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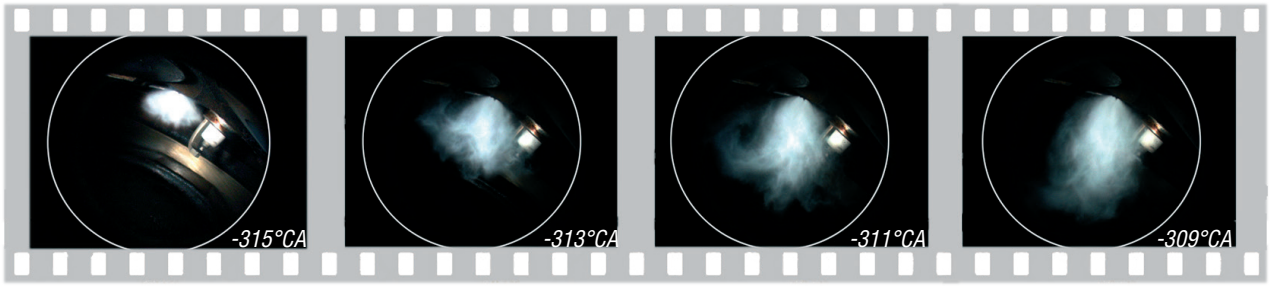
EngineMaster *inspex*

In-cylinder endoscopic imaging for spray and combustion visualization and quantitative optical indication in real engines

For the optimization of near-production internal combustion engines (ICE) endoscopic imaging can be applied to visualize in-cylinder phenomena. Key-hole imaging using endoscopes is a minimally invasive technique to monitor real-time in-cylinder processes such as fuel spray injection, ignition, combustion and soot formation. In combination with standard pressure indication endoscopic imaging links engine performance and emissions with in-cylinder phenomena such as pre-ignition, wall wetting and particle generation.

In addition to in-cylinder visualization **EngineMaster *inspex*** imaging systems provide quantitative information on spray geometry, flame propagation as well as soot temperature in combination with the appropriate analysis options.

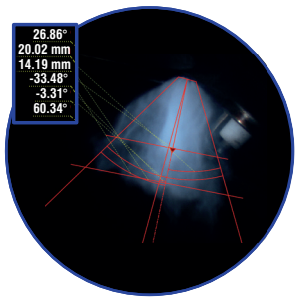


Crank-angle resolved spray imaging of gasoline direct ignition

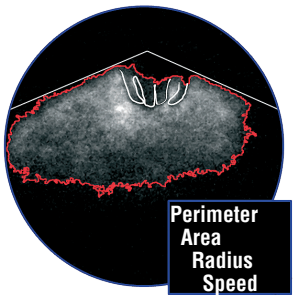
Soot formation in GDI engine during first cycles of a cold start at fixed crank angle position

Applications

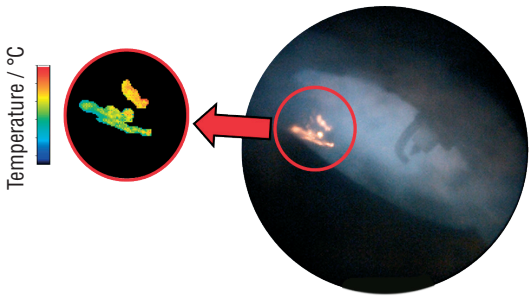
- spray visualization: propagation, geometry, wall interaction (wetting)
- combustion visualization: on-set of ignition, abnormal combustion (e.g. LSPI, knocking), flame propagation, in-situ soot formation



Spray geometry



Flame propagation



Temperature from soot pyrometry

Indicated engine parameters

- spray geometry
- flame propagation
- soot temperature

LaVisionUK Ltd
2 Minton Place / Victoria Road
Bicester, Oxon / OX26 6QB / United Kingdom
E-mail: sales@lavision.com / www.lavisionuk.com
Phone: +44-(0)-870-997-6532 / Fax: +44-(0)-870-762-6252

LaVision GmbH
Anna-Vandenhoeck-Ring 19
D-37081 Göttingen / Germany
E-mail: info@lavision.com / www.lavision.com
Tel. +49-(0)551-9004-0 / Fax +49-(0)551-9004-100

LaVision Inc.
211 W. Michigan Ave. / Suite 100
Ypsilanti, MI 48197 / USA
E-mail: sales@lavisioninc.com / www.lavisioninc.com
Phone: (734) 485 - 0913 / Fax: (240) 465 - 4306

