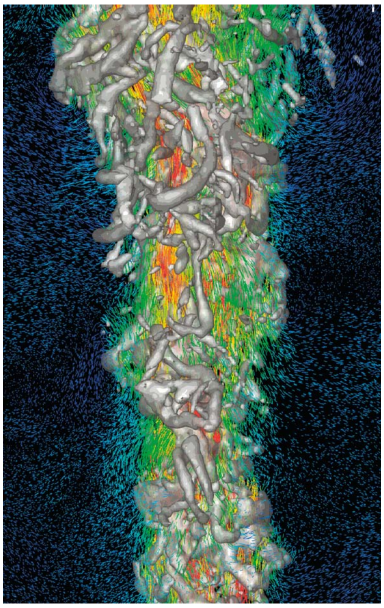
FlowMaster

Advanced PIV / PTV Systems for
Quantitative Flow Field Analysis

LaVision

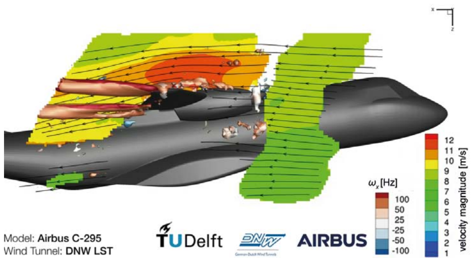
FOCUS ON IMAGING

LaVision's pioneering innovations



Tracking of helium-filled soap bubbles, courtesy DLR Göttingen

3D camera MiniShaker L



Velocity magnitude contours, isosurfaces of Q-criterion colored by axial vorticity, streamlines and vector field around a model of an Airbus C-295. Measurements performed with robotic PIV, courtesy TU Delft

LaVision is the leading supplier of laser imaging systems for a wide range of scientific fields such as fluid mechanics (aerodynamics, microfluidics), combustion (automotive, power generation) as well as spray and particle diagnostics (engines, pharma).
Non-intrusive in nature, optical instruments offer unique capabilities for multi-parameter flow measurements with high spatial and temporal resolution. Our measurement equipment is used in well-known R&D labs all over the world. Largely customer oriented, we offer user-friendly, reliable and high quality products.
The LaVision team has extensive professional experience in laser and camera technology, imaging techniques for flow analysis, spectroscopy and digital image processing. LaVision cooperates with leading research institutions and companies around the globe. These factors have led to numerous innovations which form the basis of our **FlowMaster** measurement systems.

1997:
- first commercially available highly sensitive 12 bit PIV CCD camera system

1998:
- **Stereo-PIV** presentation at the Lisbon conference
- simultaneous 2-phase flow field analysis

2000:
- **Time-resolved PIV** to determine fluid dynamic coupling effects in **time** and **space**
- endoscopic PIV setups
- flow tagging based on molecular tracers

2001:
- **Micro-PIV** for micron scale resolution

2001-2005:
- successful participation in the PIV challenges, a comparison of PIV/PTV algorithms of research teams worldwide

2004:
- Stereo-PIV **self-calibration,** a tool for the correction of even large misalignments between calibration plate and laser light sheet

2006:
- **Tomographic PIV,** a novel technique for instantaneous volumetric velocity field measurements

2010:
- introduction of **Adaptive PIV** for enhanced accuracy and resolution
- implementation of PIV analysis on GPUs (graphics processing units)
- first PIV systems with sCMOS cameras

2011:
- 8 camera Tomo-PIV wind tunnel measurement campaign with a new record in volume flow field resolution
- first underwater tomographic PIV measurement system

2012:
- multi-frame pyramid correlation for time-resolved PIV

2014:
- successful participation in the PIV challenge presenting the best results in Tomographic PIV

2015:
- publication of **PIV uncertainty** quantification from correlation statistics and introduction of the first commercial software to include PIV uncertainty quantification

2016:
- only commercial software using the time-enhanced particle tracking method **Shake-the-Box** (STB), award-winning method on the 4th PIV challenge in 2014

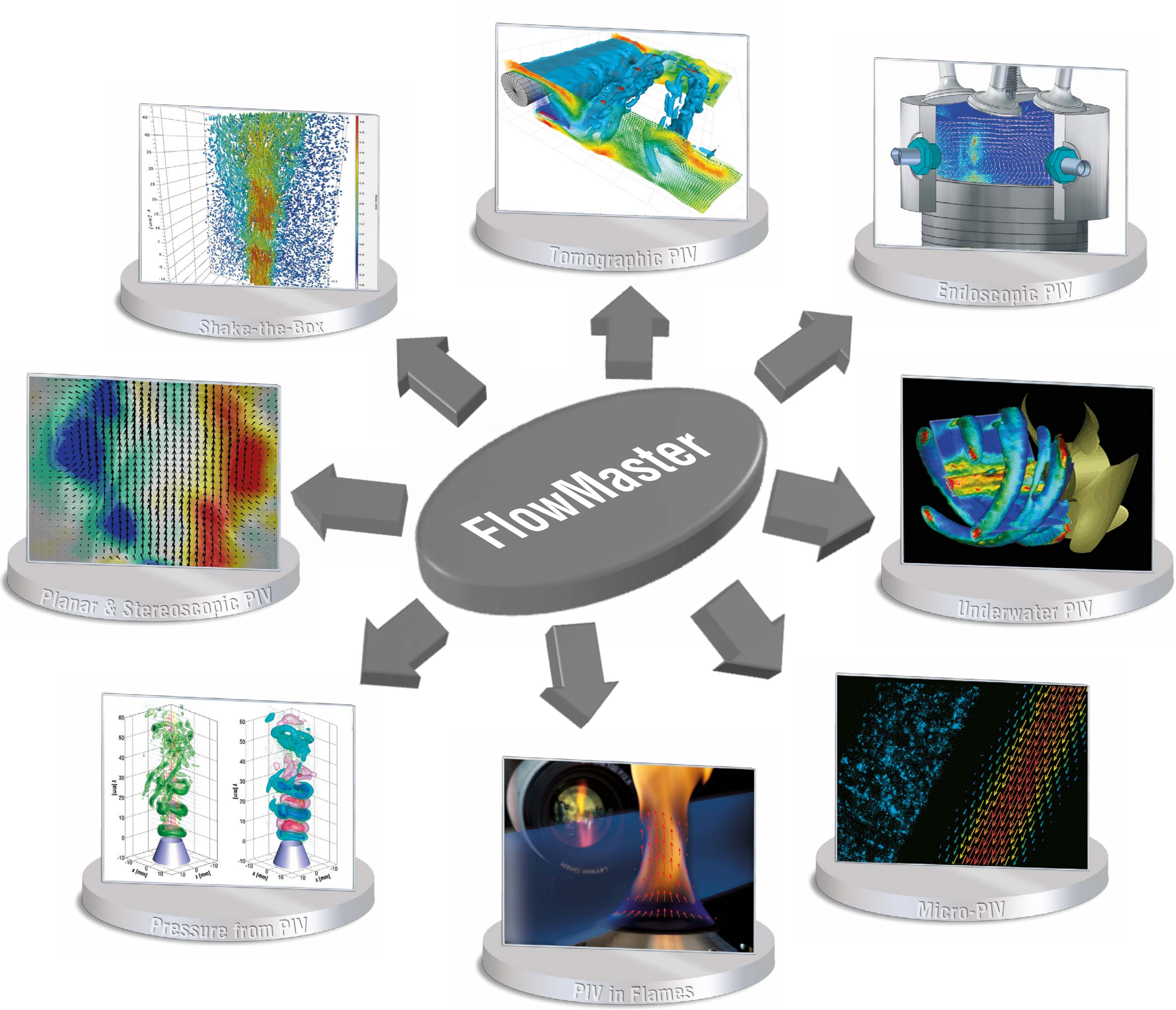
2017:
- release of the **Minishaker** - a multi-camera system easy to set up and operate for 3D flow field imaging
- inclusion of **pressure field computation** from PIV and STB data
- first commercial system delivering **Helium-filled soap bubbles** (**HFSB**), i.e. seeding particles for large-scale measurements in air

2018:
- release of the first multi-camera system with integrated laser illumination and robotics: **MiniShaker Aero Robotic**
- release of **Multi-pulse Shake-the-Box**

Integrated turn-key systems with unique measurement capabilities

LaVision has designed the **FlowMaster** system family, a highly flexible and powerful Particle Image Velocimetry (PIV) system. It is based on our extensive experience and our tradition of technical communication with our customers. With components including continuous wave and pulse lasers, high-speed and sCMOS cameras, all of them conveniently controlled with a precise timing unit, a **FlowMaster** system can be adapted to a wide range of measurement demands in all fields of fluid dynamics.

