standard.

Despite the proven applicability there was a continued effort to implement alternative or refined algorithms to reach partially rivalling goals. The trade-off in processing time versus accuracy was investigated by looking at different reconstruction schemes comparing MART to MLOS, MinLOS, MTE and MTE-MART [3] and later FastMART and SMTE.

2. Volume Self-Calibration

Any multi-camera optical method that is based on analysing images of illuminated tracer particles needs in the initial step a calibration that allows to map positions in the different camera images to real world coordinates. For planar (light sheet) techniques the registration of the camera images is needed for a single plane (or in fact a thin volume) only and this is routinely achieved by imaging a calibration target with markers of known size and distance to each other positioned in that plane prior to the measurement. The resulting mapping function with either polynomials of third order or a pin-hole model is refined in a second step by taking particle images and reducing a remaining error by analysing the disparity map which shows a translation and rotation error resulting from residual misalignments of the target in relation to the real light sheet plane (self-calibration). This procedure (if well-implemented in software) reduces the typical errors from 5-20 pixels to only 1 pixel.

Although measurements in volumes do not rely on an alignment of the target in a certain plane an accurate calibration is of much higher importance because the subsequent steps of reconstruction of particles in space and volumetric cross-correlation have extremely high requirements for subpixel accuracy in order for the algorithms to converge well in iterative steps. The tomographic reconstruction step requires that each voxel position in space is mapped to a camera pixel position with an error less than 0.4 pixel [1], preferably less than 0.1 pixel. This has to be achieved for 3 to 4 cameras and for all positions in the whole imaged volume.

Volume Self-Calibration also works with disparity maps (or rather a number of maps in different z-planes) like planar self-calibration but the path to gain these maps is a lot more complex because it has to cope with triangulation errors, high number of camera views, high density of particle images, overlapping particle images and 'ghost' particles (appearing from increased seeding density).

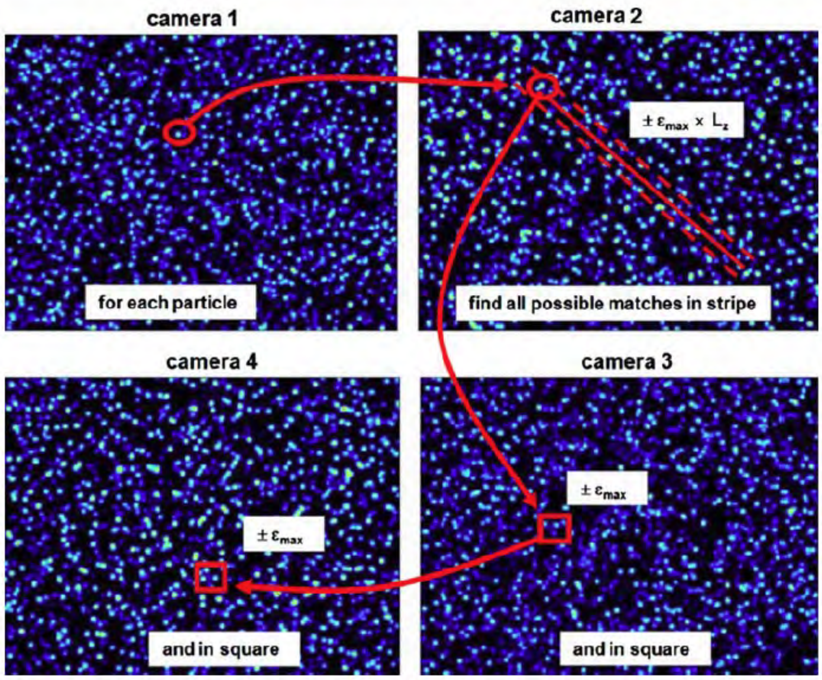


Figure 2. Particle triangulation procedure [4]

The solution is to apply an appropriate clustering technique and using not all particles but only the brightest, for example, 10%. With several steps of image pre-processing and local intensity renormalisation and building up statistics over a number of image sets it is achieved to improve significantly the contrast of the reconstructed volume and the quality of the vector field in terms of higher correlation values and improved signal-to-noise ratios [4].

