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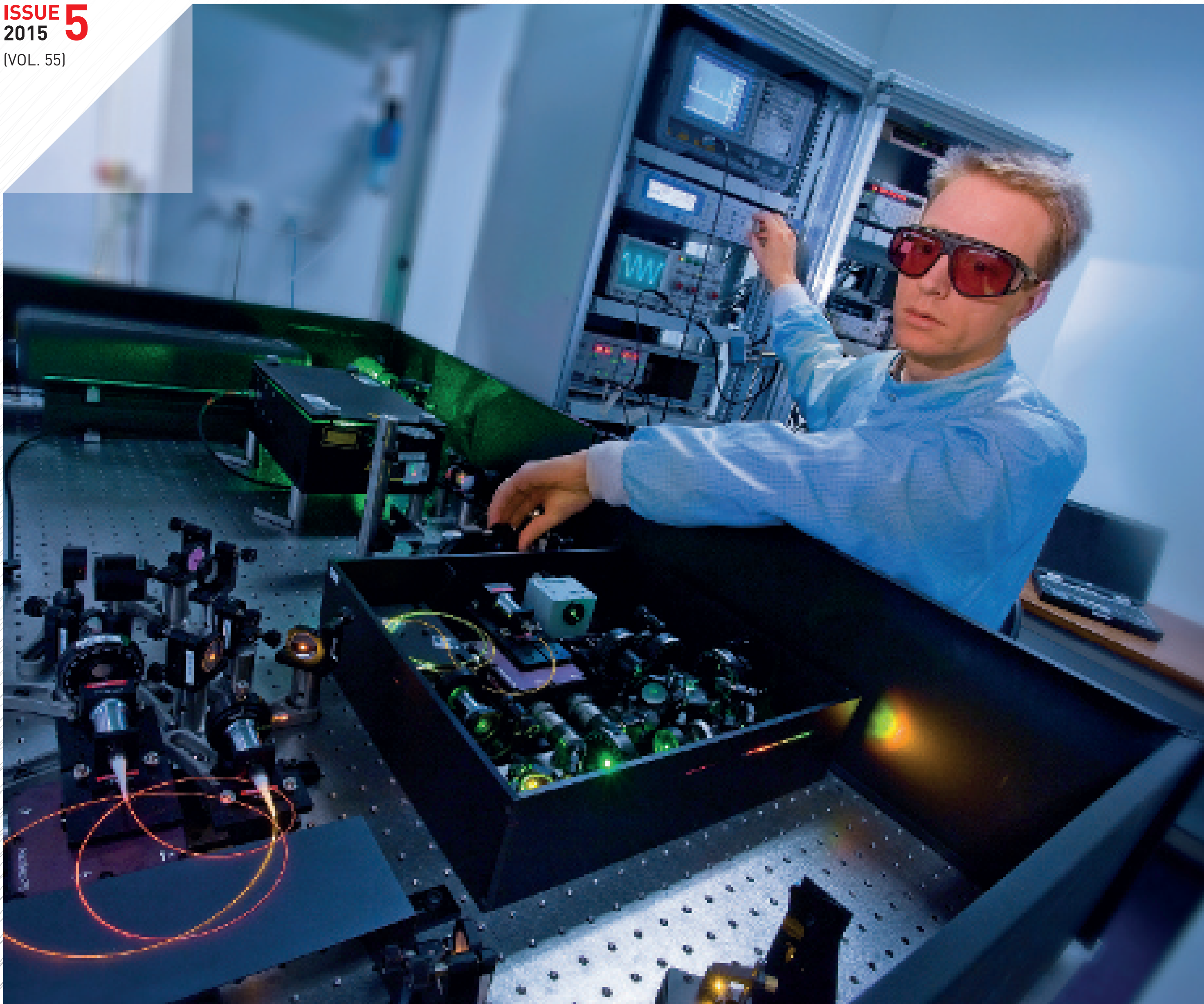

- **PRECISION FAIR** PREVIEW
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- eLISA **ACTIVE** MIRROR
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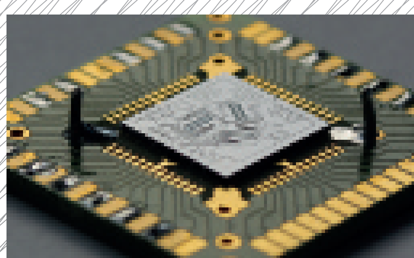

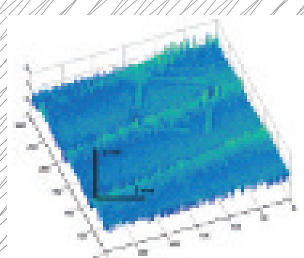

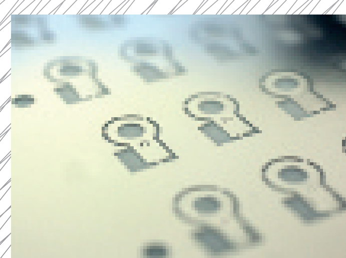

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Professional journal on precision engineering and the official organ of DSPE, the Dutch Society for Precision Engineering. Mikroniek provides current information about scientific, technical and business developments in the fields of precision engineering, mechatronics and optics.
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*The main cover photo (featuring the VSL frequency comb interferometry set-up) is courtesy of VSL/ Peer de Wit. Read the article on page 5 ff.*

# IN THIS ISSUE

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## FEATURES

# TO TAIWAN

Maybe not top of Dutch minds, but Taiwanese industry is of particular interest to the Netherlands. The main industries in Taiwan are ICT, machinery and semiconductors. Taiwan has a large market share of around 30% of the global semiconductor industry. This makes Taiwan a very interesting market for Dutch semiconductor companies and precision engineers. In 2013, Dutch exports to Taiwan in the semiconductor industry were above two billion Euros, and there is still room for growth. From the DSPE perspective, the recent initiative of the Taiwan Society for Precision Engineering is noteworthy.

Last year in June, I moved to Taiwan to start working for the Netherlands Trade & Investment Office (NTIO). The NTIO is the formal representation of the Dutch government in Taiwan and has as its mission to promote and support cooperation between Taiwanese and Dutch institutions and companies in the fields of commerce, science, technology, culture and agriculture. My job is supporting Dutch companies doing business in Taiwan and promoting the key sectors of the Netherlands in Taiwan in order to generate more business, cooperation and investments.

In order to enable Dutch businesses to succeed in the Taiwanese market, the NTIO provides economic services and organises sector promotion events. A good example of a High-Tech promotion event the NTIO organises on a yearly basis is the Holland High Tech Pavilion at the SEMICON Taiwan exhibition, the world's most important trade fair for the semiconductor industry and the only fair in this industry that is still growing. SEMICON Taiwan is *the* event in the area of microelectronics manufacturing, nanoelectronics, MEMS, photovoltaics and related high-tech electronics. The Holland High Tech Pavilion offers Dutch businesses the chance to exhibit at one of their display areas.

This September we welcomed the biggest Dutch semiconductor delegation ever, including nine Dutch companies and TNO, at the Holland High Tech Pavilion, which gave Dutch SMEs a great opportunity to start doing business in Taiwan. This was a great success as many of the companies managed to find new Taiwanese customers and business partners to further develop semiconductor and precision engineering applications. The importance of the SEMICON and the semiconductor industry for Taiwan was underlined at the SEMI Gala Dinner, where the opening speech was given by the president of Taiwan, Mr. Ma Ying-Jeou.

After helping Dutch companies in Guangzhou to succeed on the Chinese market for two years, my move to Taiwan was very pleasant. Taiwan is a great place to live as it offers a combination of a very developed high-tech driven economy within a traditional Chinese context.

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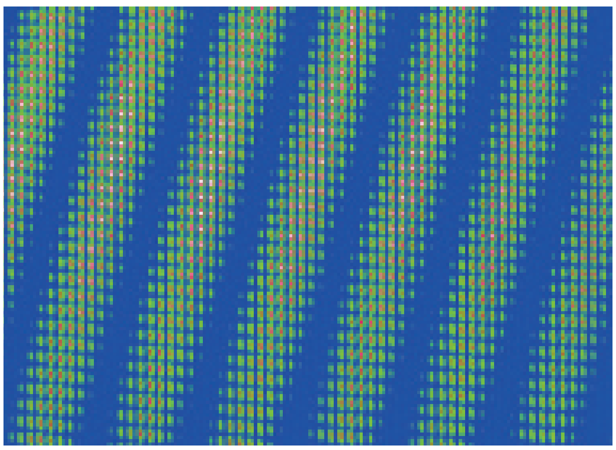
*diederikvandertoorn@ntio.org.tw, www.ntio.org.tw*

*Diederik van der Toorn and his NTIO colleague at the Holland High Tech Pavilion on the SEMICON Taiwan 2015.*

# COMBING WITH LIGHT

**A femtosecond frequency comb laser is a powerful tool in metrology, not only as an instrument for measurement of optical wavelengths, but also as an instrument for highly accurate distance measurement. Since a frequency comb laser emits a large number of known wavelengths simultaneously, it allows for interferometry with all these wavelengths in parallel. In this way a wealth of information on the distance to be measured is obtained, which enables absolute distance measurement with interferometric accuracy.**

STEVEN VAN DEN BERG



*Interferometry with thousands of wavelengths simultaneously.*

## Introduction

Already since 1983 the meter has formally been related to the second in the SI systems of units, by defining the meter as the distance that is travelled in vacuum in 1/$c$ second. Here, $c$ is the speed of light in vacuum, which is fixed at $c$ = 299,792,458 m/s. Although this definition can directly be applied for measuring very long distances, simply by measuring the time that a pulse of light needs to travel to reach a certain target (e.g. the moon), it is not very practical to measure short distances with such a 'time of flight' method.

Alternatively, interferometry has proven a very powerful and accurate method for measuring distances or displacements. Here, the wavelength of laser light serves as a 'ruler' for measuring the path-length difference of an interferometer. The distance is expressed in terms of an integer number of wavelengths plus a wavelength fraction. To trace back this measurement to the definition of the meter, the wavelength of the laser needs to be known. With the speed of light being fixed, the wavelength $\lambda$ is related to the optical frequency via the simple relationship $\lambda = c / f$, with $f$ the optical frequency.

To obtain traceability of length measurement to the SI second, the optical frequency $f$ thus needs to be measured with respect to a time standard, e.g. an atomic clock. With the invention of the optical frequency comb at the beginning of this century the measurement of optical frequencies has been simplified tremendously. The national metrology institute of the Netherlands, VSL, operates such a frequency comb on a regular basis for optical frequency measurements.
Here, however, we will focus on another application of the frequency comb, which is direct distance measurement with the comb. We exploit the frequency comb as a source that emits thousands of wavelengths simultaneously and perform interferometry with all these wavelengths in parallel. The strength of this method is that it enables the measurement of absolute distances with high accuracy, without the need to generate a displacement. This is a large advantage compared to single-wavelength interferometry, which is usually based on fringe counting and requires a linear guidance and an uninterrupted beam path during the measurement.

To access the information that is available from the thousands of interfering wavelengths, we have developed a high-resolution spectrometer that is able to separate the closely spaced wavelengths. By analysing the output of an

**AUTHOR'S NOTE**

Steven van der Berg is a principal scientist at the Dutch National Metrology Institute VSL in Delft, the Netherlands. Part of this was presented at the DSPE Optics and Optomechatronics Symposium 2015 (see also page 29 ff.).

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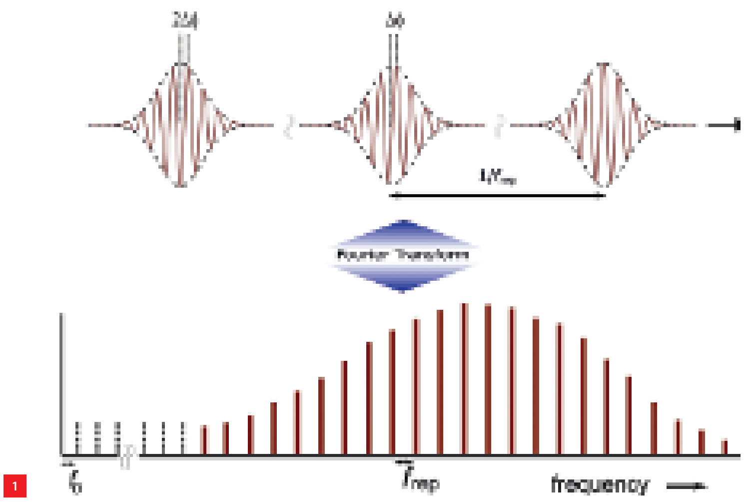
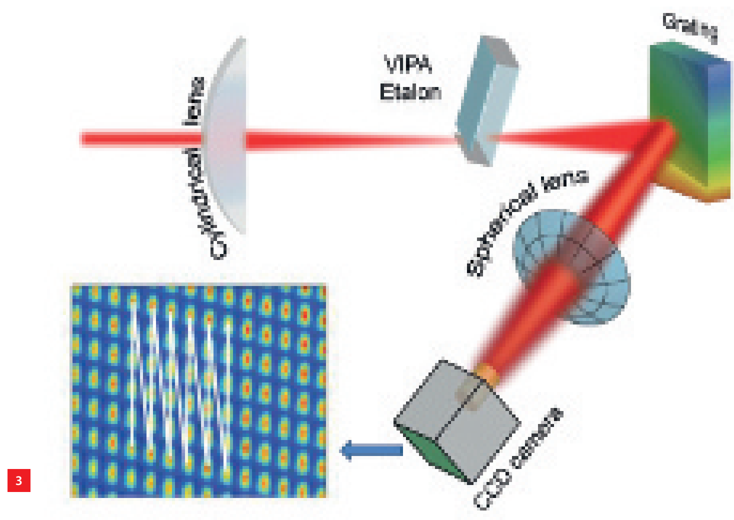


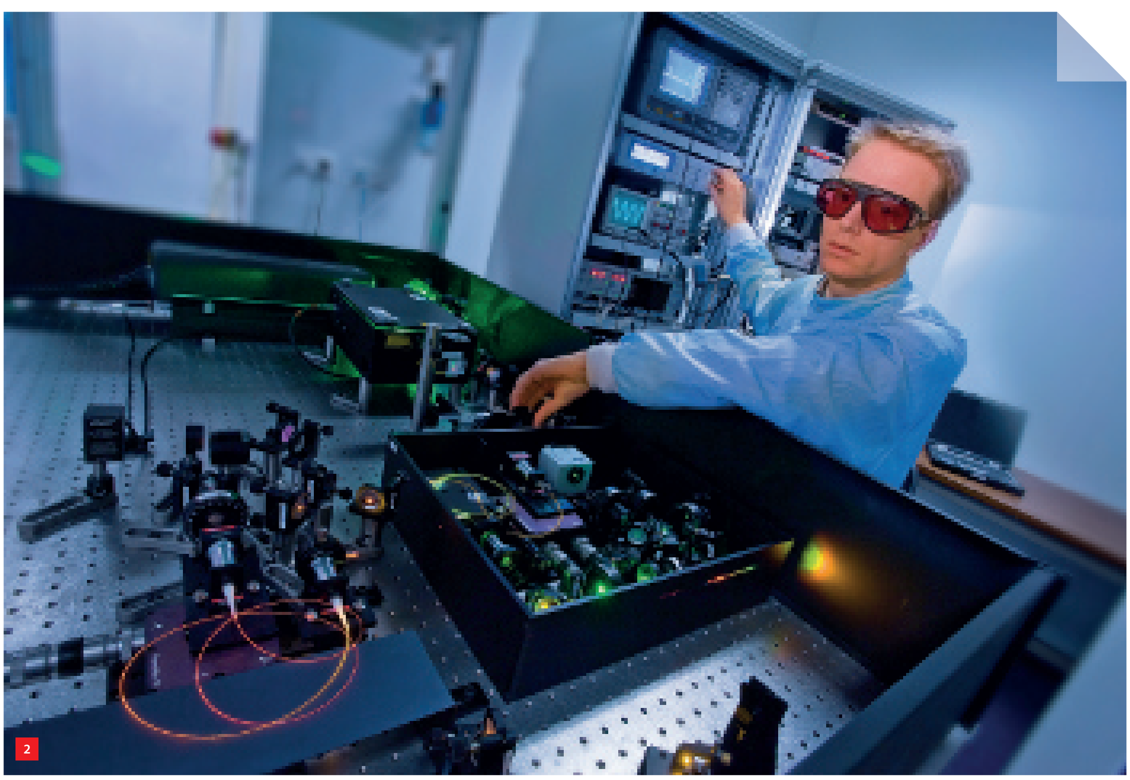

interferometer with the spectrometer, a distance can be derived [1]. Recently we have applied this method to the measurement of distances up to 50 m [2].

## Femtosecond frequency comb

An optical frequency comb laser is a pulsed laser that emits ultrashort (femtosecond) pulses with a repetition frequency of typically 100 MHz to 1 GHz. The optical spectrum of such a laser contains a large number of frequencies, which are equally spaced (see Figure 1). This is where the name ‘frequency comb’ comes from.

The frequency difference between neighboring laser frequencies is equal to the repetition frequency of the laser. VSL operates a frequency comb that is based on a titanium-sapphire laser, emitting pulses at a 1 GHz repetition frequency (see Figure 2).

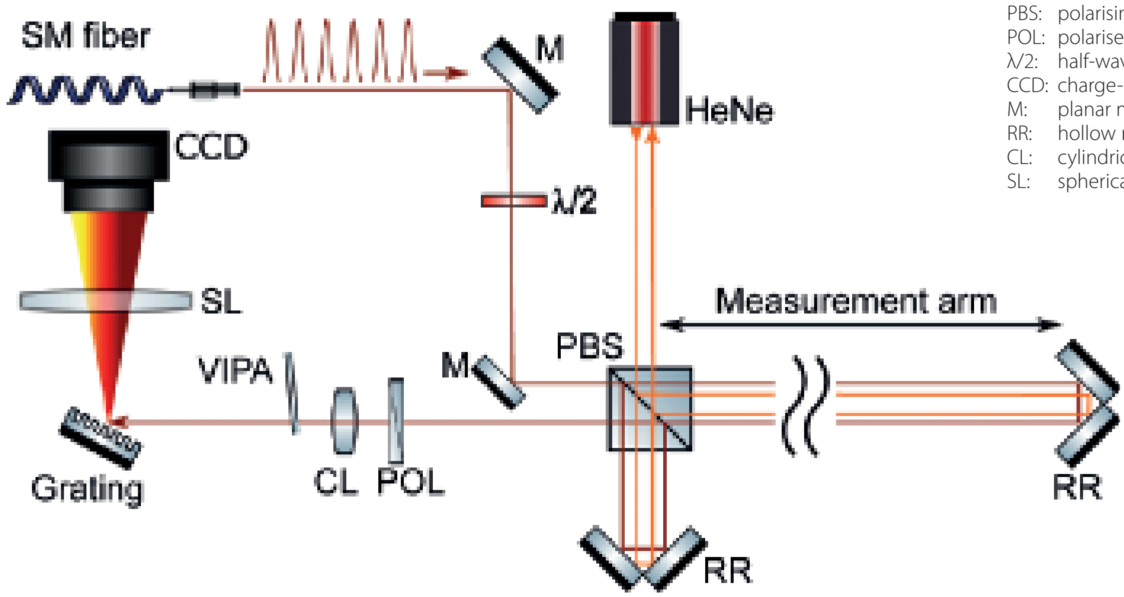
The optical spectrum of the Ti:Sapphire laser ranges roughly from 810 to 830 nm and consists of about 9,000 individual wavelengths. The repetition frequency of the laser is stabilised with respect to the atomic clock, which fixes the mutual spacing between the comb frequencies.



1 *Visualisation of the pulse train emitted by a femtosecond laser and its corresponding spectrum of optical frequencies. In reality the spectrum contains ten thousands of optical frequencies (wavelengths).*

2 *The VSL frequency comb in operation. The coloured fibers broaden the spectrum that is emitted by the Ti:Sapphire laser over the full visible spectrum, which is used for optical frequency calibration. For distance measurement the original Ti:Sapphire spectrum is used, ranging from 810 to 830 nm.*

3 *High-resolution spectrometer based on a VIPA and a grating for unravelling the frequency comb spectrum. The white arrow indicates how the full comb spectrum is reconstructed by stitching vertical lines together. Here, only a small part of the camera image is shown for clarity; in reality a vertical line contains about fifty unique dots.*




PBS: polarising beam splitter
POL: polariser
λ/2: half-waveplate
CCD: charge-coupled device camera
M: planar mirror
RR: hollow retro-reflector
CL: cylindrical lens
SL: spherical lens

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*4 Schematic overview of the measurement set-up for comparing distance measurement up to 50 m with a counting helium-neon laser and a frequency comb. The comb light is delivered to the set-up with a single-mode (SM) fiber. The HeNe laser (orange line) and comb laser (red line) measure the displacement quasi-simultaneously.*

A single frequency in the comb can be described as $f_p = f_0 + p \cdot f_{rep}$, with $p$ a large integer number ($10^5$ to $10^6$) and $f_0$ an offset frequency. Both $f_{rep}$ and $f_0$ are stabilised on the level of $10^{-11}$ in 1 second averaging time, which means that all emitted wavelengths are stabilised at that level as well.

## High-resolution spectrometer

In order to fully exploit the large number of wavelengths that are emitted from the frequency comb laser for distance measurement, it is required to spectrally separate them. For this purpose we developed a high-resolution spectrometer, based on a 'virtually imaged phase array' (VIPA) and a grating, which is inspired on VIPA applications in telecommunications and high-resolution spectroscopy [3,4].

A VIPA is an etalon with high-reflectivity coatings, which generates an angular dispersion in the vertical plane. The free spectral range of the etalon is 50 GHz, which means that optical frequencies with a frequency difference of 50 GHz are emitted from the VIPA at the same angle. Therefore, a grating is introduced to spectrally separate these frequencies in the horizontal plane. Subsequently, the light is imaged onto a camera with a lens, revealing the individual laser modes of the frequency comb as dots. The VIPA spectrometer set-up is illustrated in Figure 3.

The full comb spectrum is reconstructed by stitching the vertical lines together. In order to do this correctly, a few reference markers are generated on the camera by sending the beam of a tunable single-mode laser along the same path, while simultaneously measuring the wavelength with an independent wavemeter. The accuracy of the wavemeter is within 100 MHz, which is accurate enough to unambiguously determine the absolute wavelength of each dot.

## Massively parallel interferometry

For the distance measurement we have constructed a Michelson interferometer with a measurement arm that can be changed over a distance of 50 m by moving a carriage along a straight linear guidance. The displacement is not only measured with the frequency comb, but also with a conventional counting laser interferometer for comparison. The set-up is shown in Figure 4.

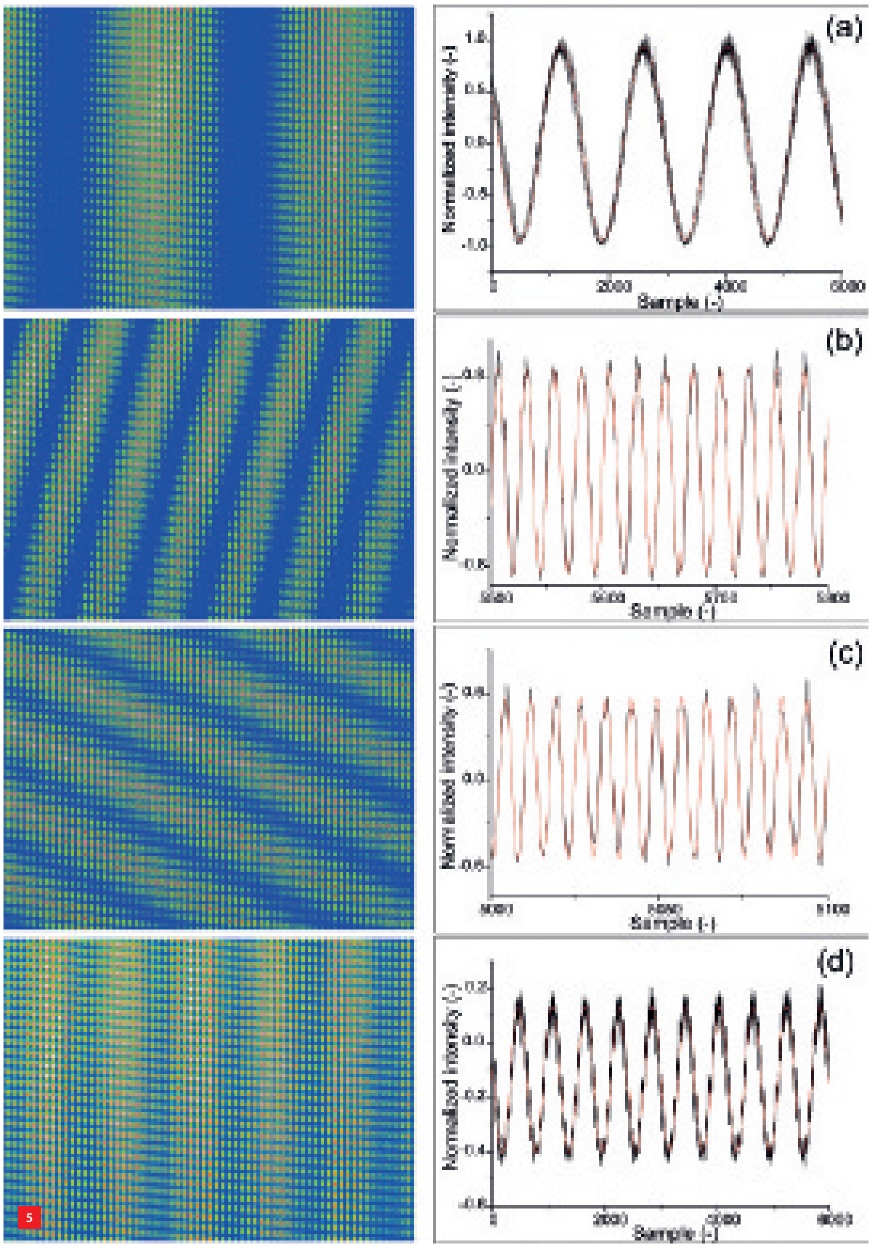
The output of the Michelson interferometer is spectrally resolved with the VIPA spectrometer. As shown in Figure 5, simultaneous interference at many wavelengths occurs. We have measured such interference patterns at various distances ranging from 0 to 50 m. On the right hand side the reconstructed spectra are shown. From the measured phase change as a function of wavelength a distance can be derived, as will be discussed below.

## Spectral interferometry

Measuring the wavelength dependent interference is called spectral interferometry. From the phase change as a function of wavelength a distance is derived, which was already demonstrated in various configurations [5,6]. The interference term can be written as:

$$I(\lambda) = I_0 \cos\left(\frac{2\pi \cdot 2L \cdot n}{\lambda}\right) \tag{1}$$

Here, $I_0$ is the intensity of the light sent into the interferometer, $L$ is the path-length difference of the interferometer arms (single path), $\lambda$ is the vacuum




**5** *Interferometry with thousands of wavelengths simultaneously for four distances. Spectral interferometry images are shown on the left. For clarity only 1/4 of the CCD chip area has been selected. On the right side the reconstructed spectra are shown. The x-axis with the sample number has been scaled differently for these graphs to clearly visualise the fringes.*
*(a) ≈ 0 m.*
*(b) 5 mm.*
*(c) 20 m.*
*(d) 50 m.*

wavelength, and $n$ is the refractive index of the medium, usually air. The total accumulated phase can be written as:

$$\varphi = \frac{4\pi L n}{\lambda} = \frac{4\pi L n f}{c} \qquad (2)$$

Here, $f$ is the optical frequency and $c$ is the speed of light in vacuum.
In Figure 6 we show simulated spectra for a delay of 5 and 6 mm, respectively, to illustrate the interference and phase change as a function of wavelength.

The phase change as a function of optical frequency can be written as:

$$\frac{d\varphi}{df} = \frac{4\pi L}{c}\left[n + f\frac{dn}{df}\right] = \frac{4\pi L}{c} n_g \qquad (3)$$

With $n_g$ the group velocity refractive index of air. This leads to the following expression for the distance $L$:

$$L = \frac{d\varphi}{df}\frac{c}{4\pi n_g} \qquad (4)$$

In practise we determine the phase change as a function of frequency by fitting a cosine with the measurement data.