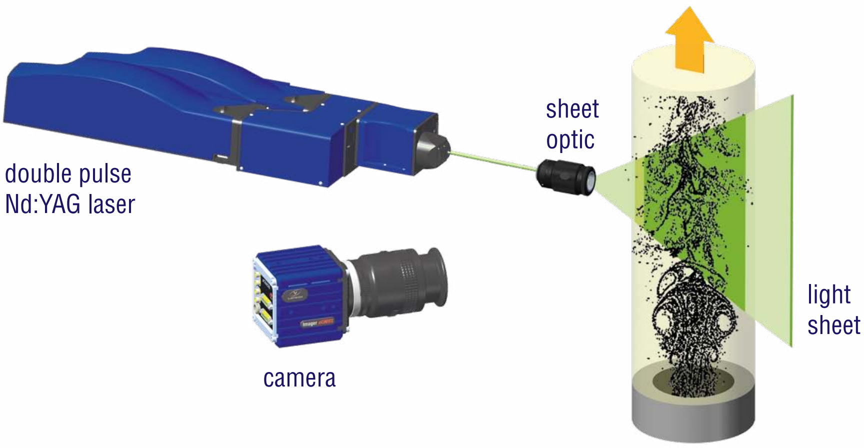
In a **FlowMaster** system, algorithms and hardware are controlled by **DaVis**, a software package offering the capabilities necessary for two and three dimensional flow field analysis. The quality of a PIV measurement strongly depends on the abilities of the applied algorithms. LaVision continuously offers the best PIV algorithms for calculation and validation, like deformed interrogation windows, volume self-calibration, PIV uncertainty quantification including propagation, the award-winning Shake-the-Box algorithm and much more.



A 2D **FlowMaster** system can be easily upgraded to a stereo and full 3D measurement system. **FlowMaster** is part of a complete family of light sheet and volumetric imaging systems designed for the investigation of combustion, spray, flow and aerodynamic applications. Therefore, a combination of PIV with additional methods, such as laser-induced fluorescence (LIF), can be used to gain further insights into physical and chemical processes.

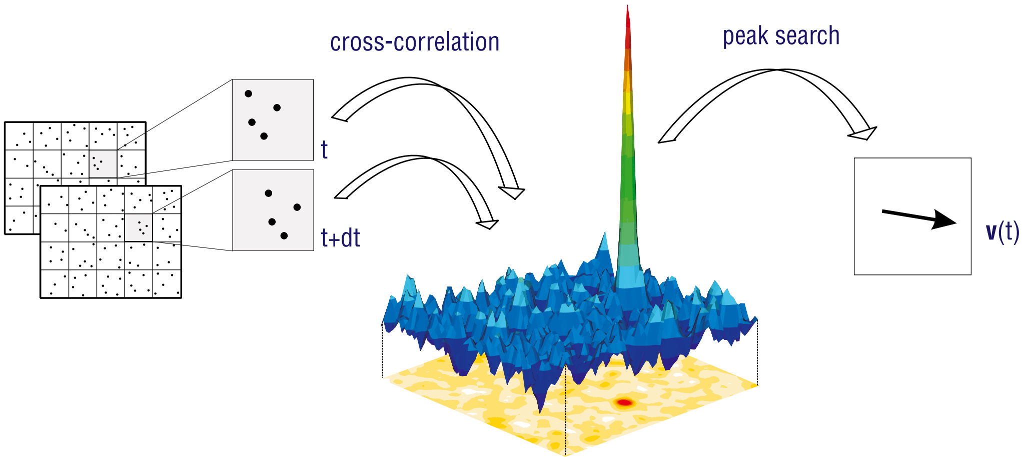
Basic principle of 2D cross correlation planar PIV

The **FlowMaster** system family is designed to measure instantaneous 2D- and 3D-velocity fields using the well-established Particle Image Velocimetry (PIV) technique. The flow is seeded with small particles which follow the flow. For planar PIV, the particles are illuminated by a thin (laser) light sheet, and the light intensity scattered by the tracer particles is recorded by one or more cameras.



For a single velocity snap-shot, the light source is fired twice, and the two illuminations are recorded by a dedicated high-resolution double-frame PIV-camera capable of taking two images shortly after another. Alternatively, for time-resolved PIV, a high-speed camera with frame rates typically larger than 1 kHz is used together with a high-repetition-rate laser, recording a series of images to observe the detailed flow dynamics with a high temporal resolution.

The recorded image is divided into small interrogation windows. During the time interval dt between the laser shots, the particles of each interrogation window move by a displacement ds. The velocity is then given by the ratio ds/dt. Cross-correlation between two corresponding interrogation windows in subsequent images yields a correlation map of possible particle displacements. The position of the highest peak in the correlation plane indicates the most likely mean displacement ds of the particles in this window.

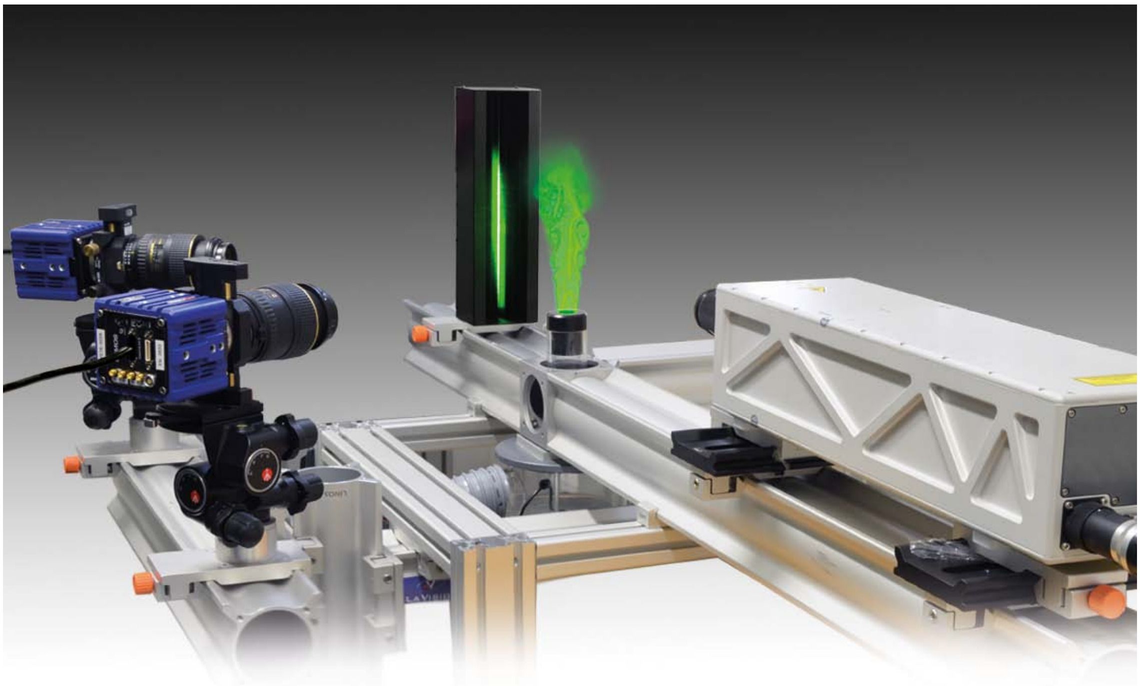


The displacement vectors of all interrogation windows are finally transformed into a complete instantaneous velocity map. This basic principle of PIV processing has been improved by LaVision using highly advanced state-of-the-art techniques like the multi-pass predictor-corrector schemes[1] with image deformation according to the local velocity gradient field for higher accuracy and spatial resolution. For time-resolved PIV, a variety of multi-frame techniques are available like the pyramid correlation[2] , which performed excellent in the PIV Challenge[3].
With images from a single camera, 2D-PIV (2D2C, 2-dimensional, 2-component) calculates the two velocity components. A 2D-PTV algorithm for particle tracking is also available.

As part of an international collaboration[4,5], LaVision has implemented an uncertainty quantification method based on correlation statistics[6]. This technique is able to provide an uncertainty value for individual instantaneous velocity vectors for planar 2D- and Stereo-PIV. Uncertainty propagation provides uncertainties also for derived quantities such as vorticity and Reynolds stress[7].

Principle of Stereoscopic PIV

With **FlowMaster** Stereo-PIV, all three velocity components (u, v, w) in a light sheet are measured (2D3C). It is based on the principle of stereoscopic imaging: two cameras capture the image of the illuminated tracer particles from different angles. Scheimpflug lens arrangements keep all areas of the measurement planes in focus.

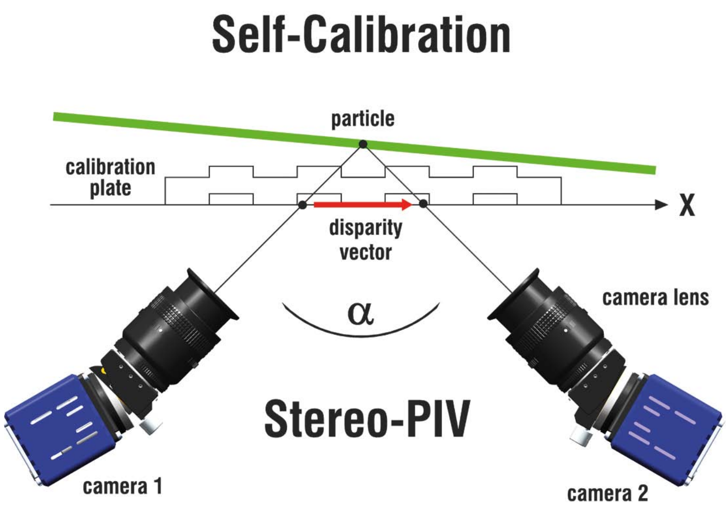


An initial calibration procedure viewing a (dual-level) calibration plate typically at the position of the light sheet computes the mapping functions between measurement volume and camera images. Often some misalignment between the reference plane defined by the calibration plate and the true measurement plane remain, which introduces some errors in the final velocity field. Subsequent **Stereo-PIV self-calibration** using actual PIV recordings has become the standard procedure to correct even large misalignments[8].