Even though the need for Volume Self-Calibration was driven by Tomo-PIV for high seeding densities it was also proven to be beneficial for conventional 3D-PTV where typically the seeding density needed to be low thus enabling that technique to go to higher spatial resolution.

3. Sequential Motion Tracking Enhancement (SMTE)

With the availability of stable and accurate reconstruction algorithms for tomographic PIV with dual-frame (frame-straddling) recordings came the desire to extend these also to time-resolved measurements. The latter are realised with high-framerate cameras so that often a huge number of images needs to be handled and so the speed of calculations plays a dominant role. For low seeding densities (< 0,05 particles per pixel) the identification of 'ghost particles' which appear during the analysis at intersecting lines of camera views when two or more cameras show a particle image there is comparably easy. But at higher seeding densities this is a time-consuming step and therefore a 'motion tracking enhancement' algorithm using a time-sliding-kernel was developed. This utilises already calculated previous velocity information (of typically 3-5 time instances) to predict the flow field of the following step and suppresses ghost particles efficiently enough to increase the accuracy of the results but at the cost of an even longer calculation time.

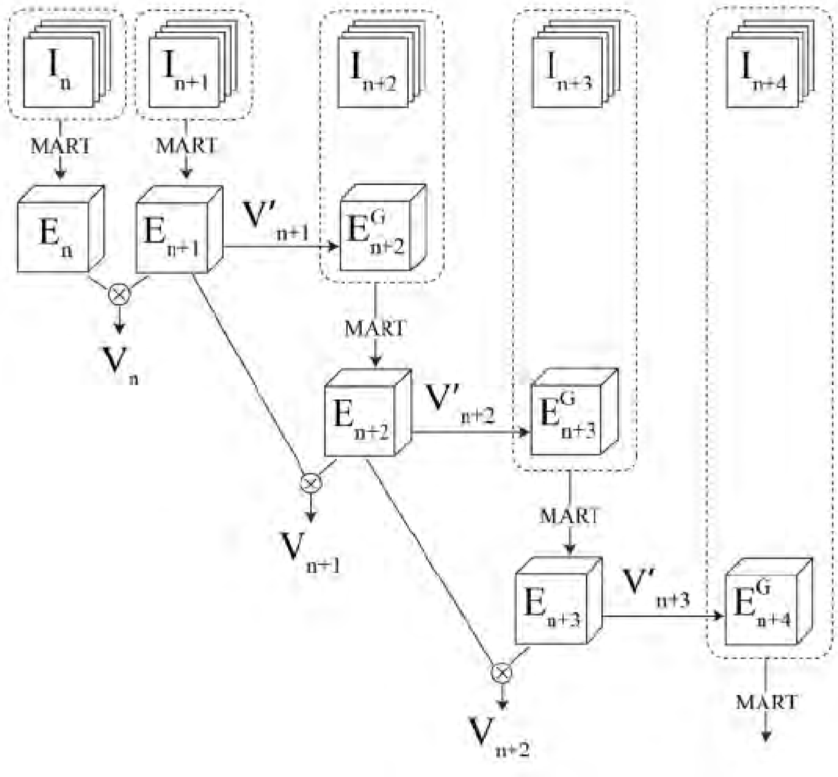


Figure 3. principle of SMTE-MART [5]

The break-through for this approach is SMTE-MART ("Sequential Motion-Tracking Enhanced (SMTE) Reconstruction for Time-Resolved Tomographic PIV") [5] in which only one previous reconstruction and flow field is used for an 'enhanced initial guess' for the reconstructed volume so that this time-marching-kernel propagates a previous reconstruction forward in time. This reduces the number of reconstruction steps and reduces the effort for detection of ghost particles drastically so that the computation time is in the range of 'standard' MART with the benefit of higher accuracy.