Due to the periodicity of the pulse train, the interference patterns are repeating themselves: pulse overlap occurs when the total path-length difference of the interferometer equals a multiple of the pulse-to-pulse distance $L_{pp}$, with $L_{pp} = c/(f_{rep} \cdot n_g)$. An arbitrary distance $L_t$ is then written as:

$$L_t = \frac{1}{2} m L_{pp} + L \qquad (5)$$

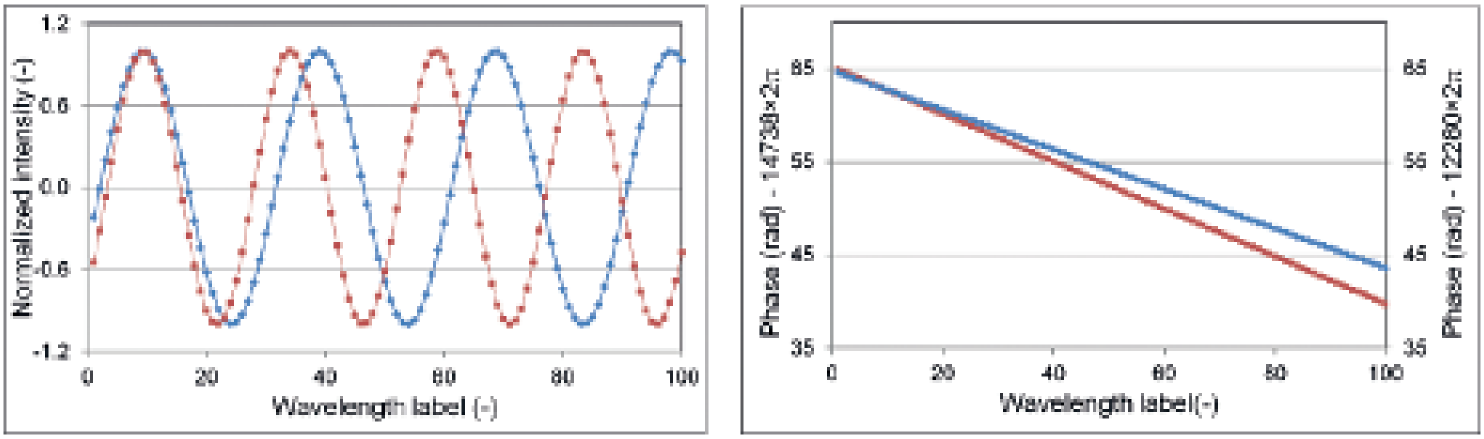
To determine $L_t$, the integer $m$ needs to be known. Therefore, it is necessary to know the distance to be measured with an accuracy better than $L_{pp}/2$. This is a relaxed requirement, with $L_{pp} \approx 30$ cm for our system, which can easily be fulfilled by measuring the approximate distance with a simple electronic distance meter, time-of-flight measurement or even a measurement tape.

## Homodyne interferometry

So far, the absolute wavelength of each dot has not yet been used, but we know the phase of each wavelength from its relative position on the cosine fit. This information can be used to determine the distance for a particular wavelength $\lambda_p$ via:

$$L_p(\lambda) = \left(q_p + \frac{\varphi_{p,fit}}{2\pi}\right)\frac{\lambda_p}{2n_p} \qquad (6)$$

Here, $q_p$ is an integer number, and $n_p$ is the (phase) refractive index of $\lambda$. The phase $\varphi_{p,fit}$ is obtained from the cosine fit. Note that $q_p >> m$, since $\lambda_p << L_{pp}$. The measurement uncertainty resulting from Equation 6 is

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6 *Simulated spectral interferometry for a distance L equal to 5 mm (blue) and 6 mm (red), respectively. The graph on the left shows the simulated intensity, the graph on the right the phase. The absolute phase (4πL/λ) has been offset by an arbitrary multiple of 2π for both distances. For clarity only 100 wavelengths are shown. Note that at zero delay the absolute phase would equal zero for all wavelengths.*

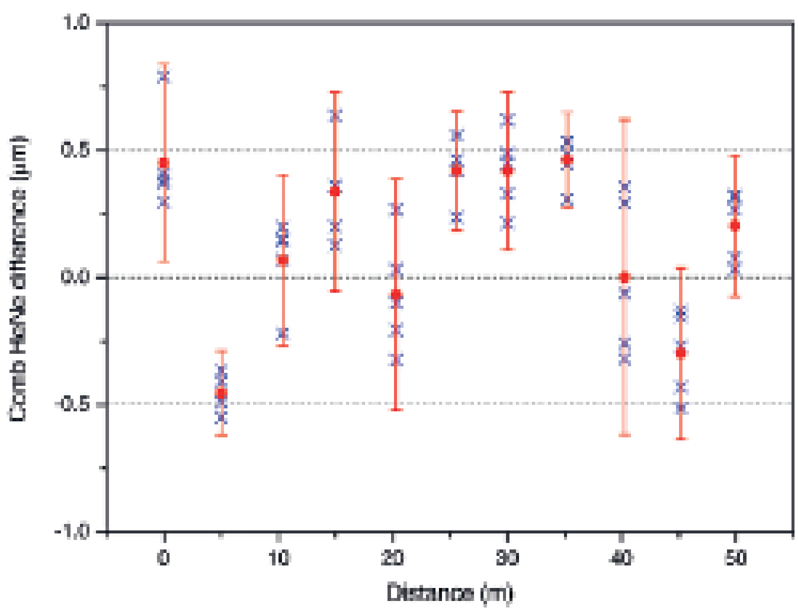
expected to be smaller than the measurement uncertainty resulting from Equation 5, since the uncertainty on the phase is multiplied by $\lambda_p$ instead of $L_{pp}$. For a practical measurement other contributions to the measurement uncertainty arise, like wavelength (in)stability and, dominating in our case, the (in)stability of the interferometer itself.

## Measurement results and discussion

Based on the measurement data presented in Figure 5 and the analysis described above, we have determined the distance for measurements up to 50 m. The results are summarised in Figure 7, showing the difference between the counting laser interferometer and the comb meassurement. An agreement between both methods is found within 1 μm over the full length of the measurement bench for each individual measurement, and < 500 nm when averaged over five measurements. At a distance of 50 m this is a relative agreement within $10^{-8}$.

Remarkably, the agreement between the measurements with HeNe and frequency comb laser and the corresponding standard deviation are independent from the distance that is measured. This is explained by environmental vibrations that are coupled to the moving carriage of the 50 m measurement bench, dominating the measurement uncertainty, independent from the position of the carriage on the guidance.

We have analysed the measurement data to derive a distance based on homodyne interferometry as well, following Equation 6. Although the measurement results based on homodyne interferometry were expected to be more accurate than those based on spectral interferometry, the results are very similar for these measurements. Both methods agree with each other within 100 nm for all distances. The expected superior performance of homodyne interferometry is hidden by the aforementioned environmental vibrations that dominate the measurement uncertainty of this comparison. The total estimated measurement uncertainty for a coverage factor $k = 2$ (corresponding to a 95% coverage interval) is 0.75 μm for spectral interferometry, against 0.69 μm for homodyne interferometry. This is in good agreement with the observations in Figure 7.




7

7 *Observed differences between the frequency comb distance measurement, based on spectral interferometry, and the counting laser interferometer. The error bars indicate twice the standard deviation over the five measurements.*

## Conclusion

We have shown that a frequency comb can be exploited as a powerful source for absolute distance measurement. Due to the wealth of information available from the thousands of wavelengths present in the comb, the range of non-ambiguity is very large compared to single-wavelength interferometry. This allows for absolute distance measurement with high accuracy, without the need to generate a displacement.

With the prospect of frequency comb lasers becoming smaller, cheaper and easier to operate, the presented method may find a wide range of applications. Based on the uncertainty of the phase measurement, an accuracy on the level of a few nm may be feasible in vacuum and a vibration-free environment. The measurement range and best achievable accuracy will ultimately be limited by the coherence length of the light and thus the accuracy of the reference clock.

## Acknowledgement

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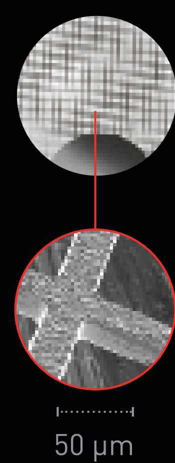


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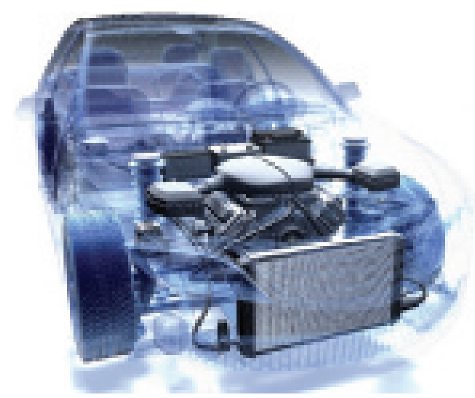
# Motorsport to Automotive

**An important part of vehicle development is Driver-in-the-Loop testing and there is an increasing need to start this level of testing earlier in the process, often before a representative prototype is available. To meet this need a wide range of driving simulators are available with the most sophisticated systems now able to support detailed vehicle engineering.**

The vehicle model is a critical component in these systems and the capability of the platform to support vehicle engineering activities is determined by the fidelity of this model. Using Modelica modelling language, Claytex can produce high fidelity vehicle models that include every vehicle system consisting of MultiBody mechanics, electrical, thermal, fluids and control systems. Dymola, a Modelica modelling and simulation tool, is used to transform these models into efficient

simulation code that can run in real-time and be coupled to the Driver-In-the-Loop simulation platform.



These technologies have been developed in motorsport and applied in Formula 1 and NASCAR for many years enabling the teams to evaluate detailed geometry changes or new technologies before arriving at the race track. The same technology is now being applied for road cars to enable a wide range of engineering activities including handling, active safety systems, ride, NVH and control system integrity.

Modelica can be used to create MultiBody vehicle dynamics models that can be run in real-time in a driver-in-the-loop simulator. Modelica allows to easily include the electric motors, power electronics and energy storage devices associated with a hybrid or electric powertrain and to include the thermal management of these systems as part of the simulation.

In order to control the physical models, accurate but realistic sensing of the system model must be possible. This will include realistic representation of sensor and actuator dynamics and injecting faults into the sensor and actuator models to enable robust controller development.

**Meet with Claytex at Precision Fair on 18th & 19th November, Stand 216, to find out more.**
**Claytex will be presenting a paper on Wednesday 18th November at 12:05. 'Sensor Accuracy in Vehicle Safety'**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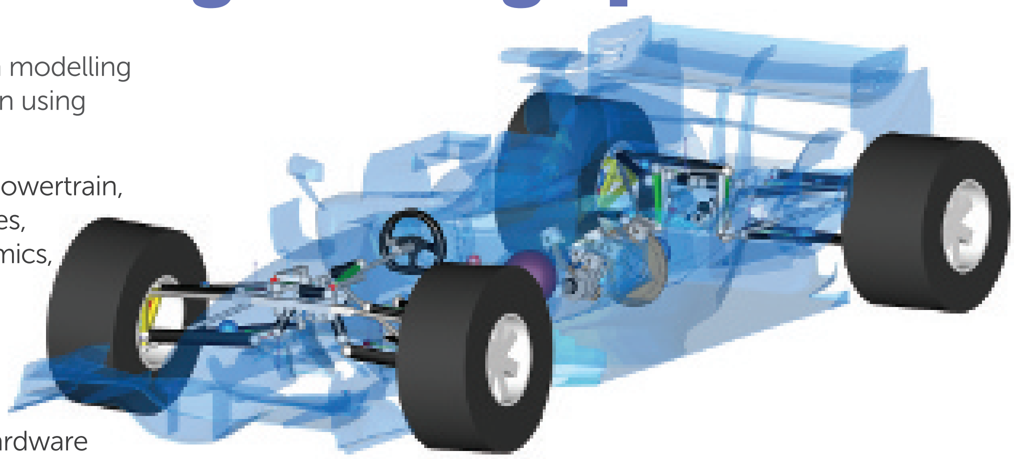

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# BETWEEN PRECISION TECHNOLOGY AND BIG SCIENCE

**On 18 and 19 November 2015, the fifteenth edition of the Precision Fair will once again be the international meeting point for precision technology. This free event at the NH Conference Centre Koningshof in Veldhoven, the Netherlands, features over 300 exhibitors (specialised companies and knowledge institutions) and is expected to attract some 4,000 visitors. The two-day lecture programme lists fifty presentations, including a special Big Science track on Wednesday 18 November. The International Meet & Match Event will be hosted on both fair days.**

Precision Fair 2015

The exhibition of the Precision Fair covers a wide array of fields, including optics, photonics, calibration, linear technology, materials, measuring equipment, micro-assembly, micro-connection, motion control, surface treatment, packaging, piezo technology, precision tools, precision processing, sensor technology, software and vision systems. The lecture programme features a variety of topics, from motion control and additive manufacturing to model-based systems engineering and open innovation. A sneak preview of a few innovations is presented on the following pages.

## Business potential

A special keynote track is devoted to Big Science projects like CERN (nuclear research), ITER (nuclear fusion energy), E-ELT (astronomy) and the research facilities ESRF (synchrotron radiation) and ESS (neutron source). The tenders for these projects offer considerable opportunities for Dutch suppliers, but they have not yet fully utilised that business potential. At the Precision Fair, high-tech suppliers can learn about recent technological developments and new tenders.

## Awards

Just before closing each fair day, event partner DSPE will organise an award ceremony. On Wednesday 18 November, the Rien Koster Award will be presented to a mechatronics engineer/designer who has made a significant contribution to the field of mechatronics and precision engineering. On Thursday 19 November, the Wim van der Hoek Award (also known as the Constructors Award) will be presented to the person with the best graduation project in the field of design in mechanical engineering at one of the three Dutch universities of technology.

With the overwhelming programme the Precision Fair has in store, resulting from fifteen years of evolution in the fair concept, every visitor can be considered a winner. Media partner Mikroniek will report on the highlights in its December issue. ■

INFORMATION AND FREE REGISTRATION
WWW.PRECISIEBEURS.NL

*Impression of a previous Precision Fair, showing the SmarAct stand. SmarAct develops, produces and distributes piezo-based micro- and nano-positioners, advanced control systems, tools for the micro and nano world, as well as complete micro- and nanomanipulation systems.*

# INNOVATIONS ON DISPLAY

### Heidenhain
## Quadra-Chek 3000 measurement data processing system

To increase the precision and efficiency of measurement processes on high-accuracy measurement machines, Heidenhain has developed the Quadra-Chek 3000, an electronic system for processing measurement data. It evaluates camera images from measurement and profile projectors, measuring microscopes and video testing machines.

The video tools integrated in the Quadra-Chek 3000 can be used to define measurement points and calculate geometric elements. The measurement result is displayed graphically on a touch screen, and the function buttons alongside the screen, which include a button to start an automatic run-through of the measurement process, allow the operator to maintain a full overview of the process at all times.

The Measure Magic automatic geometry detection system quickly and accurately measures 2D elements. The system compensates for any mechanical inaccuracies in the measuring machine and uses filters to prevent the measured values being negatively affected by any contamination. ■

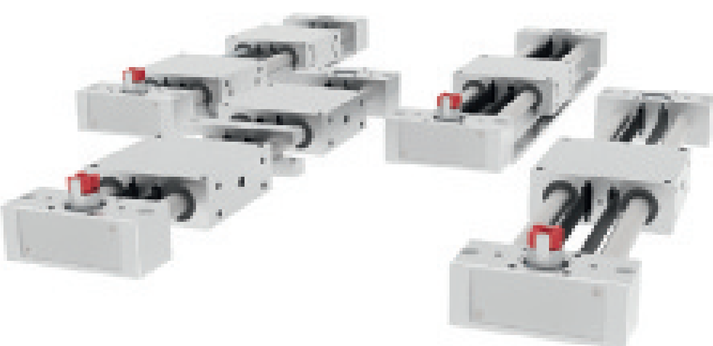
WWW.HEIDENHAIN.NL

### Stamhuis Lineairtechniek
## KS toothed belt systems

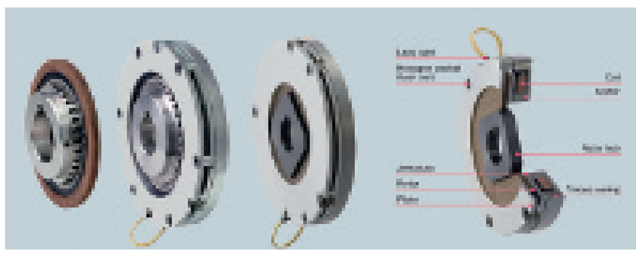
Stamhuis Lineairtechniek presents new KS toothed belt systems for the OEM market. The KS technology is based on the well-known ball bushing guide combined with a toothed belt drive, for which high-end HTD toothed belts with steel insert are used. These systems are particularly suited for very short cycle times and high-accuracy repeatability, as required for packaging and production machines.

The KS toothed belt systems are characterised by high-dynamic behaviour and their accuracies are within 0.2 mm (positioning) and 0.1 mm (repeatability), respectively. Lengths range up to 1,000 mm (stroke), 2,000 mm (with central support) and 3,000 mm (with axial support). The standard system comprises one carriage and, optionally, two carriages (either left-right driven or one driven, one free) are available. A stainless steel version can be fitted according to customer specification on request. ■

WWW.STAMHUISLINEAIR.NL



### Ammertech
## Space- and energy-saving spring-actuated brakes



Ammertech, an independent importer of bearings, power transmissions and couplings since 1978, recently expanded its product range to include brakes from Miki Pulley, a Japanese manufacturer of motion control and power transmission equipment. The spring-actuated BXR type brake model is an electro-magnetic brake actuated by spring force in the non-energised state that is used for retention and panic braking.

The ultra-slim design of the brake, featuring the same high torque, provides space savings and allows the engineer to design within smaller dimensions. The brake is best suited to embedding into a servo motor or robot due to low idle abrasion and low inertia achieved by utilising the light-weight rotor.

Miki Pulley BXR brakes are specifically designed for high accuracy. They have two different types of connections between the hub and the rotor plate, namely, the square hub and the spline hub. Both aim to reduce backlash to an absolute minimum. With the spline hub, backlash values as low as 0.2° can be achieved. ■

WWW.AMMERTECH.NL

## SIOS Meßtechnik
# Calibration interferometer for 5-DoF measurements

SIOS presents the new calibration interferometer SP 15000 C5, with a length measuring range of at least 15 m. It is designed for high-accuracy linear, angular and straightness calibrations on positioning axes, making synchronous and continuous 5-DoF (degrees of freedom) measurements possible, with horizontal and vertical straightness components measured by pivotable optics. A 90° beam deflection also makes it possible to measure vertical axes.

The angular resolution is 0.01 arcsec on a pitch and a yaw angular range of –5° to +5° while the length resolution is 0.1 nm. Straightness measurements are possible over a range of –4 mm to +4 mm with a resolution of 10 nm in an axial zone of 6.5 m.

Applications of these calibration interferometers are the simultaneous acquisition of five DoFs on guides and rails and the calibration of high-precision axes, machine tools and coordinate measuring machines as well. Easy handling and simultaneous multi-DoF measurement lead to significant time savings associated with improved metrological parameters compared to conventional methods. ■

WWW.SIOS.DE

## PM-Bearings
# PMMR micro roller tables

PM-Bearings presents a new generation of micro roller tables, the PMMR type, providing an accurate positioning solution within the smallest dimensions. Manipulators, precision metrology systems and micro-assembly machines are typical applications where precision, tight tolerances and available space are critical.

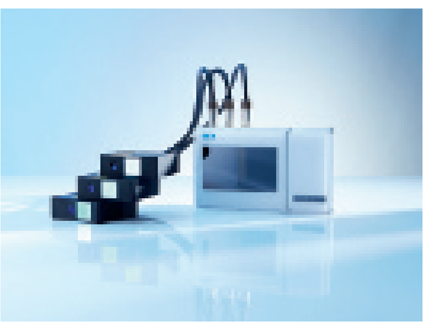
The smallest PMMR version measures only 7 x 4 x 10 mm$^3$ and weighs only 3 g, but it can easily move up to 10 kg without play. At lower loads this yields a longer lifetime. Another advantage of a cylinder roller bearing compared to a ball bearing is 40% higher stiffness.

The PMMR comes in three sizes, with lengths ranging from 10 to 80 mm, strokes from 5 to 70 mm and $C_{dyn}$ from 110 to 1,020 N, and they can operate at a maximum speed of 2 m/s and accelerations of up to 200 m/s$^2$. The PMMR micro roller tables are suitable for cleanroom and vacuum environments. Specific customer design modifications are available on request. ■

WWW.PMBEARINGS.NL

## SICK
# OD Precision optical measuring system

SICK presents its latest developments in the area of measuring and positioning, including the OD Precision, featuring high accuracy, linearity, the finest of resolutions and material-optimised measurement algorithms. Sensor head variants for differing measurement ranges allow µm-accurate measurements of height profiles and material thicknesses (e.g. of glass) in numerous tasks. This also applies for high-speed applications, as the OD Precision achieves measurement and output rates of up to 10 kHz.



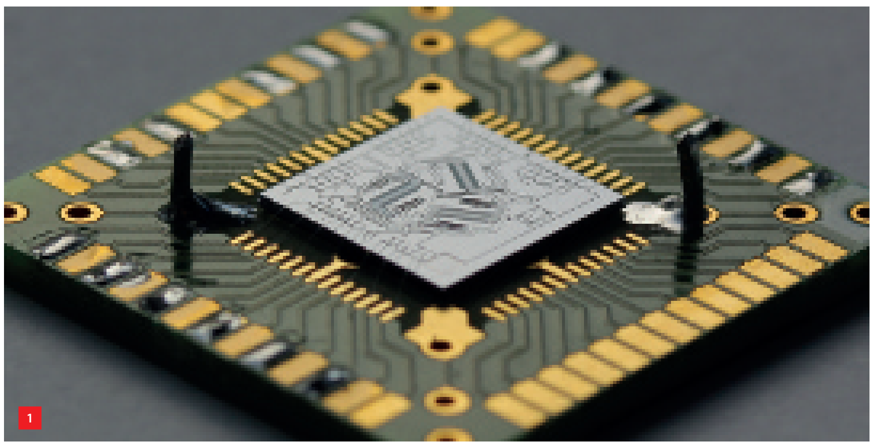
The OD Precision series offers a total of eight sensor head variants for five different measurement ranges, from the close-range version (24 - 26 mm) to the long-range design (300 - 700 mm). The sensor heads for the shorter measurement distances are available with an extremely small or a wide light spot. The use of a wide light spot ensures balancing over a larger area and eliminates possible interfering factors such as surface scratches. Another highlight of the OD Precision is its glass thickness measurement, for which the system only requires a single sensor head. ■

WWW.SICK.NL

# ACCURATE SMALL-SCALE MANIPULATION

**A 3-DoF micro-electromechanical (MEMS) stage has been designed with an innovative integrated feedback system based on thermal sensors. The stage is integrated in the device layer of a silicon-on-insulator-wafer, which means that no assembly is required and the stage can be fabricated using only a single mask. The range of motion is over 160 μm in two directions and 325 mrad of rotation, which exceeds the range of motion of existing MEMS stages by far.**

BRAM KRIJNEN, KOEN SWINKELS, DANNIS BROUWER, LEON ABELMANN AND JUST HERDER



1 *One of the fabricated 3-DoF MEMS stages. The device is wire-bonded to a printed circuit board for electrical connection. The die has a size of 8x8 mm² and the positioning stage fits on a wafer surface area of only 6x6 mm².*

From the 1980s on there has been a strong increase in the number of applications that use actuation or sensing based on micro-electromechanical systems (MEMS). One of the first examples is an accelerometer integrated in IC technology. Many applications have been reported since, such as digital micromirror devices for projectors, pressure sensors, gyroscopes, and flow sensors [1] [ 2]. Due to their small size and low cost, MEMS are also becoming increasingly popular in consumer products, for example in the Nintendo Wii for motion sensing, in digital cameras for image stabilisation, and in smartphones for sports tracking and navigation. MEMS are all around us, nowadays.

MEMS applications do not only benefit from their small volume and low cost, they can also provide superior performance. By scaling down from the macro- to the microscale, the mass of structures ($m \sim r^3$) decreases more rapidly than their stiffness ($k \sim r$), which inherently means a higher eigenfrequency and a faster response time. This opens up a range of interesting applications for MEMS-based positioning stages.

Here, the design, fabrication, and experimental evaluation of a miniature planar positioning stage with integrated feedback (Figure 1) are presented. The complete system has a wafer surface area of only 6x6 mm² and is able to position an end-effector with an in-plane range of motion of 160 μm in *x*- and *y*-direction and a rotation of 325 mrad.

Stage motion with three DoFs (degrees of freedom) is realised by means of an eccentric connection of three single-DoF shuttles using leaf springs (Figure 2). The positions of the single-DoF shuttles determine the position and rotation

**AUTHORS' NOTE**

Bram Krijnen is a mechatronic systems engineer at Demcon in Enschede, the Netherlands. The work presented here is part of his Ph.D. work (2014) at the University of Twente (UT), the Netherlands. Part of this work was laid down at the UT in the M.Sc. thesis (2012) of Koen Swinkels; he is currently starting his own company, focussed on web-based interactive learning. Dannis Brouwer is associate professor in the Mechanical Automation and Mechatronics group at the UT. Leon Abelmann is research group leader in the field of nanotechnology and magnetism at the Korean Institute of Science and Technology in Saarbrücken, Germany, and professor at the UT and at the Saarland University, Germany. Just Herder is professor at Delft University of Technology, the Netherlands, and at the UT in the field of interactive mechanisms, mechatronics and robotics.

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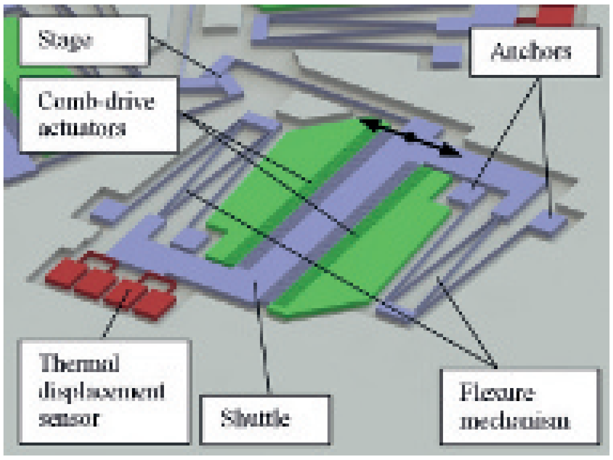


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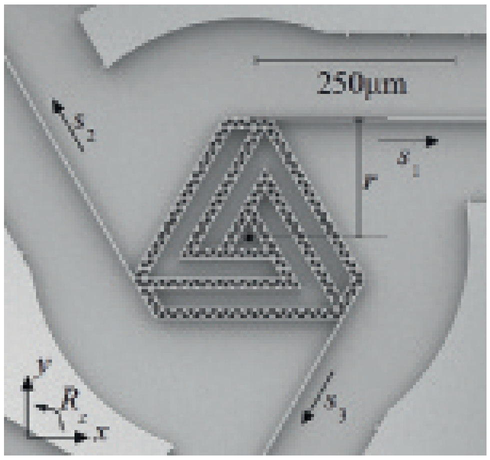



3

of the 3-DoF stage. The single-DoF shuttles each consist of two electrostatic actuators, two flexure mechanisms and a position sensor for feedback. Actuation is provided by electrostatic comb-drives which are straight-guided by flexure mechanisms. Two flexures are used to prevent rotation of the shuttle [3]. Since a comb-drive actuator can only apply an attractive force, two comb-drives are used per shuttle, to enable motion in opposite directions. The position of each shuttle is measured by a thermal displacement sensor [4] [5].

The sensor consists of two heaters that are resistively heated. Heat is conducted through air towards the 'cold' shuttle. Therefore, the temperature of the heaters changes when the overlap changes and thus the stage position changes. This results in a measurable change in the electrical resistance of the heaters, due to the PTC (positive temperature coefficient) effect in silicon.