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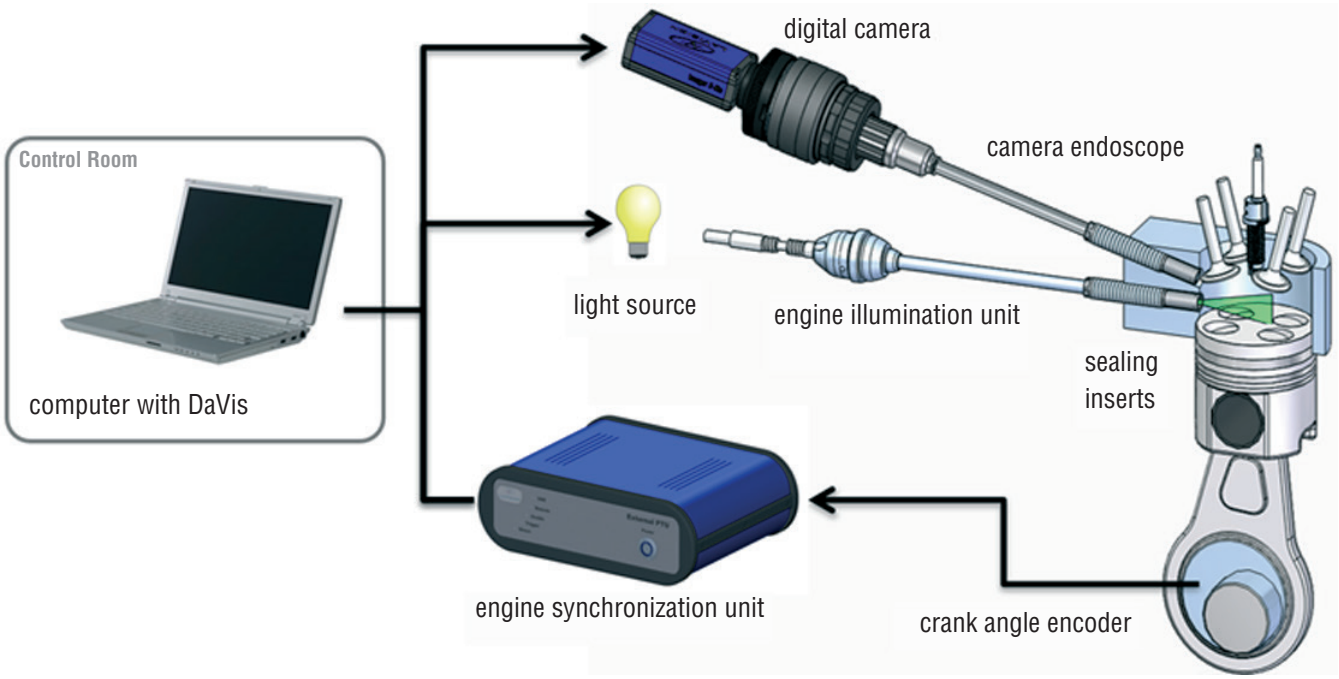
EngineMaster *inspex* systems

EngineMaster *inspex* systems include all components required for endoscopic imaging in combustion engines, including endoscopes, cameras and light sources.

At the heart of each system are LaVisions highly precise **PTU X** timing and engine synchronization unit and the **DaVis** software. This combination sets **EngineMaster *inspex*** apart from other products by offering many advanced triggering features and engine specific recording options for highest image quality, whilst maintaining maximum flexibility.

DaVis software not only controls recording with multiple cameras and devices but also gives access to a comprehensive image processing tool box as well as efficient data management. Engine sealing and equipment mounting are also available from LaVision to provide complete endoscopic imaging solutions.



System features

- direct visualization of the entire in-cylinder combustion cycle
- quantitative imaging of engine parameters
- full engine synchronization with advanced triggering features
- crank angle synchronized recording (low-speed / phase locked)
- crank angle resolved multiple cycle recording (high-speed)
- minimally invasive endoscopic illumination and imaging
- high transmission endoscopes (visible, UV)
- high resolution digital color, monochrome, intensified (UV) cameras
- engine adaptation including engine sealing sleeves

LaVisionUK Ltd
2 Minton Place / Victoria Road
Bicester, Oxon / OX26 6QB / United Kingdom
E-mail: sales@lavision.com / www.lavisionuk.com
Phone: +44-(0)-870-997-6532 / Fax: +44-(0)-870-762-6252

LaVision GmbH
Anna-Vandenhoeck-Ring 19
D-37081 Göttingen / Germany
E-mail: info@lavision.com / www.lavision.com
Tel. +49-(0)551-9004-0 / Fax +49-(0)551-9004-100

LaVision Inc.
211 W. Michigan Ave. / Suite 100
Ypsilanti, MI 48197 / USA
E-mail: sales@lavisioninc.com / www.lavisioninc.com
Phone: (734) 485 - 0913 / Fax: (240) 465 - 4306

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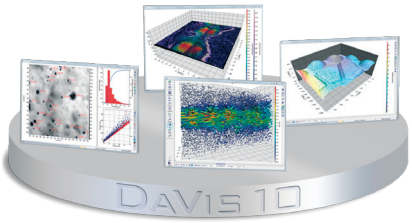
Engine synchronization unit

At the heart of each LaVision imaging system is the **PTU X** timing unit. Together with the **DaVis** software, this is the key for the many unique features that make **EngineMaster *inspex*** systems ideal solutions for engine applications:

- fully synchronized recording with a precision better than 50 ps
- live synchronization to engine
- recorded images synchronized to the engines crank angle position
- flexible triggering options
- control and synchronization of multiple cameras, intensifiers and light sources with individual timing offsets and operation parameters to get the best performance from each component
- unique integrated control for high-speed cameras for optimized image quality
- efficient memory utilization for extended recording duration
- engine specific recording modes for analysis of transient phenomena, e.g. cold start