This expands the measurement range for Stereo-PIV, e.g. to internal flows such as biomedical flows, micro channel flows or internal combustion engine cylinders where insertion of a calibration target is impractical or impossible.

Advantages of Stereo-PIV Self-Calibration

- ultimate accuracy: reduction of calibration errors
- user-friendly: no need to align calibration plate exactly with light sheet
- in-situ calibration: refinement using recorded measurement data
- time saving for fixed camera assembly: calibration can be prepared off-site
- easy multi-plane scanning: all scanning positions calibrated at once



Laser light sheet misaligned with the calibration plate position

References:

[1] Scarano, Riethmuller, Exp Fluids (2000) 29(1):51-60
[2] Sciacchitano, Scarano and Wieneke, Exp Fluids (2012) 53:1087–1105
[3] Kähler et al. Exp Fluids (2016) 57:97
[4] Neal et al., Meas. Sci. Technol. (2015) 26 074003
[5] Neal et al., Meas. Sci. Technol. (2015) 26 074004
[6] Wieneke, Meas. Sci. Technol. (2015) 26 074002
[7] Sciacchitano and Wieneke, Meas. Sci. Technol 27 (2016) 084006
[8] Wieneke, Exp Fluids (2005) 39: 267-280

Tomographic PIV (3D3C/4D3C)

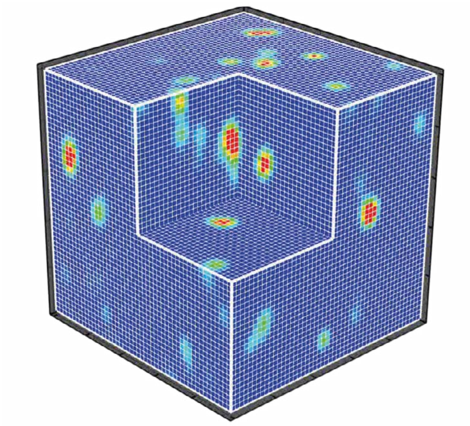
Principle of Tomographic PIV

Tomographic PIV[9] extends the stereoscopic approach to the third dimension.

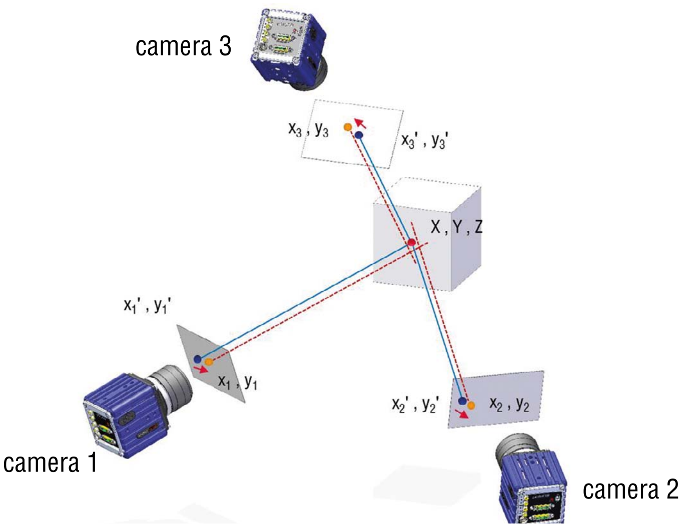
From the recordings by multiple cameras, all three velocity components in a volumetric flow field become accessible (3D3C).

At least two cameras record the light scattered by particles in the illuminated measurement volume. A tomographic reconstruction algorithm using the Multiplicative Algebraic Reconstruction Technique (MART) reconstructs the 3D light intensity distribution. 3D cross correlation of interrogation volumes recorded at different instants in time yields the displacement velocity field.

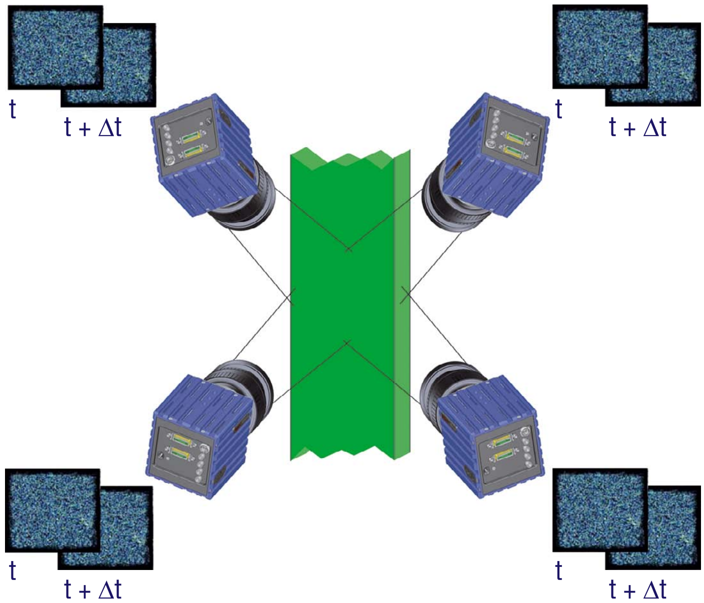
High-speed cameras and high-repetition-rate pulsed lasers or high-power LED illumination pave the way for time-resolved volumetric flow fields (4D3C) extracting the most complete information in the measurement volume with velocity, acceleration and even pressure fields.



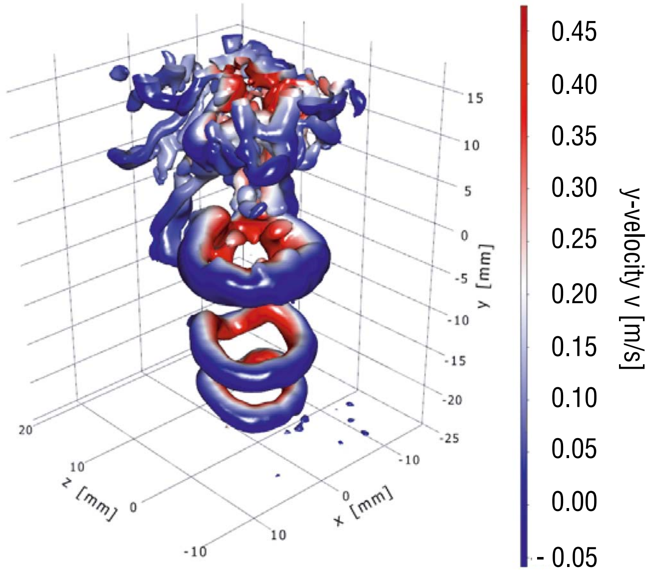
MART reconstruction yielding the 3D intensity distribution in the overlap region of the cameras



Volume self-calibration: recorded particle images are used for correcting remaining disparity errors



Tomographic PIV with 4 cameras in double-frame mode



Jet exiting a circular nozzle visualized in DaVis 10 with isosurfaces of the swirling strength λ_2, courtesy TU Delft

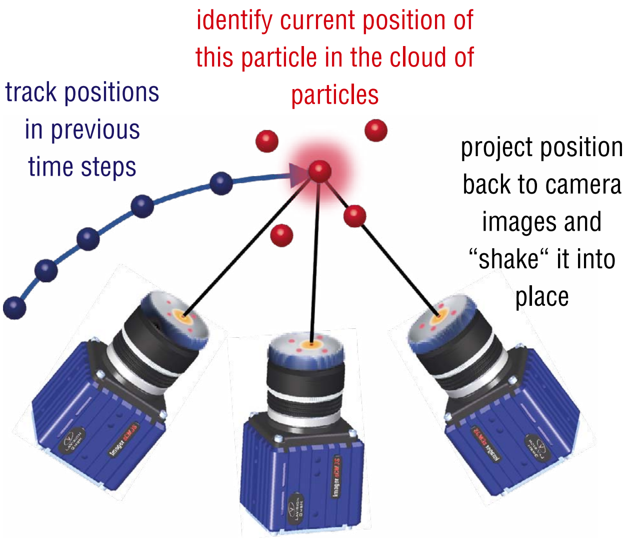
The patented volume self-calibration method refines and reduces the inaccuracies of the 3D calibration[10]. It has become an indispensable processing step for Tomographic PIV and Shake-the-Box.

New algorithms like Motion Tracking Enhancement (MTE[11]) and Sequential MTE[12] for time-resolved data significantly increase the spatial resolution and accuracy of the measurement. Even three-dimensional flow field computation with 2 cameras become possible.