4. redefining 3D-PTV : "Shake-the-Box"

Usually measurement techniques do not see any revolutionary new developments once they are evaluated and established and main innovations are implemented in enhanced algorithms which refine the method. This is different with 3D-PTV which undergoes major changes now and is taken to a new level with the development of 'Shake-the-Box' [6] so that much higher seeding densities can be analysed and spatial resolutions reached which were for conventional 3D-PTV inaccessible. Two pre-requisites for this outstanding new approach were the developments of IPR (iterative particle reconstruction) and OTF (optical transfer function).

This novel approach to the evaluation of time resolved particle-based tomographic data is bas seizing the on time information contained in such datasets. A very fast and accurate tracking of nearly all particles within the measurement domain is achieved at seeding densities comparable to the thresholds for tomographic PIV. The method relies on predicting the position of already tracked particles and refining the found position by an image matching scheme (‘shaking’ all particles within the measurement ‘box’ until they fit the images: ‘Shake The Box’ - STB). Differently from conventional PTV a slow and often ambiguous triangulation (for particle identification) is performed only for particles newly entering the measurement volume while the majority of particles is known from a reconstruction of the previous time step and thus already identified. In detail this previous reconstruction is forwarded in time by the previous velocity field and so a qualified guess for the new reconstruction is available. This does not only eliminate ghost particles but also speeds up the analysis because the comparison of the guess with the actual image is fast due to the very close match that is already achieved.

The first 4-5 images which do not have a reliable history are in the initialisation phase reconstructed with tomo-PIV before going to the STB analysis.

Once being identified the particles are added to the table of known or tracked particles and these are the first ones to be matched in the next step. After the successful match they are deleted from the image so that only new or unknown particles are left. These can be identified by triangulation and should that not be successful the small number of left over particles can be ignored.

STB was in the meantime successfully applied to several experimental data sets and new publications show up continuously. The examples given below in figure 4 and figure 5 are from the early phase of STB in 2013 when it was applied to data of a measurement over periodic hills in a water flume. The recording rates were 500 Hz and 1000 Hz.

Right now the method still requires a suitable time resolution so that consecutive images show enough similarity for the particle distribution guess to be successfully matched to the image but there are promising approaches now to make STB applicable to frame-straddling data.