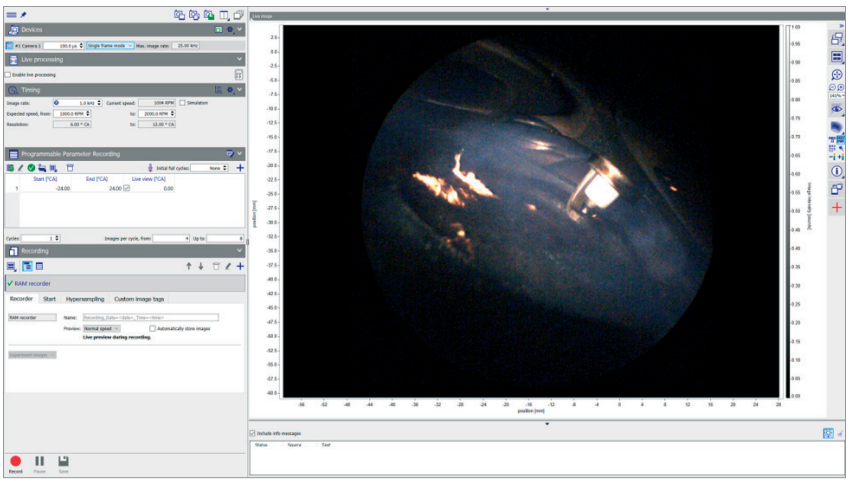
Recording and processing DaVis software



The second key component to **EngineMaster *inspex*** systems is the **DaVis** software. This fully integrated software platform provides precise control and timing of all hardware components and image recording via the **PTU X**. Particularly the simultaneous control and synchronization of multiple devices with kHz recording rates has taken many years to development to meet the demanding requirements of applications such as in-cylinder imaging. Many engine-specific recording features have been developed to make engine experiments more efficient (e.g. rotary decoder, programable parameter recording (**PPR**), **Hypersampling**) and also make synchronization with transient applications, such as the cold start, possible.

DaVis also takes care of all data management and image processing requirements. There are many useful features that enhanced engine-based imaging such as perspective calibration (to dewarp images) or vibration correction to remove vibrational movement in image sequences. The extensive portfolio of optional analysis modules gives access to advanced image processing and quantitative measurement techniques, such as spray geometry analysis, flame propagation analysis and soot pyrometry.

All these capabilities are combined in the single software platform **DaVis**.



LaVisionUK Ltd
2 Minton Place / Victoria Road
Bicester, Oxon / OX26 6QB / United Kingdom
E-mail: sales@lavision.com / www.lavisionuk.com
Phone: +44-(0)-870-997-6532 / Fax: +44-(0)-870-762-6252

LaVision GmbH
Anna-Vandenhoeck-Ring 19
D-37081 Göttingen / Germany
E-mail: info@lavision.com / www.lavision.com
Tel. +49-(0)551-9004-0 / Fax +49-(0)551-9004-100

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Ypsilanti, MI 48197 / USA
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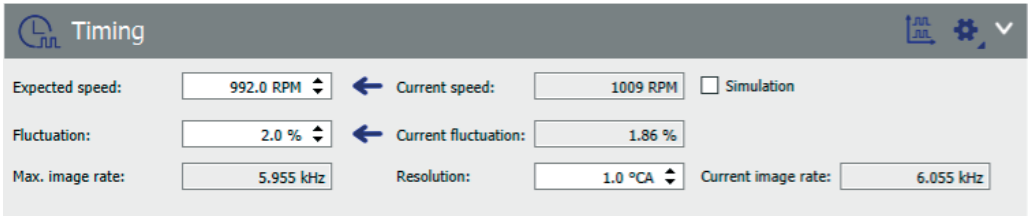
Engine optimized recording features

EngineMaster *inspex* systems have some unique features that have been developed specifically for imaging in engines:

Rotary encoder for engine synchronization

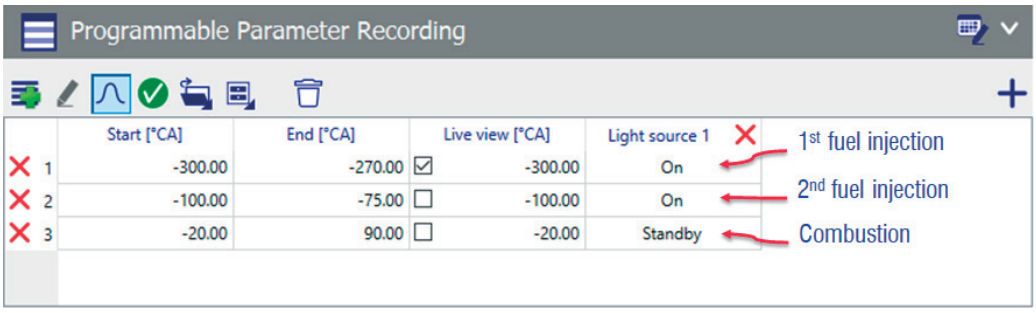
The fully integrated hardware rotary encoder handels synchronization of all devices controlled by DaVis to an internal combustion engine. For both low-speed (phase-locked, taking an image at a selected engine crank angle) and high-speed imaging (crank angle resolved recording) the rotary encoder precisely synchronizes the imaging to the engines crank angle position even for uneven running engines. As an input the encoder requires the trigger and crank angle division markers (CDM) from the engine. The encoder works with 2-stroke and 4-stroke engines and can handle CDM resolutions down to 0.1° crank angle. The rotary encoder feature is included in all **EngineMaster *inspex*** systems.



In live mode the encoder allows grabbing images at a specified crank angle. In low-speed recording Alternatively, a scan can be initiated where an image is taken at a different crank angle for each cycle. For high-speed recording mode a crank angle range is recorded for a number of consecutive cycles.

Programmable Parameter Recording (PPR)

High-speed imaging is inherently limited by the costly on-board memory of the camera. When recording continuously over an IC engine cycle many images are accumulated even for phases of the engine cycle where no visual analysis is possible or of interest. This leads to large amounts of unwanted data and shorter overall recording times. Programmable Parameter Recording (**PPR**) allows the programming of optimum recording parameters at different phases of the process (e.g. fuel injection, combustion).



