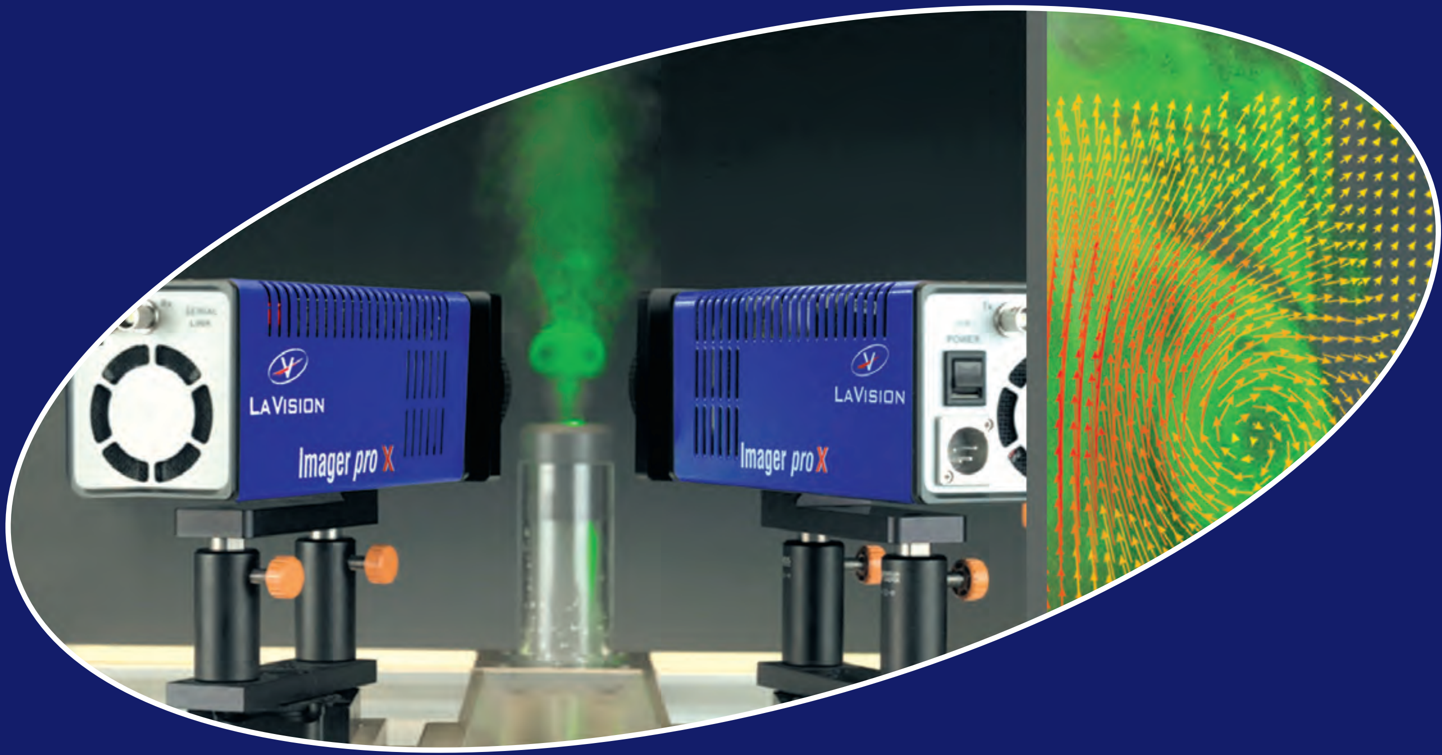


FlowMaster

Advanced PIV / PTV Systems for
Quantitative Flow Field Analysis

LaVision

FOCUS ON IMAGING

FlowMaster

Integrated Turn-Key Systems with unique Measurement Capabilities

LaVision designed the most flexible and powerful commercial PIV system family **FlowMaster**, based on our application knowledge and our tradition of technical communication with our customers. LaVision continuously offers the best PIV algorithms for calculation and validation, like deformed interrogation windows or the unique regional median filter for data validation.