## Geometry and pull-in

Control of the position of the 3-DoF stage by position control of the three shuttles requires kinematic mapping between the shuttles and the stage. Taking the eccentricity $r$ into account, the positions of the three shuttles ($s_1$, $s_2$, and $s_3$) exactly define the position of the stage in $x$, $y$, and $R_z$ (Figure 3). The matrix that defines the kinematic relation between the shuttle and the stage is called the geometric transfer function, GTF. A linearised GTF around the neutral position can be given analytically:

$$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} = \mathrm{GTF}_{1A} \cdot \begin{bmatrix} x \\ y \\ R_z \end{bmatrix}$$

$$\mathrm{GTF}_{1A} = \begin{bmatrix} 1 & 0 & -r \\ -1/2 & 1/2\sqrt{3} & -r \\ -1/2 & -1/2\sqrt{3} & -r \end{bmatrix}$$

2 *One of the shuttles connected to the 3-DoF stage. Each shuttle is suspended by two double tilted-beam flexures to constrain its movement to a line. The shuttle is actuated by electrostatic comb-drives and the shuttle position is measured by a thermal displacement sensor.*

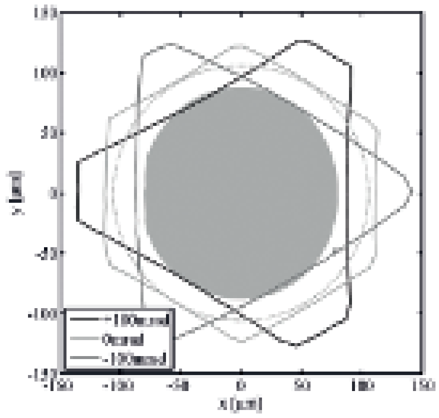
3 *A scanning electron microscope (SEM) image of one of the fabricated stages. Three equal shuttles are eccentrically connected to the stage with eccentricity r. The positions of the three shuttles $s_1$, $s_2$ and $s_3$ uniquely define the position of the stage in x and y and rotation $R_z$*

For large deflections from the neutral position the stage position will no longer behave as a linear function of the shuttle positions. A multi-body model in SPACAR [6] was used to determine the non-linear GTFs of higher order numerically. A wide range of forces was applied to the shuttles; the resulting set of shuttle and stage displacements was used as input for a least-squares curve-fitting algorithm to determine the GTFs and their inverses. For this, the Matlab function *mldivide()* was used. The second-order numerical GTF, for example, has a matrix size of 3x9:

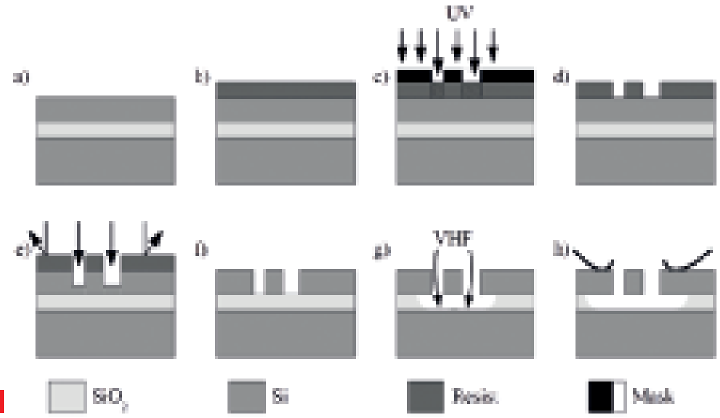
$$\begin{bmatrix} s_1 \\ s_2 \\ s_3 \end{bmatrix} = \mathrm{GTF}_{2N} \cdot \begin{bmatrix} x \\ y \\ R_z \\ x^2 \\ y^2 \\ R_z^2 \\ xy \\ xR_z \\ yR_z \end{bmatrix}$$

Using a GTF of order 4 instead of 1 allows to reduce the error between actual and approximated stage position roughly by a factor of 100, to less than 50 nm and less than 2 mrad for all stage displacements below ±100 µm and all stage rotations below ±450 mrad. Since the complete system is a well-constrained flexure-based design, the device is expected to act repeatably. Determination of the (higher-order) GTFs of the actual devices should enable the reduction of the stage position errors in a similar way.

The major problem that limits the displacement of electrostatically actuated stages is pull-in. Pull-in is the instability that occurs when the lateral electrostatic forces due to the application of an actuation voltage cannot be compensated by the lateral stiffness of the finger or flexure mechanism. This effect can play a role in individual fingers and in entire flexure mechanisms. Both cases are often destructive to the device and need to be avoided.



4 *The range of motion of the 3-DoF stage for zero and +/–100 mrad rotation. The dash-dotted circle is the largest circle that fits in the hexagon at zero rotation; the radius of this circle is called the stroke (106 μm). The filled area shows the positions that have been reached experimentally at zero rotation.*




5 *A schematic overview of the fabrication process based on an SOI wafer. The top silicon layer (Si) is structured by DRIE, the insulator layer ($SiO_2$) is etched by VHF. See the text for the complete list of process steps.*

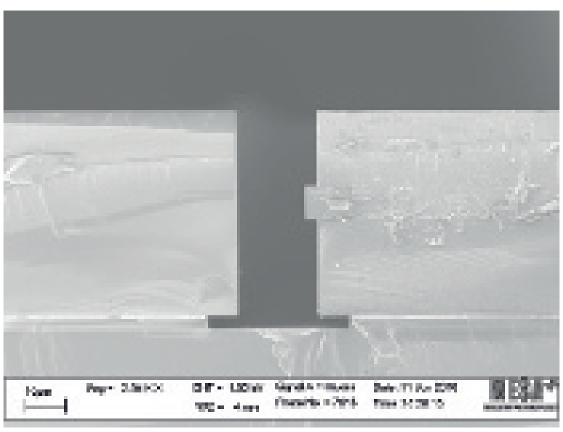
Finger pull-in can be quite easily avoided by choosing more or thicker comb-drive fingers. Choosing a flexure mechanism is a tougher challenge, since it requires a) a low actuation stiffness, b) a high lateral stiffness in neutral and deflected state, and c) a good approximation of a straight line to avoid asymmetrical electrostatic forces. A double parallelogram flexure (a 'folded flexure') typically gives a good straight-line approximation and low actuation stiffness, but suffers from a large drop in lateral stiffness when deflected. Tilting the beams of the folded flexure slightly inwards constrains the DoF of the intermediate body, which directly results in a higher lateral stiffness at large deflections: the 'tilted folded flexure'.

SPACAR was used to calculate the range of motion of single-DoF shuttles and the complete 3-DoF stage [7]. Electrostatic forces were included in these models. For a 3-DoF stage the range of motion is roughly given by a hexagon (Figure 4); each edge is determined by pull-in of one of the electrostatic actuators. When an additional rotation of the stage is required, the range of motion of the stage becomes more asymmetrical. The largest circle that can be fitted in the hexagon at a specified stage rotation is called the stroke. At zero rotation the stage has a stroke of 106 μm, for a rotation of 100 mrad this reduces to 84 μm.

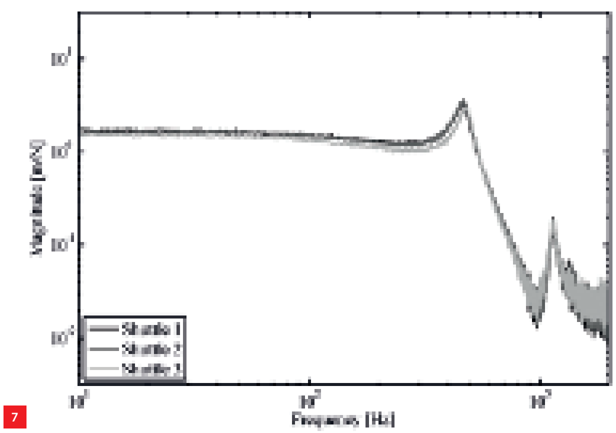
## Single-mask fabrication

The 3-DoF stages were fabricated in a silicon-on-insulator (SOI) wafer. An SOI wafer consists of three layers: a thick substrate layer, a thin intermediate oxide layer for insulation, and a top single-crystal silicon device layer. The device layer is typically processed to create the desired structures. The process steps are:

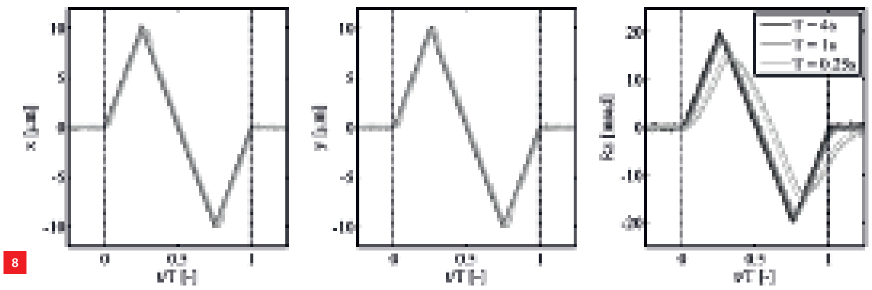
a. The starting point is an SOI wafer.
b. Photoresist is applied by spin coating and baking.
c. A mask is prepared by laser writing and the photoresist is exposed to UV light through the mask.
d. The photoresist is developed.
e. Directional deep reactive-ion etching (DRIE) is used for structuring of the silicon device layer.
f. The remaining photoresist is removed.
g. Vapour-phase hydrofluoric acid (VHF) is used for isotropic etching of the buried oxide layer ($SiO_2$).
h. Before use, the devices need to be diced, wire-bonded and packaged.



6 *SEM image of the cross-section of a fabricated device, clearly showing the result of the directional DRIE and isotropic VHF etching. The additional protrusion on the vertical edge is probably a splinter as a result of breaking the wafer.*




7 *Identification of the 3-DoF stage in the frequency domain. The first resonance frequencies of the shuttles (~470 Hz) and the $R_z$ mode (1,144 Hz) can be distinguished.*



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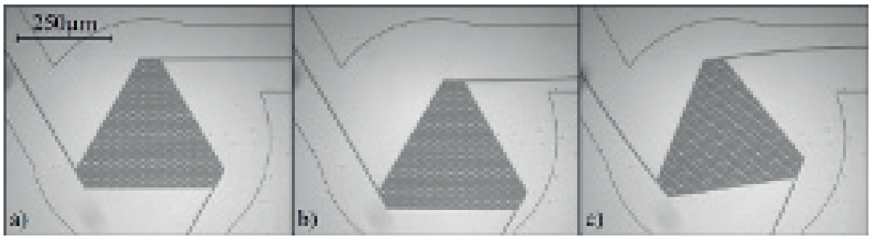


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8 *A motion profile in x, y, and $R_z$ with different speeds provided as a setpoint to the control loop. Control of the stage rotation is slower, since the equivalent stiffness is higher. The stage response is given by dashed lines (simulated) and continuous lines (measured), respectively.*

9 *The stage in various positions. The displacement and the rotation of the stage were determined by video analysis.*
*(a) Neutral position.*
*(b) Deflected position (displacement x = +60 µm, y = −60 µm).*
*(c) Rotated position ($R_z$ = +160 mrad).*

These steps correspond to the schematic process overview in Figure 5.

In this case the device layer had a thickness of 25 µm, which is therefore also the height of the devices. Lithography followed by DRIE limits the minimum feature size and minimum trench width of the design to 3 µm. An aspect ratio of 3:25 is safe for directional DRIE. VHF etching of the buried oxide layer was used to release thin and perforated structures from the substrate. The cross-section of a fabricated device in Figure 6 shows the result of the directional DRIE and isotropic VHF etching.

## Closed-loop positioning

For achieving stable position control of the 3-DoF stage, the system was identified in the frequency domain. White noise was applied to the input of the comb-drive actuators of each shuttle and the sensor response of the corresponding shuttle was measured; the frequency responses from shuttle force to shuttle position are shown in Figure 7.

For giving the frequency response a physical meaning, the actuation voltage is converted to the actuation force ([N]) and the sensor voltage is converted to the shuttle displacement ([m]). Using this transformation, the horizontal line at low frequencies is the inverse of the mechanical stiffness of the shuttles. The stiffness of the shuttles was 0.6 N/m and the first resonance frequencies of 470 Hz correspond to the decoupled modes in $x$ and $y$. The resonance frequency of 1,144 Hz was found in the identification of each shuttle – it corresponds to the $R_z$ mode of the system, in which the stage shows a pure rotation caused by equal translations of the shuttles.

Controllers with only an integral action were used for position control of the shuttles to eliminate the static error. The cross-over frequency was set to 25 Hz and a first-order motion profile was applied as a setpoint for the controllers. The resulting stage motion was a pure motion in $x$, $y$, and $R_z$ of the stage, demonstrating stable control by controlling the positions of the three shuttles. Reduction of the period from 4 s to 0.25 s clearly shows that the rotational movement has a higher stiffness and thus the closed-loop rotational motion shows a larger servo error (Figure 8).

The stroke of the 3-DoF stage was determined by describing circles with increasing radius in the $xy$-plane. Pure rotations were also applied. The 3-DoF stage was able to reach a stroke of 161 µm in $x$, 175 µm in $y$, and a rotation of 325 mrad. An image of the stage in neutral, deflected, and rotated position is given in Figure 9. Since the measurement of the actual pull-in stroke is probably destructive, measurements were stopped at approximately 80% of the expected range of motion.

## Asymmetry

Theoretically, the stroke in $x$ and $y$ should be equal, but in practice there is a deviation in the leaf spring thickness as a function of the leaf spring angle on the wafer surface. This results in a different stiffness in $x$- and $y$-direction and hence an asymmetric stroke. This deviation was not corrected for during this measurement.

Anyhow, the range of motion of over 160 µm in two directions and 325 mrad of rotation exceeds that of existing MEMS stages by far. ■

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*We have not been able to participate in the Precisie Fair due to lack of space.*

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BRECON GROUP - IF THE RIGHT CONDITIONS ARE CRUCIAL

# UPCOMING **EVENTS**

**1-6 November 2015, Austin (TX, USA)**
### 30th ASPE Annual Meeting
Meeting of the American Society for Precision Engineering, introducing new concepts, processes, equipment, and products while highlighting recent advances in precision measurement, design, control, and fabrication.

ASPE.NET

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**2-6 November 2015, Leiden (NL)**
### LiS Academy Summer School Manufacturability
Summer school targeted at young professional engineers with a limited knowledge of and experiences with manufacturing technologies and associated manufacturability aspects.

WWW.LISACADEMY.NL

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**18-19 November 2015, Veldhoven (NL)**
### Precision Fair 2015
Fifteenth edition of the Benelux premier trade fair and conference on precision engineering, organised by Mikrocentrum. Some 300 specialised companies and knowledge institutions will be exhibiting in a wide array of fields, including optics, photonics, calibration, linear technology, materials, measuring equipment, micro-assembly, micro-connection, motion control, surface treatment, packaging, piezo technology, precision tools, precision processing, sensor technology, software and vision systems. Read the preview on page 13 ff. The fair features ceremonies for the Rien Koster Award (Wednesday 18 November) and the Wim van der Hoek Award (Thursday 19 November), which are both organised by DSPE.

Precision Fair 2015

WWW.PRECISIEBEURS.NL

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**19 November 2015, Veldhoven (NL)**
### DSPE/euspen Symposium
About a year ago euspen (European Society for Precision Engineering) approached DSPE to propose collaboration in order to expand the Dutch certification program for commercially available precision engineering courses to the European level. Now they jointly organise a symposium during the second day of the 2015 Precision Fair.
The title of the symposium, aimed at precision engineers and their (HR) managers, is: "Post-graduate education in precision engineering – Today and tomorrow". Speakers will include David Billington (Executive Director of euspen), Jan Willem Martens (Chairman of the DSPE Certification Program) and HR managers from high-tech companies, sharing their views on post-graduate compentence development needs. See also page 37.

WWW.DSPE.NL

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**24-26 November 2015, Teddington (UK)**
### Topical Meeting: Micro/Nano Manufacturing Workshop
Workshop at the National Physical Laboratory, organised by euspen and supported by the EMRP Joint Research Project "Multi-sensor metrology for microparts in innovative industrial products". Contributions are expected from METAS, PTB, LNE and NPL.

WWW.EUSPEN.EU

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**25 November 2015, Utrecht (NL)**
### Dutch Industrial Suppliers Awards 2015
Event organised by Link Magazine, with awards for best knowledge supplier and best logistics supplier, and the Best Customer Award.

WWW.LINKMAGAZINE.NL

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**1 December 2015, Hilvarenbeek (NL)**
### Motion & Drives 2015
New theme day organised by Mikrocentrum. Motto: "Your motion in control".

WWW.MIKROCENTRUM.NL

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**8-9 December 2015, Amsterdam (NL)**
### International MicroNanoConference 2015
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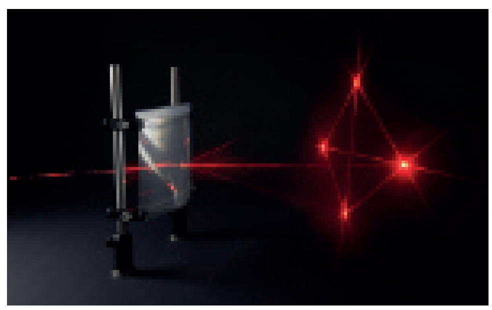

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# STAYING ALIGNED WHEN MEASURING GRAVITATIONAL WAVES

**An active mirror mechanism to correct for seasonal alignment errors of the evolved Laser Interferometer Space Antenna (eLISA), a future ESA space mission meant to accurately detect gravitational waves, has been designed, realised and tested by TNO. The mechanism is supposed to move ±2.5° in a whole year with extreme accuracy. The design utilises Haberland hinges and piezostepper actuators, and yields satisfactory frequency-domain open-loop performance. A closed-loop controller design based on the measured dynamics complies with the requirement of just 5 nrad/√Hz of jitter on the mirror angle.**

GERT WITVOET AND JET HUMAN

## Introduction

Nearly a century ago, in 1916, Albert Einstein predicted the existence of tiny ripples in the shape of space-time, which would propagate as waves. Although there is evidence for their existence, these gravitational waves have never been measured directly. The evolved Laser Interferometer Space Antenna (eLISA) [1] from the European Space Agency (ESA), tentatively scheduled for launch in 2034, is meant to change all that.

eLISA will consist of three spacecraft flying in a triangular formation mutually $10^9$ m apart in an earth-like orbit around the sun, each carrying a free-flying proof mass. A passing gravitational wave will slightly disturb the distances between the masses; eLISA will have to measure these distances with an extreme accuracy in the order of $10^{-11}$ m for successful detection of the wave.

Needless to say, the eLISA mission still faces scientific and technological challenges to be solved, one of which is constellation breathing. While orbiting the sun the mutual orientation of the spacecraft will vary, hence the angle between the eLISA arms slightly changes over a period of a year. In the Telescope Pointing (TP) concept this is accounted for by rotating each of the six complete optical assemblies (two on each spacecraft).

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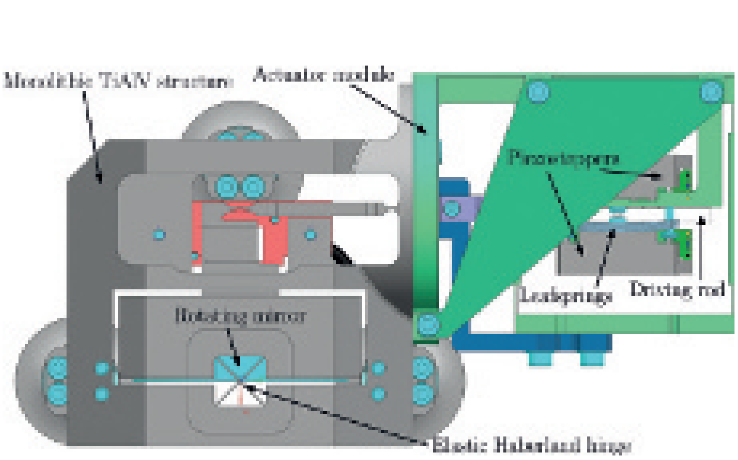
As a promising alternative, Airbus Defence & Space (Airbus DS) has developed the In-Field Pointing (IFP) concept [2], in which only a small tilt mirror, located in an intermediate pupil plane of the telescope, provides the means to steer the beam. Compared to TP, the IFP concept has several advantages, since it comes with actuation of a much smaller mass, and possibly allows smaller payload sizes and simpler payload architectures [2] [3].

The feasibility of the IFP concept will be demonstrated in an experiment that Airbus DS is currently developing [3]. The In-Field Pointing Mechanism (IFPM), responsible for actuating the tilt mirror, is one of the critical components in this experiment. TNO carried out the design and realisation of this IFPM, on which there are high stability requirements. In this design TNO has built upon earlier eLISA heritage with the Fibre Switching Unit Actuator (FSUA) and the Point-Ahead Angle Mechanism (PAAM) [4] [5], which had similar stability requirements, and successful breadboard tests with the IFPM actuation principle [6].

Here, the IFPM design and realisation will be discussed, together with some first test results (in a normal laboratory environment). Up to what is reasonably measurable in such a lab environment, the results show that the IFPM is indeed compliant with the requirements.



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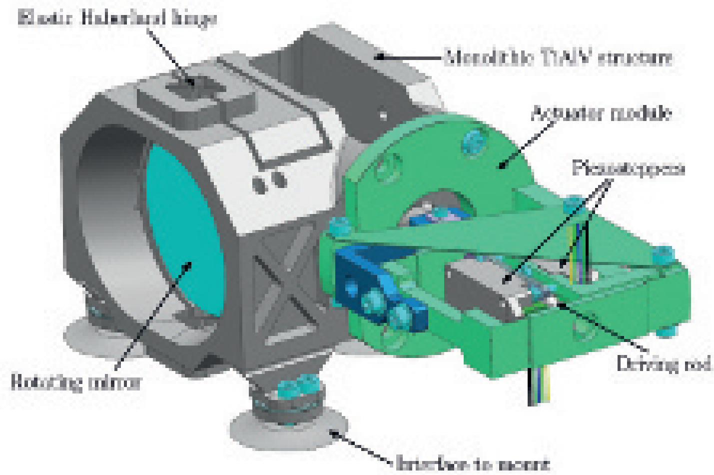

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## Hardware design and realisation

The heart of the IFPM is a 50 mm flat tilt mirror, which needs to rotate ±2.5° in a whole year (equivalent to ±5° beam pointing) to accommodate for the above described constellation breathing. When eLISA is performing scientific measurements (science mode), the mirror should rotate with 12.5 nrad/s, with a maximum jitter of just 5 nrad/√Hz over a large frequency range. This combination of relatively large stroke and high accuracy requires the dynamic range of the IFPM to be in the order of $10^7$ [2]. Moreover, the mirror is not allowed to introduce more than 3 pm/√Hz of noise on the optical path length of the beam.

### *Design concept*

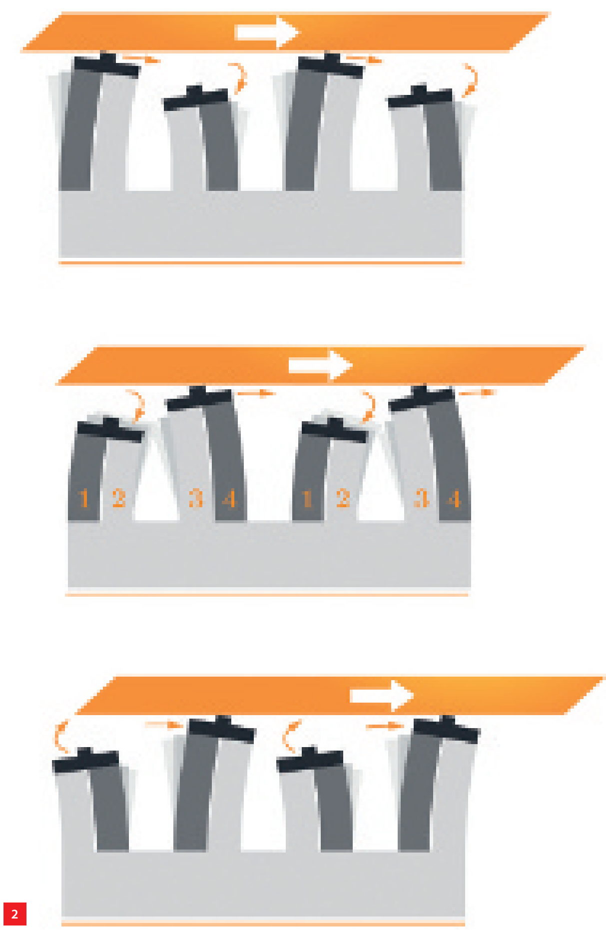
In the IFPM design, illustrated in the CAD drawings of Figure 1, the rotation of the mirror is guided by two Haberland hinges, which are part of a single monolithic TiAlV structure. Their axis of rotation coincides with the mirror surface, thereby minimising the cross-coupling between the angular motion and optical path-length variations. The mirror is connected to a translational actuator module via a stiff lever through the mirror rotation axis; this way the actuation force acts parallel to the mirror surface, which minimises surface distortions.

Since the free-flying proof masses in eLISA should be free of any parasitic force, no electromagnetic forces are allowed on the optical bench, and hence the actuation possibilities are limited for IFPM. A trade-off study eventually led to the choice of a piezostepper concept, and after some successful breadboard tests [6] the Piezo LEGS walking actuator by PiezoMotor Uppsala was selected.

1 *CAD model of the latest IFPM design.*
*(a) Top view.*
*(b) Side view.*

2 *Operating principle of the walking piezo-actuator. Due to the ellipsoidal movement of the tip of the legs, the ceramic rod moves in horizontal direction. The numbers indicate the phases; same-phase piezos are fed with the same voltage. (Image courtesy of PiezoMotor)*

The operating principle of this walking piezo-actuator is illustrated in Figure 2. Each actuator encompasses two sets of legs (depicted are two times two legs, the used piezostepper has two times three legs), where each leg consists of two pieces of piezo-electric material with a



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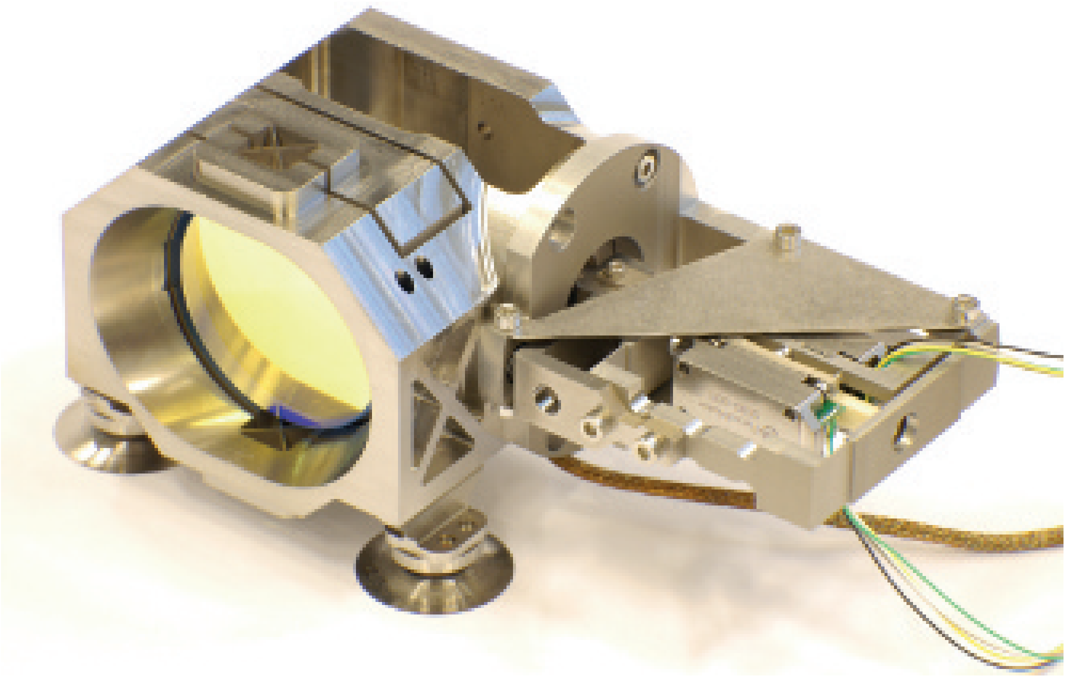


3 *The realised two-stepper IFPM. Photo: TNO / Gert Witvoet.*

ceramic tip. By applying different voltages to each piezo the legs will elongate and bend. A proper choice of the four driving voltages (phases) then causes an ellipsoidal movement of the tips of the legs, thereby creating a walking motion. As a result, a ceramic driving rod pushed against the legs with the right preload will move in horizontal direction.