The advantages of **PPR** are:

- record only relevant phases of the engine cycle, reducing data and increasing number of consecutive cycles that can be captured
- individually set the recording and device parameters for each phase, enabling the optimal recording of different phenomena in the same engine cycle, for example:
  - illumination control: on/off, intensity
  - image intensifier gate (exposure time) for UV imaging
  - PIV dt interframe time

LaVisionUK Ltd
2 Minton Place / Victoria Road
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Phone: +44-(0)-870-997-6532 / Fax: +44-(0)-870-762-6252

LaVision GmbH
Anna-Vandenhoeck-Ring 19
D-37081 Göttingen / Germany
E-mail: info@lavision.com / www.lavision.com
Tel. +49-(0)551-9004-0 / Fax +49-(0)551-9004-100

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Ypsilanti, MI 48197 / USA
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Hypersampling

Image quality of high-speed cameras can suffer from recording at fluctuating engine speeds. Engine speeds do not just change during transient operation but typically fluctuate within each engine cycle to a certain extent, even under stationary operation. Fluctuating recording rates often lead to image artefacts.

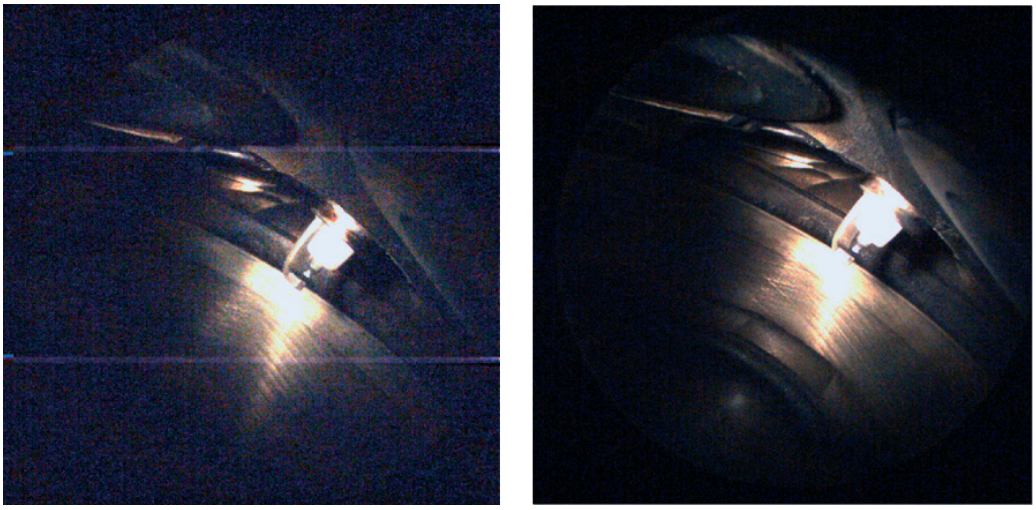

Image artefacts: e.g. bright horizontal lines appear in images without Hypersampling (left). When recording with Hypersampling (right) no artefacts are visible.

Hypersampling is an advanced recording technique that allows the camera to capture images at a fixed recording rate while storing the exact engine crank angle position at which each image was recorded. During data viewing or processing the recorded images are then mapped to a specific crank angle.

Hypersampling is an upgrade for high-speed imaging and requires an additional digital sampler. It can be combined with **PPR** to reduce data volumes and increase productivity.

The advantages of **Hypersampling** are:

- optimal image quality for all engine-based recordings even for stationary engine conditions with speed fluctuations
- transient engine operation with large variations in engine speed
- hypergate feature for selective recording of specific cycles. Designed for skip fire operation or to pick interesting parts of long test cycles (e.g. WLTP, RDE)

LaVisionUK Ltd
2 Minton Place / Victoria Road
Bicester, Oxon / OX26 6QB / United Kingdom
E-mail: sales@lavision.com / www.lavisionuk.com
Phone: +44-(0)-870-997-6532 / Fax: +44-(0)-870-762-6252

LaVision GmbH
Anna-Vandenhoeck-Ring 19
D-37081 Göttingen / Germany
E-mail: info@lavision.com / www.lavision.com
Tel. +49-(0)551-9004-0 / Fax +49-(0)551-9004-100

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Ypsilanti, MI 48197 / USA
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Cold start add-on

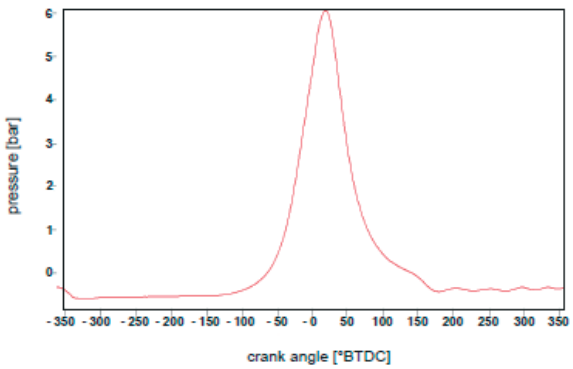
Since the operation during the first few cycles of an engine start are highly variable and the emissions during this time can be significant, detailed analysis of the cold start is crucial for meeting emission regulation targets. In terms of imaging, it is also highly challenging. The cold start add-on for **Hypersampling** allows the recording of engine cold start. The recording can be started before the engine starts or set to start automatically with the first movement of the engines crank.

The cold start add-on requires **Hypersampling**. The main features are:

- starting options before engine start or with start of rotation
- switching from time-based domain prior to engine start to crank angle-based domain once the engine is rotating.
- the first few engine cycles can be recorded in full length before switching to a defined crank angle range to optimize memory usage. Multiple crank angle subranges can be defined in combination with **PPR**.