LaVision's Pioneering Innovations

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

1999:
- development of a new **3D-PTV** technique
- integration of a high resolution **2K x 2K PIV** camera

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
- **Dual Plane PIV** based on Stereo-PIV systems for determination of 3D vorticity or acceleration

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

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

2005:
- **FlowMaster MITAS**: optical inverted microscope with 3D translation stage under complete computer control

2006:
- **Tomographic PIV,** a novel technique for instantaneous 3D velocity field measurements

2009:
- first time ever large-volume-Tomo-PIV with 4 x 16 Mpixels

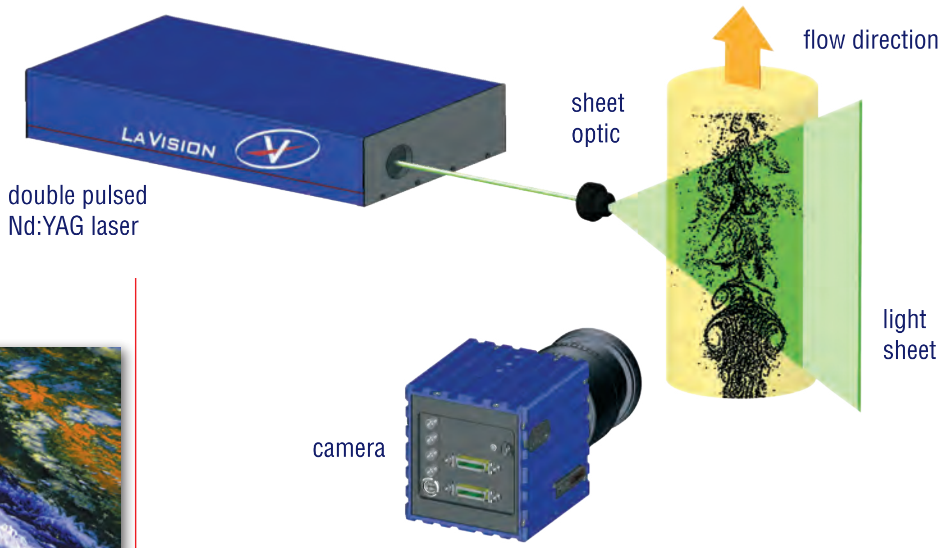
2010:
- introduction of **Adaptive PIV** for enhanced accuracy and resolution
- implementation of PIV analysis on GPUs (graphics processing units)
- first Stereo- and Tomo-PIV systems with sCMOS cameras

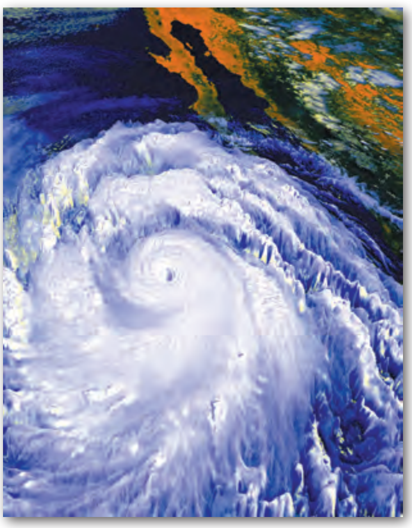
2011:
- 8 camera Tomo-PIV wind tunnel measurement campaign with a new record in volume flow field resolution
- first underwater-volume measurement system delivered

Advanced PIV / PTV Systems based on Mie Scattering and LIF

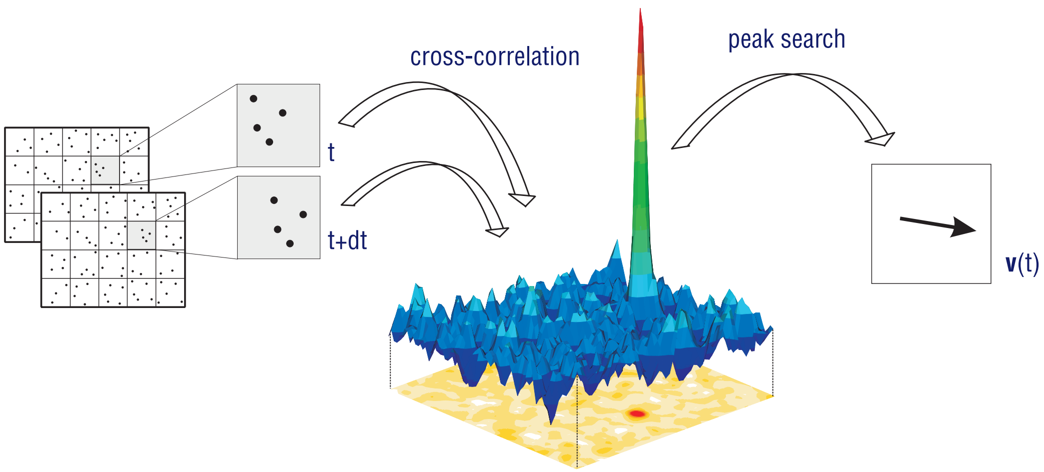
FlowMaster is part of a complete family of light sheet imaging systems designed for the investigation of combustion, spray, flow and aerodynamic applications. The versatile **FlowMaster** models are application oriented, meeting a wide range of measurement requirements due to their modular and flexible system design.