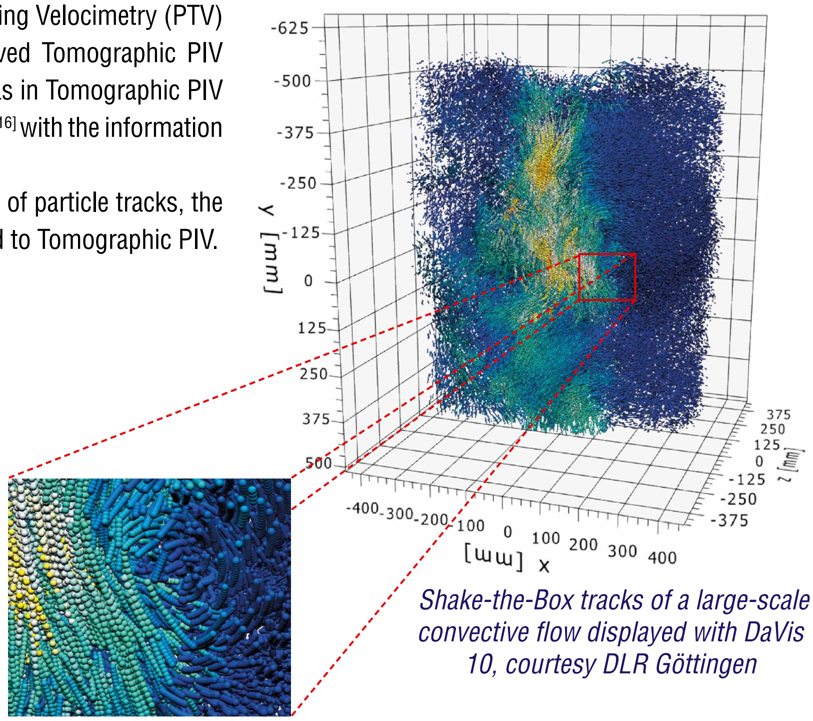
Further details about Tomographic PIV are available in Scarano[13] and Raffel et al.[14].

Lagrangian Particle Tracking: Shake-the-Box

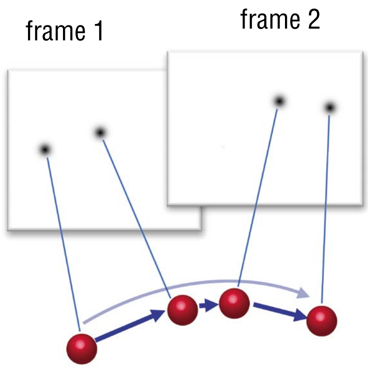
Shake-the-Box[15] is the most advanced 4D Lagrangian Particle Tracking Velocimetry (PTV) technique. With a hardware compatible to **FlowMaster** time-resolved Tomographic PIV setups, it retrieves particle tracks even for flows as densely seeded as in Tomographic PIV recordings. Shake-the-Box combines iterative particle reconstruction[16] with the information of particles moving in time.
Besides the unsurpassed precision for velocity and acceleration data of particle tracks, the speed increase with Shake-the-Box is a factor of 10 to 100 compared to Tomographic PIV.



Shake-the-Box working principle

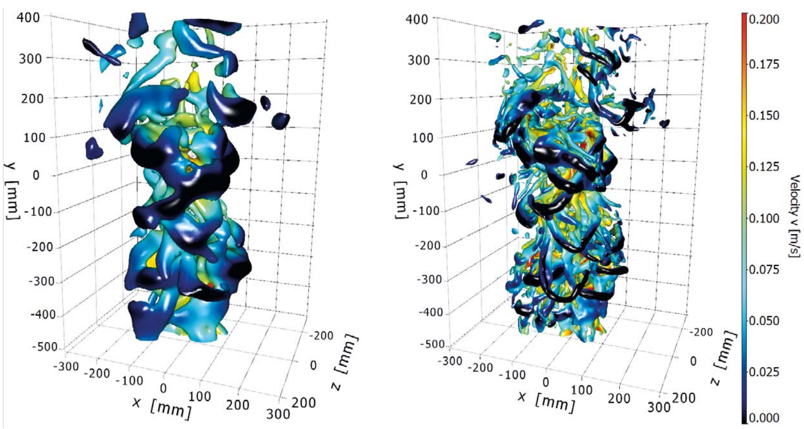


Shake-the-Box tracks of a large-scale convective flow displayed with DaVis 10, courtesy DLR Göttingen



4-pulse Shake-the-Box with 2 pulses in each frame

Double-frame **Multi-pulse Shake-the-Box** extends the application range to flows with very high velocities that cannot be recorded with a time-resolved system. Each frame is illuminated with one or two light pulses. Finally, DaVis retrieves short particle tracks from each double-frame image, yielding velocity and acceleration data.



Vorticity isosurfaces in the convective flow shown above (recordings courtesy DLR Göttingen), left: binning convert-to-grid, right: VIC#

Particle tracks give a good impression of the flow topology. For further flow analysis a reliable conversion to a regular vector grid is preferable. Here, DaVis offers two options: A convert-to-grid method based on binning provides a fast preview of the results. A second method based on modern data assimilation, utilizes physical laws (Navier-Stokes and vorticity transport equation, e.g. VIC+[17]) for an unsurpassed grid resolution, which is further extended to VIC# in DaVis 10 with a novel multigrid solver and the ability of applying additional physical constraints[18].

References:
[9] Elsinga et al., Exp Fluids (2006) 41: 933
[10] Wieneke, Exp Fluids (2008) 45: 549
[11] Novara et al., Meas. Sci. Technol. 21 (2010) 035401
[12] Lynch and Scarano, Exp Fluids, (2015) 56: 66
[13] Scarano, Meas. Sci. Technol. 24 (2013) 012001
[14] Raffel et al., Particle Image Velocimetry: A Practical Guide, Springer Berlin (2018 3rd ed.)
[15] Schanz et al., Exp Fluids (2016) 57:70
[16] Wieneke, Meas. Sci. Technol. 24 (2013) 024008
[17] Schneiders and Scarano, Exp Fluids (2016) 57:139
[18] Jeon, 18th International Symposium on Flow Visualization, 2018

DaVis – Data Acquisition and Visualization

Innovative flow field analysis for PIV / PTV

LaVision's Data acquisition and Visualisation software package (DaVis) combines fully integrated hardware control and high-end algorithms with a modern user interface with interactive control and live feedback. DaVis is the ideal tool of choice for PIV and PTV applications.

Timing control of all hardware components

A convenient access to the synchronization of **FlowMaster** hardware components is assured by the programmable timing unit (PTU).

- multi-camera support
- support for double-frame and time-resolved image acquisition
- synchronization and timing control of light sources, cameras, traverses
- phase-locked measurements

Optimal recording parameters

The live feedback of focus quality and image contrast in selectable image regions facilitates a fast camera and laser setup. A smooth workflow is of huge benefit in environments where operation time is a significant cost factor like in wind tunnels or towing tanks.

Easy calibration

A good calibration is essential. Calibration targets are available in a wide range of sizes. LaVision offers its patented volume self-calibration to correct for remaining 3D calibration errors and the stereo self-calibration to optimize stereoscopic flow measurements.

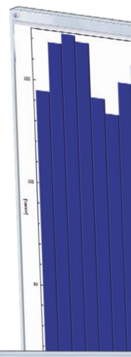
- automatic marker detection
- single image calibration with dual-level target
- compensates even strong distortion
- 3^{rd}-order polynomial or pinhole camera model
- user-friendly stereo self-calibration and volume self-calibration

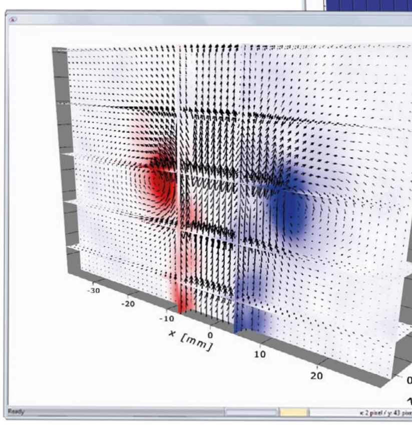
Image preprocessing

- automatic masking with immediate feedback
- user-defined masking with arbitrary shape, multiple automatic masking algorithms available: high-pass filter, general n x n filter, criteria based
- two-phase separation on structure differences
- removal of unwanted image features (e.g. reflections), large library of filter functions

Vector field processing

- scalar fields: rotation, divergence, stress, instantaneous and average pressure
- statistics: mean, rms, uncertainties, PDF, scatter plots
- contour maps, streamlines, streaklines
- space and space-time correlation
- proper orthogonal decomposition (POD)
- user-defined operations