Signal sampling

An optional analog-to-digital sampling unit can be added to **EngineMaster *inspex*** systems. This is requirement for using **Hypersampling** which uses the digital inputs of the device. In addition upto 8 analog signals can sampled with upto 1.25 MHz (single channel) or up to 1 MHz (multi-channel multiplexing). This enables the synchronized recording of other engine relevant information (e.g. in-cylinder pressure trace) together with the imaging data.



In-cylinder pressure trace from a fired engine

LaVisionUK Ltd
2 Minton Place / Victoria Road
Bicester, Oxon / OX26 6QB / United Kingdom
E-mail: sales@lavision.com / www.lavisionuk.com
Phone: +44-(0)-870-997-6532 / Fax: +44-(0)-870-762-6252

LaVision GmbH
Anna-Vandenhoeck-Ring 19
D-37081 Göttingen / Germany
E-mail: info@lavision.com / www.lavision.com
Tel. +49-(0)551-9004-0 / Fax +49-(0)551-9004-100

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Ypsilanti, MI 48197 / USA
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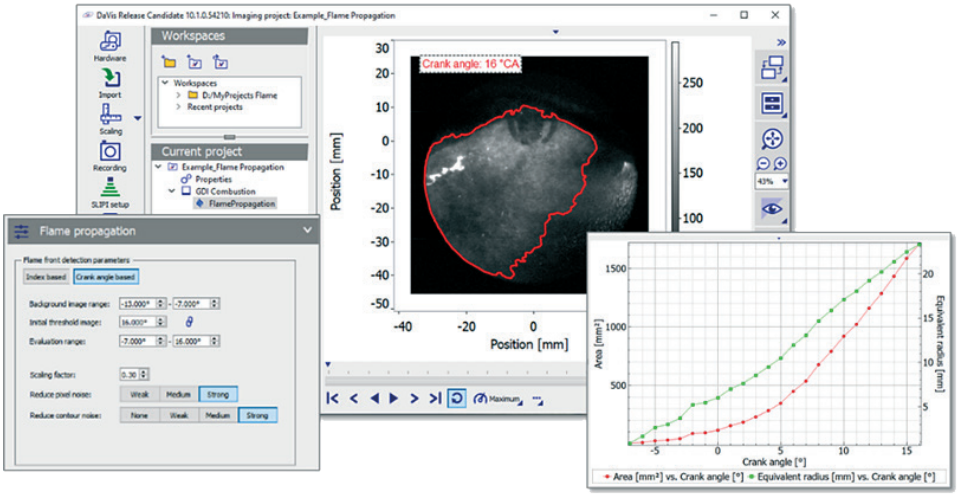
Quantitative in-cylinder imaging

EngineMaster *inspex* systems can be used for engine-relevant quantitative analysis of endoscopic images with optional **DaVis** modules.

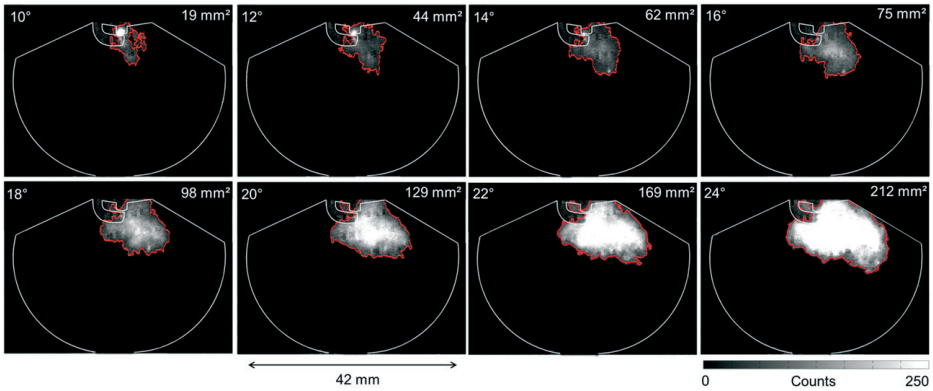
Flame propagation speed

LaVision's **Flame Front Propagation** module has been designed to detect and track early flame front propagation in internal combustion engines. This information is used to determine flame initiation behaviour, cycle-to-cycle combustion stability and as an input parameter for further thermodynamic analysis. The implemented flame front detection algorithm automatically detects the early flame front under challenging in-cylinder conditions, such as weak chemiluminescence of early flame and background reflections.



The algorithm provides the following information:

- flame front perimeter visualization
- projected flame area
- equivalent flame radius
- flame propagation rate



Flame propagation and flame radius increase in GDI combustion. Images courtesy of Shawal, S., Goschütz, M., Schild, M., Kaiser, S. et al., „High-Speed Imaging of Early Flame Growth in Spark-Ignited Engines Using Different Imaging Systems via Endoscopic and Full Optical Access," SAE Int. J. Engines 9(2):2016, doi:10.4271/2016-01-0644

LaVisionUK Ltd
2 Minton Place / Victoria Road
Bicester, Oxon / OX26 6QB / United Kingdom
E-mail: sales@lavision.com / www.lavisionuk.com
Phone: +44-(0)-870-997-6532 / Fax: +44-(0)-870-762-6252

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Anna-Vandenhoeck-Ring 19
D-37081 Göttingen / Germany
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Tel. +49-(0)551-9004-0 / Fax +49-(0)551-9004-100