The piezostepper principle is friction-based and thus relatively stiff, while providing tens of Newtons of holding force. The stroke is only limited by the length of the driving rod, and is thus in principle infinite; the step size is only limited by the resolution of the digital-to-analog (D/A) converter generating the voltages for the legs, and can thus be in the order of 0.1 nm or less (one full actuator cycle is typically a few µm). As such, the complete IFPM assembly utilises a hard actuator concept, which is both accurate, and stiff enough to potentially withstand launch loads.

### *Design improvements*

The initial IFPM design [6] had an actuator module in which three of such piezosteppers were combined in a triangular orientation, pushing against a triangular driving rod. The choice for three steppers was partly motivated by launch load and redundancy considerations, and partly to combine the guidance of the driving rod and preloading of the piezosteppers in one single component. However, thorough testing of this module showed that the nominal preload on the piezosteppers was too high and the distribution of the preload over the different legs was very uneven. It turned out that the performance of the actuator is very sensitive to such preload deficiencies, causing unreproducible erratic open-loop motion.

It was therefore decided to redesign the actuator module to a two-stepper concept. In this planar configuration, shown in Figure 1, two piezosteppers are pushed on either side of a rectangular driving rod; the preload distribution along the legs is now much better defined and is tunable via the bolts through the leafsprings with which one of the piezosteppers is connected to the actuator module.

### *Realisation*

The updated actuator module has been manufactured and assembled, and combined with the previously realised mirror unit. The complete IFPM assembly is shown in Figure 3.

The set-up has been tested under normal laboratory conditions (room temperature, atmospheric pressure). In these tests the mirror rotation has been measured directly via a Renishaw differential interferometer. Both the reference and measurement beam are directed at the mirror; the mirror angle is calculated using the distance between the beams and their optical path-length difference.

The mechanism is also equipped with a Micro-E incremental encoder and a 20 µm pitch scale, located at a radius of 31.06 mm from the mirror rotation axis. This sensor has a 1.2 nm resolution, which is thus equivalent to 38.6 nrad of mirror rotation. The encoder is used as a feedback sensor.

The piezosteppers are fed by four high-voltage space-qualified analog Cedrat amplifiers, one for each of the four phases of the actuators. The voltage waveforms are generated by a dSpace data-acquisition system with a 16-bit D/A converter; the encoder (via a 24-bit digital encoder interface) and the interferometer (via a 16-bit A/D converter) are connected to the same dSpace system. This system offers a rapid prototyping environment in Matlab/Simulink, which provides great flexibility in measurement possibilities and controller design.

## System performance

The motion of the legs of the walking actuator is determined by the voltage distribution along the four phases as a function of time. Although the open-loop motion will never be perfectly linear, the exact shape of these voltage waveforms has a large influence on the velocity variations during an actuator cycle [7]. Pure sinusoidal waveforms are known to exhibit zero velocity at the transfer points (i.e., when one set of legs takes over from the other), which is undesirable from a performance point-of-view. Therefore, so-called asymmetric waveforms [8] have been used, where the voltage of the first phase is defined between 0 and the maximum $A$ (here 48 V) as:

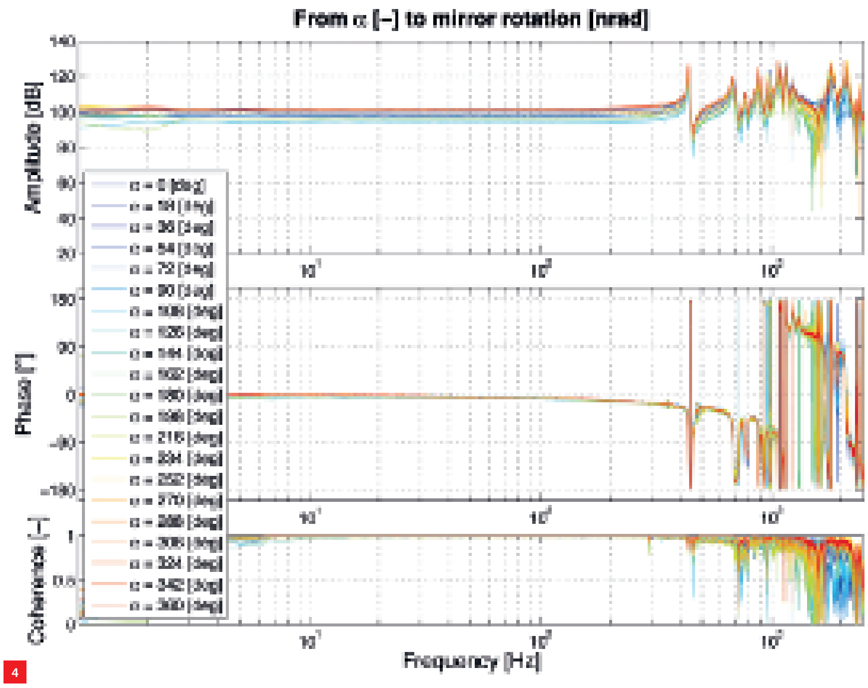
$$u_1(t) = \begin{cases} \frac{1}{2}A + \frac{1}{2}A\sin\left(2\pi\frac{\alpha(t)}{2q}\right), & \alpha(t) \in [0, q] \\ \frac{1}{2}A + \frac{1}{2}A\sin\left(2\pi\frac{\alpha(t)-1}{2(1-q)}\right), & \alpha(t) \in [q, 1] \end{cases}$$

The other three phases are shifted 90°, 180° and 270°. The actuator phase $\alpha(t)$ denotes a specific moment in the waveform cycle, and $0 < q < 1$ is the asymmetry factor where $q = 0.5$ is a pure sine wave. After some open-loop testing, $q = 0.6$ has been chosen, since this value returned the smallest velocity variations during a complete waveform cycle.

### *Frequency response function measurements*

To characterise the IFPM behaviour local frequency response function (FRF) measurements around various actuator operating points have been taken [9]. To this end, the waveforms have been set at different nominal $\alpha_{\mathrm{nom},k}$ values, around which a small amount of additional noise $\bar{\alpha}(t)$ has been added, resulting in a mirror response $y$. The local dynamics around operating point $k$ were then calculated as the ratio between the cross-power density $S_{y\bar{\alpha}}$ and auto-power density $S_{\bar{\alpha}\bar{\alpha}}$ of the two signals:

$$H_k(j\omega) = \frac{S_{y\bar{\alpha}}(j\omega)}{S_{\bar{\alpha}\bar{\alpha}}(j\omega)}$$




4 *Measured FRFs as a function of the actuator phase α. Note that 360° is equivalent to $\alpha_{nom} = 1$.*

The resulting FRFs for 21 different nominal phases $\alpha_{\mathrm{nom},k}$ along a full actuator cycle are shown in Figure 4.

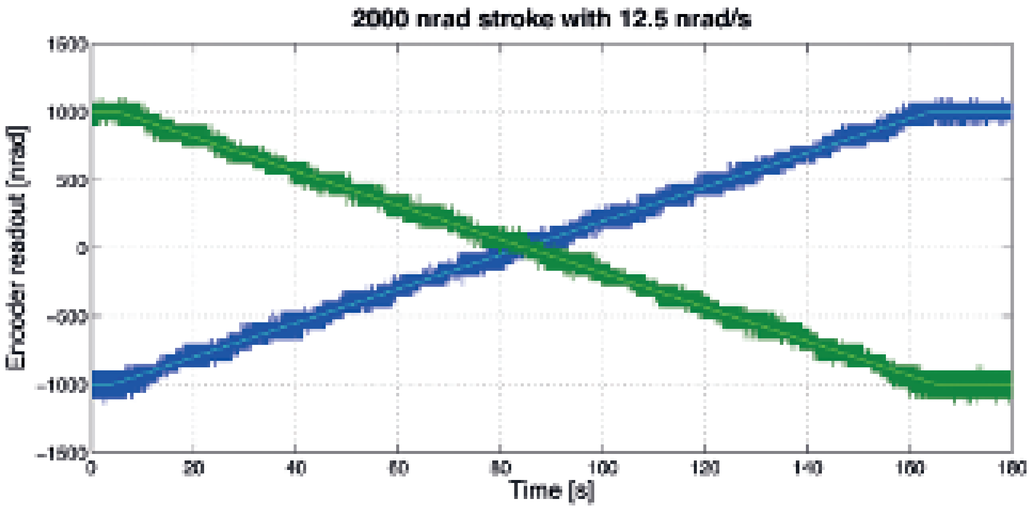
All FRFs show the same resonances and (nearly) the same anti-resonances, which implies that the dynamics are fairly constant over a full actuator cycle. The FRFs only differ in their gain, which is particularly clear for low frequencies. These local DC-gain variations of at most 9 dB can directly be attributed to the non-linear velocity variations in the open-loop motion of the piezosteppers.

### *Closed-loop performance*

The above illustrates that the friction-based Piezo LEGS actuators are not meant to provide accurate open-loop motion, hence, the IFPM has to be operated in closed loop to meet the extreme accuracy requirements.

Since the DC-gain variations along the actuator cycle are relatively small, a fixed linear controller suffices to demonstrate the IFPM performance. The designed controller consists of a PII (proportional, double integral) with a low-pass filter, whose parameters have been carefully tuned based on the measured FRFs in Figure 4. For all local FRFs the controller yields a robustly stable closed loop (55° phase margin and 3.5 dB modulus margin) with a bandwidth between 26 and 62 Hz.

Two closed-loop responses of the IFPM using the required 12.5 nrad/s science-mode velocity, both forward and backward, are shown in Figure 5. The encoder resolution

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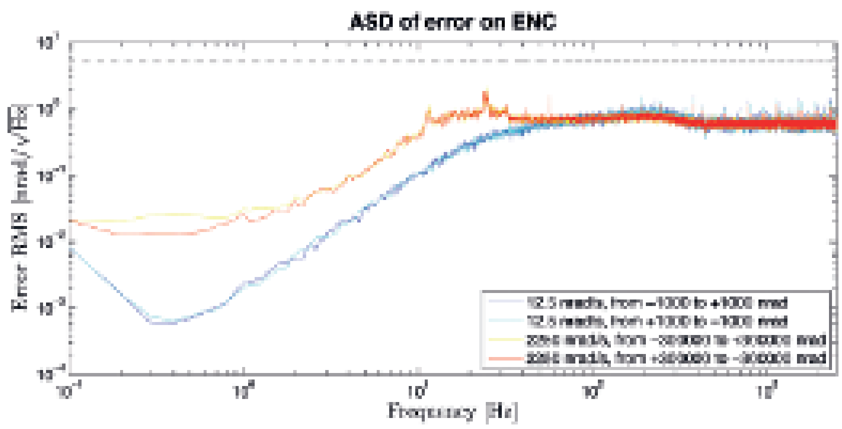
5 *Two closed-loop responses with 12.5 nrad/s mirror rotation (science mode) using the internal encoder as feedback sensor. The setpoints are drawn on top of the measured rotations.*
6 *Amplitude spectral densities of the closed-loop error.*
*(a) Measured by the feedback encoder.*
*(b) Measured by the external interferometer.*

steps are clearly visible in the response, but their effect on the amplitude spectral density (ASD) of the error is very limited, as is shown in the top plot of Figure 6. The latter plot also includes 2,250 nrad/s experiments, which are meant to demonstrate the IFPM behaviour over a much larger stroke where the piezosteppers go through a number of cycles. The dashed line indicates the 5 nrad/√Hz requirement for the jitter on the mirror angle, which is clearly met.

The bottom plot of Figure 6 shows the ASD as measured by the external interferometer during the same experiments. Indeed, for frequencies above 2 Hz this figure confirms compliance. For lower frequencies interferometer measurements are known to be very sensitive to, e.g., temperature variations and turbulence. As such, in a normal unconditioned laboratory environment it is impossible to discriminate between the actual IFPM performance and the drift in the validation measurement. Hence, we conclude that the IFPM is provisionally compliant; future environmental tests to be carried out by Airbus DS in their IFP breadboard set-up should validate its performance for extremely low frequencies.

## Conclusions

The design and realisation of the In-Field Pointing Mechanism for the eLISA mission have been presented. The mechanism encompasses a tilt mirror guided by Haberland hinges, which is actuated by walking piezo actuators in a planar configuration. Apart from relatively low DC-gain variations, the resulting dynamics are nearly constant over a full actuator cycle.

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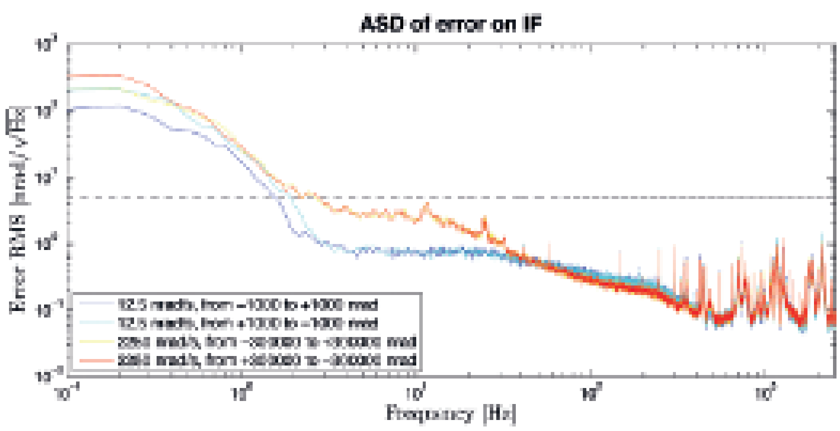


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These dynamics have been taken into account in a robust high-performance controller design. Feedback experiments have demonstrated that the IFPM can indeed be operated with high accuracy, where the resulting ASD proves compliance with the maximum allowed jitter above 2 Hz. Validation of the low-frequent performance will be carried out by Airbus DS in their environmental (vacuum) tests.

## Acknowledgments

The authors would like to thank Dennis Weise, Ewan Fitzsimons and Christina Brugger (Airbus DS) for the fruitful collaboration within the IFPM project, and Per Bendixen (PiezoMotor) for his help on improving the actuator module. ■

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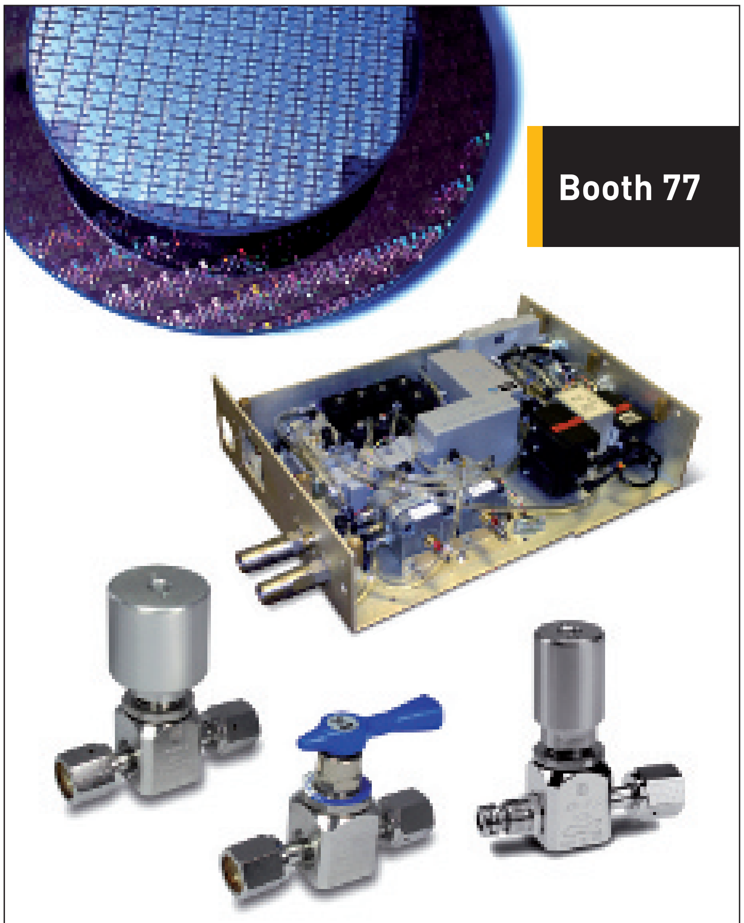


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# SYMPOSIUM PROVIDES SUCCESSFUL KICK-OFF

**Optomechatronics is an important discipline for the precision engineering and high-tech systems industry and "it's very much alive and exciting". That conclusion was drawn at the end of the DSPE Optics and Optomechatronics Symposium 2015 by chairman of the day, Jos Benschop, Senior Vice President Technology at ASML.**

The Symposium kicked off the first DSPE Optics and Optomechatronics Week, from 28 September to 2 October 2015, at Delft University of Technology, the Netherlands. The week, which featured a unique collaboration between Dutch and international organisations, comprised a symposium and two courses, and brought together outstanding speakers and lecturers from semicon to medical, from industry to academia, from Europe and abroad, presenting the latest trends and high-tech details.

The DSPE Optics and Optomechatronics Symposium 2015 was the second edition of the bi-annual event, which started two years ago in Eindhoven, the Netherlands. The target group includes engineers who can learn about the latest developments, managers who can get a quick overview of trends, and sales managers looking for new opportunities. The 2015 edition attracted over 100 attendants (Figure 1).

1 *Impression of the DSPE Optics and Optomechatronics Symposium 2015. (Photos: Sjoerd van Luijn)*

Chairman of the day was Prof. Jos Benschop, Senior Vice President Technology at ASML in Veldhoven, the Netherlands (Figure 2). In his characteristic manner, informal and witty, he introduced the speakers and directed the lively Q&A sessions after the presentations. During the breaks there was an exhibition with companies and knowledge institutes, which provided ample opportunities for knowledge transfer and networking (Figure 3).

## Optical metrology

One of the speakers was Prof. Ralf Bergmann, Managing Director of BIAS (Bremer Institut für angewandte Strahltechnik), based in Bremen, Germany. He talked about optical metrology for micro-parts and demonstrated that this can be performed using LED light sources, which provide a cheap and eye-safe alternative to lasers. The technology can be applied, for instance, in the inspection of micro-electromechanical systems.
Dr. Steven van den Berg, Principal Scientist at VSL, addressed the topic of frequency comb interferometry for absolute distance measurement; read his article on page 5 ff.

## Stable optomechanics

Ir. Ruud Beerens, Senior Architect Opto-Mechanics at ASML, discussed design guidelines for stable opto-mechanics and illustrated these with the design case of an optical position sensor. The stability of optomechanical systems is essential for the performance of ASML's lithography machines and the prevention of damage during their transport. To reduce time-to-market, concurrent engineering is employed, involving a well-structured


engineering process and close collaboration between the various disciplines.

2 *Symposium chairman of the day, Jos Benschop (ASML).*
3 *Impression of the exhibition during the Symposium.*
4 *Daniel Vukobratovich in full swing during his Optomechanics course.*

## High-tech shutter design

In a world full of advanced optomechatronic systems, there is still use for the 'good old' mechanical shutter, for instance in high-tech airborne cameras. That was the message of Dr. Wolfgang Robra, Head of Development at Hittech Prontor, based in Bad Wildbad in the Black Forest, Germany. He talked about light control by mechanical devices and presented the design of a patented system that combines diaphragm and shutter in one blade system, using piezo-actuators and position-controlled blades.

## Digital pathology

Medical technology is an important application area for optomechatronics. Dr. Bas Hulsken, CTO Digital Pathology Solutions at Philips in Eindhoven, presented the case of high-throughput slide scanners for digital pathology. Philips has developed a digital pathology solution designed around the needs of pathologists, such as better working conditions and ease of processing and exchanging data. Digitisation of the images that pathologists normally view through a microscope can enhance the operational efficiency and productivity of pathology departments. Hulsken detailed the challenges of high-speed imaging, and how these were addressed in the Philips slide scanner.

## Other speakers

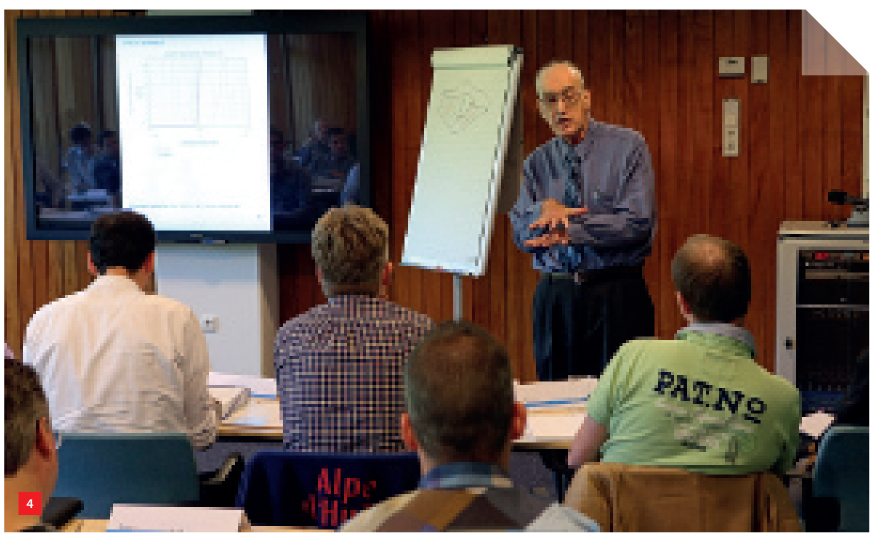
- Rik Jansen, M.Sc. (TNO): "TROPOLITE: An all free form compact imaging spectrometer for hyperspectral earth-observation"
- Dr. Nandini Bhattacharya (TU Delft): "Speckle dynamics to monitor pulsatile flow"
- Dr. Wolfgang Singer (Carl Zeiss): "Perspectives and challenges of Smart Optical Systems"
- Dr. Wenko Süptitz (SPECTARIS): "The top 5 Themes of the Photonics members"

## Courses

The DSPE Optics and Optomechatronics Week comprised two top-class courses. The 2-day Optomechanics course – targeted at (systems) engineers, Ph.D. students and technicians – covered optics and optics mounting alignment, dynamics and thermal or material stability. A wide variety of examples from space, astronomy, defence and industry was used to clarify theory, and many practical analytical tools were presented. The course was delivered by well-known expert Daniel Vukobratovich, Senior Scientist at Raytheon as well as Adjunct Professor in the College of Optical Sciences, University of Arizona, USA (Figure 4).

## Collaboration

The 4-day SMETHODS+ course provided hands-on training in design and optimisation of optical imaging systems supported by a theoretical introduction. This course was developed in a European project by seven academic institutions that are leading in optical design. It exemplified the collaboration, cross-disciplinary by nature, that is needed to foster optomechatronics. ■



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# OCT AND DHM

**Laser precision processing is inherently unstable, examples being chaotic laser-plasma and material interactions, resulting in reduced production. Therefore, a closed-loop control system was developed that is capable of providing feedback control given stochastic variations of the machining process. The system utilises existing metrology technologies (optical coherence tomography, OCT, and digital holographic microscopy, DHM) for the collection of in-situ data that are then used to correct for errors as they occur.**

KAREN YU, MARTIN SPARKES AND WILLIAM O'NEILL

## Introduction

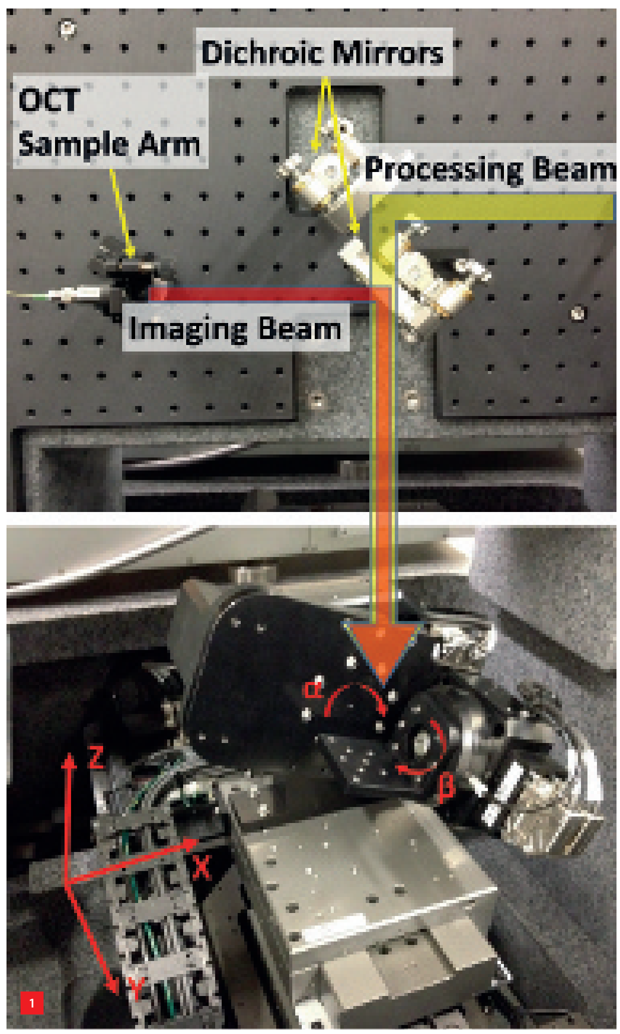
High-precision manufacturing of nano- and micro-sized objects has become increasingly prominent given current technological trends. While traditional macro-manufacturing systems rely on automatic feedback to detect errors and act immediately, this is a more difficult task when scaled down to the submicron scale.

Unlike traditional macromanufacturing processes, micro- and nanomanufacturing do not have *in-situ* feedback and quality control. This lack of monitoring when coupled with the fluctuating machining process of laser ablation results in greater processing times due to the need to regularly check the component using an external device.

One of the projects at the Centre for Industrial Photonics (see the Authors' note) is the creation of an ultra-precision processing system consisting of two levels:

- Initial bulk material removal and component characterisation (ultimately < 100 nm precision).
- High-precision (< 20 nm) finishing using the $Ga^+$ FIB (focused ion beam) technique.

The system described here is the first level of this project, designed for bulk material removal with post-processing mapping to support the FIB and for creation of < 1 μm parts with high throughput. The system utilises two imaging systems: optical coherence tomography (OCT), and digital holographic microscopy (DHM). Table 1 gives the specifications of these systems.




1 *Precision processing platform with integrated OCT imaging.*

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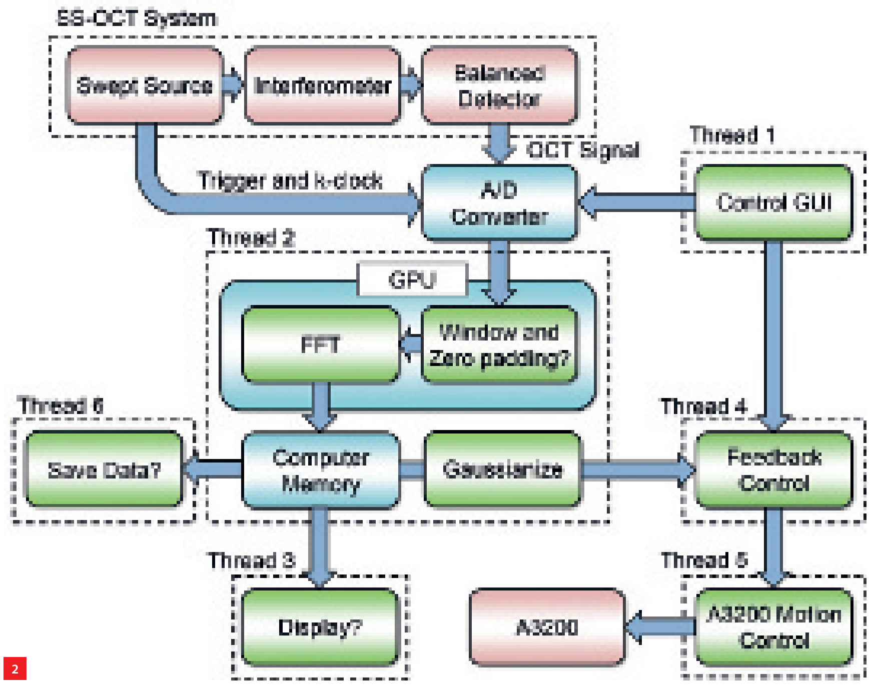


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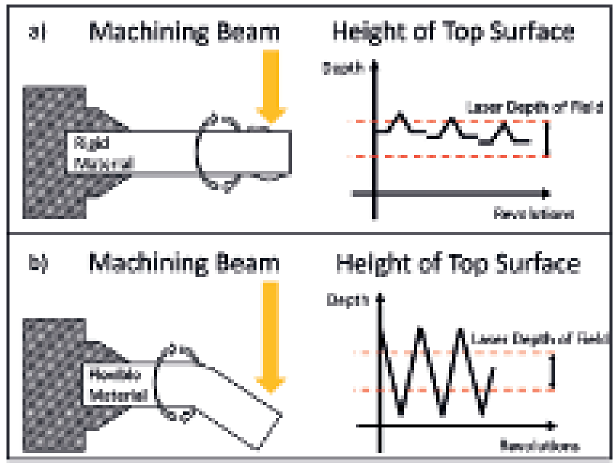


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Figure 1 shows a picture of the OCT imaging system integrated with the processing platform. For the processing laser, the platform can switch between four different wavelengths (355 nm, 535 nm, 1,030 nm, and 1,064 nm) at various repetition rates (< 1 kHz - 2 MHz) and two pulse durations (280 fs and < 15 ps) to optimise ablation for any given material. The processing itself occurs on a precision 5-axis stage (X, Y, Z, and two rotation axes), which when coupled with the imaging allows for unique processing capabilities.