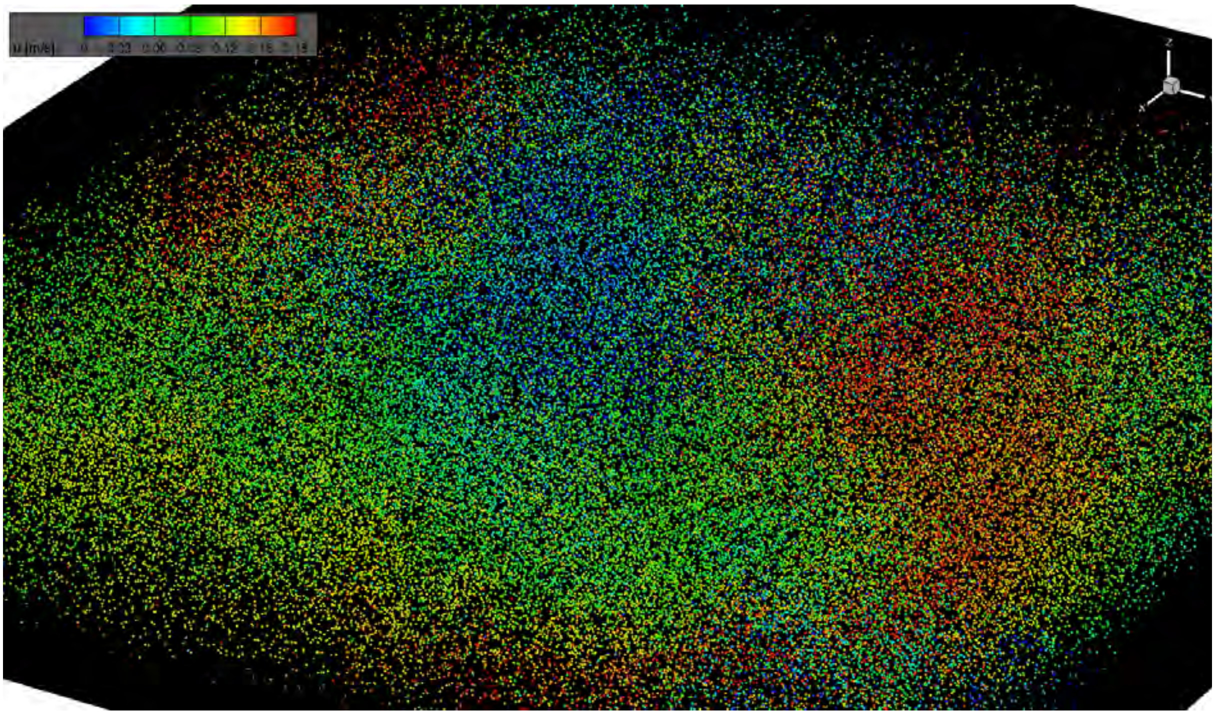


Figure 4. example ~75.000 STB tracked particles, color-coded is streamwise velocity , courtesy D. Schanz, DLR

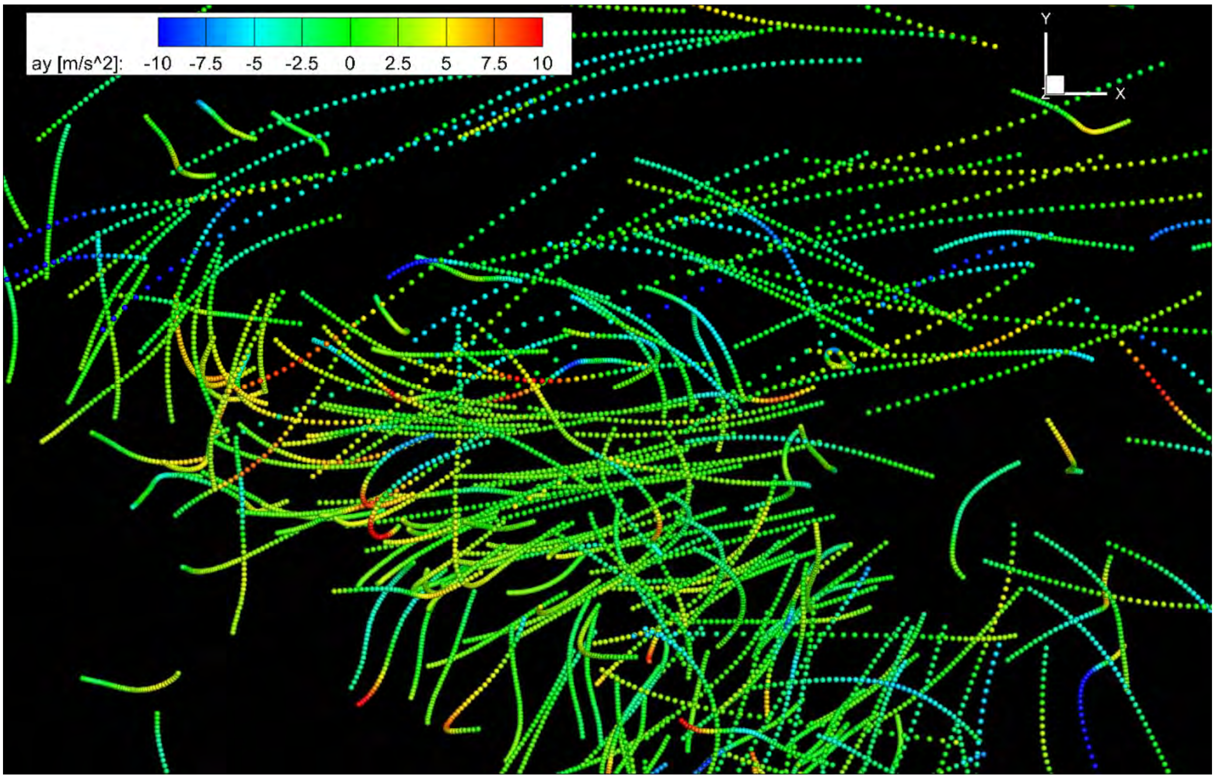
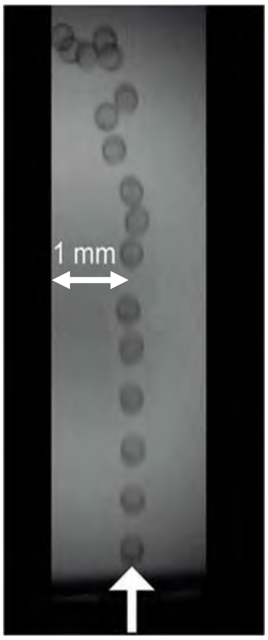