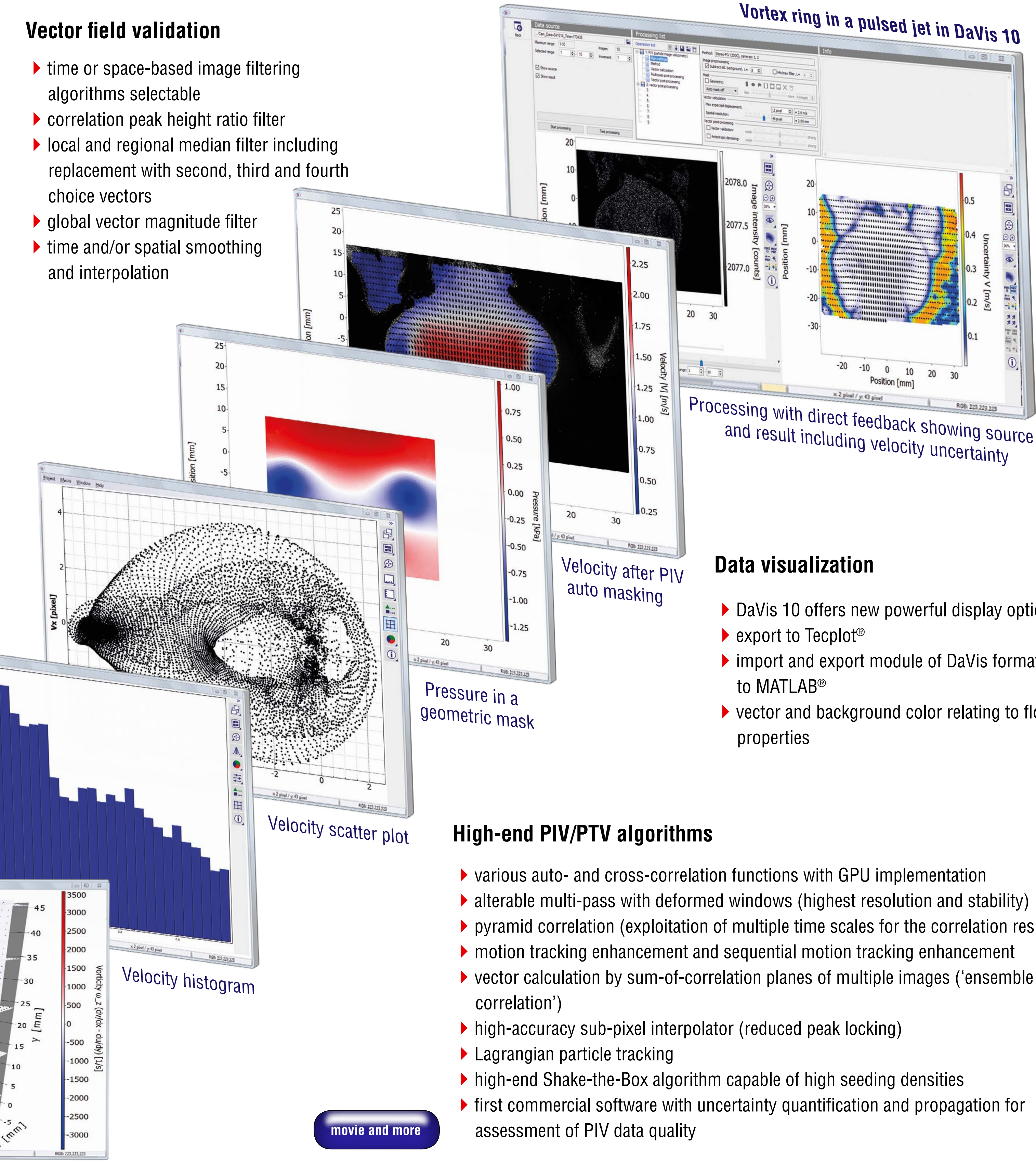
3D-display of vorticity and veloci

Optimal evaluation parameters with direct feedback

For recorded particle images, the best evaluation parameters need to be found. Here, DaVis helps with a PIV dialog comprising all steps of a 2D-PIV or Stereo-PIV operation. By simply moving sliders, automatic masking, spatial resolution and vector post-processing are controlled, and the feedback including uncertainty analysis is given immediately supporting a quick and easy PIV parameter optimization. Additionally, optional fine tuning can follow in clearly structured subdialogs.

Vector field validation

- time or space-based image filtering algorithms selectable
- correlation peak height ratio filter
- local and regional median filter including replacement with second, third and fourth choice vectors
- global vector magnitude filter
- time and/or spatial smoothing and interpolation



Vortex ring in a pulsed jet in DaVis 10

Processing with direct feedback showing source and result including velocity uncertainty

Velocity after PIV auto masking

Pressure in a geometric mask

Velocity scatter plot

Velocity histogram

ty vectors

Data visualization

- DaVis 10 offers new powerful display options
- export to Tecplot®
- import and export module of DaVis format to MATLAB®
- vector and background color relating to flow properties

High-end PIV/PTV algorithms

- various auto- and cross-correlation functions with GPU implementation
- alterable multi-pass with deformed windows (highest resolution and stability)
- pyramid correlation (exploitation of multiple time scales for the correlation result)
- motion tracking enhancement and sequential motion tracking enhancement
- vector calculation by sum-of-correlation planes of multiple images (‘ensemble correlation’)
- high-accuracy sub-pixel interpolator (reduced peak locking)
- Lagrangian particle tracking
- high-end Shake-the-Box algorithm capable of high seeding densities
- first commercial software with uncertainty quantification and propagation for assessment of PIV data quality

movie and more

Inclusion of users’ add-ons - data processing and visualization

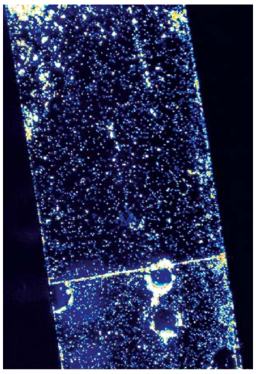
DaVis is open for user modifications based on the built-in CL macro language, which has already been used extensively by numerous users (‘C‘-Syntax: source code available). Linking of external DLLs is possible.

Wide range of aero- and hydrodynamic flow applications

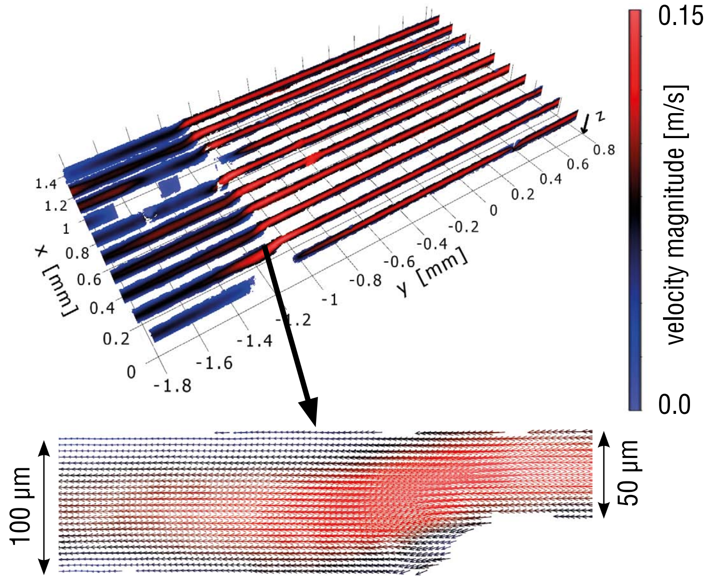
FlowMaster has been successfully used to investigate a wide range of flow phenomena in science and engineering including biological and medical applications ranging from large-scale or full-scale down to micrometer scales.
Planar and volumetric **FlowMaster** can be applied to gaseous and liquid flows and even to multiphase or reactive flows like in combustion.

Microscopic PIV

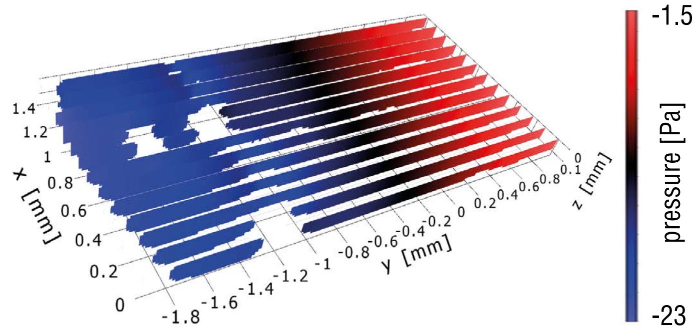
- xyz-motorization of microscope
- easy planning and repetition of measurement positions
- light delivered to the microscope via an optical fiber
- readily exchangeable filter cubes for different excitation and emission wavelengths for the use of fluorescent tracers
- planar and volumetric (tomographic and particle tracking) measurements



Particle image: backward-facing step with three air bubbles



Volumetric Shake-the-Box converted to a grid for a backward facing step

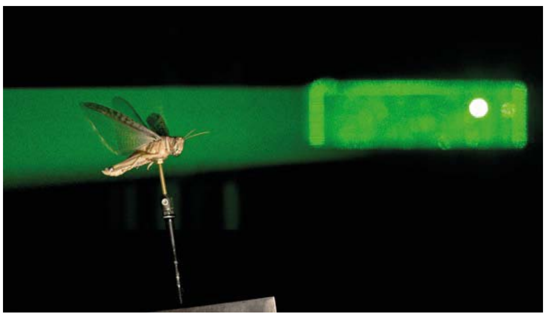


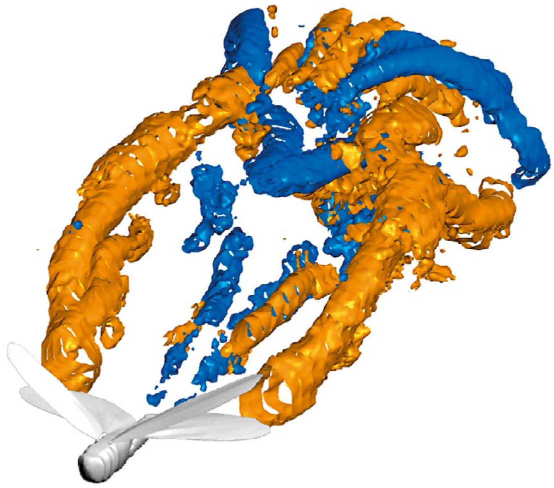
Time-averaged 3D pressure field

Time-resolved PIV

Transient phenomena, as biolocomotion and turbulent phenomena require high-speed time-resolved measurements. Full access is given to