## Optical coherence tomography

OCT is an interferometric 1D imaging technique (which can be raster-scanned for additional dimensionality) that has recently seen more widespread use in industrial process monitoring [1] [2]. The optical nature and ease of coupling in-line with a processing laser allows the system to provide high speed (100 kHz and higher) monitoring and feedback.

*Table 1. Specifications of the imaging systems.*

| | Optical coherence tomography (OCT) | Digital holographic microscopy (DHM) |
|---|---|---|
| Lateral resolution | Lens-dependent (i.e. beam spot size) | 0.5 μm |
| Axial resolution | 7.5 μm | 50 nm |
| Depth of field | > 5 mm | 5 μm |
| Imaging speed | 100 kHz | 10 Hz |
| In-situ? | Yes | Yes |

**2** *Generalised OCT control loop. The light blue represents computer hardware, red represents external hardware, and green represents computer software functions.*

**3** *When turning either a rigid rough material (a) or a flexible material (b), the top surface moves in and out of the processing laser's depth of field. Given the randomness of variation, machining the flexible material would not be possible without in-situ feedback.*

**4** *OCT system with dimensions of 12 x 16 x 32 cm$^3$.*

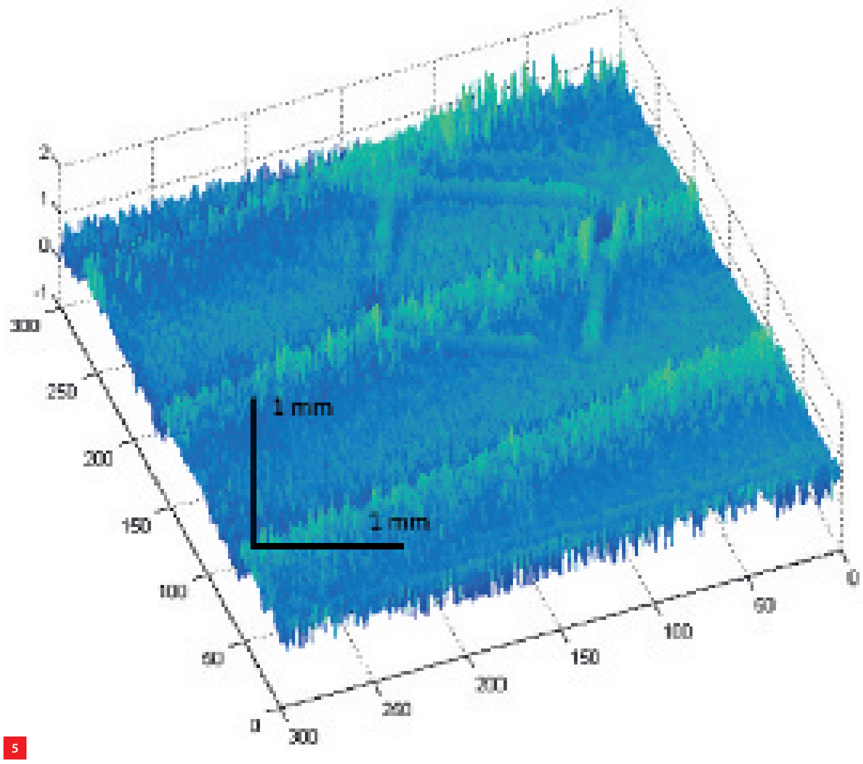
Figure 2 shows a general case for a control loop with the OCT system. Each of the threads runs in parallel, limited by the CPU and memory. This allows, for example, the user to display the processing live and observe the effects with and without feedback.

One example application that would benefit from OCT control is laser turning. In Figure 3a, it can be seen that while the material is rigid, it has an uneven surface that passes in and out of the laser's depth of field, resulting in uneven cutting. In Figure 3b the material may have an even surface, but now its flexibility results in movement through the laser's depth of field per revolution and, hence, uneven machining. Turning of carbon nanowires for field emission purposes is a specific case where the flexibility of the nanowires cause issues during processing [3]. With OCT-guided processing, the system is able to identify how much the height has changed and adjust accordingly to maintain even cutting.

The entire OCT system has been designed to be contained inside the box drawn in Figure 4, with the exception of the fibre sample arm used to integrate with a processing system. Part of the overall system design is the modular nature of the imaging system. The OCT is self-contained and can be easily moved and integrated with different machining platforms. Thus, the system can be customised to target specific industrial needs.

## Digital holographic microscopy

DHM is a technique that allows high-resolution 3D imaging of a sample. DHM is also an interferometric technique that uses a reference beam to create an interference pattern overlaid onto an image, thus capturing its phase information. As seen in Table 1, this gives resolutions in the order of tens of nanometers, at the expense of imaging speed. Figure 5 shows a DHM image taken of a square that has been cut into a mirror surface. Given the speed, DHM primarily provides pre- and post-processing analysis and in-situ monitoring at specific critical processing junctions (e.g., between layers for multilayer material removal) as opposed to immediate feedback control.

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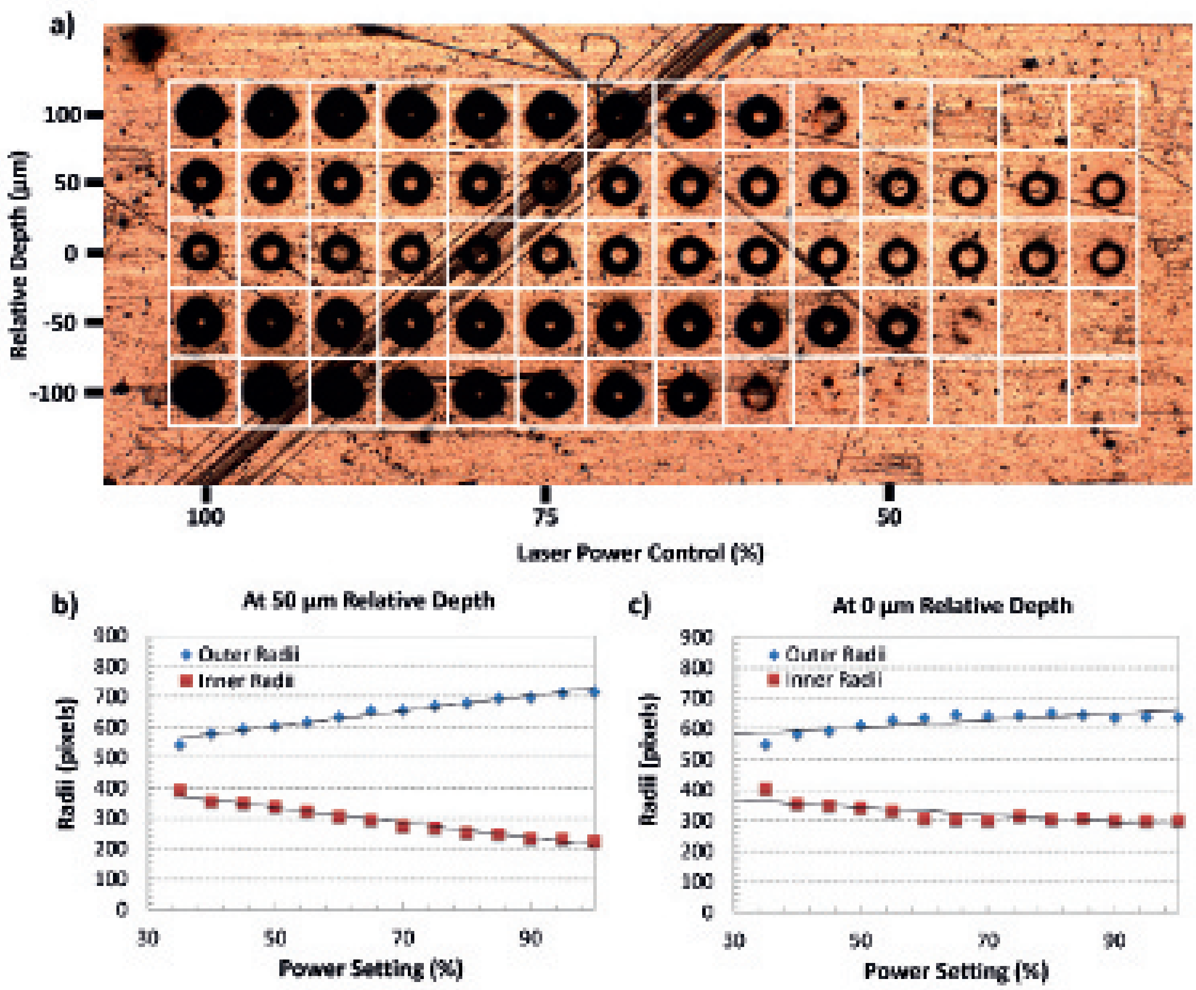


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5 DHM image of a square that has been ablated into a mirror surface.

6 Rings cut into copper at various intensities and depths (a). The disappearance of rings at the right of the image suggests the location of the focus and ablation threshold. Image analysis (b, c) provides a measure of ring thickness, used to determine the machining spot size.

Figure 5 shows an example of a pre-processing application, where the visible phase wrap on the surface of the mirror (i.e. the light green ridges) is used to correct the sample tilt: approximately 1.8 μm over 2.5 mm (~ 0.04°). A square can also be seen, which has been ablated into a mirror with a depth of 35 μm. Due to the phase wrapping, this height is difficult to resolve with a single-wavelength DHM (i.e., the height is larger than the wavelength of the source) and hence a multi-wavelength system will be used during processing to extend the axial field of view.

Figure 6 shows initialisation procedures currently tested with an optical microscope, later to be used with DHM. In this example, a system parameter mapping is done to determine the machining qualities of the processing laser on a material (in this case, copper). This mapping is automatic and is able to provide information on focal depth, machining spot size at a given depth, and quality of machining (via analysis of image intensity). When this control is coupled with DHM, the system would then be able to gather information on the material removal rate as well. This information can then be called upon during in-situ processing to conduct processing control.

## Conclusion

The system described here is a proof-of-concept system that will allow for high-speed, high-accuracy (< 1 μm) processing with closed-loop feedback control and post-process analysis for further FIB machining. By finally introducing in-situ control to precision processes, the system will reduce the industrial cost for micro and nano rapid prototyping and mass manufacturing.


## Acknowledgement

The project described here is jointly supported by IPG Photonics and EPSRC, the UK's Engineering and Physical Sciences Research Council (EP/I033491/1).



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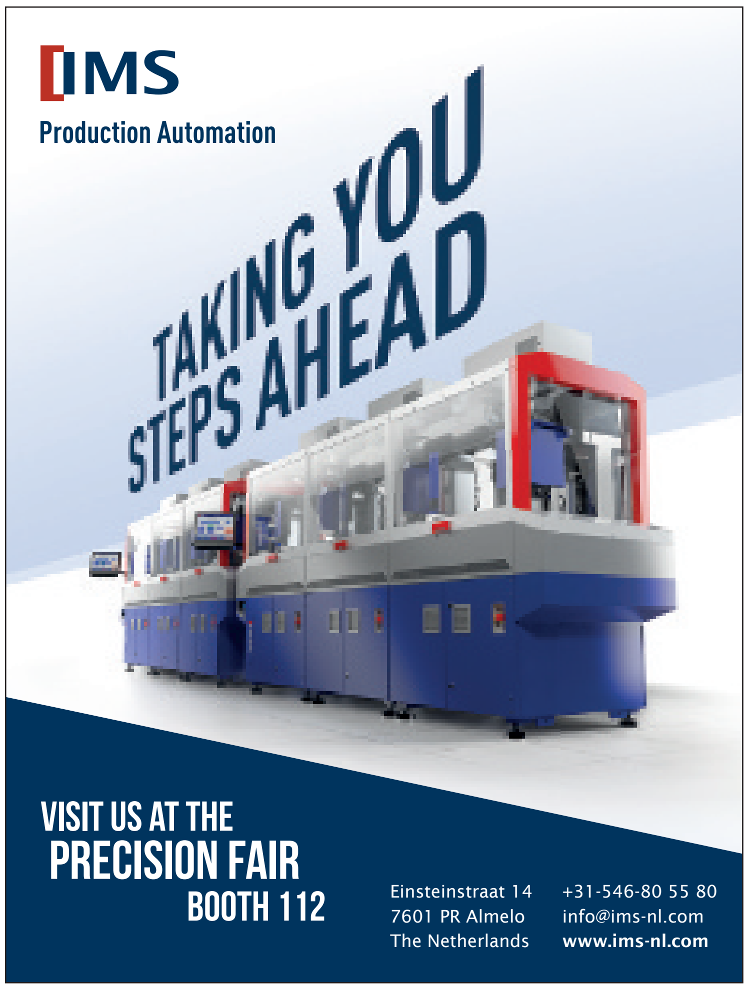

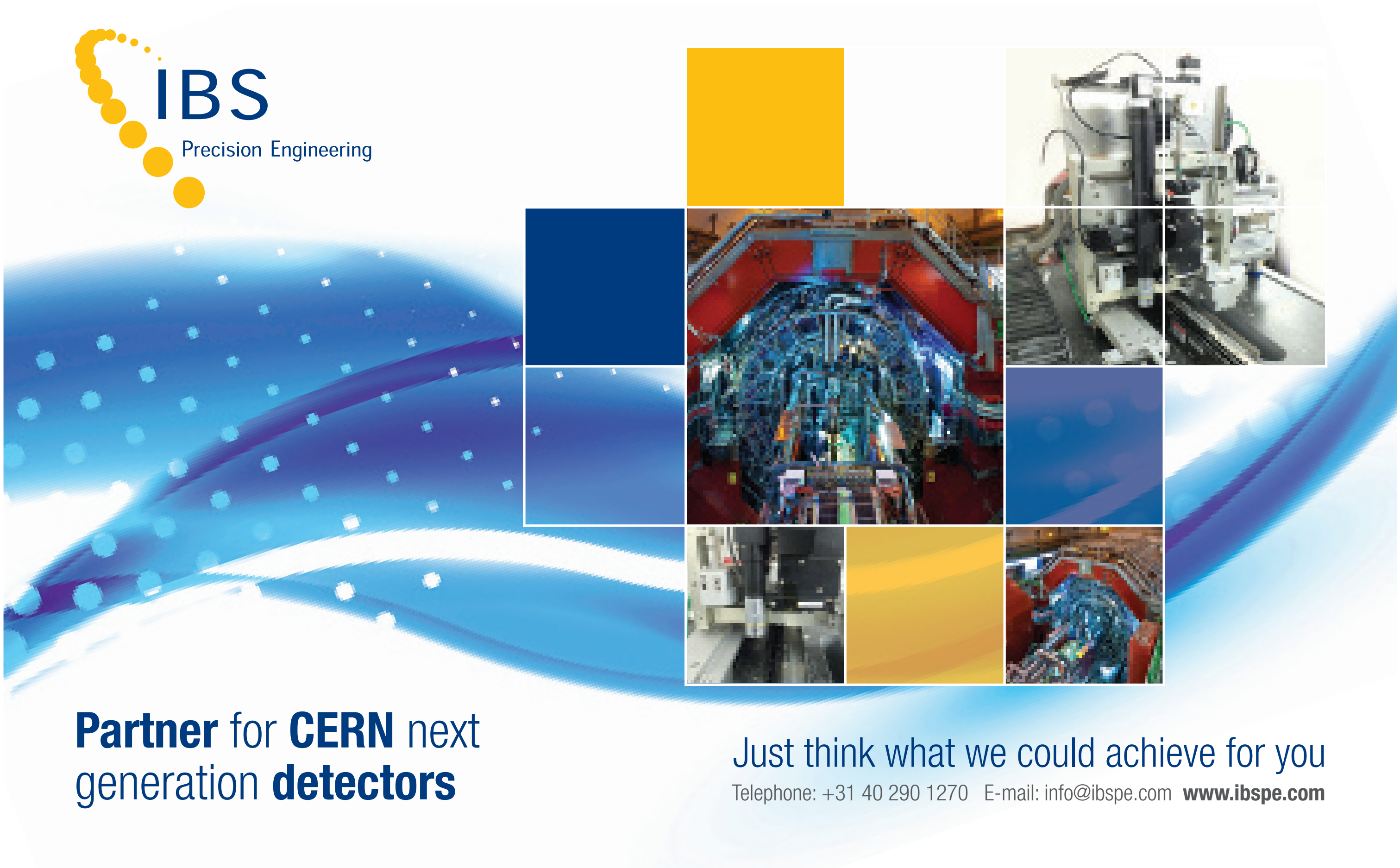
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# YPN VISIT TO THE NTS-GROUP

High-tech systems supplier, the NTS-Group is responsible for the development, engineering and assembly of opto-mechatronic systems and mechanical modules for leading original equipment manufacturers (OEMs)

Dr. Shahzad Khan, technical specialist and host of the day, welcomed the DSPE Young Precision Network (YPN) party and gave an introduction about the NTS-Group. The NTS-Group recently invested in adding system development to its (contract) manufacturing role, from build-to-print to creating specifications, although manufacturing and assembly remain their core competences.

This new role in system development was demonstrated by Dr Rens Henselmans, who described the development of a large motion module for a new combined MRI – radiation therapy system. The technical challenges and solutions were explained, along with the process from the first test set-up to prototypes and series production. During the second presentation, ir. Asma Qadir talked about a practical measurement method to determine the acoustic vibration sensitivity of precision positioning equipment.

A tour of NTS Mechatronics by Gerard Hullegie (Assembly Team Leader) gave the group a sneak peek into the assembly line at Eindhoven. The group was first shown the new cleanrooms, many of which are ISO class 6 and equipped to assemble certain ASML parts. The products being assembled included a drone with camera, an Assembléon machine, an Apostore picking machine and various lines of the Phenom-World electron microscope.

YPN would like to thank the NTS-Group for organising the visit. ■

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## New YPN board

This summer, Edwin Bos of Xpress Precision Engineering, in an attempt to rejuvenate the YPN board, handed the chair over to brothers Arjo and Jordan Bos (no relation to Edwin). The Bos brothers aim to continue the familiar YPN activities, such as company visits, and start experiments with new types of activities. For example, promoting the mechatronics discipline among students and engaging not only students from academia, but also from universities of applied sciences. Edwin Bos plans to continue his work in DSPE by organising master classes.

■ *The new YPN board members, Arjo (left) and Jordan Bos.*

## DSPE/euspen Symposium

In 2008, DSPE developed a certification program for commercially available training courses. A DSPE-certified course formally fits in the development program for the title of Certified Precision Engineer (CPE). Students earn CPE credit points for each course. A total of 25 CPE credit points is equivalent to the Bronze level, 35 points the Silver level and 45 points the Gold level (and the CPE title).

About a year ago euspen (European Society for Precision Engineering) approached DSPE to propose collaboration in order to expand the certification program to the European level. Next month, on 19 November, a DSPE/euspen symposium will be organised at the Precision Fair in close cooperation with fair organiser Mikrocentrum. This will be the formal kick-off in the Netherlands of this collaboration, aimed at the certification of existing and future training courses on a European level and leading to the European Certified Precision Engineering Course Program (ECPECP). This ECP$^2$ program reflects the demand for multidisciplinary system thinking, excellent cooperative skills and in-depth knowledge of relevant disciplines. This combined investment in education aims to create a common way of working and to facilitate networking among precision engineers which will allow for greater portability of skills throughout Europe.

The title of the symposium, aimed at precision engineers and their (HR) managers, is: "Post-graduate education in precision engineering – Today and tomorrow". Speakers will include David Billington (Executive Director of euspen), Jan Willem Martens (Chairman of the DSPE Certification Program) and Nikola Vasiljević (Postdoc at the Technical University of Denmark, DTU Wind Energy), the first Bronze-level CPE student. HR managers from high-tech companies will also be sharing their views on post-graduate competence development needs.
A similar kick-off is planned in Germany for early 2016; other European countries will follow. ■

# FLATBED PRINTER DEVELOPMENT

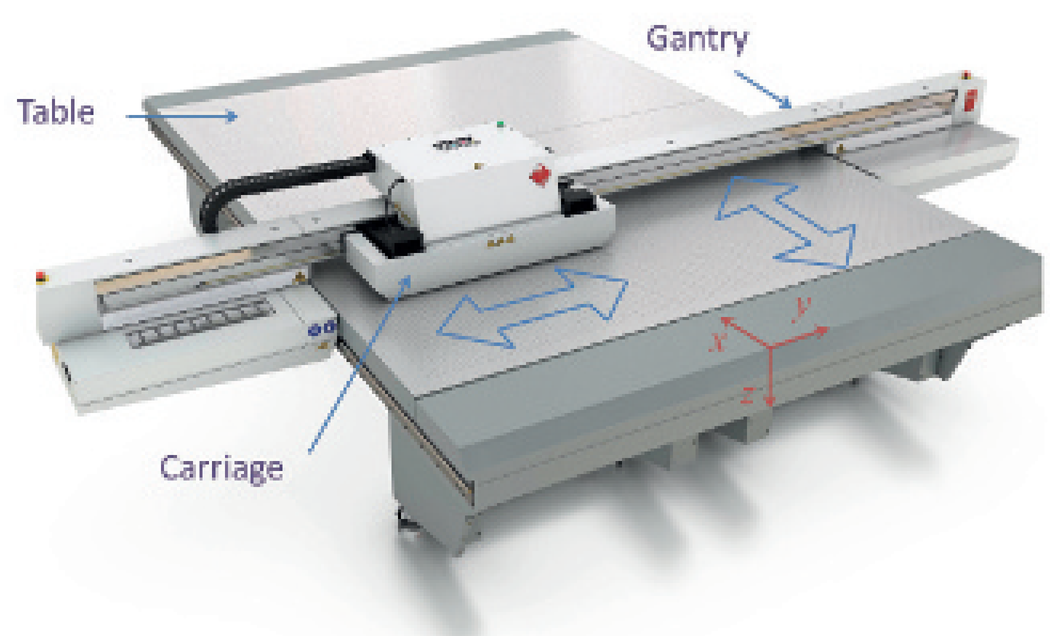
**In the scope of mechatronics development of advanced flatbed printers at Océ-Technologies, supported by Segula Technologies Netherlands, it is explained how to achieve the desired servo-control performance of a flatbed printer in a systematic and theoretically sound fashion. As a case study, one flatbed printer is considered to demonstrate the first-principle modelling and analysis of the printer dynamics, model-based control design and automatic feedforward motion control tuning, as well as improvement of the printer motion control performance.**

DRAGAN KOSTIĆ, PIETER VAN ZUTVEN, PATRICK SMULDERS, SJIRK KOEKEBAKKER AND IVAN SMITS

## Introduction

Within the increasingly competitive market of large-format printers, Océ-Technologies develops advanced flatbed printers that provide high-quality prints on rigid and flexible media [1]. An example of such a printer is "Arizona", of which the main subsystems are indicated in Figure 1:

- Table: serves as a carrier of the media to be printed and as the mainframe of the printer mechanics.
- Carriage: holds the printheads and performs printing motions in the $y$-direction of the printer coordinate frame.
- Gantry: carries the Carriage and performs printing motions in the $x$-direction.




1 *"Arizona" flatbed printer. The arrows indicate the actuated degrees of freedom. Three main printer subsystems are defined, as well as the reference coordinate frame.*

AUTHORS' NOTE

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Sjirk Koekebakker (mechatronics designer) and Ivan Smits (mechatronics/control designer) work for Océ-Technologies, based in Venlo, the Netherlands.

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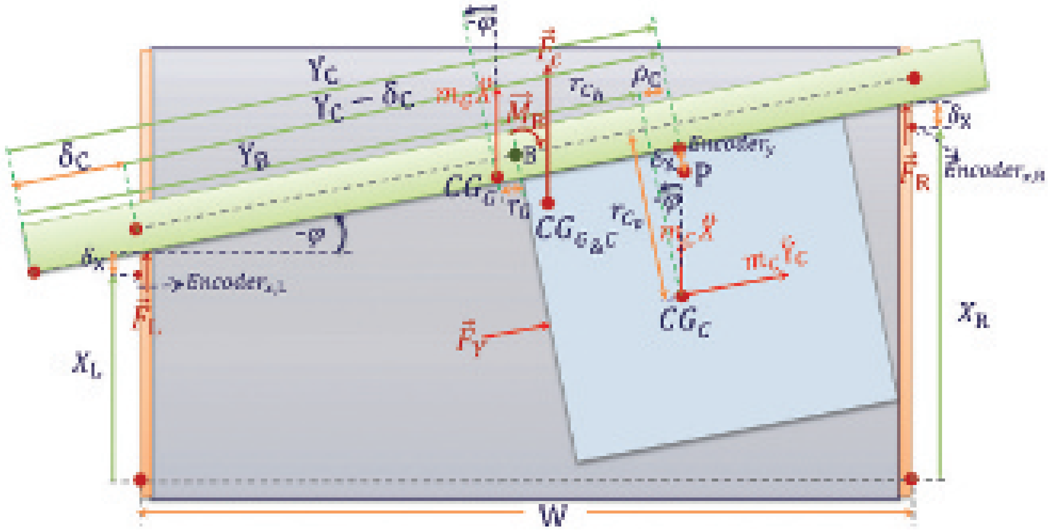


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2 *Schematic of the "Arizona" flatbed printer used for kinematic and feedforward control modelling.*

Rapidly increasing demands on the printing speed and accuracy raise various challenges during mechatronics development, volume production, and calibration of the flatbed printers. To reduce development and production lead times while ensuring the cutting-edge printer quality, Océ-Technologies has involved Segula Technologies Netherlands as a partner for product development in the domain of mechatronics [2].

Dealing with multi-body dynamics and motion control of the flatbed printers – being multi-physics systems by nature – is especially challenging due to interactions between the printer mechanical, electrical and thermal dynamics, as well as the digital implementations of the motion servo-control algorithms. To foresee interactions among different physical domains and to facilitate the achievement of challenging positioning requirements, various advanced model-based design and analysis techniques are included, such as CAD, FEA, model-based control, and dynamical and servo-control simulations.