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. Typically a pulsed laser beam is formed into a light sheet and is fired twice with a short time delay dt. Both illuminations are recorded by one double-frame high resolution CCD camera.





The recorded image is divided into small interrogation windows typically 64 x 64 down to 16 x 16 pixels in size. During the time interval dt between the laser shots the particles of each interrogation window have moved by a displacement ds. The velocity is then simply given by the ratio ds/dt. The calculation of the particle displacement ds is done by fast FFT-based cross-correlation of two corresponding interrogation windows. Additional advanced correlation algorithms are selectable for improved performance such as local adaptive window shift and deformation and correlation averaging.



Principle of Cross-Correlation PIV

The position of the highest peak in the correlation plane indicates the mean displacement **ds** of the particles in a particular interrogation window. The displacement vectors of all interrogation windows are finally transformed into a complete instantaneous velocity map.

Innovative Flow Field Analysis Algorithms for PIV / PTV

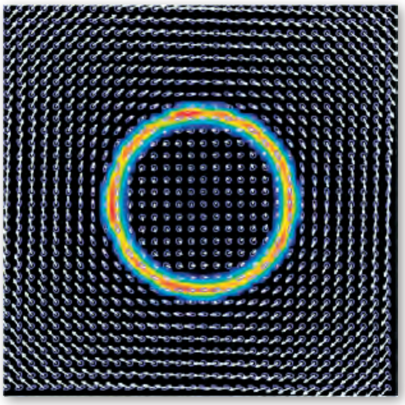
LaVision provides up-to-date flow analysis algorithms developed in close cooperation with various PIV research groups. The software is open for user modifications and extensions based on the built-in CL macro language, which has already been used extensively by many customers (‚C'-Syntax: source code available).

The flow field analysis algorithms for evaluation of PIV measurements come with the **D**ata **a**quisition and **Vis**ualisation software package **DaVis**.
DaVis is the unique software platform for the LaVision camera based systems. Its modular structure enables an easy to use integration of new algorithms and user-built macro codes.

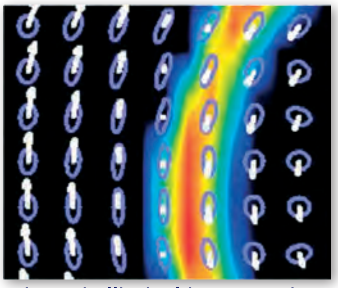
The **2D-PIV (2D2C)** software calculates the two vector components in the illumination plane. A **2D-PTV** algorithm is also available. **Stereo-PIV (2D3C)** allows the computation of all 3 velocity components including the out-of-plane component.

LaVision's new **Adaptive PIV** technology now provides an automatic calculation of the optimal local interrogation window size and shape based on flow gradients ('flow adaptivity') and image quality ('signal adaptivity'). This leads to a significant improvement in accuracy and spatial resolution, especially in regions of high flow gradients, e.g. close to walls.

Optimal Recording Parameters



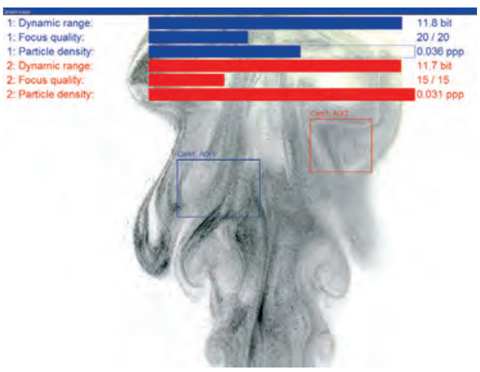
high shear rotational flow



adapted elliptical interrogation areas

Adjustment Assistant

The quality of PIV measurements is influenced by many details like focus quality and image contrast which can be difficult to judge especially for unexperienced users. The ‚adjustment assistant' in **DaVis** gives live online feedback while taking images for easy optimization of the best settings. This feature assists not only new users but is also appreciated by specialists because it speeds up the workflow and reduces setup time which is of huge benefit in environments where operation time is a significant cost factor like in wind tunnels or for towing tanks.



DaVis screenshot of adjustment assistant

The **FlowMaster** PIV software packages offer several features for highly accurate 2D and 3D particle image evaluation. New features are added continuously by LaVision's software engineers and our customers throughout the world using the CL macro language. These user programmed functions are freely distributed and can be integrated into the **DaVis** software.