- velocity
- acceleration
- time-dependence of POD-modes
- space-time correlations
- flow element tracking
- power spectra
- acceleration fields





Time-resolved Tomographic PIV: examination of the flight of a locusts, courtesy Bomphrey et al.[19]

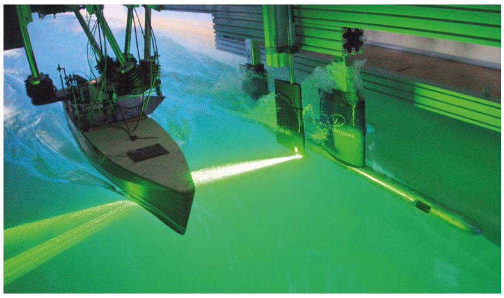
Reference:

[19] Bomphrey et al., J. R. Soc. Interface (2012) 9, 3378-3386

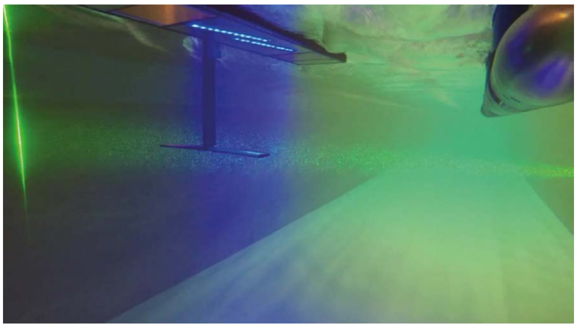
Underwater PIV

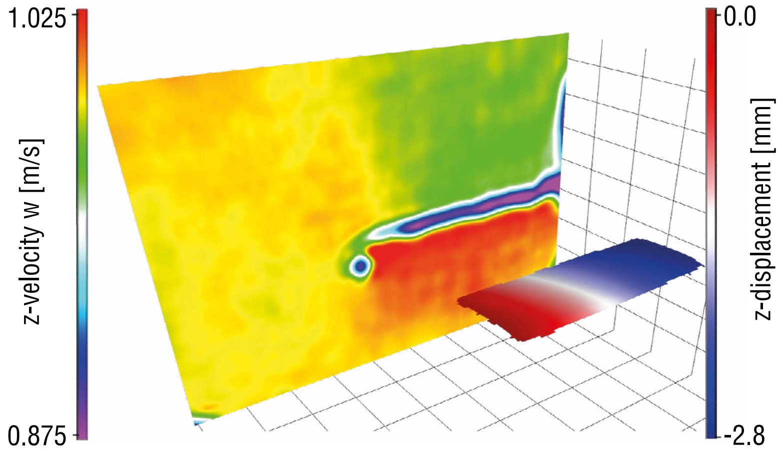
Underwater PIV systems are typically used in towing tanks or cavitation tunnels. Modular submarine housings of stainless steel have been optimized by CFD simulations and underwater experiments. Hydrofoil enclosures stiffen the vertical support tubes of the torpedoes to minimize wake and drag. Reliable PIV measurements are possible even at high towing speeds. The system is complemented with LaVision's patented self-calibration routines.

- remote control of camera lenses, Scheimpflug adapters and sheet optics via DaVis
- modular system for 2D and Stereo-PIV, Tomographic PIV and Shake-the-Box



Stereo-PIV system in a towing tank, courtesy G. Jacobi, TU Delft[20]

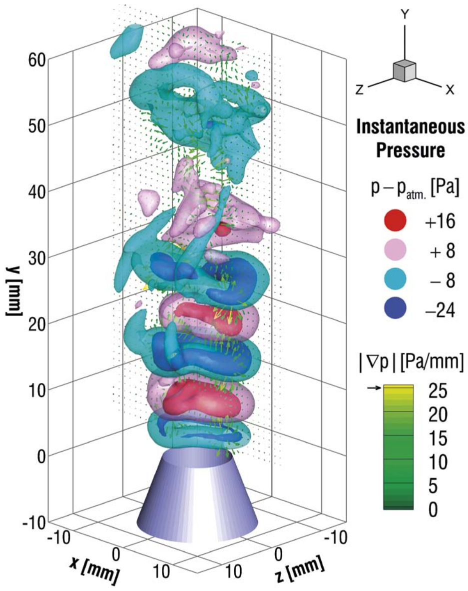


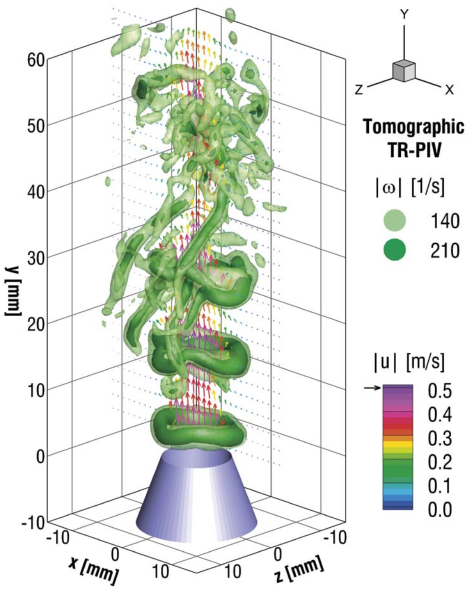


Combined PIV and DIC measurement around a wing keel in a towing tank, courtesy G. Jacobi, TU Delft

Pressure from PIV

Pressure measurements are needed in many research areas and the common measurement method is the use of pressure taps, which is costly and time-consuming and limited to a small number of points. Therefore, groups from several universities and LaVision joined forces in the European NIOPLEX[21] project which led to a **Pressure from PIV** package in DaVis 10. The LaVision 4D solver provides direct access to instantaneous and average pressure fields from 2D-, Stereo- and Tomographic PIV data as well as from sparse particle tracks (Shake-the-Box).





movie and more

Pressure for a free jet in water (recordings with courtesy of D. Violato, TU Delft)

Reference:

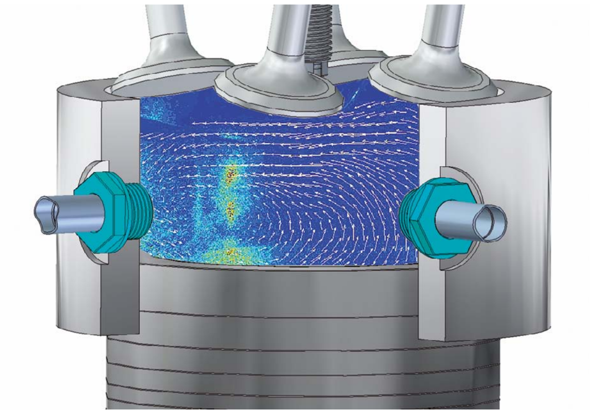
[20] More details can be found here: Jacobi et al. International Conference on Hydrodynamics September 2016
[21] van Gent et al., Exp Fluids (2017), 58(4), 33

Endoscopic PIV

With endoscopic PIV, a costly manufacturing of prototypes with large windows for optical access can often be avoided. Instead, only 8 mm holes are needed for a PIV measurement of internal aerodynamic phenomena, reactive flow fields and combustion processes. Applications include:

- turbomachinery
- aircraft engines
- compressors
- pumps
- IC engines
- pharmaceutical and live science applications

Camera endoscope mounted to a FlowMaster series camera



Instantaneous in-cylinder tumble flow, courtesy: Volkswagen

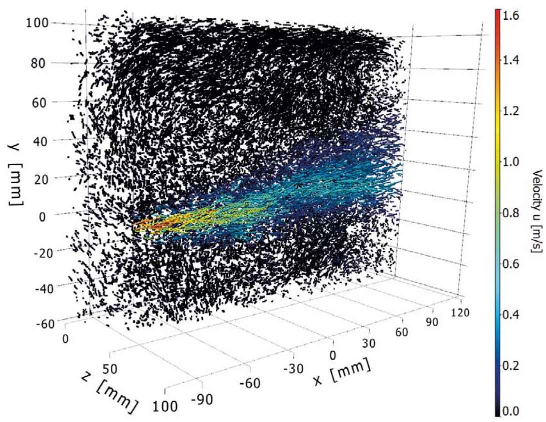
Laser endoscope forming a light sheet from a high power pulsed laser

MiniShaker L

MiniShaker 3D camera

The 4-camera MiniShaker is LaVision's compact 3D camera ideally suited for time-resolved flow measurements up to 5 m/s with a field of view as large as 52 x 31 x 20 cm^3. Double-frame Multi-pulse Shake-the-Box enables measurements with velocities higher than 50 m/s.