The necessary steps to achieve high-performance motion control of the flatbed printer include:

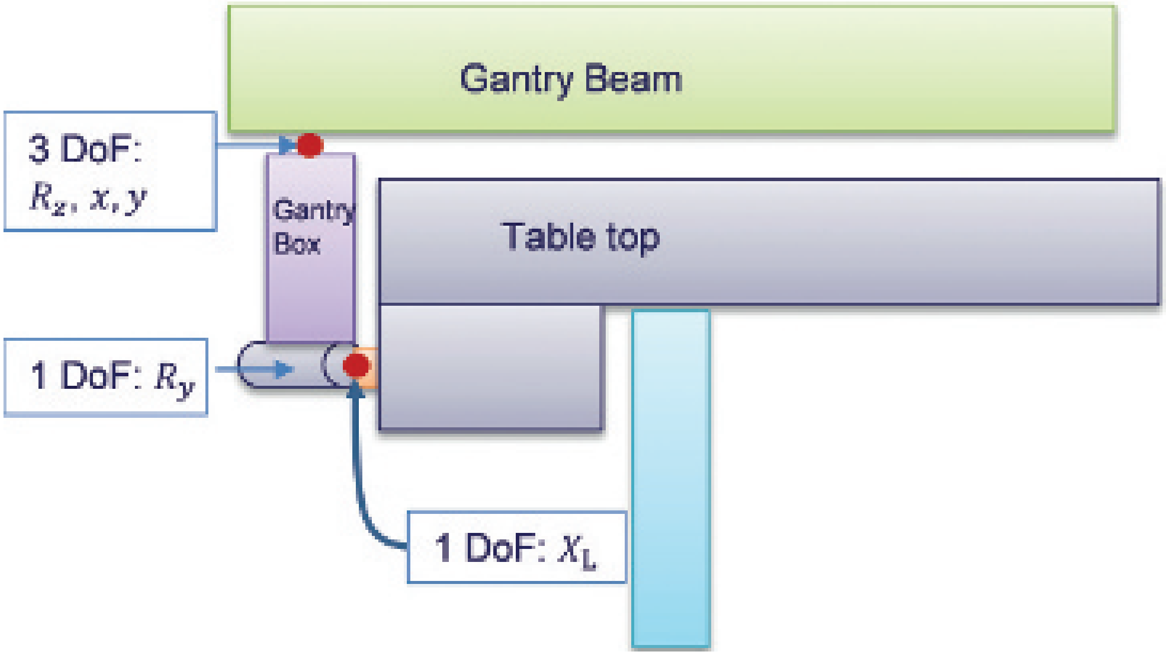
1. kinematic and dynamic modelling;
2. obtaining the model parameters from CAD models and via direct measurements and/or identification;
3. model verification by simulations and measurements;
4. motion control design;
5. motion control evaluation.

Better quality resulting from each of these steps contributes to better performance of the flatbed printer.
In particular, the modelling activities are the essential element of the mechatronics design approach. Use of the models facilitates setting proper requirements concerning design of the printer mechanics, actuation and driver electronics. Furthermore, making explicit use of the models in the control design enhances servo-control performance and enables robustness analysis with respect to variations in the printer dynamics, disturbances and environmental conditions. Consequently, thanks to the model-based approach less uncertainty is expected during development of a flatbed printer, with a higher yield in production and better reliability of the end products. In other words, development and production lead times of high-quality printers get reduced using this approach, which is an important driver for cooperation between Océ and Segula.

## Printer modelling

The literature offers various tutorials on kinematic and dynamic modelling of multi-body electromechanical systems; e.g., see chapters 7, 9 and 15 in [3]. As for kinematics, the model is a mapping between the nominal printer degrees of freedom (DoFs) and the location of the Carriage holding the printheads. The nominal DoFs comprise the actuated motion axes that are intended to provide the desired motion patterns of the printhead; in Figure 1, these are the $x$- and $y$-motion axes of the Gantry and Carriage, respectively.

The location of the Carriage can be described in terms of the translational $x,y$-position of some characteristic point of the Carriage and the orientation of the Carriage relative to the Table top. It is practical to choose the characteristic point at some printhead inside the Carriage. Figure 2 shows a schematic of the printer which is used for modelling the printer kinematics. Later on, the same figure will be instructive for modelling the rigid-body printer dynamics that are needed for the design of feedforward motion controllers.




3 *Example of internal DoFs (nominal and parasitic) of the printer.*

With reference to Figure 2, the nominal printer DoFs are the actuated translational motion axes at the left- and right-hand sides of the Gantry that are characterised by displacements $X_L$ and $X_R$, respectively, together with the actuated translational motion axis of the Carriage along the Gantry which is characterised by displacement $Y_C$. Displacements $X_L$, $X_R$ and $Y_C$ are all measured with incremental encoders. As for the translational location of the Carriage, point P is considered which has the same $y$-coordinate as the Carriage encoder (‘$Encoder_y$’ in Figure 2). The orientation of the Carriage is described in terms of angle $\varphi$.

The mapping from the nominal DoFs to the Carriage location relative to the Table top is called the forward kinematics, while the opposite is the inverse kinematics. Using Figure 2, it is straightforward to write the forward kinematics model of the flatbed printer:

$$X = X_L + \delta_X \cdot (1 - \cos\varphi) + (Y_C - \delta_C) \cdot \sin(-\varphi) \quad (1a)$$

$$\varphi = \mathrm{atan}\,((X_L - X_R) / W) \quad (1b)$$

Here, $X$ represents the translational displacement of point P in the $x$-direction relative to the Table top, $\delta_X$ and $\delta_C$ are position offsets, and $W$ is the width of the Table. The kinematics model (1) is symbolic and in closed-form, which facilitates mathematical analysis, setpoint generation and control design. As high accuracy of computation can be achieved faster with the closed-form models, these are preferred for real-time control.

Dynamic models relate motions, velocities, and accelerations of the printer DoFs with applied control inputs (forces/torques). They can be used to predict behaviour of a prototype (printer or its part) before actually building it, to analyse the dynamics and/or predict servo-control performance in a controlled (disturbance-free and/or reproducible) environment where the initial conditions can be set accurately and easily repeated, and perform different qualitative and quantitative studies in the virtual world, e.g. requirements and architecture definition, optimisation of electromechanical construction, optimal selection of actuator/sensor system, servo-control design, sensitivity analysis, etc.

Besides the nominal DoFs, practical realisations of the printers may feature a number of parasitic (hence, not intended) DoFs that are a consequence of limited stiffness and structural deformations of the printer mechanics and actuator drivetrains. These DoFs are especially excited at higher accelerations of the printer moving parts, i.e. Gantry and Carriage (Figure 1). The parasitic DoFs are typically associated with the mechanical interfaces between different printer parts.

For illustration, Figure 3 shows a breakdown of the Gantry subsystem into Gantry Box and Gantry Beam. The Box is interfaced to the Table top via the translational guiding mechanism which provides the $X_L$ motion of the Gantry. In addition to this nominal DoF, four parasitic DoFs can be attributed to the mechanical interfaces at the top and bottom sides of the Box. These DoFs are responsible for eigenfrequencies measured on the real printer.

If parasitic DoFs are observed on a physical printer, then capturing both the nominal and parasitic DoFs in a dynamic model may not be trivial, due to complexity of the interactions between different DoFs. Fortunately, modern software tools can facilitate modelling of complex electromechanical structures. One of these tools is the SimMechanics™ [4] multi-body simulation software for intuitive and user-friendly modelling of 3D multi-body systems using block-diagram descriptions of bodies, joints, constraints, and force elements. Given a block-diagram model of the multi-body system, the equations of motion are formulated and solved.

To model the dynamics of a flatbed printer, one has to:
(*i*) set-up topology of the model describing the printer mechanics, actuator dynamics, and actuator drivetrains, and then implement this topology into SimMechanics,
(*ii*) supply physical values of the model parameters, and
(*iii*) integrate the model with models of setpoint generators for the actuated DoFs, servo-motion controllers, quantisation effects and disturbances (e.g., digital control sampling, finite resolution of feedback sensors and actuator drives, measurement noise, floor vibrations, etc.).
Once the printer topology is captured in the model, the next step is to specify its parameters, so that the resulting model describes dynamics of the physical system both qualitatively and quantitatively. Kinematic parameters, such as dimensions and mutual orientations of the printer parts, are usually known with better accuracy than inertial ones, i.e. masses and moments of inertia of the parts, as well as locations of their centres of mass. It is even more challenging to supply the model with realistic values of stiffness and damping parameters of the parasitic DoFs.

The kinematic parameters can either be obtained from the existing CAD models or directly be measured on the printer. As for the inertial parameters, it is most convenient if these can be readily obtained from the CAD files. If that is not possible or turns out to be not accurate enough, then the inertial parameters have to be determined by direct measurements and/or indirectly reconstructed, e.g. via FRF (frequency response function) measurements. Ideally, the stiffness parameters can be estimated based on finite-element models (FEM). In engineering practice, it is more common to estimate these parameters based on the FRF measurements together with the damping coefficients.

Friction modelling and estimation is also an important issue [5], as friction may cause motion control problems, e.g., static errors, stick-slip phenomena, limit-cycles, etc. To obtain realistic friction parameters, direct servo-control measurements on the physical printer are required. Here, these measurements will also be illustrated with respect to automatic feedforward motion control tuning for the Gantry.

One of the most appealing features of multi-body system modelling in SimMechanics is the easy integration of the models with other Matlab functions and toolboxes, such as Simulink [6]. That greatly facilitates and speeds up the setting up of servo-control simulations of complex electromechanical structures, that in addition to description of the mechanics and actuator dynamics also incorporate setpoint generation, supervisory control, motion control algorithms, sampling effects, disturbances, etc.

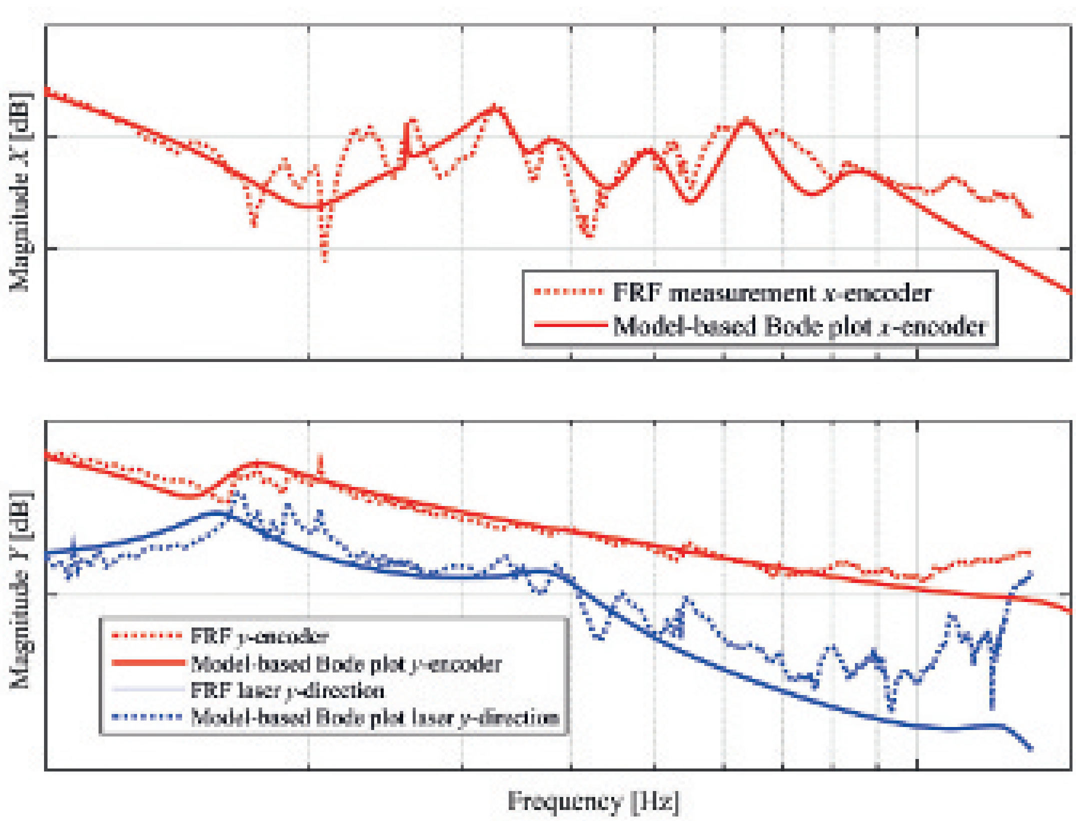
## Model verification

To enable quantitative analysis of the printer dynamics and realistic servo-control simulations, the developed model has to be verified against the physical behaviour of the actual printer. This requires a rigorous two-step verification strategy. The first step is to check whether the model reproduces FRF data measured on the physical printer. If a satisfactory match is achieved between Bode plots generated by the model and the FRF measurements, one proceeds with the second verification step: time-domain evaluation of the quantitative match between servo-control data obtained in the model-based simulations and in the actual measurements.

In the first verification step, a number of FRF measurements have to be taken into account, those measured in the servo loops of the printer motion axes (hence, transfers from the actuator forces to encoder measurements $X_L$, $X_R$ and $Y_C$, see Figure 2) together with the ones measured at characteristic locations (that are critical for printing performance). At the measurement locations where encoders are not available, responses to the actuator forces can be obtained using accelerometers, laser sensors, or various proximity measurement devices (inductive or capacitive).

Figure 4 shows examples of the measured FRF data and the corresponding Bode plots generated using the model of the flatbed printer. The plots of Figure 4a correspond to the transfer from the total force supplied by the Gantry actuators to the translational $X$-displacement of the Gantry defined by Equation 1a; these plots describe the dynamics of the control plant for the $X$-servo-control loop of the Gantry. The figure displays a satisfactory match between the measured and simulated frequency-domain data.

The plots of Figure 4b correspond to the transfer from the force supplied by the Carriage actuator to the translational

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4 *Verification of the printer model in the frequency domain.*
*(a) Measured FRF vs. model-based Bode plot of the servo loop for translational X-motion of the Gantry.*
*(b) Measured vs. model-based Bode plots of the servo loop for translational $Y_C$-motion of the Carriage together with the dynamics representing the response at a point on the Carriage to the force supplied by the Carriage actuator.*

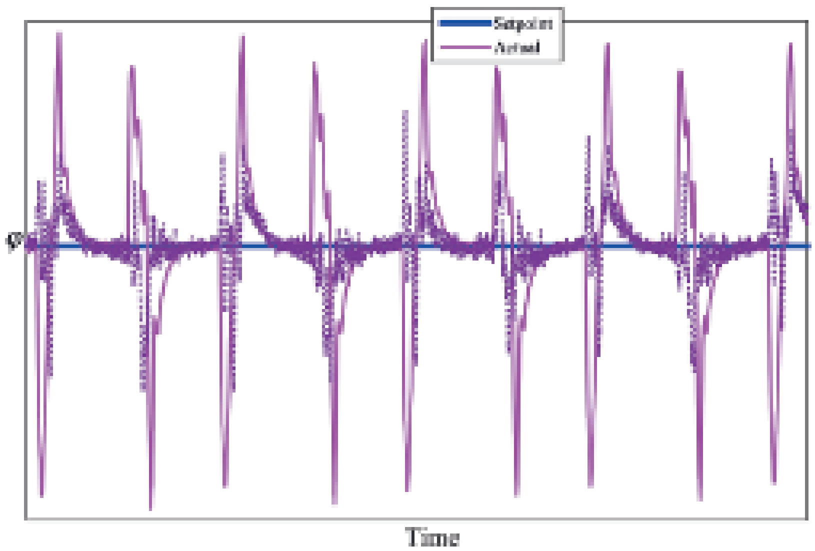
$Y_C$-displacement measured using the optical encoder (control plant for the $Y_C$-servo-control loop of the Carriage), together with the transfer from the same force to the output of a laser sensor mounted at a critical point on the Carriage. Once again, the model-based results are in good agreement with the measurements. Since a similar match is achieved at all other measurement locations, it can be concluded that the first verification step has been successfully accomplished.

In the second step, servo-control measurements are carried out on the actual printer performing different scenarios that are also simulated. The measurement results are then compared to the data rendered by the model. A satisfactory quantitative match between the simulated and measured data does imply ultimate quality of the model, since it verifies that all parts of the model are a relevant representation of the reality, including in particular the dynamical descriptions of the printer and actuator dynamics, setpoint generators, servo controllers, as well as sampling and modelled disturbance effects. For illustration, Figure 5 shows measured and simulated data that correspond to the servo-control loop of the Gantry $\varphi$-motion defined by Equation 1b.
The plots depicted in this figure represent the simulated (solid line, magenta) and measured (dotted line) $\varphi$-motions together with the corresponding setpoint (blue line). They show that the model-based results are in good correspondence with the measurements. A similar match is achieved with other servo variables and in different printing scenarios. Consequently, it can be concluded that the model is a sound representation of the reality, and that it can be used for quantitative analysis of the printer dynamics, servo-control simulations, and performance optimisations.

## Control design and performance evaluation

The objective of the servo-control algorithms for the actuated motion axes is the accurate tracking of the setpoint motion profiles that correspond to a given motion pattern of the printheads. Increasing demands on the printing performance and robustness against uncertainties in the printer dynamics and disturbance conditions motivate the use of advanced motion control methods that are capable of simultaneously addressing several control objectives: stability robustness, disturbance rejection, controlled transient behaviour, optimal performance, etc.

Of course, it is unrealistic to achieve ultimate quality in terms of all control objectives simultaneously, since these are mutually dependent and often conflicting. For instance, arbitrarily high servo-control bandwidths are not possible, since they are limited by flexible modes of the printer

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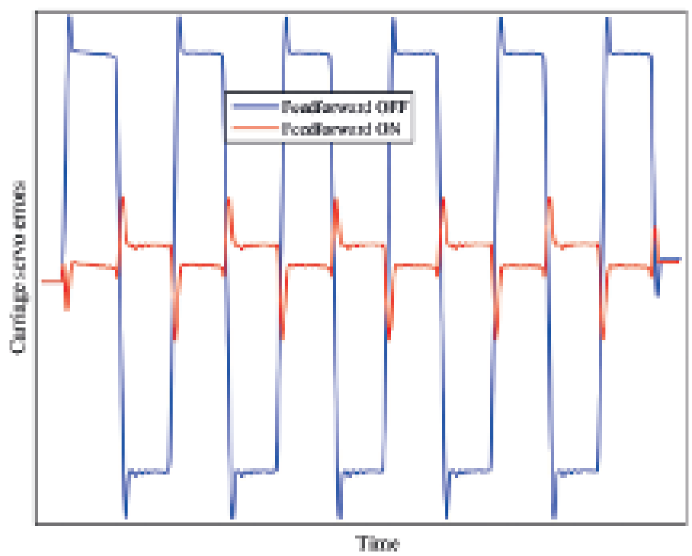


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5 *Verification of the printer model by servo-control measurements and simulations: simulated (solid) and measured (dotted) actual φ-motion of the Gantry together with the corresponding setpoint.*

6 *Carriage motion control performance improvement due to feedforward control – significant decrease of the servo-control errors when the feedforward controller is enabled.*

mechanics and actuator drivetrains, as well as phase characteristics of the servo-control plants.

Feedback motion controllers are typically tuned around the maximum cross-over frequencies admissible by the actual dynamics of the control plants corresponding to the actuated motion axes. This tuning should provide sufficient stability and performance robustness against flexibility effects, manufacturing tolerances, and disturbances affecting the printer. Information about the dynamics of the servo plants and tolerances is captured via data-driven modelling (system identification), such as the FRF measurements shown in Figure 4. The measured input/output data also reveal disturbance effects. The described strategy is clearly focused on experimental characteristics of the flatbed printer, and it is implemented in the form of loop-shaping feedback motion control design [7].

In addition to the feedback servo algorithms, the feedforward controllers are used to decouple different motion axes and to improve motion control performance. Also, the feedforward is used to compensate for parasitic dynamics that repetitively appear in the motion control loops, such as friction. To facilitate and ultimately automate design of the feedforward motion controllers, a systematic and theoretically sound strategy is followed: (*i*) physical modelling of the dynamics whose compensation requires the greatest deal of the forces supplied by the actuators of the motion axes, and, (*ii*) automatic tuning of the model parameters based on data captured during measurements on the actual printer under pure feedback motion control.

For physical modelling, the standard Euler-Lagrange formulation of equations of motion is used:

$$\boldsymbol{M}(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{c}(\boldsymbol{q},\dot{\boldsymbol{q}}) + \boldsymbol{f}_F = \boldsymbol{f} \tag{2}$$

Here, $\boldsymbol{q} = [X\ \varphi\ Y_C]^T$, $\dot{\boldsymbol{q}}$ and $\ddot{\boldsymbol{q}}$ are the first and second time-derivatives of $\boldsymbol{q}$, respectively, $\boldsymbol{M}$ is the inertia matrix, $\boldsymbol{c}$ is the column vector of stiffness and damping effects, $\boldsymbol{f}_F$ is the column vector of friction forces and moments, and $\boldsymbol{f} = [F_C\ M_B\ F_Y]^T$. With reference to Figure 2, $F_C$ and $M_B$ are defined as follows:

$$F_C = F_L + F_R \tag{3a}$$

$$M_B = 0.5W(F_L - F_R) \tag{3b}$$

Here, $F_L$ and $F_R$ are the forces supplied by the actuators at the left- and right-hand sides of the Gantry, respectively. The actuation force of the Carriage is denoted by $F_Y$.

The dynamic model (2) can be represented linearly in parameters that are formed by combination of the inertial and friction coefficients of the printer mechanics [8]. The corresponding linear representation of the dynamic model has a so-called regression form:

$$\boldsymbol{R}(\boldsymbol{q},\dot{\boldsymbol{q}},\ddot{\boldsymbol{q}})\mathbf{p} = \boldsymbol{f} \tag{4}$$

Here, $\boldsymbol{R}$ is the regressor matrix and $\mathbf{p}$ is the vector of parameters. Apparently, matrix $\boldsymbol{R}$ has as many rows as $\boldsymbol{f}$ has elements (hence 3), while its number of columns equals the number of parameters from vector $\mathbf{p}$. The regression model (4) allows automatic estimation of $\mathbf{p}$ even in a hypothetical case when these parameters are not available or are only partially known, or – more realistically – if these parameters are not known with sufficient accuracy. Availability of an accurate estimate $\hat{\mathbf{p}}$ of the parameter vector is essential for effectiveness and high-quality performance of the feedforward controller:

$$\boldsymbol{f}_{ff} = \boldsymbol{R}\left(\boldsymbol{q}_{setpoint}, \dot{\boldsymbol{q}}_{setpoint}, \ddot{\boldsymbol{q}}_{setpoint}\right)\hat{\mathbf{p}} \tag{5}$$

Here, $\boldsymbol{f}_{ff}$ represents the column vector of the feedforward control signals for the Gantry $X$- and $\varphi$-servo loops as well as for the Carriage $Y_C$-servo loop, respectively, and '*setpoint*' in the subscripts identifies setpoint profiles.

To achieve an accurate estimate of $\mathbf{p}$, a servo-control measurement on the flatbed printer is carried out under pure feedback control. For persistency of excitation, it is recommended to perform a printing scenario which involves high accelerations/speeds and long printer steps. In such a scenario, one has to measure signals that appear in the regression model (4): $\boldsymbol{q}$, $\dot{\boldsymbol{q}}$, $\ddot{\boldsymbol{q}}$, and $\boldsymbol{f}$. Assuming that $\xi$ data points of each signal are measured at time instants $t_1, t_2, \ldots, t_\xi$, then by virtue of Equation 5 the following system of equations can be formed:

$$\boldsymbol{\Phi} \cdot \mathbf{p} = \boldsymbol{y} \tag{6}$$

Here,

$$\boldsymbol{\Phi} = \begin{bmatrix} \boldsymbol{R}\left(\boldsymbol{q}(t_1), \dot{\boldsymbol{q}}(t_1), \ddot{\boldsymbol{q}}(t_1)\right) \\ \boldsymbol{R}\left(\boldsymbol{q}(t_2), \dot{\boldsymbol{q}}(t_2), \ddot{\boldsymbol{q}}(t_2)\right) \\ \vdots \\ \boldsymbol{R}\left(\boldsymbol{q}(t_\xi), \dot{\boldsymbol{q}}(t_\xi), \ddot{\boldsymbol{q}}(t_\xi)\right) \end{bmatrix} \tag{7a}$$

$$\boldsymbol{y} = \begin{bmatrix} \boldsymbol{f}^T(t_1) & \boldsymbol{f}^T(t_2) & \cdots & \boldsymbol{f}^T(t_\xi) \end{bmatrix}^T \tag{7b}$$

From (6), one can determine a least-squares estimate of $\mathbf{p}$:

$$\hat{\mathbf{p}} = \boldsymbol{\Phi}^{\#}\boldsymbol{y} \tag{8}$$

Here, '#' denotes a matrix pseudo-inverse [8].

For the sake of intuitive illustration of the procedure described by Equations 2 to 8, only the equation describing the dynamics of the Carriage is considered. It appears as the last one in formulation (2) of the flatbed printer dynamics:

$$m_C\ddot{Y}_C + b_C\dot{Y}_C + F_{F,C} = F_Y \tag{9a}$$

$$\left(1 - \operatorname{sgn}(\dot{Y}_C)\right)\frac{\max(-v_t, \dot{Y}_C)}{-v_t}F_{Coulomb-,Y} + \operatorname{sgn}(\dot{Y}_C)\frac{\min(v_t, \dot{Y}_C)}{v_t}F_{Coulomb+,Y} = F_{F,C} \tag{9b}$$

Here, $\ddot{Y}_C$ and $\dot{Y}_C$ are the Carriage acceleration and speed, respectively, $m_C$ is the mass of the Carriage, $b_C$ is an effective damping incorporating viscous friction and damping of the Carriage actuator drivetrain, and $F_{F,C}$ is a piecewise-linear approximation of the Coulomb friction [5] in the same drivetrain. A practical convenience of this continuous approximation is that it prevents abrupt changes of the feedforward control signal when the Carriage speed changes its sign:

$$\operatorname{sgn}(\dot{Y}_C) = \begin{cases} 1, & \text{if } \dot{Y}_C > 0; \\ 0, & \text{elsewhere.} \end{cases} \tag{10}$$

In Equation 9b, different Coulomb friction coefficients $F_{Coulomb-,Y}$ and $F_{Coulomg+,Y}$ are considered for negative and positive Carriage speeds, respectively. Parameter $v_t$ specifies a threshold on $\dot{Y}_C$ above which a value of the Coulomb friction changes from a piecewise-linear approximation to a constant.
By virtue of Equation 4, Equations 9a and 9b are combined to write down the following regression model:

$$F_Y = \mathbf{r}_C^T(\dot{Y}_C, \ddot{Y}_C)\mathbf{p}_C \tag{11a}$$

$$\mathbf{r}_C(\dot{Y}_C, \ddot{Y}_C) = \begin{bmatrix} \ddot{Y}_C & \dot{Y}_C & \left(1 - \operatorname{sgn}(\dot{Y}_C)\right)\frac{\max(-v_t, \dot{Y}_C)}{-v_t} & \operatorname{sgn}(\dot{Y}_C)\frac{\min(v_t, \dot{Y}_C)}{v_t} \end{bmatrix}^T \tag{11b}$$

$$\mathbf{p}_C = \begin{bmatrix} m_C & b_C & F_{Coulomb-,Y} & F_{Coulomb+,Y} \end{bmatrix}^T \tag{11c}$$

Given the data $\dot{Y}_C$, $\ddot{Y}_C$, and $F_Y$ measured on a flatbed printer, elements of the parameter vector $\mathbf{p}_C$ can be estimated using Equation 8. The resulting estimate $\hat{\mathbf{p}}_C$ is then implemented in the feedforward motion controller of the Carriage:

$$F_{Y,ff} = \mathbf{r}_C^T(\dot{Y}_{C,setpoint}, \ddot{Y}_{C,setpoint})\hat{\mathbf{p}}_C \tag{12}$$

For verification of servo-control performance improvement thanks to the feedforward control, Figure 6 shows servo-control errors representing differences between the setpoint and actual motions of the Carriage. Two servo-error signals are shown in this figure, both measured on the "Arizona" flatbed printer: one signal is obtained when the feedforward law (Equation 12) is not applied and another one when it is actually used for motion control of the Carriage.

Apparently, the servo errors are much lower when the feedforward control is applied. Similar servo-control performance improvements are achieved using the feedforward motion control laws for the Gantry $X$- and $\varphi$-servo loops. That is the ultimate verification of the correctness of the physical model of the feedforward controller, as well as of the accuracy of automatic model-based tuning of the feedforward parameter vector $\hat{\mathbf{p}}$.

## Conclusion

While assisting Océ-Technologies to achieve challenging requirements on the printing speed, accuracy, robustness against flexibilities in the printer mechanics, and insensitivity to environmental disturbances, Segula utilises a systematic mechatronics approach which incorporates different model-based design and analysis techniques, including CAD, FEM, servo-control simulations, system identification, loop-shaping control design, and model-based feedforward control. Benefits of that framework have been demonstrated by various model-based simulation and measurement results that facilitate realisation of "first time right" flatbed printer designs and mitigate risks for failure costs after physical realisation of these printers or their parts.