Figure 5. A few selected tracks with 40 time steps each, color-coded is spanwise acceleration , courtesy D. Schanz, DLR

5. Helium-filled Soap Bubbles for large-scale volumetric PIV/PTV

A niche of PIV that has for a long time (over two decades) not seen any progress or innovation or even general solutions is 'large-scale' PIV. Even planar measurements needed to tackle the challenges by stitching together results from small domain measurements (between 10x10 cm² and 50x50 cm² in air) to gain a large field overview. Dropping prices of suitable cameras (even with increasing numbers of pixels) allow for the use of several PIV systems in parallel but the main drawback was the lack of matching seeding particles. For fundamental research of unsteady flows and turbulence the desire to resolve small scale phenomena is well served by standard PIV systems and aerosol droplets or water vapour of around 1 µm in size and faithfully following a flow. But these particles are too small to be recorded and too weak in their light scattering behaviour to enable measurements in dimensions of square meters which would be of interest for engineering tasks in larger wind tunnels. The idea to use helium-filled soap bubbles with a good balance of liquid film thickness and helium volume to become neutrally buoyant in air showed the right direction but there were no commercially available products that overcame the difficulties of producing a high enough number of bubbles in a controllable manner with a narrow size distribution of the right dimensions (in early days 1 to 2 mm bubbles proved to be too large).

The development of a generator for HFSBs at the DLR in 2008 gave this approach a new momentum and with several steps of improvements now a well-refined bubbles seeder that creates a high number of 300 µm Helium-filled soap bubbles per unit time is available (figure 6). Thorough investigations of the bubbles in terms of slip velocity (below 0,2 m/s) and relaxation time (around 10 µs) were published [8]. Different academic and industrial users participated in the refinement and qualification of that device and two examples of recent measurement campaigns are given below.



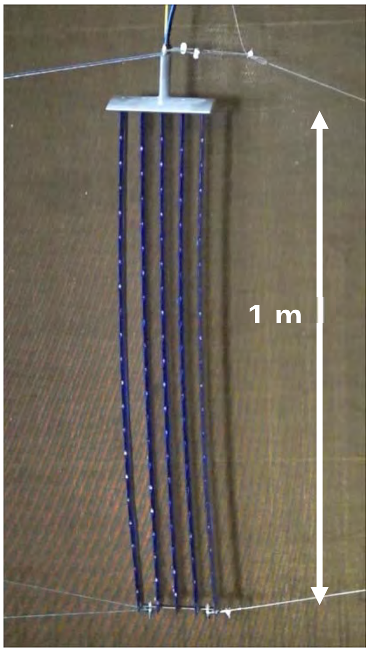


Figure 6. Helium-filled soap bubbles at nozzle exit

Figure 7. Array of 5 times 20 nozzles in wind tunnel

6. Application of Large Scale Tomographic PIV in a Quarter Scale Automotive Wind Tunnel

An earlier measurement campaign at Loughborough University / UK showed that a tomographic volume measuring 500mm x 500mm x 500mm could capture the whole wake of a quarter scale generic squareback road vehicle. A single helium-filled soap bubble (HFSB) generator was used to seed the flow. This experiment showed that tomographic PIV was valuable in determining the whole wake topology. Further, the instantaneous vector fields could be analysed using Proper Orthogonal Decomposition (POD) to examine the most relevant dynamic features of the wake. However, this experiment showed insufficient seeding and vector resolution, meaning subtle velocity gradients easily detected by planar techniques were lost. The recommendations from this work were to improve seeding density, thus improving the vector output. [9]