Calibration

- single image calibration with dual-level target
- compensates even strong distortion
- wizard guided Stereo-PIV self-calibration
- 3rd order polynomial or pinhole camera model fit

Image Preprocessing

- masking with arbitrary shape, user-defined, automatically criteria based, high-pass filter, general n x n filter
- two phase separation on structure differences
- removal of unwanted image features (e.g. reflections)

PIV Algorithms

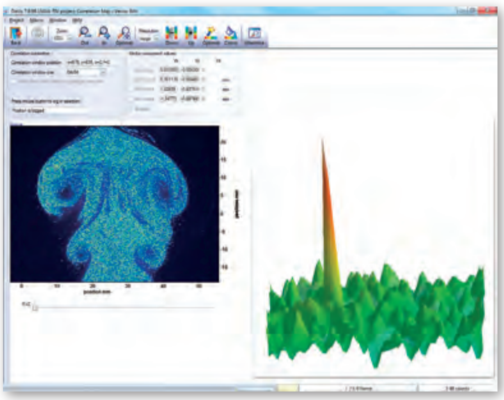
- various auto- and cross-correlation functions: standard FFT, normalized
- advanced 2D and 3D particle tracking algorithms for lower seeding density
- vector calculation by sum-of-correlation planes of n images ('ensemble correlation')
- adaptive multi-pass with deformed windows (highest resolution and stability)
- high-accuracy sub-pixel interpolator (no peak locking)
- correlation with dynamically deformed interrogation windows

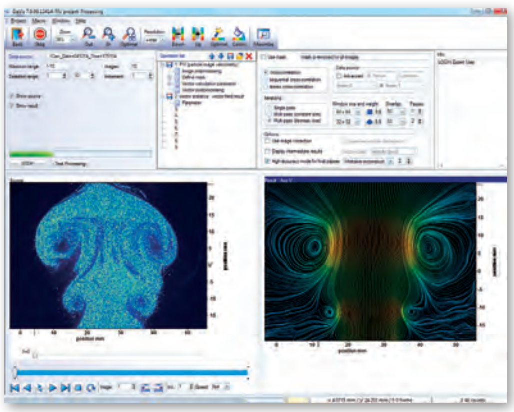
Vector Postprocessing and Validation

- correlation peak height ratio filter
- local and regional median filter incl. replacement with second choice vectors
- global vector magnitude filter
- time and/or spatial smoothing and interpolation

Vector Field Processing

- scalar fields: rotation, divergence, stress
- statistics: mean, rms, PDF, scatter plots
- contour maps, streamlines, streaklines
- vortex analysis: center, strength and velocity
- space and space-time correlation
- user-defined operations
- proper orthogonal decomposition (POD)





DaVis – the graphical user interface to PIV algorithms

Wide Range of Aero- and Hydrodynamic Flow Applications

FlowMaster systems have been successfully used to investigate a wide range of flow phenomena occuring in science and engineering, as well as in biological and medical applications.
Using **FlowMaster**, PIV can be applied to gaseous and liquid flows and even to multiphase or reactive flows like combustion.

courtesy: Franzius-Institut, Hannover

highly modular, stereoscopic 3D underwater PIV system

courtesy: Bomphrey/Henningsson: Oxford Animal Flight Group

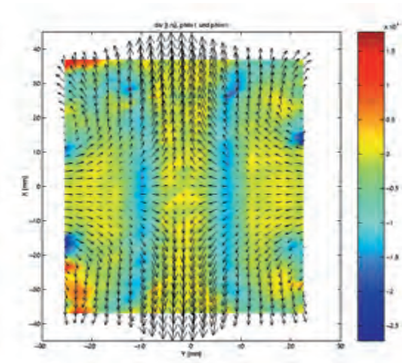
Tomo-PIV examination of the flight characteristics of locusts

Aero- and Hydrodynamics

- 3D-velocity field using stereo imaging
- multi camera support
- automatic calibration procedure
- improvement of flow analysis near surfaces by effective stray light suppression
- time resolved and high resolution PIV
- modular submersible underwater PIV systems (2D-, Stereo-PIV, Tomo-PIV)

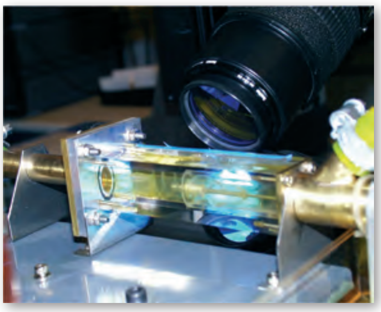
IC-Engine Flow

- phase-locked measurements of in-cylinder flow
- readout of encoder signal
- small optical access for laser light sheet and camera through small holes with endoscopic methods



courtesy: Mielenz, Uni Bochum

flow field of two flat flames in counterflow



courtesy: Berlin Heart AG

Stereo-PIV in the model of an implantable blood pump

Reactive Flows

- correlation with temperature field
- seeding with high temperature resistant TiO_2 particles
- molecular tracer detection

Biomedical/ Biological Applications

- monitoring of blood flows in veins and arteria
- microfluidic imaging systems to improve the blood flow around heart valves
- visualization of slipstream turbulence behind insects in three dimensions and at an unprecedented resolution

FlowMaster basic 2D-PIV systems can easily be extended to application for more sophisticated flow problems. **Stereo-** or **Tomographic PIV** are offered for more detailed flow analysis. **FlowMaster** can be upgraded to a combined **PIV-LIF system**, e.g. LaVision´s **SprayMaster** or **FlameMaster** system. For this purpose the **FlowMaster** cameras can be utilized with image intensifiers.