The described framework is generically applicable to diverse mechatronics domains, including lithographic machines, robots, electron microscopes, X-ray and MRI scanners, automotive systems, etc. ■


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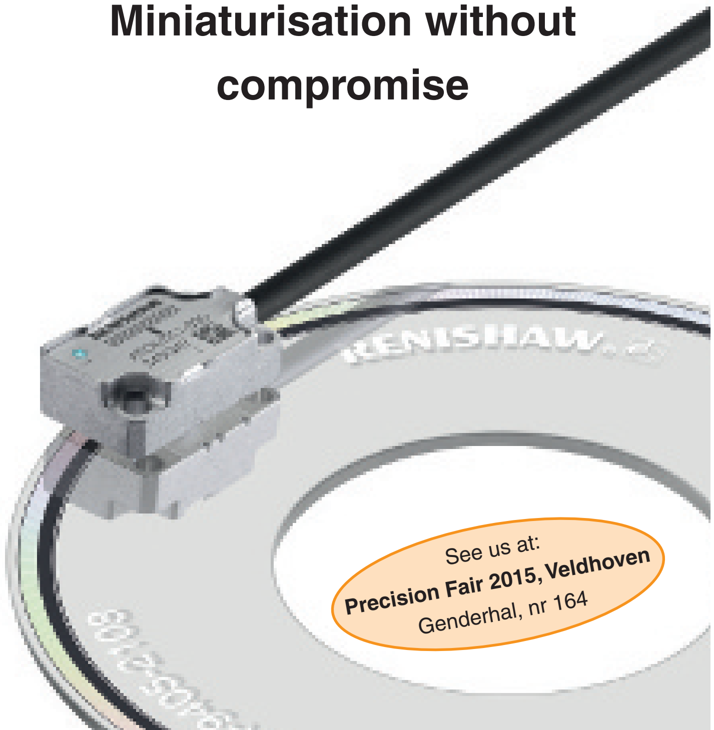


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# MINIATURISATION, VOLUME PRODUCTION AND HIGH QUALITY

**Miniaturisation is driving innovation in the medical device sector, where demand for minimally invasive diagnostic and treatment devices is growing exponentially. Very often these smaller and smaller devices are becoming more and more complex. When it comes to the manufacture of metal precision medical devices, the role of photo-etching is increasing. In fact, often it is the only process that can achieve the results demanded for extreme and safety-critical applications.**

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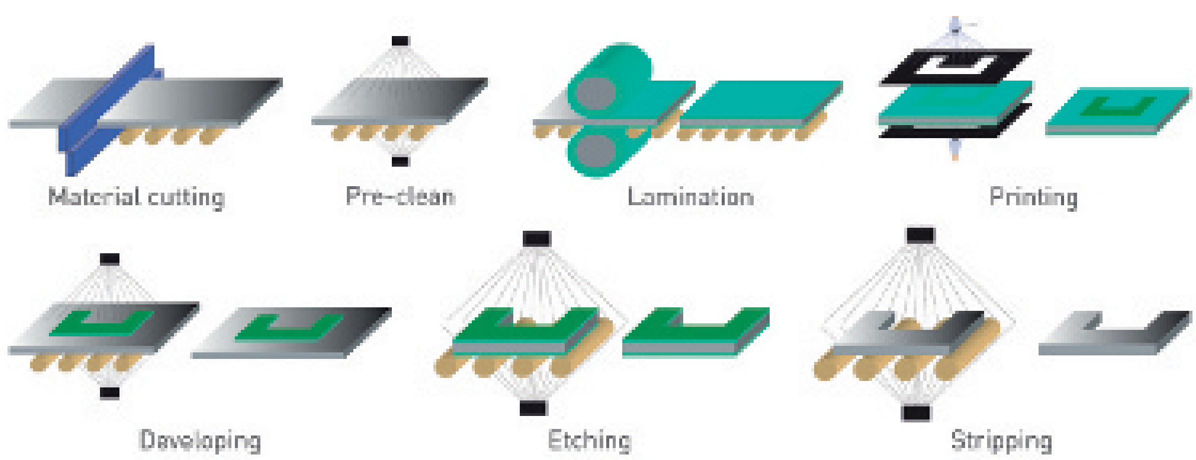
ALBERT TSANG

In the medical device sector, OEMs are constantly searching for new and innovative solutions, key market drivers being the efficient and cost-effective volume production of ever smaller devices, while at the same time ensuring compliance with an array of quality standards.

The usual advantages of making smaller parts (such as reduced material usage, reduced weight, and reduced cost) are exacerbated by the requirement for less invasive treatments. In addition, the opportunities for diagnosis and treatment that are available if functioning devices can be swallowed, ingested, or inserted in the body are huge, and constantly stimulate innovation in the micro-manufacturing field.

## Choice of process

When it comes to metal parts and components, an increasing number of medical device OEMs are assessing and embracing the use of photo-etching as the manufacturing process of choice [1] [2]. Photo-etching is a versatile and increasingly sophisticated metal machining technology, with an ability to mass manufacture complex and feature-rich metal parts and components. The process uses photo-resist and etchants to chemically machine selected areas accurately, and is characterised by retention of




1 *Schematic of the photo-etching process.*

material properties, burr-free and stress-free parts with clean profiles, and no heat-affected zones (see Figure 1).

Coupled with the fact that photo-etching uses easily re-iterated and low-cost digital tooling, it provides a cost-effective, highly accurate, and speedy manufacturing alternative to traditional machining technologies such as metal stamping, pressing, CNC punching, and laser and water-jet cutting.

Traditional machining technologies can produce less than perfect effects in metal at the cut line, often deforming the material being worked, and leaving burrs, heat-affected zones, and recast layers. In addition, they struggle to meet the detail resolution required. If OEMs require runs up to a few million, and precision is key, then photo-etching with its lower tooling costs is often by far the most economic and accurate process available.

Another factor to consider in process selection is the thickness of the material to be worked. Traditional processes tend to struggle when applied to the working of thin metals, stamping and punching being inappropriate in many instances, and laser and water cutting causing disproportionate and unacceptable degrees of heat distortion and material shredding, respectively. While photo-etching can be used on a variety of metal thicknesses, one key attribute is that it can work on ultra-thin sheet metal, down to 10-micron foil.

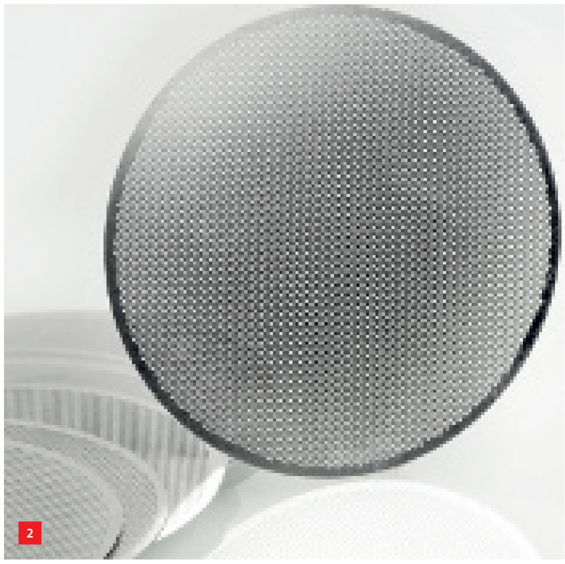
It is in the manufacture of complex and feature-rich precision parts that photo-etching really finds its perfect application. The nature of the process means that feature complexity is not an issue, and in many instances, photo-etching is the only manufacturing process that can accommodate certain part geometries.

Active in the field for many decades, Precision Micro is constantly pushing the boundaries of what is possible in the process, making advances in etchant chemistry, and developing the process to embrace more and more metals, and enhance accuracy. Therefore, many medical device OEMs partner with Precision Micro in the manufacture of often complex and safety-critical products.

## Medical device case studies

### *Micro-filters*

When applied to the manufacture of customised meshes and filters (Figure 2), photo-etching is characterised by a number of process advantages. Lead times are reduced, as are contingent costs, because tooling set-up and iterations (which are often necessary) are quick and relatively simple.

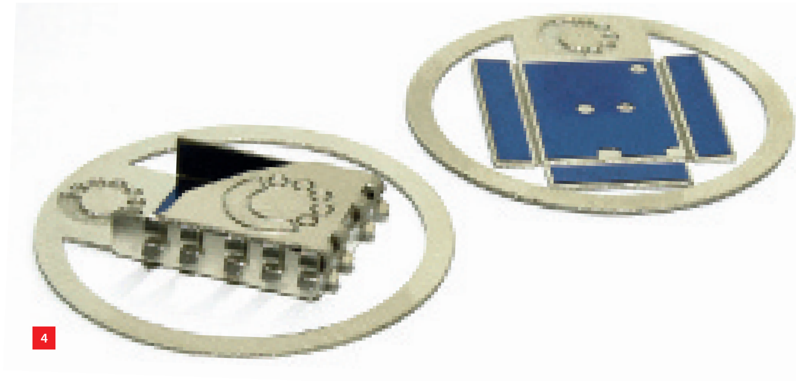


2 *For the manufacture of customised meshes and filters photo-etching offers a number of process advantages.*

Being digital, the tooling for photochemical etching can be manipulated on screen with ease and take a matter of hours rather than the days or weeks as with traditional processes.

Also, special features and various aperture shapes can be incorporated in a single mesh without any cost penalty. Using the photo-etching process, etched meshes up to 1,500 mm by 600 mm can be can incorporated and a wide range of materials can be processed. Varying bar sizes and open-area ratios can be incorporated to control flow rates across the mesh, and the photochemical etching process allows for far greater open areas than is possible using alternative processing technologies due to its ability to produce tiny and intricate wire sizes.
When compared with meshes that are woven, the single-part meshes and grids that are produced via photo-etching are characterised by their consistent cross-sectional thickness and accuracy of aperture shapes and sizes. Also, as they are manufactured from a single piece of metal, they are slimmer, have greater integrity, are robust when being handled, and they exhibit better electrical properties with no risk of poor contacts at the weave intersect. Custom borders can be added for additional strength.

A medical device OEM had a blood filtration product that was frustrated by using a hugely expensive, time-consuming, and — due to the production of burrs on the underside of the component — inefficient and ineffective laser fabrication process. The job for Precision Micro was to pierce a 78 mm diameter, 50 µm thick stainless steel disc with over 130,000 apertures, each being 100 µm in diameter on a staggered pitch of 200 µm with a maximum allowable tolerance of ± 10 µm against a standard tolerance for photochemical etching of ± 25 µm.



3 *Combination of the Laser Evolved Etch Process with advanced wire-erosion techniques improves the quality of medical saw blades.*

4 *A screening can that sits in a pacemaker. On the right a component of the can pre-assembly; the blue represents the dielectric coating. See text for further explanation.*

As the photochemical etching process (unlike the previously used laser process) allowed for the etching of all holes simultaneously, the micro-filters were produced – burr- and stress-free – in a fraction of the time and therefore afforded the OEM a cost-effective route to mass production.

### *Medical saw blades*

A new process route has been developed in partnership with a leading medical device OEM that reduces the cost of many precision sharp parts including sagittal/oscillating orthopeadic saw blades. Traditionally, such sharp-toothed blades have been manufactured using laser technology followed by precision grinding in order to achieve the required tooth off-set. A combination of Precision Micro's Laser Evolved Etch Process with advanced wire-erosion techniques has improved part quality in a more economic and efficient manner (Figure 3).

Tooth off-set and blade topography are achieved using the depth-etch technique with dissimilar patterns on each side of the blade. An etch resist is applied to both surfaces and a pattern is exposed on each side simultaneously using Laser Direct Imaging. This guarantees top/bottom pattern alignment. The exposed plate is then developed, revealing the metal to be etched away. The depth-etch process erodes the metal from both sides simultaneously, generating the required topography but leaving the blade securely within the overall metal sheet.

Depending on the part and the material type, photo-etching can become a little uneconomical above 1.5 mm thicknesses due to the amount of time involved in the chemistry. Because of this, Precision Micro profiled the blades using Advanced Wire-EDM. Even though it meant a second operation, it was a far more cost-effective solution.

Sheets are stacked and machined to produce hundreds of blades in a single cycle. The process can achieve tolerances of < ± 5 μm that cannot be achieved using other metal cutting techniques. The Advanced Wire-EDM process is able to generate parallel sidewalls with accuracy more than sufficient to create the ultra-sharp tooth profile required.

The blades are manufactured from a hardened, Sandvik martensitic stainless steel, characterised by its very good corrosion resistance, high toughness, and excellent fatigue strength. The process is at ambient temperature, so the blades are not subject to thermal stress, and all the original material properties are maintained.

### *Implantable screening cans for pacemakers*

Precision Micro has developed its own dielectric coating process for the inside of shielding cans where the possibility of arcing exists between circuitry and the grounded shielding can, which is especially useful for medical device OEMs involved in the manufacture of active electronic medical devices. Arcing can occur as a result of turn-on spikes or surges (electromagnetic pulses) caused by external stimuli, and can obviously be very damaging to such electronic medical devices.

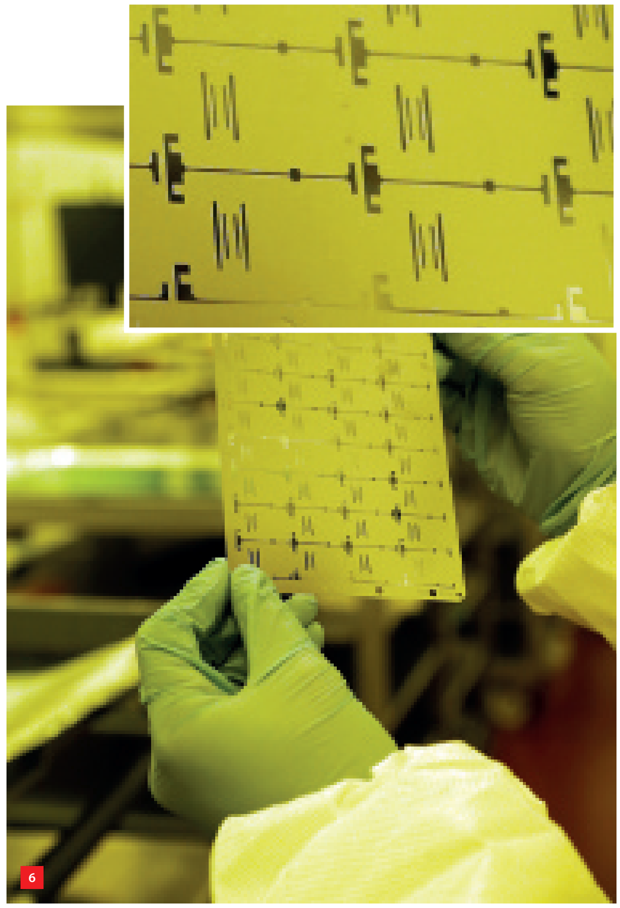
In one case, the dielectric coating process was applied to the small screening can that sits in a pacemaker to stop electromagnetic/radio-frquency interference (Figure 4). The insulative coating can be applied selectively to inside surfaces of the shielding can considered most susceptible to arcing, enabling cans to be designed to fit in with reduced profile requirements.

The ability to reduce the overall height of a can helps to meet the miniaturisation requirements of modern electronics assemblies and can also improve attenuation by minimising the linear dimension of apertures which in broad terms governs the efficiency of the shielding can.

Branded 'MicroSafe', this exceptionally even coating is pinhole-free and has no detrimental effect on the shielding efficiency of the formed can. Adhesion to the substrate metal (usually nickel silver) is excellent, and the upper operational temperature is claimed to be in excess of 260 °C.

### *Flat springs for a hearing aid application*

For the manufacture of flat springs used in a hearing aid application, material performance and integrity were critical. The diaphragm needed to flex absolutely precisely over and



5 *Photo-etched flat springs for a hearing aid application.*
6 *Photo-etching is the manufacturing process of choice for the biosensors of Highland Biosciences; the inset shows a close-up of the biosensors.*

over again, and so competing machining processes such as stamping, pressing, and punching – which induce either compressive, tensile, or shear stresses in the metal being processed – struggled to produce consistent quality parts.

In addition, the extremely thin nature of the springs – ranging as they do from 38 to 100 μm – coupled with their small overall size (4 mm x 8 mm), introduced other manufacturing challenges. It was vital that these parts exhibited clean profiles, which was achievable through the photo-etching process, and parts that were burr-free.

The thin flat springs used in the hearing aid had to be produced with extremely low tolerances. To accommodate the fine tolerance of ± 25 μm, various tooling iterations were required, which was possible to do cost-effectively and quickly with the photo-etching process as the tooling is digital.

### *Biosensors*

Highland Biosciences (Duncanston, UK), creator of leading-edge diagnostics technologies, partnered with Precision Micro to develop and manufacture a miniaturised 'tuning fork' biosensor. The component forms an essential part of a microviscometer, which has the potential to improve the safety of a number of medical procedures by providing results conveniently at the point of need.

The biosensor design consists of three micro-engineered stainless steel tines, which resonate thousands of times a second, detecting microscopic changes in film thickness, density, and viscosity of a liquid sample, and converting the presence of bacterial toxins into an electronic signal (see Figure 6).
With a tight innovation cycle needed, and a reliance on the material properties being unaffected during manufacture, both stamping and laser cutting were ruled out as viable methods of both prototype and production parts.

Instead, photo-etching was chosen using tightly controlled chemistry to selectively remove metal with micron accuracy, imparting no stress or burr on the base material. As every biosensor produced required a perfectly clean surface to ensure consistent adhesion of the surface coating, a dedicated post-process cleaning operation was developed, supported by 100% automated optical inspection.

## Conclusion

Throughout history, medical advances have been made due to technological innovation, and in effect, photo-etching is just another technological innovation that enables the design, manufacture, and clinical use of groundbreaking medical devices. Not only will the technology allow for the manufacture of complex precision devices, but in many instances it is the only metal processing technology that can cost-effectively and repeatably manufacture mass-produced parts to the standards necessary in many medical applications. ■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# **CPE** COURSE CALENDAR

| **COURSE** (content partner) | CPE points | Provider | Starting date (location, if not Eindhoven) |
|---|---|---|---|
| **BASIC** | | | |
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| Design Principles | 3 | MC | 9 March 2016 |
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| Thermal Effects in Mechatronic Systems (MA) | 3 | HTI | to be planned |
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| Applied Optics (T2Prof) | 6.5 | HTI | to be planned |
| Applied Optics | 6.5 | MC | 3 March 2016 |
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| Electronics for Non-Electronic Engineers – Basics Digital Electronics (T2Prof) | 3.5 | HTI | 5 September 2016 |
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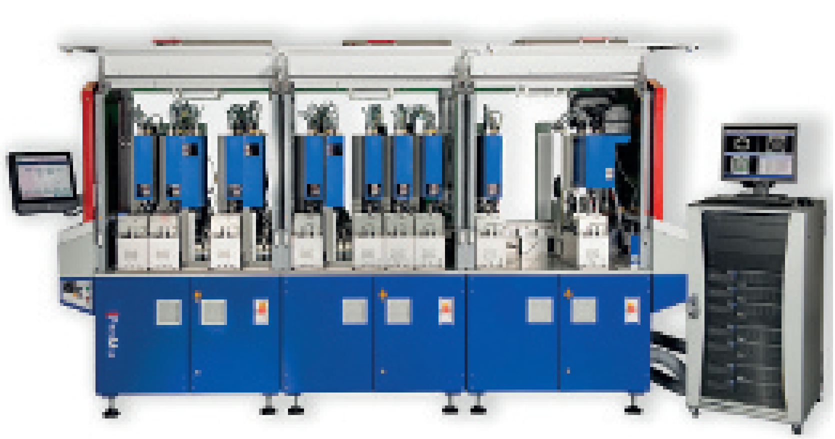
# DESIGNING A COMPLEX, COMPACT, FAST AND LIGHTWEIGHT TRAY HANDLER

**For the value engineering of a tray handler to be integrated in its ProMu generic production platform, IMS collaborated with KMWE, a specialist in high-tech machining, assembly and engineering/development. The challenge was to reduce the cycle time for component placement, to make the module lightweight and to integrate the previously external tray handler within the clean ProMu environment. After a steep learning curve, a series of ProMu production lines equipped with the latest generation of tray handlers is now being shipped to China.**

**EDITORIAL NOTE**

This article was based on an interview with Ilse Buter, Marketing Manager at IMS, Ben Schrijver, Competence Manager at IMS, and Peter Veldkamp, Account Manager at KMWE.

The ProMu is one of the generic production platforms of IMS. It was designed for the rapidly evolving market of smart devices and components, which demands for fast (cycle times in the order of seconds), flexible and highly accurate production of smart device components. The ProMu can be equipped with its own clean environment, so a cleanroom is not required. The ProMu is especially suitable for production of very small-sized products, such as components for hearing aids and components for mobile phones, such as loudspeakers and camera modules.

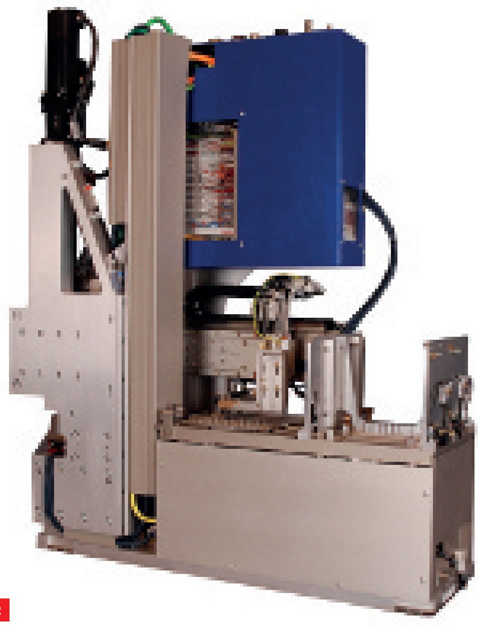


1 *A production line with three ProMu platforms, incorporating eight component supply units with one tray handler each, as well as other supply and output units, also with tray handlers. On the right is the line's control unit, featuring data tracking and storage.*

Typically, a production line for a complex device consists of one or more ProMu platforms in a serial line-up, each performing a number of process steps in producing and assembling a device (Figure 1). This may involve up to ten or even more different components, for each of which a programmable component supply unit, including a tray handler, is incorporated in the platform.

## Value engineering

Previous generations of IMS production platforms are equipped with external tray handlers ('external' meaning attached to the platform, but positioned outside its footprint). In 2010, IMS engaged KMWE for the first time in a value engineering project on the tray handler. The number of components as well as the complexity of the movements of submodules (tray stackers and destackers) were reduced, the control hardware was integrated within



2 *The complete module for component supply, including the tray handler. The blue box is the control cabinet for the complete (IMS) module; the (KMWE) tray handler controls are integrated in the grey box (bottom right).*

the tray handler frame and cheaper alternatives for purchase parts were selected. These modifications reduced assembly and testing time and achieved a cost reduction of 40%.

## Redesign

In 2013, IMS started a full redesign project. The tray handler was to be integrated within the CleanAir environment of the ProMu, which put strict constraints on the dimensions of the module, and its cycle time was to fit within the total of 1 sec cycle time specified for the ProMu. Within this very short time span, component placement had to be performed faultlessly and accurately. Naturally, reducing cost and decreasing assembly time were again on the wish list.

## Set-up

A tray handler can contain up to 20 trays, each with 99 component positions, for prolonged uninterrupted operation. Trays are loaded and unloaded by hand. The tray handler comprises:

- storage sites for filled and empty component trays (see Figure 2),
- a conveyor (with an index drive that makes sure that the next component can always be picked up at the same position),
- a placement arm (a linear motor with a component-specific (vacuum) pick-up head).

## Lightweight

One of the design challenges was to make the tray handler lightweight. Its total mass should not exceed 20 kg because of limitations on the maximum load of the full ProMu system on a cleanroom floor. Therefore, the tray handler is made out of aluminium and smart construction principles were applied to minimise the amount of material required

# Partners

**KMWE**

Headquartered in Eindhoven, the Netherlands, KMWE is specialised in the high-mix, low-volume, high-complexity machining of functional critical components and the (cleanroom) assembly and engineering of fully tested mechatronic systems for the aerospace & defence, semiconductor, medical & diagnostics and industrial automation markets. With sixty years of experience, an international supplier network and over 550 employees, KMWE now is a global player with offices and partnerships in the Netherlands, Malaysia, India and Turkey.

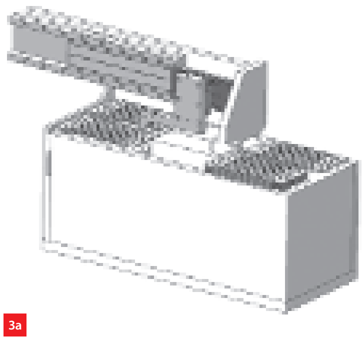
The capabilities of KMWE include machining (high-speed machining, high-performance machining, super-alloys), sheet metal fabrication, thermal spraying, assembly (of complex mechatronic systems, in a clean(room) environment), engineering and additive manufacturing

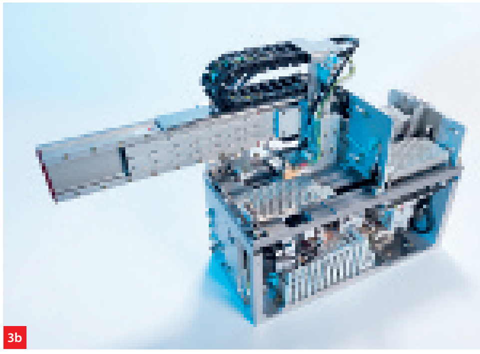
**IMS**

Based in Almelo, the Netherlands, IMS specialises in turnkey production lines for small, complex products in the personal electronics, medical and automotive markets. The size of the products lies in the micrometer range and typical products are sensors, actuators and connectors. IMS (Integrated Mechanization Solutions) started as the internal mechanisation department of the Almelo branch of Texas Instruments and became an independent company in 1999. Now, IMS is a member of the WWINN Group, dedicated to enhancing customers' production capabilities with advanced production equipment, consultancy and service.

IMS focusses on the development and supply of production lines. Within IMS there is a research group dedicated to improving the feasibility of products and processes through scientific analysis, test set-ups and prototyping (DfA & DfM). For production automation IMS uses various standard production platforms with interchangeable production modules, ranging from platforms for semi-automatic production to fully automatic high-speed production.

WWW.KMWE.COM WWW.IMS-NL.COM





3 *Design of the tray handler showing the base frame that contains the storage sites for the trays and the linear motor for component placement.*
*a Schematic layout.*
*b Realisation.*

4 *The production cell at KMWE, with a DMU Evo milling machine on both sides of the robot. The robot is loading the material and will store the finished products in the centre of the cell.*

5 *The dovetail clamping method.*

to achieve a stable and stiff construction. On the other hand, to limit machining time (and cost), care was taken in the design that minimum material content would not equal maximum material removal.

## Precision

The design of the tray handler is shown in Figure 3. The relative position accuracy of the linear motor used for component placement is 0.5 μm. The specification for the accuracy of the complete tray-handling system is 100 μm. The ProMu platform provides for a basic assembly accuracy better than 10 μm, and optionally an accuracy down to 1 μm (3σ) can be achieved. This requires the highest degree of suppressing vibration transfer from the platform to the positioning unit. Other design challenges include the prevention of electrostatic discharge and the product-specific tooling for component pick-up and placement. Only minimal contact faces between component and pick-up head are allowed, to prevent damaging the component.

## Production

A crucial element of the production procedure is the machining of the base frame of the tray handler. The box acts as the reference for component placement, so it has to fit precisely to the ProMu platform. This requires the highest degrees of flatness of the bottom of the box. A correct sequence of machining operations is essential to prevent the introduction of stresses in the material. At KMWE, the base frame is manufactured in a production cell with a DMU Evo 70 milling machine (Figure 4), which is loaded and unloaded by a robot in 24/7 operation. The Evo 70 is suited for batch sizes of 10-20 for products with dimensions like those of the base frame.
A highly efficient dovetail clamping method (patented by KMWE) enables 5-axis machining in one set-up (Figure 5).

## Close collaboration

During the tray-handler project, IMS and KMWE engaged in a close collaboration that went beyond the classic OEM-supplier relationship on a build-to-print basis. Here, IMS provided the specifications (technical and budget) and the concept design and KMWE was in charge of the design, drawing upon its competence in handling technology.

KMWE's activities included producing functional models, detail engineering, prototyping and testing, manufacturing and plug & play delivery, while the final commissioning was a shared responsibility. There was a steep learning curve regarding the design and its manufacturability, with the partners sharing their creativity and KMWE engineers learning a lot about conceptual design.