A recent repetition of a similar experiment [10] used 3 HFSB generators and allowed a comprehensive study of the seeding density at different tunnel velocities. The position of the seeding rakes was changed and the turbulence intensity in the working section was measured. It was found that increasing tunnel velocity reduced seeding density; however vector resolution remained sufficient even at speeds above 30m/s.

The object for this study was an axisymmetric body with a diameter D=160mm and length 5D=800mm (figure 8). It was known that this type of body produces low frequency azimuthal wake behaviour. This behaviour was earlier captured using stereoscopic PIV slices within the wake, but as the slices are not temporally linked the behaviour of the wake in three dimensions could not be reliably determined.

Tomographic PIV and its ability to capture the wake in its entirety has provided this capability. The whole wake has been captured in a single measurement and compared to stereoscopic PIV measurements taken at multiple planes within the wake (figure 9). The volume measured 250mm x 250mm x 250mm and the spatial resolution was found to be sufficient to capture the significant flow features.

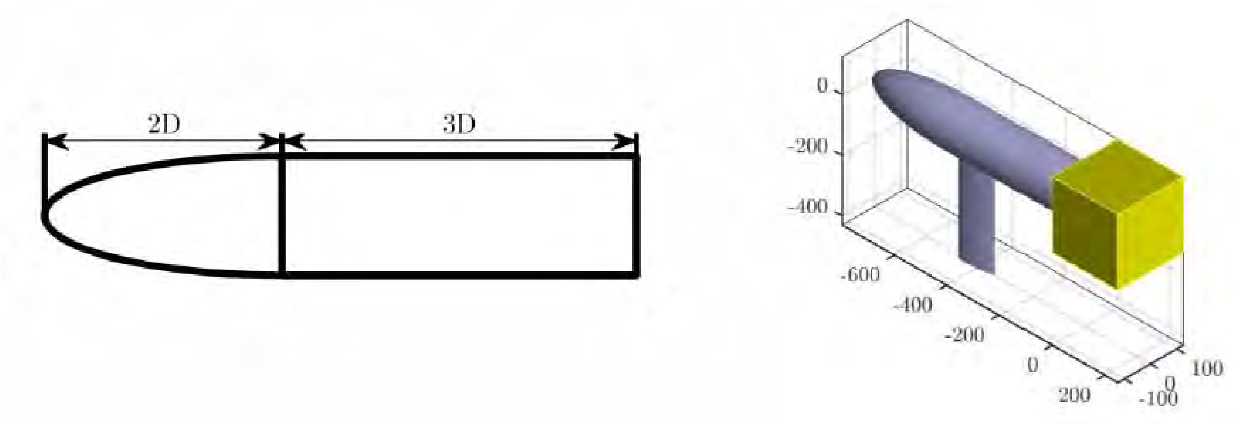


Figure 8. Axisymmetric body with the location of the tomographic volume in yellow