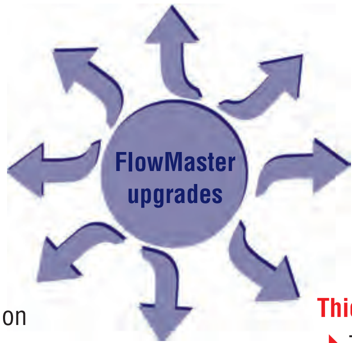
courtesy: DNW (German-Dutch Wind Tunnels)

Stereo-PIV
- 3 velocity components in the light sheet

Microscopic PIV
- PIV for micro scales

SprayMaster
- patternation
- drop sizing
- evaporation

Tomographic PIV
- 3D3C-vector field in a complete volume
- fully digital recording and processing



Underwater PIV Systems
- horizontal and vertical assemblies, standard or customized, compact or traversed, minimum weight

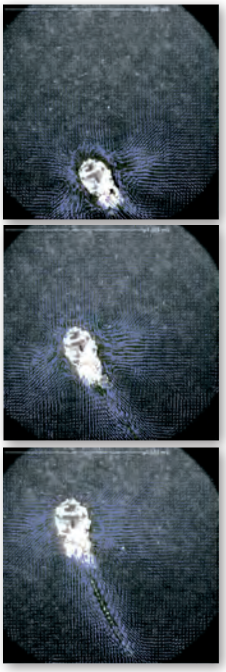
FlameMaster
- OH, NO - formation
- species distribution
- temperature fields
- air/fuel ratios
- soot formation

PIV-LIF Combination
- e.g. 2-color PIV
- multi phase flows
- PIV + OH-LIF, NO-LIF

Thick-sheet Stereo-PIV
- Tomographic sheet reconstruction
- full 3D gradient tensor

The extended system functionality given by the various upgrades is well integrated into the **DaVis** software environment.

FlowMaster
Time-Resolved PIV



flow induced by a moving 100 µm plankton recorded at 1 khz frame rate

FlowMaster Time-Resolved PIV opens new areas of fluid dynamic analysis. It combines the spatial information of digital PIV with the temporal evolution of each point.
The system measures velocity and acceleration fields and turbulence quantities of transient phenomena. The time-resolved PIV information opens a new area for velocity derivations or correlations in time. With time-resolved PIV the user is able to calculate temporally dependent quantitative turbulence information. It provides information about:

- time dependence of POD-modes
- vortex characteristics with time
- space-time correlations
- flow element tracking
- power spectra
- acceleration fields
- flow time scales

LaVision‘s **FlowMaster Time-Resolved** systems include state-of-the-art digital high-speed cameras with 1, 2 or 4 Mpixel resolution. Up to 16 kHz frame rate at full resolution and several hundreds of kHz frame rate at reduced resolution are available. Single or dual cavity high-repetition rate solid state lasers with a wide range of pulse energies can be selected. All components are integrated and controlled from the **DaVis** software.
Special correlation algorithms (‘pyramid correlation’) take advantage of the additional time information.

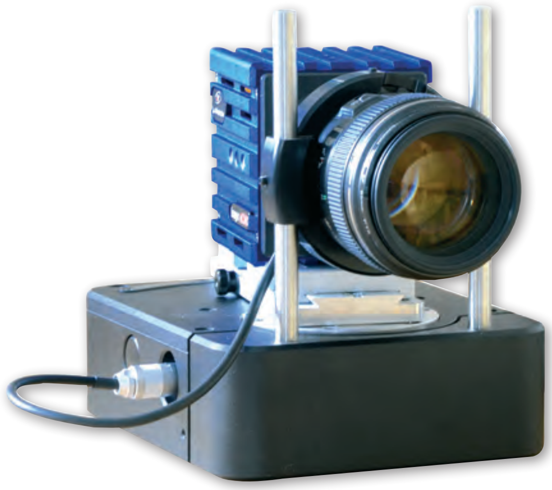
FlowMaster
Stereo-PIV

Remote Control of Scheimpflug Condition, Aperture, Focus

Stereoscopic Imaging

FlowMaster Stereo-PIV is a straight forward extension of the **FlowMaster** 2D concept and enables the measurement of all three velocity components inside a light sheet. Stereo-PIV is based on the principle of stereoscopic imaging: two cameras capture the image of the illuminated flow particles from different angles. Scheimpflug lens arrangements keep all areas of the image planes in focus.