- MiniShaker L with a large stereo angle for high precision of the depth component
- small-aperture MiniShaker S is perfectly suited for measurements with small optical access and
- MiniShaker Aero for multi-position measurements with robotic support
- fast and easy to setup

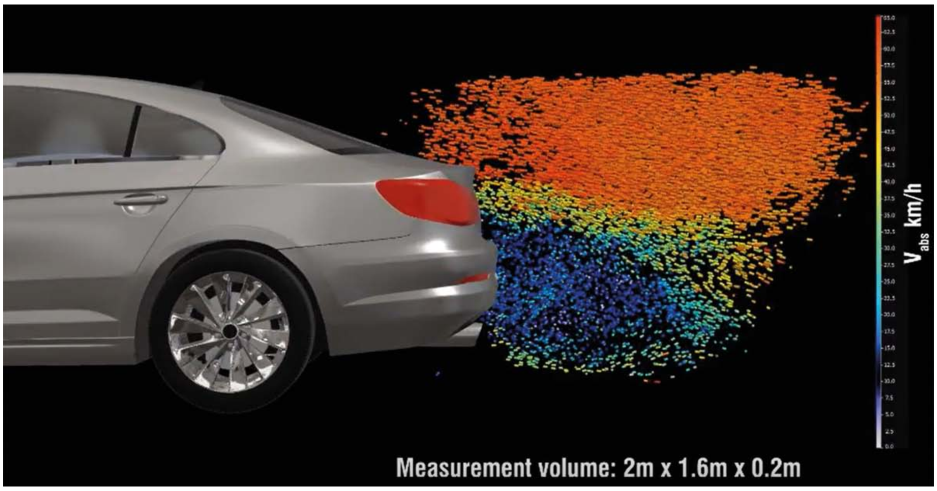


Shake-the-Box particle tracks plotted in DaVis 10: a water jet measured with MiniShaker L and LED illumination

LED-Flashlight 300

Large-scale measurements with Helium-filled Soap Bubbles and high-speed recording

Compared to common air-flow seeding with oil droplets, Helium-filled soap bubbles (HFSB) increase the scattering signal by a factor of more than 10000. Time-resolved or multi-pulse Shake-the-Box and Tomographic PIV measurements become possible for measurement volumes even larger than 1 m^3



Measurement in the wake of a full-scale Volkswagen Sedan

Fluid Supply Unit

Aerodynamically optimized HFSB linear nozzle array

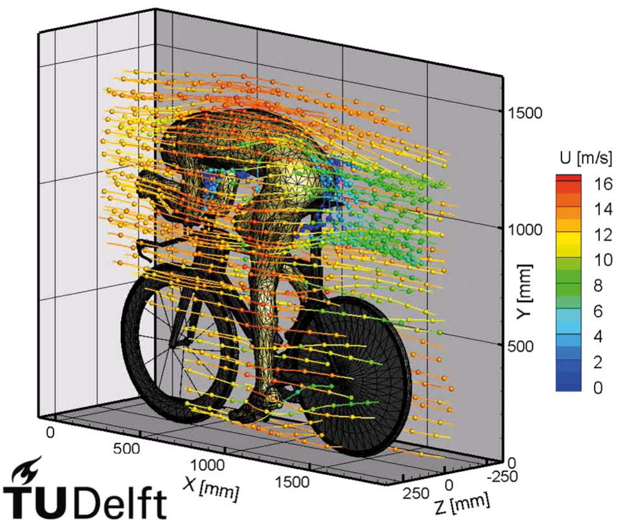
movie and more

- typically 4 high-speed cameras
- high-speed laser or high-power LEDs illumination for large FOVs and deep volumes
- Fluid Supply Unit with remote seeding control
- Shake-the-Box and Tomographic PIV software package

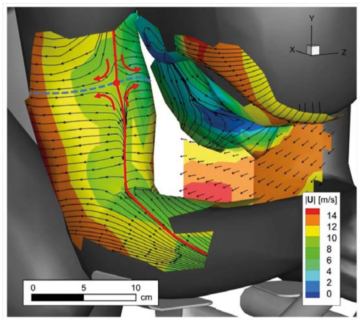
Robotic scanning

The 3D camera MiniShaker Aero mounted to a robotic arm combined with LaVision‘s volume self-calibration and Shake-the-Box software is the system of choice for an easily calibrated and installed system. Full-scale flow fields around large objects are recorded in a short time.

The MiniShaker with 4 cameras enclosed in a rigid housing makes a single calibration sufficient for measurements at multiple positions. In each position of the robotic arm, volumetric data are acquired, which can be stitched together into a large-scale flow field. Coaxial illumination delivered by a laser fiber with its exit in the middle of MiniShaker head enables measurements even in occluded areas.



Streamlines measured with Shake-the-Box around a full-sized cyclist, courtesy TU Delft[22]



Near-surface streamlines, close-up at elbow

MiniShaker Aero on a robotic arm

movie and more

Reference:

[22] Jux et al., Exp Fluids (2018), 59:74

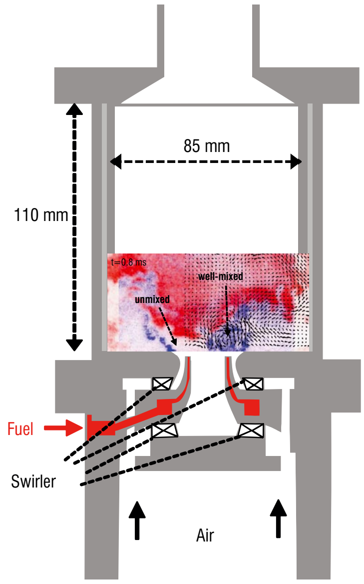
Multi-parameter laser imaging in flames

The modular **FlowMaster** system can be extended into a multi-functional system providing in-situ and online flame imaging with quantitative information about species and particle concentration, flame composition and flame temperature based on the following techniques:

- **Tracer-Laser-Induced Fluorescence** (Tracer LIF) for fuel imaging and mixture preparation
- **Tunable LIF** for flame front measurement and information on flame species and radicals
- **Rayleigh Thermometry** for flame temperature measurement,
- **Raman Imaging** for information on gas composition and flame temperature
- **Laser-Induced Incandescence** (LII) for soot concentration and particle size

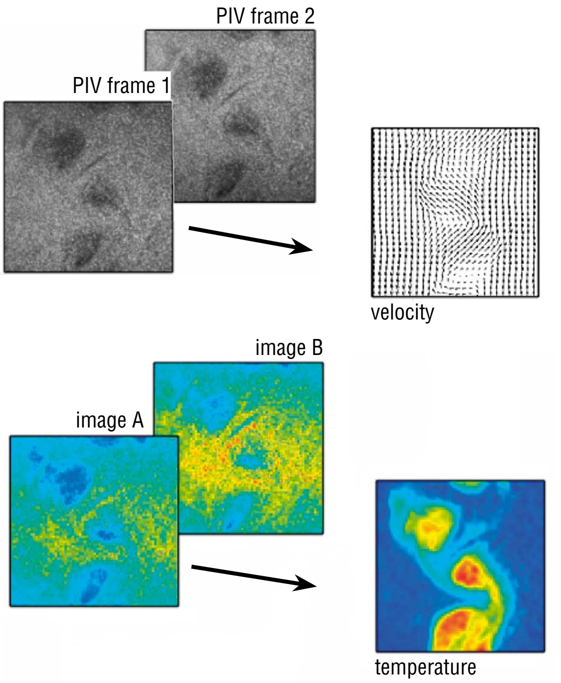
Simultaneous high-speed (10 kHz) laser imaging:

OH-PLIF	Reaction zone
Acetone-PLIF	Fuel transport
PIV	Flow structure



Unsteady interactions of flow, fuel-air mixing and combustion in a lean partially-premixed turbulent swirl flame, courtesy of M. Stöhr et al., German Aerospace Center (DLR)[23]

Reference:
[23] Stöhr et al., Proceedings of the Combustion Institute (2014)

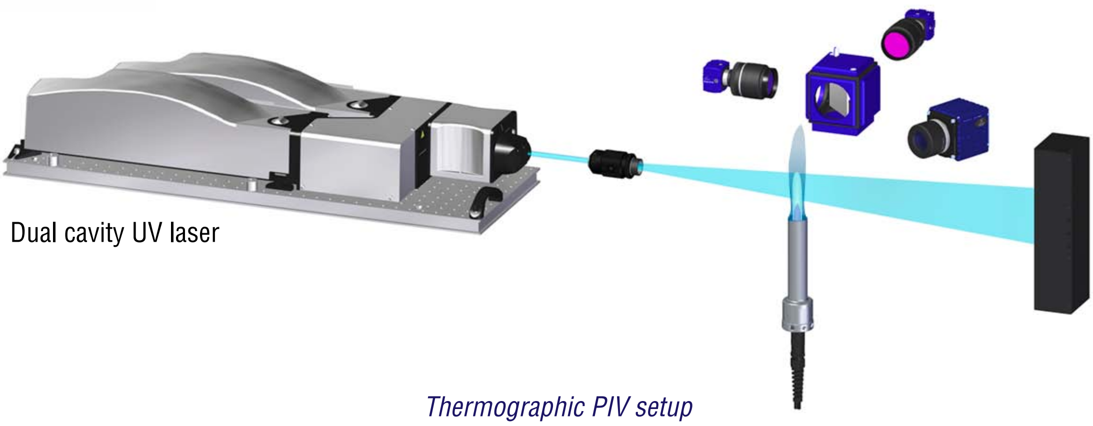


Courtesy: F. Beyrau et al., University Magdeburg

Thermographic PIV

Tracer particles from thermographic phosphor materials can add temperature information to the classical PIV approach. Illuminated by UV light, these particles emit temperature dependent phosphorescence. Utilizing this characteristic, sufficiently small particles can track velocity and gas temperature even in turbulent flows.