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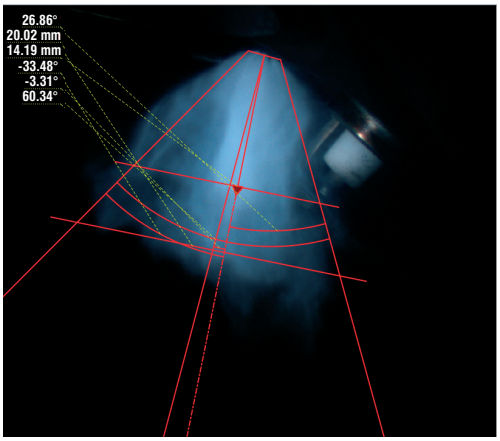
Spray geometry analysis

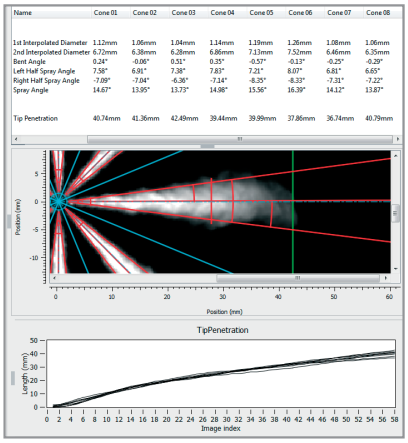
LaVision's **SprayMaster Geometry** module extracts spray plume morphology and geometry information using global spray illumination. This versatile module reveals spray information from endoscopic images from internal combustion engines. For the analysis of multi-hole injectors (e.g. automotive fuel sprays) spray cones are separated and individual geometry information is obtained for each cone.

Spray plume geometry and propagation

- spray cone angle measured at a fixed distance or from the interpolated rim
- bent angle (deviation from orifice axis) and both half angles to indicate the symmetry and direction of the spray plume
- tip penetration to represent the propagation of the spray
- angular spray density plot to show the uniformity of the spray



GDI fuel spray geometry from in-cylinder endoscopic image



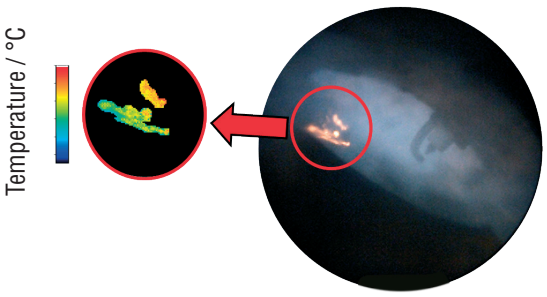
Analysis of single a spray plume in multi-hole diesel fuel injection

Soot pyrometry

Particle emissions need to be reduced in both diesel and gasoline engines. LaVision's **Pyrometry** module provides soot temperature from endoscopic images. Each detection system requires individual calibration. This requires a known black body calibration source.

Soot pyrometry imaging provides:

- soot temperature



Soot temperature in GDI engine after cylinder wetting

Endoscopic measurement of soot temperature in a propane flame

LaVisionUK Ltd
2 Minton Place / Victoria Road
Bicester, Oxon / OX26 6QB / United Kingdom
E-mail: sales@lavision.com / www.lavisionuk.com
Phone: +44-(0)-870-997-6532 / Fax: +44-(0)-870-762-6252

LaVision GmbH
Anna-Vandenhoeck-Ring 19
D-37081 Göttingen / Germany
E-mail: info@lavision.com / www.lavision.com
Tel. +49-(0)551-9004-0 / Fax +49-(0)551-9004-100

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Ypsilanti, MI 48197 / USA
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Phone: (734) 485 - 0913 / Fax: (240) 465 - 4306

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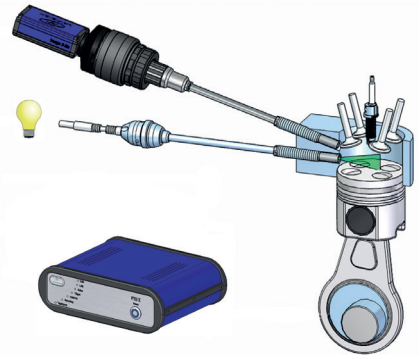
EngineMaster *inspex* configurations

LaVision offers three pre-configured turnkey endoscopic imaging solutions for in-cylinder spray and combustion visualization. The systems combine endoscopic illumination for spray and background contour illumination, a high-quality imaging endoscope and a choice of three different camera types. All systems come with a **PTU X** with the rotary decoder add-on for engine synchronization as well as a computor with **DaVis** installed for recording and image processing.



EngineMaster *inspex*	Low-speed	High-speed	High-speed laser
Description	crank angle sync. cycle-based imaging	crank angle resolved imaging	crank angle resolved imaging
Recording scheme	~1 image / cycle	~1 image / crank angle	~1 image / crank angle
Time resolution / motion freeze	Min. exposure time 34 µs	Min. exposure time ~1 µs	Pulse width ~190 ns @10 kHz
Light source	Cold light source (cw)		High speed laser 1-30 kHz
Illumination endoscope	Engine illumination unit with fibre coupling (ø 8 mm; ø 4 mm for HS-laser) for in-cylinder contour and spray illumination		
Camera endoscope	Camera endoscope for visible wavelength range (ø 8 mm)		
Camera	High sensitivity color camera 100 Hz (1936 x 1216)	Compact high-speed color-camera 6.4 kHz (1024 x 1024) 22.5 kHz (512 x 512)	High performance high-speed color camera 10.86 kHz (1280 x 960) 30.03 kHz (640 x 480)
Engine sync.	PTU X, rotary decoder	PTU X, rotary decoder, HS (options: PPR, Hypersampling, cold start)	
Analog sampling	(optional)	ADC included (required for Hypersampling) 8 analog signals (e.g. in-cylinder pressure)	
Computer	Compact imaging controller		High-performance PC (Raid, 10 GigE)
Control software	DaVis		