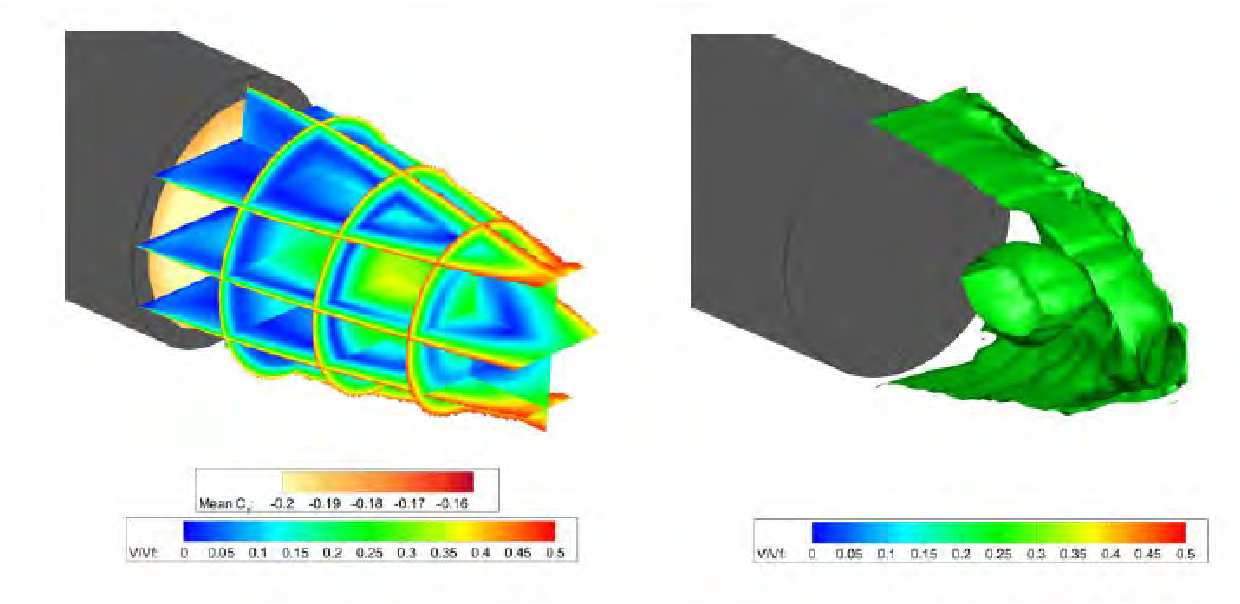


Figure 9. Stereoscopic PIV planes (left) showing normalized velocity magnitude and single tomographic measurement (right) showing an iso-surface of normalized velocity magnitude at 0.25V/Vf

7. Large Scale Time Resolved TOMO-PIV in a full-scale automotive Wind Tunnel

In automotive wind tunnel tests it is advantageous to be able to test full size real products instead of scaled down models because the effort of model preparation and modification can be saved and the measurement results can be trusted to be unaffected by scaling influences. Enabled by the recent developments as outlined above for the first time a full size sedan Passat B8 could be used for tomographic PIV measurements in an aerodynamic wind tunnel (figure 10) with a nozzle exit area of 37,5 m² at Volkswagen AG in Wolfsburg, Germany [11].

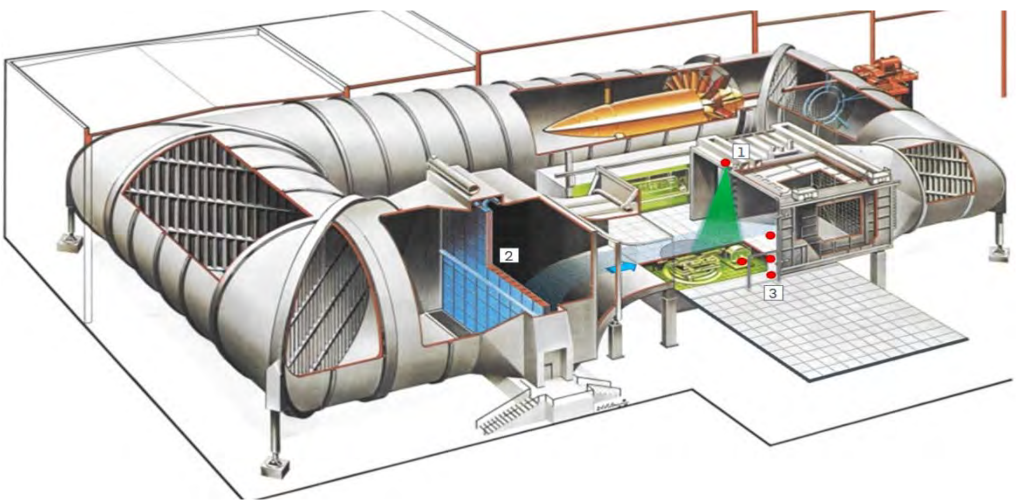


Figure 10. wind tunnel and experimental setup, 1. high-speed laser, 2. high-speed cameras, 3. HFSB generator nozzles