While one camera can only measure the projection of the particle movement perpendicular to its optical axis, the combination of two camera projections enables the reconstruction of the "real" particle displacement inside the measurement volume. In this way a complete set of vectors containing all three velocity components is recorded. This setup uses the same principle as human eyesight.

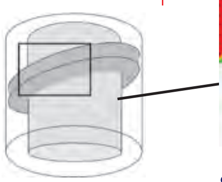


FlowMaster Scheimpflug setup

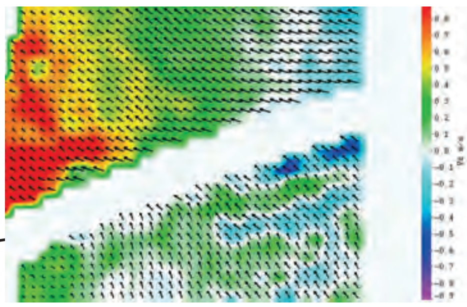
manual Scheimpflug setup

Stereo-PIV Self-Calibration

The **Self-Calibration** method is a unique, patented tool for **Stereo-PIV** to correct even large misalignments between calibration plate and laser light sheet. It is a standard feature of the **DaVis Stereo-PIV** software package.



measurement area



single vector field (color = w-component)

With **Stereo-PIV Self-Calibration** the exact location and thickness of all planes in space are determined by computation of disparity maps on the recorded particle images.

Stereo-PIV Self-Calibration does not require the calibration target to be placed within the flow field. Internal flows such as biomedical flows, micro channels or internal combustion engine cylinders where insertion of a calibration target is impractical or impossible, can now be measured using Stereo-PIV techniques.

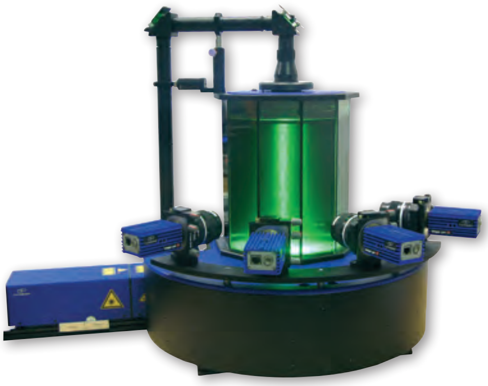
Advantages

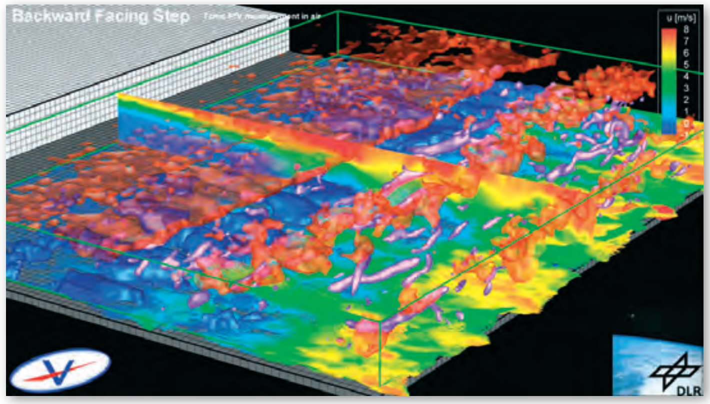
- **ultimate accuracy**: elimination of calibration errors
- **user-friendly:** free positioning of calibration plate, no need to align calibration plate exactly with light sheet
- **easy volume-scanning:** all scanning positions calibrated at once
- **ex-situ calibration**: calibration plate outside the measurement volume
- **time-saving:** calibration can be prepared off-site

FlowMaster
Tomographic PIV

Instantaneous 3D3C-Vector Field in a Complete Volume

Tomographic Particle Image Velocimetry (**Tomo-PIV**) is a novel technique for 3D velocity measurements. Velocity information results from three-dimensional particle pattern cross-correlation of two reconstructions obtained from subsequent exposures. The technique is fully digital and allows high seeding (information) density and provides dense vector fields compared to sparse 3D-particle tracking. The method is truly instantaneous across the volume, as opposed to scanning PIV. **Tomo-PIV** is suited for fast flows requiring small dt's between exposures and allows an easy extension to high time resolution using high-speed cameras.