The extension of a standard PIV setup to a PIV and thermometry setup is straightforward. Apart from the PIV equipment, a frequency tripling crystal for the generation of the UV light and two standard cameras with two spectral filters are required.

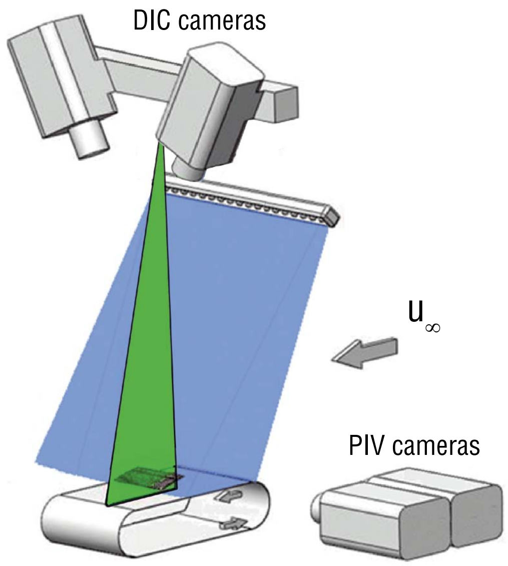


Thermographic PIV setup

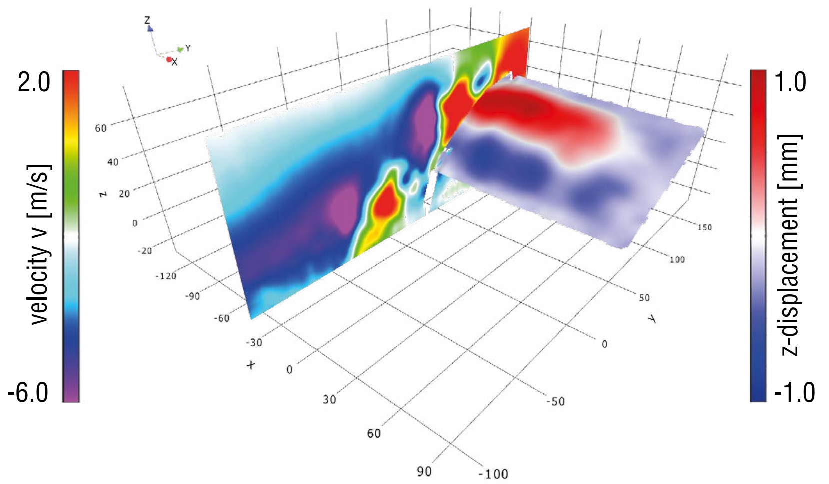
Simultaneous PIV and Digital Image Correlation (**DIC**) yields both the flow field information as well as object shape and deformation and the structural dynamic response. This combined measurement approach enables a comprehensive analysis of fluid-structure interaction (FSI) phenomena, which can be complex and non-linear, especially with modern materials and flexible lightweight components. FSI effects are present in many different applications:

- ships and underwater structures
- heart valves and biomechanics
- wave energy and wind energy generation systems
- flutter effects of aircraft wings
- internal mechanics of pumps
- micro air vehicles
- urban building design

When considering state-of-the-art biologically inspired wing designs (bionics), the complex dynamics of such systems can only be experimentally investigated through non-intrusive, full-field techniques such as PIV and DIC. Below, a high-speed Stereo-DIC and side-by-side 2D-PIV setup was used for simultaneous and synchronized measurements of the flow around a flexible membrane and its structural response including ground-effects[24]. This can provide insights into insect and bird flight mechanisms, which were previously unavailable due to the highly dynamic and extremely sensitive nature of this type of application.

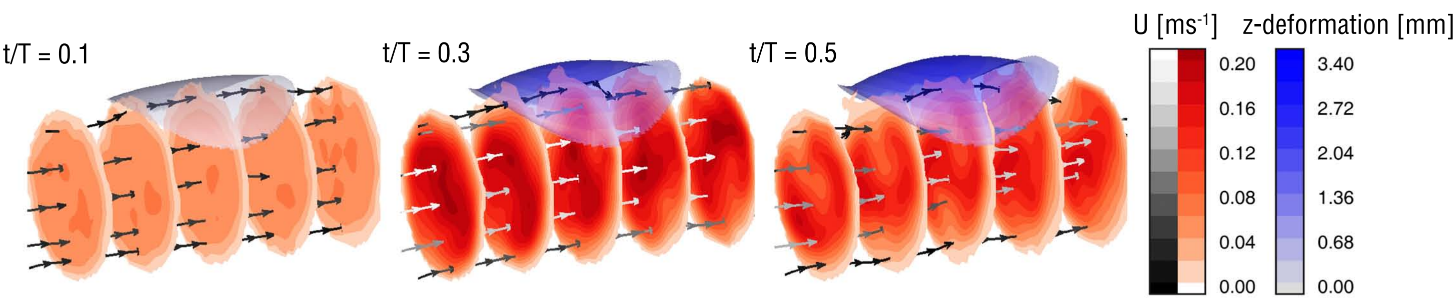


Setup: test wing above a rotating steel belt in a wind tunnel: LED and laser illumination from above, two PIV cameras recording from the side, two DIC cameras recording from the top, courtesy of R. Bleischwitz et al., Southampton University[24]



Visualization of instantaneous snapshot of PIV-measured vertical velocity component and membrane wing fluctuations

Also Tomographic PIV or Shake-the-Box particle tracking can be combined with DIC. Below, Tomo-PIV measures fluid flow in a simplified aneurysm model, whereas DIC delivers data on the wall deformation. A pulsing flow is driven through a flexible tube incorporating a thin walled section that protrudes with each pulse, revealing the flow development and membrane deformation.



Streamlines and contours overlaid on slices through the flow reveal the instantaneous flow structure in the fluid volume in conjunction with the degree of wall deformation, courtesy N. Philips, Structure & Motion Laboratory, Royal Veterinary College

Reference:

[24] Nila et al., RAeS Applied Aerodynamics Conference (2016)

FlowMaster
System Components

Depending on the application, LaVision's **FlowMaster** systems integrate different light sources and cameras:

Standard PIV/PTV cameras	Model	Features
	Imager sCMOS	combining extreme sensitivity with high dynamic and frame rate
	Imager *SX* 4M	compact 4 million pixel model with 30 Hz frame rate
	Imager *SX* 6M Imager *SX* 9M	excellent image quality, low noise, high sensitivity, with 6 or 9 million pixel and 150 ns interframe time
	Imager *LX* 16M Imager *LX* 29M	advanced progressive scan, fully programmable CCD cameras, high quality images, combined with high spatial resolution

High-speed PIV/PTV cameras	Model	Features
	Imager *HS* 4M	4 million pixel, high image quality, fast data transfer and frame rates up to 1279 Hz at full resolution
	Photron cameras (HighSpeedStar)	up to 4 million pixel CMOS cameras with frame rates up to 25.6 kHz at full resolution and 1 MHz frame rates at reduced resolution, up to 288 GB on board RAM and extremely high sensitivity
	Phantom cameras	
	MiniShaker 3D cameras	3D camera with 4 sensors with frame rates of 121 Hz at full resolution and up to 1 kHz at a reduced resolution of 704 x 358 px each sensor

Imaging Optics
- Scheimpflug lens mounts for oblique viewing (remote controlled)
- volume optics
- long distance microscopes
- epi-fluorescent microscopes for Micro-PIV

Filter
- small bandwidth for background suppression

Beam Delivery
- laser guiding arm
- multi-purpose high-power mirrors
- laser endoscopes
- laser fibers

Light Sheet Optics
- adjustable focus and divergence
- wide angle setups

Seeding
- air: DEHS, water or oil droplets, Helium-filled soap bubbles
- water: particles for Mie-scattering and fluorescence measurements

Triggering
- synchronization for all operation modes
- versatile, programmable PC-based timing unit PTU
- 32 trigger channels
- ready on demand by external trigger
- phase-locked measurements

Processor
- parallel processing (multi processor computers)
- multiple computer setups (master/slave configurations)
- Windows 10 64 bit operation system

Illumination
- double-pulse or high-repitition rate laser systems
- high-power volumetric LED illumination

Scanning
- 1- to 3-axis translation stages
- flexible robotic systems

LaVision experts are devoted to providing the best high-end solutions which are involved in the latest research in all fields of fluid dynamics measurements. This yields high flexibility for modification and adaptation in high-end research and development.
LaVision offers customer workshops, short courses and in-house trainings.

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