Risk sharing was part of the deal, based on mutual commitment and open communication. After a first order with a number of platforms being delivered to the customer, there was a long period of uncertainty about a follow-up. However, KMWE stayed in touch with IMS and continued to work on optimisation of the design. So when the follow-up order was received, early this year, only minimal engineering was required before KMWE could start production of the next series of tray handlers.

## Accelerating

A large number of ProMu platforms, incorporating the tray handler, is now being shipped to a Chinese customer. IMS and KMWE continue to collaborate on innovating and manufacturing the tray handler for new ProMu orders from other customers and for new IMS production platforms which are even more flexible to enable device manufacturers to follow accelerating market developments. ■

# MICROMACHINING: THE POWER OF LIGHT

**The continuous development of lasers, beam manipulation systems and high-precision workstations has increased the possibilities of material processing with lasers. Next to the semiconductor market, other markets are discovering the benefits of using the unique processing capabilities of lasers. Especially for the fine-mechanical sector the use of ultrashort-pulse lasers, such as high-accuracy femtosecond lasers, has opened new possibilities in manufacturing high-precision parts.**

**EDITORIAL NOTE**

This article was contributed by Reith Laser.

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In 1988, Reith Laser was one of the first in the Netherlands to start a laser machining workshop. Over the years, it has grown to become a leading company in precision laser machining for industrial applications. Reith continues to explore the possibilities of laser micromachining, for various applications, including micro-structuring of surfaces and machining of metal foils.

Based in Wijchen, near Nijmegen, the Netherlands, Reith Laser counts over forty employees and covers five laser application areas: welding, cutting, drilling, marking and micromachining. Many products involve the combination of various laser processes and the assembly of machined parts. A wide range of industries is being served, from medical and aerospace to semicon, tool making and machine building. The customer base is centred around the high-tech Eindhoven region in the Netherlands, and extends into Belgium and Germany.


1 *ISO class-7 cleanroom laser production facility.*

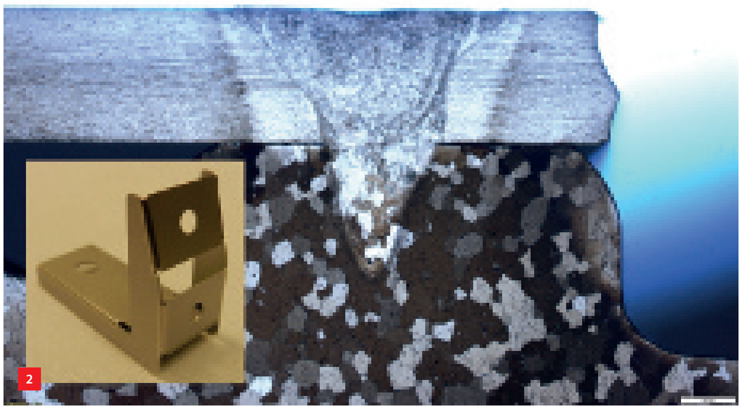
## The Swiss Connection

In 2011, Reith Laser established a Swiss sister company, Class 4 Laser Professionals, specialised in industrial laser applications (micro-cutting of metal, crystal and ceramic products; drilling of high-aspect-ratio holes; welding of challenging materials) and training. Reith profiles its sister company also as a second source (back-up) for customers.

WWW.CLASS4LASER.CH

## Facilities

Currently, Reith Laser has twenty-three different laser systems, many of them with four- to six-axis manipulators for the laser heads allowing 3D machining of products. Reith offers series production as well as prototyping and research (related to specific jobs), covering projects from engineering to manufacturing and testing. Additional facilities include an ISO class-7 cleanroom (Figure 1) for machining and assembly of high-tech semicon and medical products; cleaning (degreasing) equipment; leak testing



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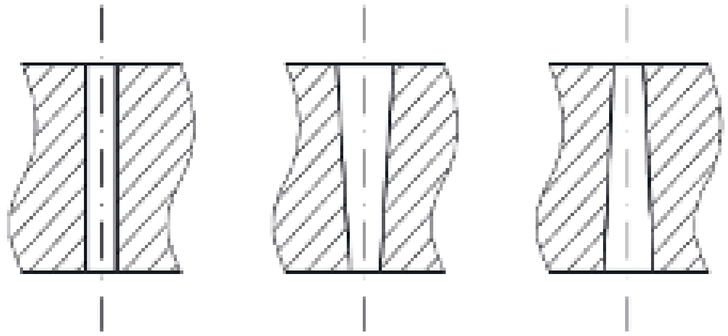

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equipment for vacuum applications; a metallurgical laboratory for inspecting laser welds by making cross-sections (Figure 2); and a conditioned measuring room for 2D and 3D checking of dimensions and flatness of machined products.

After obtaining both ISO 9001 and 13485 (general and medical, respectively) quality certificates, Reith now is focusing on DPM-62 certification, regarding operator (re-)qualification for the aerospace industry.

## Micromachining

Since 2008, Reith is using picosecond lasers for fine-mechanical ablation, cutting, marking and micro hole drilling. A short laser pulse time leads to less heat input into the product, hence the name 'cold ablation'. Less heat input results in less distortion.

Market demand is for smaller products with even higher accuracy. The use of ultrashort-pulse laser technology is necessary to meet the next-level specifications. Femtosecond ($10^{-15}$ s) laser technology in combination with rotating beam steering tools opens up a new application area for the laser as a high-end production tool.

**2** *Cross-section of a micro laser weld of dissimilar metals.*

**3** *Different hole designs when applying trepanning technology in combination with rotating beam optics.*

**4** *SEM-pictures of laser-drilled holes.*
*(a) Straight design.*
*(b) Conical design.*
*(c) Square hole.*

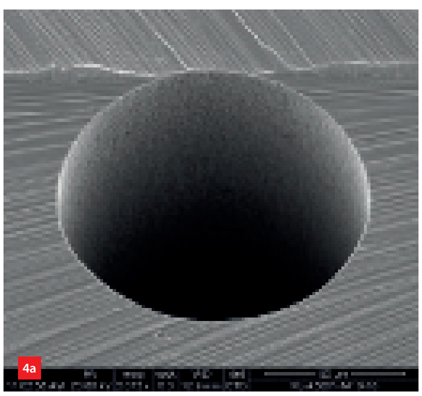
## Freedom of shape

The use of special drilling optics leads to great freedom of shape. An example is trepanning, a drilling technique in which an orbital movement is applied to the laser beam for core-drilling a part (Figure 3). Different drilling strategies can offer free selection of taper (cylindrical/positive/negative). Drilling different hole configurations (Figure 4) within one part is also possible.

Burr-free holes, with roundness tolerances within 1%, drilled under a contact angle up to 45°, can be made in the same process. With no tool wear the reproducibility is very high. The accuracy of laser-drilled high-aspect-ratio holes also sets higher requirements to measuring equipment and techniques.

## Applications

The extended drilling techniques offer new opportunities for instance in the production of spray nozzles for the printing industry, improved gas regulation in automotive parts or downscaling tolerances in mass-flow controllers in the chemical industry. Next to micro-drilling, the femtosecond laser can also be used for micro-cutting applications. Typical examples are surgical tools such as electrodes for deep brain stimulation or vascular micro-stents. ■



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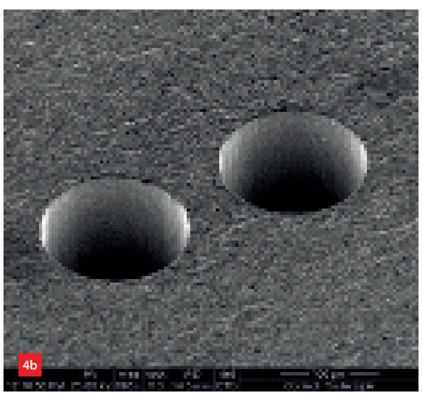

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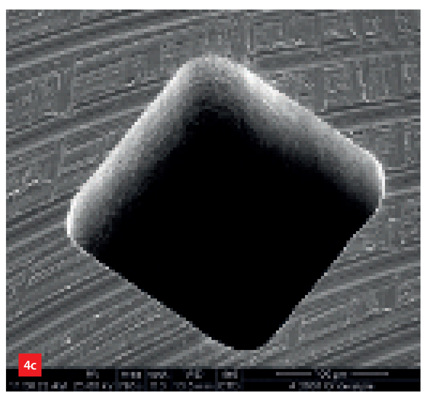


4c

# Ertec – offering SMEs efficiency in precision component production

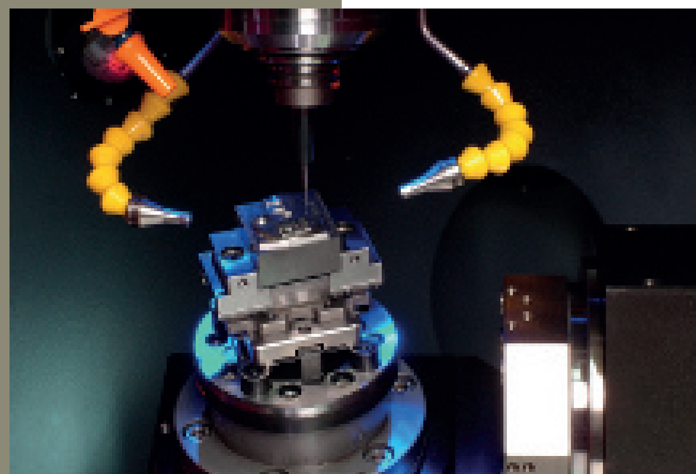
**Ertec supports metalworking manufacturers and suppliers with advice, software and hardware for enhancing efficiency and accuracy of their production, particularly by means of automation. Based on many years of experience Ertec develops solutions in cooperation with leading suppliers to increase the competitiveness of its customers.**

A balanced combination of machine, tools and clamping technology provides the accuracy that metalworking manufacturers and suppliers increasingly require. As a representative of System 3R, Ertec, based in Nuenen, the Netherlands, offers a complete gamut of reference systems for the clamping of precision components. As production trends towards higher precision, Ertec is fully prepared to meet the demand for sophisticated reference systems.

Take the Matrix chuck (Figure 1), a new generation specially developed for heavy machining, when speed and precision are crucial, applied for instance in the production of lenses in one setting. Its repeatability is 0.002 mm. And an even more impressive example is MacroNano, the series for quick clamping of workpieces with 'nanoprecision' (Figure 2). This clamping system links the production chain through an ultra-precision coupling for both workpiece and tool holding. Repetition accuracy stays within 0.001 mm.

1 *The Matrix chuck.*

In close cooperation with the client, Ertec also designs and builds automation systems for the production of small to medium-sized series based on robots for workpiece loading. Such a system may consist of two machining centres, a handling robot and a pallet warehouse for the workpieces, based on a System 3R reference system. Ertec is a representative of Liebherr, a specialist in the automation of workpiece handling at machining centres and other machine tools. Being a total solution supplier, Ertec also regards software for control of 24/7 production cells, as well as for planning and organisation, as one of its key competencies.



2 *MacroNano clamping system on a Kern Nano machining centre.*

Efficiency is the thread that runs through the Ertec programme, for example by supporting the production process on the cutting and checking level with special tools for slotting and shaping, engraving and deburring. Ertec also offers the complete programme of concentricity gauges from Spreitzer. These gauges are used for inspection tasks on external, internal and flat faces on rotating parts, such as determining the concentricity of two or more diameters or measuring axial run-out. The true running accuracy of a workpiece is 0.002 mm.

For many years Ertec has been a partner of SMEs, manufacturers and main suppliers specialised in the production of precision components for high-tech industries such as automotive, aerospace, semiconductor and medical. In all cases Ertec can provide the means to make production more automated, more efficient and more precise. ■

**INFORMATION**
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# Obituary: Jim Bryan

On June 28th 2015, Jim Bryan, a pioneer in the precision engineering sector, passed away. James Bevan Bryan was born in 1926, and was a founding member of the American Society for Precision Engineering (ASPE).
He graduated with a degree in Industrial Engineering from the University of California, Berkeley in 1951 and went on to work with the Westinghouse Electrical Corporation, before starting work at the Lawrence Livermore National Laboratory in 1955 under the Nobel Laureate Ernest O. Lawrence. He stayed here for over thirty years, and in 1986 at the time of his retirement he was the Metrology Group Leader.

Jim Bryan was associated with – and received numerous awards from – an array of industry bodies, receiving for instance an ASPE Lifetime Achievement Award in 1991, and was also closely involved with the activities of euspen (European Society for Precision Engineering and Nanotechnology), receiving a euspen Lifetime Achievement Award in 2000 before becoming an Honorary Member in 2003.

Many associated with euspen either worked with or were touched by the huge impact that Jim had on the field of precision engineering, and indeed he was considered by many as the founder of what can be referred to as "modern precision engineering". His euspen award in 2000 was presented for "his tireless promotion of precision engineering philosophies, principles, innovations, practices, and standards through research and teaching." With his focus on metrology as applied to the precision engineering sector, his contributions were extensive and diverse.

Professor Pat McKeown, euspen Founding President, shares his thoughts. "Jim had boundless enthusiasm for precision engineering, pushing forward its frontiers by innovation, establishing rules, use of accurate vocabulary and nomenclature, advancing standards, and encouraging especially young people to succeed in the field." Another former euspen President, Professor Paul Shore reinforces the humour and passion with which Jim Bryan imparted his knowledge. "Jim made engineering fun! He was incredibly focused, and had a special aptitude of making the details of precision engineering clear but intriguing. It felt like he was putting his arm around you and pointing you in the right direction. I will miss him hugely!"

*(contributed by euspen)*

## Industry 4.0-ready

Anticipating trends such as Industry 4.0 and big data, IMS, based in Almelo, the Netherlands, has developed a production line which is more flexible than ever before: the Metis 4.0. Earlier this month, it was presented at the Motek trade fair for automation in production and assembly in Stuttgart, Germany. With the Metis 4.0, IMS aims to help companies develop and produce innovative, small products in Europe against lower investments.

The Metis 4.0 introduces a scalable production capacity, a programmable process sequence and a reconfigurable machine lay-out. It consists of a basic platform and process modules. By adding or removing platforms and process modules, the production line can easily be reconfigured for production of a different product or production volume. As a result, as many product types and units as needed can be fabricated on one production line. The investment in this platform adjusts to the production requirements. IMS collaborates with sister company ESPS for the application of robotic systems in this concept.

Read also the article on page 51 ff.

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FAULHABER

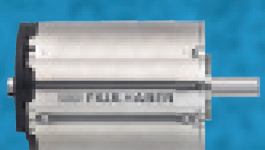
FAULHABER Applications

Light as air

FAULHABER Drive Systems are taking off in cabin equipment

More and more passengers appreciate it when they discover that comfort features previously reserved for the premium classes have found their way into economy. The seat, entertainment centre, window blind systems and more – the trend is towards individual electric control and operation. To ensure that the additional technology required for this does not result in an excessive increase in weight, drive solutions are needed that combine maximum performance and absolute reliability with minimum weight and compact design. This is why airlines all over the world have opted for FAULHABER's know-how and expertise.

www.faulhaber.com/cabin-equipment



WE CREATE MOTION



# Fully-automated and integrated cleaning step using $CO_2$ snow

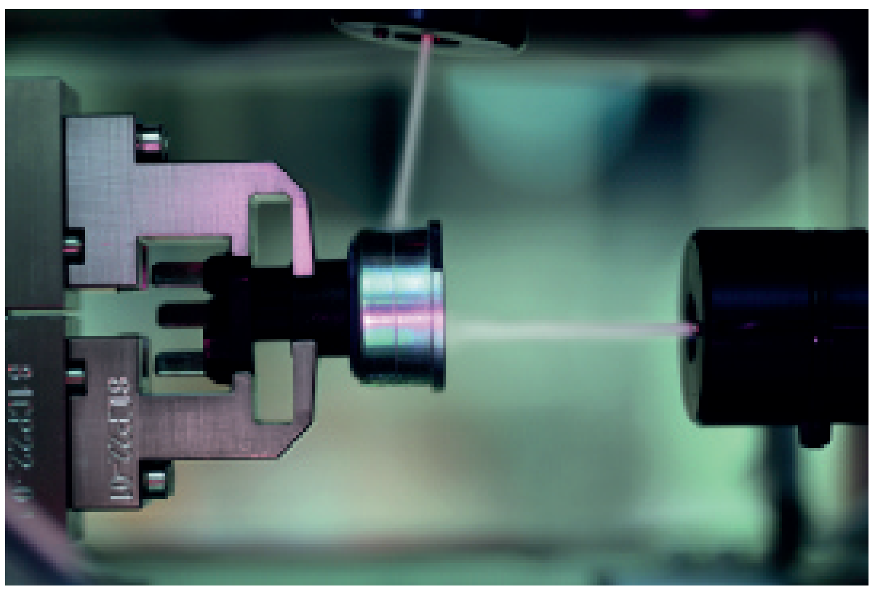
Assembly and joining processes, such as screwing, pressing or welding, generate unavoidable contamination. This can be avoided using an integrated precision-cleaning solution, such as the quattroClean system from acp. Featuring a minimum footprint and short cycle times, the system cleans components in a gentle manner in a dry, selective process.

The quattroClean snow-cleaning system from acp – advanced clean production GmbH, based in Ditzingen, Germany – reliably removes filmy and particulate contaminants in an assembly line's one-piece flow – even from delicate and finely-structured surfaces. The system uses a dry cleaning method and, depending on requirements, whole components or just specific areas thereof can be cleaned. The space-saving device can be integrated into an assembly or joining process and is easy to automate.

Liquid carbon dioxide is guided through the patented two-component ring nozzle and expands on exiting to form fine $CO_2$ crystals. This core jet is then bundled by a jacketed jet of compressed air and accelerated to supersonic speed. The easy-to-focus jet of snow and compressed air has a temperature of –78.5 °C as it exits the nozzle. On impacting on the surface to be cleaned, a combination of thermal, mechanical, sublimation and solvent effects occur. This ensures that not only particulate contaminations, such as chips, abrasion and tiny flaky burrs are reliably removed, but also filmy contaminations, for example residues of lubricants and pastes, smoke traces from laser-welding processes and flux residues from soldering steps.

Consequently, the system can clean off contaminants that compressed air would be unable to remove. The aerodynamic force of the jet of snow and compressed air also ensures that detached contaminant particles are transported away from the component and sucked into the system's work chamber. The crystalline carbon dioxide converts fully to gas during the cleaning step, meaning that the cleaned component is dry straight away.

WWW.ACP-MICRON.COM



*Fitted with two nozzles, the quattroClean system simultaneously cleans the inner and outer surfaces of a product in an inline assembly process.*

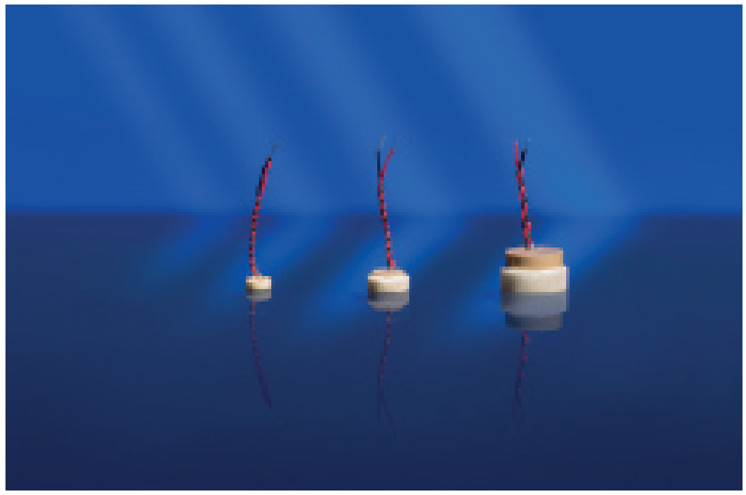
# Piezoceramic discs at the 'heart' of ultrasonic sensors

Transducers are always the most important components in an ultrasonic sensor. As transmitters, they convert electrical signals into ultrasound; and as receivers, they convert the very low pressure fluctuations of ultrasound in the air to electrical signals. Piezoceramic discs, which act as the 'heart' of the transducer, therefore play a key role.

SECO Sensor Consult with headquarters in Coburg, Germany, a specialist for ultrasonic transducers, has been developing and manufacturing piezo-based ultrasonic transducers for air and gas applications, which are used in various fields since 1996. Depending on the version, the transducers operate at frequencies of 60 kHz to 600 kHz, achieve ranges from 10 m down to 1 cm and at high resolutions in the millimeter range with repeatability rates of less than 10 ms. Possible applications include automation technology, printing machines, packaging technology and many other fields.

In ultrasonic transducers, the piezoceramic discs are glued to a specially adapted layer that transmits the sound energy effectively to the medium of air or gas. To achieve the best possible results, only proprietary adaptive material is used, consisting of a particularly light epoxide filled with hollow glass spheres. An electrical line soldered to the piezoceramic then completes this functional elementary oscillator. Normally, it is then fixed into cases using PU casting resin. This serves as protection for the mechanical system, reactionless holding and electrical shielding.

The piezoceramic used in the transducer must also meet high requirements. As key components, they also considerably influence the quality of the transducer and therefore the sensors. They are obtained from SECO's main supplier, PI Ceramic. They meet SECO's standards on quality and can be easily adapted to the respective application requirements because, in addition to the material selected for each application, it is possible to realise different geometric versions and resonant frequencies.



*In ultrasonic transducers, the piezoceramic discs are glued to a specially adapted layer that transmits the sound energy effectively to the medium of air or gas. (Photo courtesy of SECO, photographer: Christian Hesselbach)*

The piezos, 'Made in Germany', distinguish themselves also by their very strict tolerances of the relevant piezoelectric parameters (resonant frequency, electrical capacitance and coupling coefficients) for ultrasound performance. They also have very high surface cleanliness. This allows optimum, solid and at the same time, elastic bonding to the adapted layer.

WWW.SECO-SENSOR.DE

WWW.PI.WS


## MathWorks release

Last month, leading developer of mathematical computing software, MathWorks introduced Release 2015b with a range of new capabilities in MATLAB and Simulink. New features of the MATLAB programming environment include a new execution engine for faster code execution; hardware support for iOS sensors, Raspberry Pi 2, and BeagleBone Black; and functions for creating, analysing and visualising graphs. Updates of the Simulink graphical environment for simulation and model-based design include referenced projects for creating reusable components and simplifying large modeling projects; and design optimisation with faster parameter estimation and response optimisation.

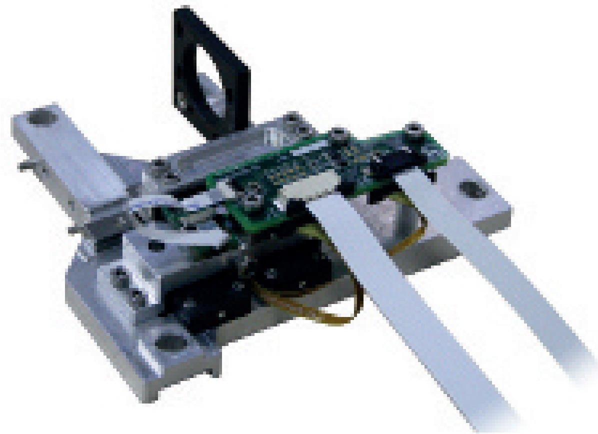
WWW.MATHWORKS.COM

# Single-axis linear focussing stage

A miniature autofocussing stage which can operate under flight conditions for shock and vibration with extreme temperature variation and intense orientation changes has been developed by the piezo-ceramic motor and systems manufacturer Nanomotion, based in Israel. The direct-drive piezo-ceramic motor technology is characterised by extreme accuracy and precise movement with high resolution and low settling times, coupled with extensive velocity and force dynamics.

The single-axis linear focussing stage and motion system directly drives an optronic device with a mass of around 25 to 35 g over 20 mm travel to within 2.5 µm accuracy, based on an encoder resolution of 0.25 µm. With shock to 40g and vibration to 12g, the stage, which features a preloaded bearing arrangement, achieves the high accelerations and fast settling times required to maintain focussing. The stage mechanics fit into a footprint of less than 65 x 45 mm$^2$ and weighs less than 50 g. Temperature extremes of –40 °C to +50 °C can be tolerated.

The piezo-ceramic motor used in the focussing stage is Nanomotion's Edge 4X, which provides 1.3 N of force with a maximum velocity of 200 mm/sec. Proven applications for Nanomotion's piezo-ceramic technology include non-uniformity correction (NUC) shutters and variable-aperture devices on aeronautical and military instruments as well autofocus stages for target acquisition and FLIR spectroscopy equipment.



The stage is available from Nanomotion's representative in the UK, motion control specialist Heason Technology.

WWW.NANOMOTION.COM

WWW.HEASON.COM


DSPE / EUSPEN SYMPOSIUM

Thursday 19 November, 2015 | 10:30 - 13:00 | Precision Fair, Veldhoven

POST GRADUATE EDUCATION IN PRECISION ENGINEERING
TODAY AND TOMORROW

MORE INFO
about the CPE program,
see PAGE 37
of this magazine

INVITATION for Precision Engineers, their managers and HR managers.

KICK OFF in the Netherlands of the DSPE/euspen launch of the European Certified Precision Engineering Course Program (ECP$^2$) leading to the European ECP$^2$ title.

SPEAKERS including David Billington (Executive Director, euspen), Jan Willem Martens (Chairman Certification Program, DSPE), Nikola Vasiljević (postdoc Technical University of Denmark, DTU Wind Energy, reached bronze level in the CPE Program (25 points)) and HR manager from ASML, sharing their view on post graduate development needs.

www.precisiebeurs.nl > Program Thursday 19 November

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## Development

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The LiS is a modern level 4 MBO school, with a long history (founded in 1901). The school encourages establishing projects in close cooperation with industry and scientific institutes, allowing for high level "real life" work. Under the name LiS-Engineering and LiS-Academy the school accepts contract work and organizes education for others.

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## Electrical Discharge Machining (EDM)

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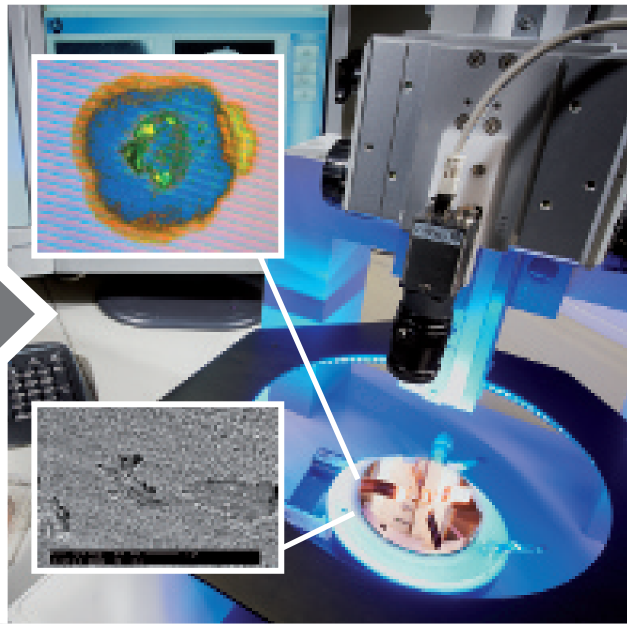

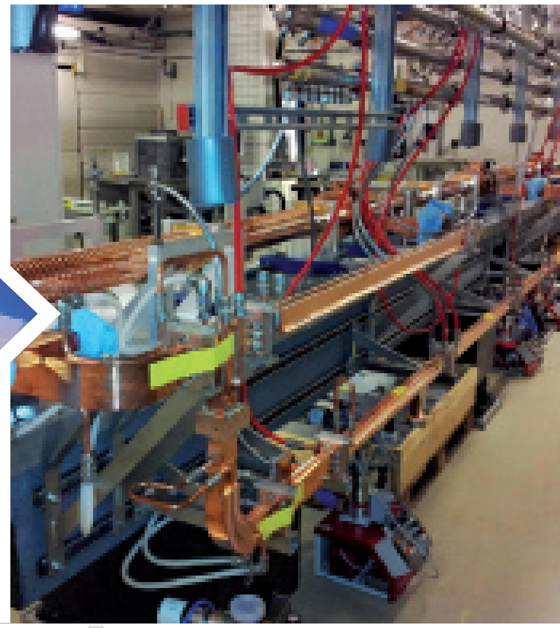

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