EngineMaster *inspex* applications

EngineMaster *inspex*		Low-speed	High-speed	High-speed laser
Endoscopic imaging	**Spray visualization**	★★	★★	★★★
	Combustion visualization	★★	★★★	★★★
	Transient phenomena*	★	★★★	★★★
Quantitative analysis	**Spray geometry**	★★★	★★	★★★
	Flame propagation	★	★★★	★★★
	Soot pyrometry**	★★★	★★★	★★★
OH* UV imaging		Requires suitable image intensifier and UV endoscope		

*for abnormal combustion phenomena, e.g. knocking, upgrades to faster cameras are recommended
**Pyrometry should be carried out on self-emission signals only without additional illumination

LaVisionUK Ltd
2 Minton Place / Victoria Road
Bicester, Oxon / OX26 6QB / United Kingdom
E-mail: sales@lavision.com / www.lavisionuk.com
Phone: +44-(0)-870-997-6532 / Fax: +44-(0)-870-762-6252

LaVision GmbH
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D-37081 Göttingen / Germany
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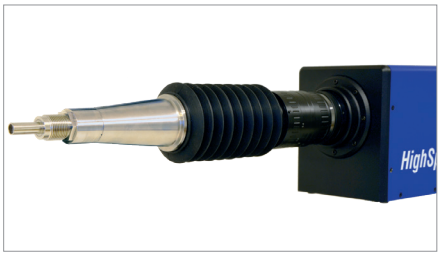
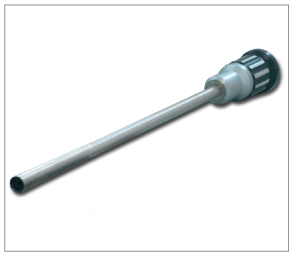
System components

In addition to the above pre-configured systems **EngineMaster** ***inspex*** systems can be tailored to specific requirements.

Endoscopes and illumination probes

LaVision offers a range of camera endoscopes and illumination units for global illumination of the combustion chamber. For imaging in the visible range there are 8 mm and 6.5 mm diameter endoscope series. Specialist high transmission UV endoscopes are available for flame front imaging (OH*). For advanced laser imaging applications, e.g. Particle Image Velocimetry (PIV), laser light sheet endoscopes complete the offered range. All camera and illumination endoscopes have been developed and optimized specifically with in-cylinder imaging in mind.


Sealing inserts and mounting

The interface to the engine is the most complicated part of endoscopic imaging in IC engines. LaVision offers a standard sealing insert that can with stand up to 300 bar. However, all engines are different and, in many cases, a customized sealing insert will be required. LaVision can design these to specific requirements.

Equally, for mounting of the imaging equipment standardized parts can be implemented or fully integrated customized solutions can be provided.

Cameras




LaVision has a large portfolio of digital cameras that can be controlled by the **DaVis** software. Working closely with some of the major camera manufacturers ensures that the latest camera technology is available. Particularly for high-speed imaging, the boundaries of speed and resolution are push forward frequently. A suitable camera or combination of cameras can be found for different in-cylinder applications:

- high resolution low-speed cameras for phase-locked imaging (one image per engine cycle at a defined crank angle).
- high-speed cameras with a wide range of speed and image resolution for crank angle resolved high speed imaging. Recording rates range from several thousand frames per second (fps) at full resolution to beyond 100.000 at reduced camera resolution to capture abnormal combustion events
- the cameras are available as color and monochrome versions. While color imaging provides information for intuitive combustion analysis, monochrome cameras provide highest sensitivity and spatial resolution and are more suitable for intensified UV imaging.
- for UV imaging, e.g. OH* visualization, low-speed and high-speed image intensifiers are available. They can be coupled with most digital cameras.
- double exposure cameras with short dt for PIV
- IR-cameras can also be incorporated into an imaging system for surface thermometry (not endoscopic). This is important for component thermal analysis not just in ICE but also electric powertrains.
- users owning cameras compatible with **DaVis** can register these for a small fee to be able to use them with **DaVis** as well as having access to LaVision's outstanding support services.

LaVisionUK Ltd
2 Minton Place / Victoria Road
Bicester, Oxon / OX26 6QB / United Kingdom
E-mail: sales@lavision.com / www.lavisionuk.com
Phone: +44-(0)-870-997-6532 / Fax: +44-(0)-870-762-6252

LaVision GmbH
Anna-Vandenhoeck-Ring 19
D-37081 Göttingen / Germany
E-mail: info@lavision.com / www.lavision.com
Tel. +49-(0)551-9004-0 / Fax +49-(0)551-9004-100

LaVision Inc.
211 W. Michigan Ave. / Suite 100
Ypsilanti, MI 48197 / USA
E-mail: sales@lavisioninc.com / www.lavisioninc.com
Phone: (734) 485 - 0913 / Fax: (240) 465 - 4306

LAVISION

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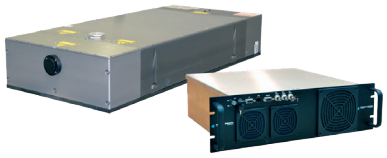
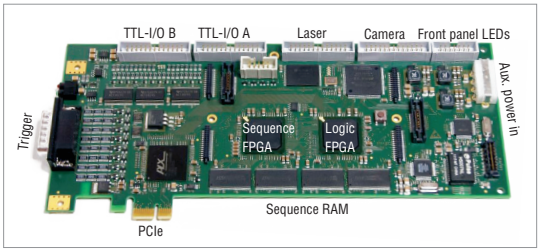
Illumination



For combustion visualisation only, additional illumination is not strictly required as the flame self-emission provides sufficient light. For other applications, such as fuel spray visualization, external illumination is necessary. Our portfolio includes different illumination sources, depending on the light requirements. Typically, cold light sources (cw) are used for spray and combustion chamber contour visualization. For high demands on motion freezing or extremely short exposure times, pulsed laser illumination is required.