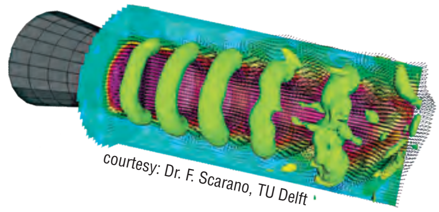


courtesy: Dr. A. Schröder, DLR Goettingen

Tomographic PIV measurement of flow field (iso-vorticity) behind a backward facing step

Applications

- turbulence research
- 3D-flow structure visualization
- full 3D-vortex analysis
- flow-structure-interaction

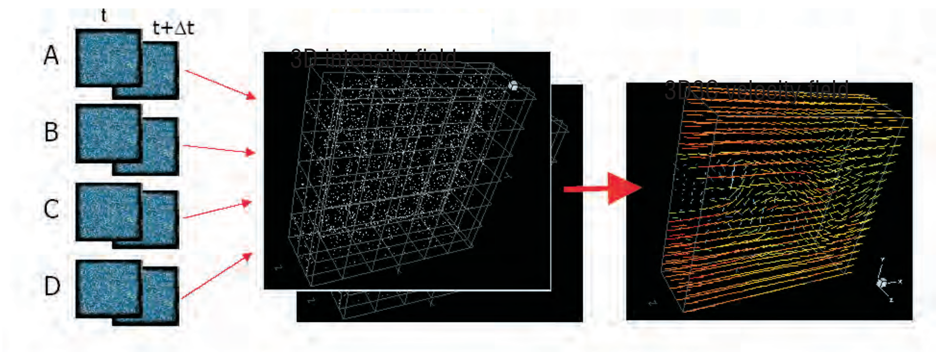


courtesy: Dr. F. Scarano, TU Delft

laminar jet from a circular nozzle, Re_D= 5,000

Principle of Tomographic PIV

Tracer particles within the measurement volume are illuminated by a high power pulsed light source and the scattered light pattern is recorded simultaneously from typically 4 viewing directions using CCD cameras. The 3D particle distribution is reconstructed by a tomographic reconstruction algorithm (MART) as a 3D light intensity distribution for each voxel. The particle displacement within a chosen interrogation volume is then obtained by the 3D cross-correlation of the reconstructed particle distribution at the two exposures, using advanced iterative multi-grid algorithms with deformed interrogation windows. Calibration errors are automatically corrected by the patented LaVision **Volume Self-Calibration** procedure.

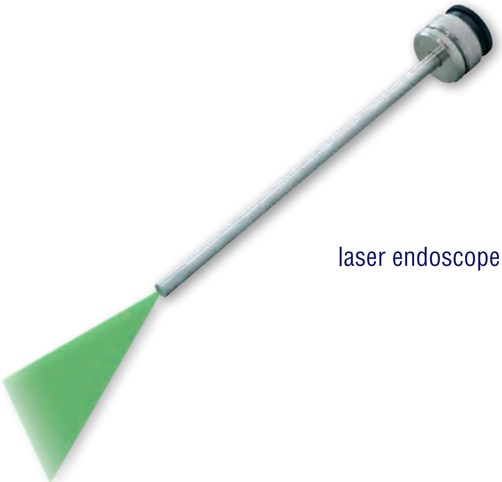


FlowMaster

Endoscopic PIV

Camera and Laser Endoscopes for limited Optical Access

PIV measurements in IC engines, turbo machinery or pumps usually require the manufacturing of costly prototypes with large windows to gain optical access. Using LaVision's endoscopic PIV system has enormous advantages in these experiments. Small optical access of only 8 mm holes enables PIV measurements in a much easier way and therefore reduces the costs and complexity of the required prototype.



laser endoscope

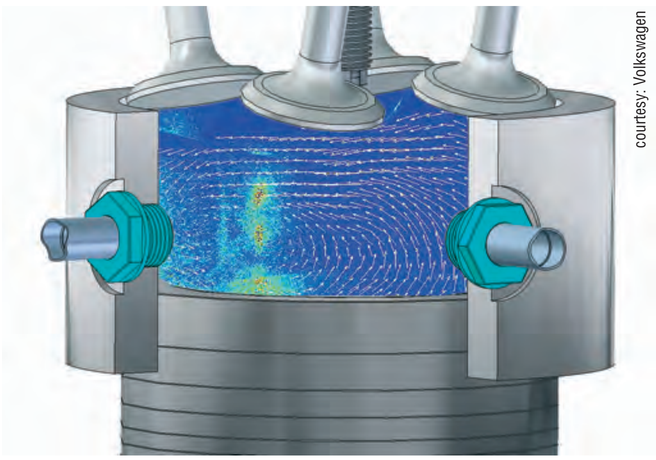
camera endoscope

LaVision´s **laser endoscope** generates a laser light sheet from a high power pulsed laser. It is designed to fit at the outlet of the **Laser Guiding Arm** (articulated arm) and consists of a thin steel tube at the end. Image acquisition is done by a specially developed **camera endoscope** which can easily be mounted to a **FlowMaster** series camera together with a lens.