The PIV system's hardware consisted of 4 Phantom VEO 640 cameras being able to record 4 MPixel images at up to 1,5 kHz temporal resolution. Illumination was provided by a Photonics Industries 2 x 30 mJ laser and Helium-filled soap bubbles seeding was provided by 6 linear nozzle arrays with 10 nozzles each of a LaVision HFSB generator.
The measurements were performed at 120 km/h free stream velocity in a measurement volume of 2300 mm x 1500 mm x 400 mm (1,38 m³). Flow field calculations were done with Tomo-PIV and Shake-the-Box for comparison purposes and both methods were found to be applicable and giving valuable results.

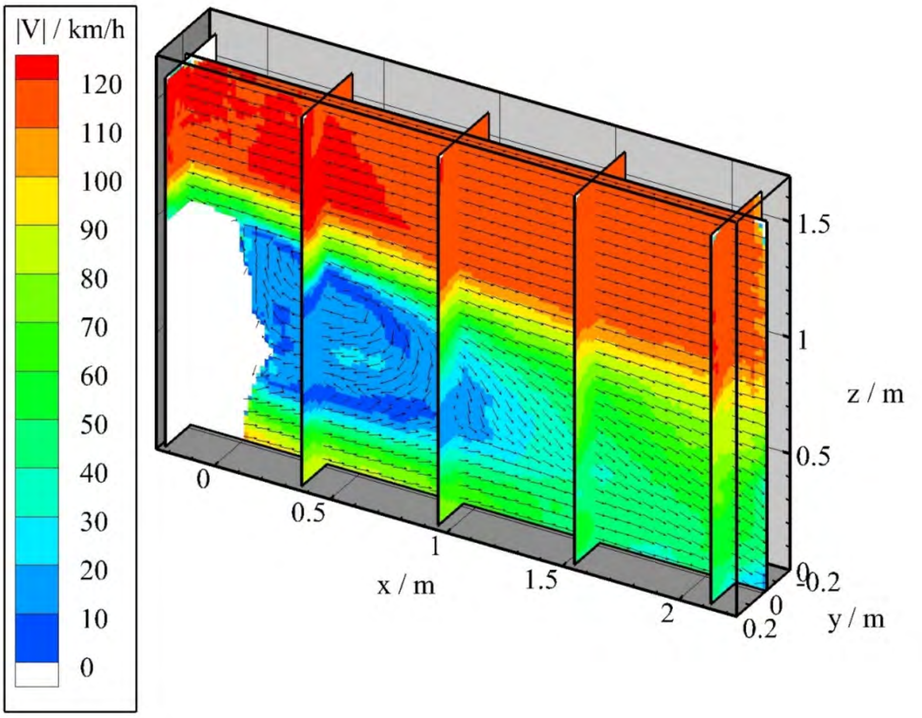


Figure 12. Tomo-PIV result using FastMART and Direct Correlation, only every third vector displayed for better clarity

The target to measure time-resolved mean velocity fields in a large volume with a spatial resolution and accuracy fit for validating numerical simulation codes was well achieved.
Since no traversing or a need for multiple PIV systems was involved the reduction of wind tunnel usage time as compared to smaller patches measurements with scanning and stitching the technique proved feasible and useful for such industrial applications.

8. Conclusion

A summarising overview of enabling factors for fluid mechanics measurements in volumes was given and some of the key enabling developments were outlined. It can be deducted that not single isolated developments or inventions bring the measurement techniques forward but even the most ingenious ideas can only become feasible for a wider range of researchers when they are accompanied by or embedded in a framework of enabling technologies. As highlight the new 'Shake-the-Box' method seems to be qualified to change the possibilities in volumetric velocity measurements significantly and it can be expected to quickly gain a lot of attention.

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