Engine synchronization / PC

Central to LaVision imaging systems is the **PTU X** timing unit. Three models are available: external with USB communication, PC internal PCIe interface and a 19° rack mountable unit also with USB communication. The **PTU X** must be combined with a PC running the **DaVis** software. Depending on the requirements this can be a laptop computer, high performance PC or industrial PC. An analog/digital sampler can be added to record additional analog signals (required for **Hypersampling**).



Extended ICE imaging Applications

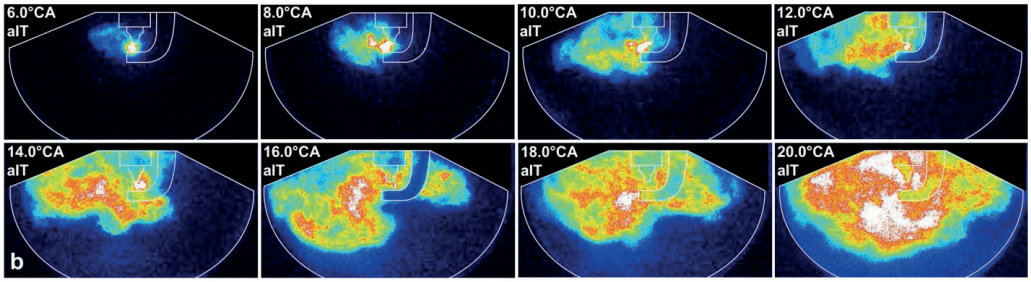
LaVision offers more equipment to upgrade or combine with **EngineMaster *inspex*** systems for further IC engine relevant imaging applications.

UV imaging

For more detailed early flame front visualization UV imaging of the OH* radical is the method of choice. OH* self-emission is very weak and requires high transmission optics as well as image intensification. LaVision offers a **high efficiency UV camera endoscope** with outstanding image quality due to high transmission and chromatic performance over a wide range of wavelengths in the UV. Combined with LaVisions low-speed and high-speed **image relay optics** (IRO) intensifiers UV any **EngineMaster *inspex*** system can be upgraded for UV endoscopic imaging.

UV endoscopic imaging applications:

- combustion diagnostics
- Laser Induced Fluorescence (LIF)
- chemiluminescence
- UV spray analysis
- UV tracer LIF



Endoscopic imaging of early flame propagation inside an IC-engine, courtesy of M. Goschütz et al, University of Duisburg-Essen, SAE Paper 2014-01-1178

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Next evolution of ultra-high-speed imaging

The advances in high-speed camera development continuously extend the limits of speed and resolution. For example, the latest TMX camera series with backside illumination technology offers frame rates up to 300,000 fps at unprecedented resolution of 640 x 384 pixels.
To capture abnormal combustion events such as engine knock camera frame rates beyond 100,000 fps are required. With the latest cameras on offer this is now possible with **EngineMaster *inspex***.

Next evolution of ultra-high-speed for endoscopic imaging applications:

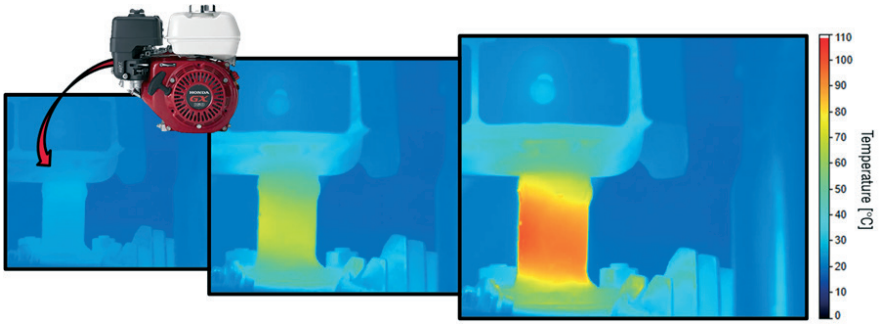
- abnormal combustion events
- low-speed pre-ignition (LSPI)
- engine knock

IR thermometry

Infrared (IR)-thermometry is the most common technique used for surface temperature imaging. Precise thermography is currently not possible endoscopically in the mid-IR and far-IR wavelengths used by most thermal imagers. However, in IC and also electric engine development thermal management and knowledge of surface temperatures of engine components are of importance. Combining an IR camera with an **EngineMaster *inspex*** system gives the ability to measure surface temperatures with full engine crank angle synchronization. The ImageIR series cameras offer high-performance infrared imaging solutions featuring high frames rates and excellent temperature resolution from ambient up to 1200 °C.

IR thermometry applications:

- surface thermometry
- engine component thermal analysis with engine synchronized imaging



Exhaust manifold of small power generator heating up during engine cold start

Ordering information

Part number	Description
EngineMaster *inspex*	Select from 3 pre-configured system options: - Low-speed - High-speed - High-speed laser Or select a customized hardware configuration
1105031	DaVis Spray Geometry module
1105069	DaVis Flame Propagation module
1105065	DaVis Pyrometry module

Apr-23

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