Applications

- internal aerodynamic phenomena
- turbomachinery, aircraft engines, compressors, pumps
- IC engine flows, tumble and swirl studies
- reactive flow fields, industrial reactors, combustion studies
- pharmaceutical and medical applications

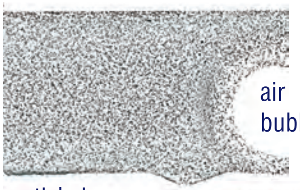
Synchronized IC-Engine Flow Investigations



instantaneous in-cylinder tumble flow applying endoscopic imaging

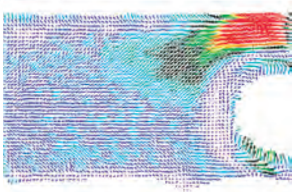
FlowMaster
Micro-PIV

The **FlowMaster Micro-PIV** systems are designed to measure velocity fields of particle seeded flows with micron scale spatial resolution using PIV techniques.



air bubble

particle image



vector field

micro channel with air bubble

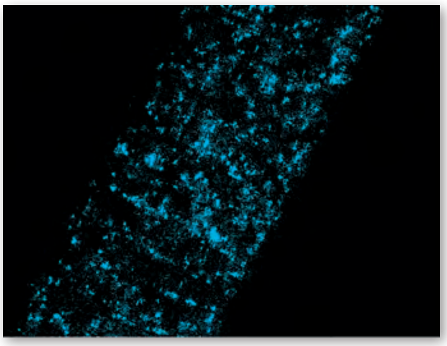
stereoscopic Micro-PIV setup

Conventional PIV applied to Microscopic Systems

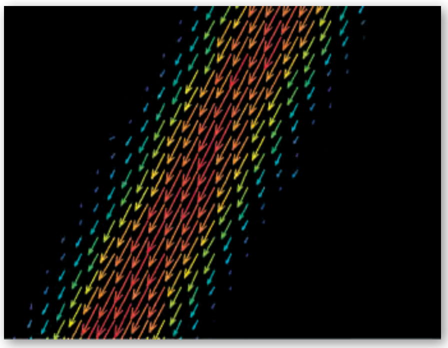
The light source is a double pulsed Nd:YAG laser that is focused by an epifluorescent microscope with a high numerical aperture on a microfluidic device. The microflow is seeded with fluorescent particles. A microscope lens collects the particle signal that has a longer wavelength than the illuminating light. This signal is separated from the laser light by a filter cube and is recorded by a **FlowMaster** series camera. The double frame images are evaluated with conventional PIV algorithms.

FlowMaster
MITAS

The **FlowMaster MITAS** laser imaging system comprises a fully motorized 3-axis microscope stage with a high performance controller and a high precision microscope objective. For standard applications a small DPSS laser for pulsed illumination and a highly sensitive, dual-frame multiple-exposure camera is used. A system PC with built-in synchronization unit controls the complete laser imaging system. The xyz (focus)-traverse system of the **FlowMaster MITAS** can be operated manually using a joystick or the device control manager in **DaVis** , which contains a position list with a number of positions. Every position can be added, edited and deleted and an **easy repeatability of each position** is guaranteed after e.g. lens exchange. The light is delivered through an optical fiber to the microscope. A built-in pilot LED is used for target focusing. The filter cube exchange box allows a fast adaptation for different excitation and emission wavelengths.



particle image of a 200 µm channel



corresponding vector field

FlowMaster
System Components

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

Standard PIV camera	Model	Features	High-speed PIV camera	Model	Features
	Imager sCMOS	combining extreme sensitivity with high dynamic and frame rate		Imager *pro* HS 4M	4 Mpixel, best image quality, fastest data transfer
	Imager SX 4M	compact 4 Mpixel model with 30 Hz frame rate		HSS 3G HSS 4G HSS 5.1 HSS 7 HSS 8 HSS X	1 Mpixel CMOS cameras with kHz frame rates and high sensitivity
	Imager *pro* SX 5M	compact, 5 Mpixel high resolution			
	Imager *pro* LX 16M	highest resolution CCD		Phantom v211 Phantom v311 Phantom v611 Phantom v711 Phantom v1210 Phantom v1610	
	Imager *pro* X 2M Imager *pro* X 4M Imager *pro* X 11M	most widely used PIV camera family			

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

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

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 7 64 bit operation system

Laser
- double-pulse Nd:YAG laser systems from different suppliers
- covering a wide range of output energy

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